APPENDIX F

Draft Joint Technical Support Document

National Vehicle and Fuel Emissions Laboratory

Office of Transportation and Air Quality

U.S. Environmental Protection Agency

Office of International Policy, Fuel Economy,
and Consumer Programs

National Highway Traffic Safety Administration

U.S. Department of Transportation

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Draft Joint Technical Support Document:

Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards

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Executive Summary

The Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) are issuing a joint proposal to establish new standards for light-duty highway vehicles that will reduce greenhouse gas emissions and improve fuel economy. The joint proposed rulemaking is consistent with the Presidential Memorandum issued by President Obama on May 21, 2010, requesting that NHTSA and EPA develop through notice and comment rulemaking a coordinated National Program to reduce greenhouse gas emissions and improve the fuel economy of light-duty vehicles for model years 2017-2025. This proposal, consistent with the President's request, responds to the country's critical need to address global climate change and to reduce oil consumption**.** . EPA is proposing greenhouse gas emissions standards under the Clean Air Act, and NHTSA is proposing Corporate Average Fuel Economy standards under the Energy Policy and Conservation Act, as amended. These standards apply to passenger cars, light-duty trucks, and medium-duty passenger vehicles, covering model years 2017 through 2025. They require these vehicles to meet an estimated combined average emissions level of 163 grams of CO_2 per mile in MY 2025 under EPA's GHG program, and 49.6 mpg in MY 2025 under NHTSA's CAFE program and represent a harmonized and consistent national program (National Program). These standards are designed such that compliance can be achieved with a single national vehicle fleet whose emissions and fuel economy performance improves each year from MY2017 to 2025. This document describes the supporting technical analysis for areas of these jointly proposed rules which are consistent between the two agencies.

NHTSA and EPA have coordinated closely to create a nationwide joint fuel economy and GHG program based on consistent compliance structures and technical assumptions. To the extent permitted under each Agency's statutes, NHTSA and EPA have incorporated the same compliance flexibilities, such as averaging, banking, and trading of credits, off-cycle credits, and the same testing protocol for determining the agencies' respective fleet-wide average proposed standards. In addition, the agencies have worked together to create a common baseline fleet and to harmonize most of the costs and benefit inputs used in the agencies' respective modeling processes for this joint proposed rule.

Chapter 1 of this Draft TSD provides an explanation of the agencies' methodology used to develop the baseline and reference case vehicle fleets, including the technology composition of these fleets, and how the agencies projected vehicle sales into the future. One of the fundamental features of this technical analysis is the development of these fleets, which are used by both agencies in their respective models. In order to determine technology costs associated with this joint rulemaking, it is necessary to consider the vehicle fleet absent a rulemaking as a "business as usual" comparison. In past CAFE rulemakings, NHTSA has used confidential product plans submitted by vehicle manufacturers to develop the reference case fleet. In responding to comments from these previous rulemakings that the agencies make these fleets available for public review, the agencies created a new methodology for creating baseline and reference fleets using data, the vast majority of which is publicly available.

Chapter 2 of this document discusses how NHTSA and EPA developed the mathematical functions which provide the bases for the proposed car and truck standards. NHTSA and EPA worked together closely to develop regulatory approaches that are fundamentally the same, and have chosen to use an attribute-based program structure based on the footprint attribute, similar to the mathematical functions used in the MYs 2012-2016 rule. The agencies revisited other attributes as candidates for the standard functions, but concluded that footprint remains the best option for balancing the numerous technical and social factors. However, the agencies did adjust the shape of the truck footprint curve, in comparison to the MYs 2012-2016 rule. The agencies also modified the way the car and truck curves change from year to year compared to the MYs 2012-2016 rule. In determining the shape of the footprint curve, the agencies considered factors such as the magnitudes of CO_2 reduction and fuel savings, how much that shape may incentivize manufacturers to comply in a manner which circumvents the overall goals of the joint program, whether the standards' stringencies are technically attainable, the utility of vehicles, and the mathematical flexibilities inherent to the statistical fitting of such a function.

Chapter 3 contains a detailed analysis of NHTSA and EPA's technology assumptions on which the proposed regulations were based. Because the majority of technologies that reduce GHG emissions and improve fuel economy are identical, it was crucial that NHTSA and EPA use common assumptions for values pertaining to technology availability, cost, and effectiveness. The agencies collaborated closely in determining which technologies would be considered in the rulemaking, how much these technologies would cost the manufacturers (directly) in the time frame of the proposed rules, how these costs will be adjusted for learning as well as for indirect cost multipliers, and how effective the technologies are at accomplishing the goals of improving fuel efficiency and GHG emissions.

Chapter 4 of this document provides a full description and analysis of the economic factors considered in this joint proposal. EPA and NHTSA harmonized many inputs capturing economic and social factors, such as the discount rates, fuel prices, social costs of carbon, the magnitude of the rebound effect, the value of refueling time, and the social cost of importing oil and fuel.

Chapter 5 of this draft TSD discusses proposed adjustments and credits to reflect technologies that improve air conditioner efficiency, that improve efficiency under other off-cycle driving conditions, and that reduce leakage of air conditioner refrigerants that contribute to global warming. The air conditioner credits are similar to the MYs 2012-2016 rule, with two notable exceptions: NHTSA is proposing to allow A/C efficiency improvements to help come into compliance with fuel economy standards, and a new air conditioner test procedure is introduced to help capture efficiency credits. NHTSA is now also allowing off-cycle improvements to help manufacturers come into compliance with fuel economy standards. A list of some technologies and their credits and a streamlined methodology is provided by the agencies to help simplify the credit generating process. Chapter 5 also discusses proposed adjustments to encourage "game changing" technologies (such as hybridized powertrains) for full-size pickup trucks.

Chapter 1: **The Baseline and Reference Vehicle Fleet**

The passenger cars and light trucks sold currently in the United States, and those which are anticipated to be sold in the MYs 2017-2025 timeframe, are highly varied and satisfy a wide range of consumer needs. From two-seater miniature cars to 11-seater passenger vans to large extended cab pickup trucks, American consumers have a great number of vehicle options to accommodate their needs and preferences. Recent volatility in oil prices and the state of the economy have demonstrated that consumer demand and choice of vehicles within this wide range can be sensitive to these factors. Although it is impossible to precisely predict the future, the agencies need to characterize and quantify the future fleet in order to assess the impacts of rules that would affect that future fleet. The agencies have examined various publicly-available sources, and then used inputs from those sources in a series of models to project the composition of a baseline and reference fleet for purposes of this analysis. This chapter describes this process.

The agencies have made every effort to make this analysis transparent and duplicable[a]. Because both the input and output sheets from our modeling are public,[1] stakeholders can verify and check NHTSA's and EPA's modeling, and perform their own analyses with these datasets.

1.1 Why do the agencies establish a baseline and reference vehicle fleet?

In order to calculate the impacts of the proposed future GHG and CAFE standards, it is necessary to estimate the composition of the future vehicle fleet absent those proposed standards in order to conduct comparisons. EPA and NHTSA have developed a comparison fleet in two parts. The first step was to develop a baseline fleet based on model year 2008 data, discussed further below. NHTSA and EPA create a baseline fleet in order to track the volumes and types of fuel economy-improving and CO_2-reducing technologies which are already present in the existing vehicle fleet. Creating a baseline fleet helps to keep, to some extent, the agencies' models from adding technologies to vehicles that already have these technologies, which would result in "double counting" of technologies' costs and benefits. The second step was to project the baseline fleet sales into MYs 2017-2025. This is called the reference fleet, and it represents the fleet volumes (but, until later steps, not levels of technology) that the agencies believe would exist in MYs 2017-2025 absent any change due to regulation in 2017-2025.

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[a] In endeavoring to be transparent and duplicable in every aspect of the analysis supporting the joint proposed rules discussed in this TSD, the agencies seek to facilitate public participation in the rulemaking process consistent with Executive Order 13563 (76 Fed. Reg. 3821, Jan. 21, 2011) and OMB Circular A-4 (September 17, 2003, *available at* http://www.whitehouse.gov/omb/circulars_a004_a-4/ (last accessed Aug. 15, 2011)).

After determining the reference fleet, a third step is needed to account for technologies (and corresponding increases in cost and reductions in fuel consumption and CO_2 emissions) that could be added to MY 2008-technology vehicles in the future, taking into account previously-promulgated standards, and assuming MY 2016 standards are extended through MY2025. This step uses the Omega and Volpe models to add technologies to that MY 2008-based market forecast such that each manufacturer's car and truck CAFE and average CO_2 levels reflect baseline standards. The models' output, the reference case, is the light-duty fleet estimated to exist in MYs 2017-2025 without new GHG/CAFE standards covering MYs 2017-2025. All of the agencies' estimates of emission reductions/fuel economy improvements, costs, and societal impacts for purposes of this NPRM are developed in relation to the agencies' reference cases. This chapter describes the first two steps of the development of the baseline and reference fleets. The third step of technology addition is developed separately by each agency as the outputs of the OMEGA and Volpe models (see Chapter 3 of the TSD for an explanation of how the models apply technologies to vehicles in order to evaluate potential paths to compliance).

1.2 The 2008 baseline vehicle fleet

1.2.1 Why did the agencies choose 2008 as the baseline model year?

The baseline that EPA developed in consultation with NHTSA for the 2012-2016 final rule was comprised of model year 2008 CAFE compliance data (specifically, individual vehicles with sales volumes disaggregated at the level of specific engine/transmission combinations) submitted by manufacturers to EPA, in part because full MY 2009 data was not available at the time. For this NPRM, the agencies chose again to use MY 2008 vehicle data as the basis of the baseline fleet, but for different reasons than in the 2012-2016 final rule. First, MY 2008 is now the most recent model year for which the industry had what the agencies would consider to be "normal" sales. Complete MY 2009 data is now available for the industry, but the agencies believe that the model year was disrupted by the economic downturn and the bankruptcies of both General Motors and Chrysler. CAFE compliance data shows that there was a significant reduction in the number of vehicles sold by both companies and by the industry as a whole. These abnormalities led the agencies to conclude that MY 2009 data was likely not representative for projecting the future fleet for purposes of this analysis. And second, while MY 2010 data is likely more representative for projecting the future fleet, it was not complete and available in time for it to be used for the NPRM analysis. Therefore, for purposes of the NPRM analysis, the agencies chose to use MY 2008 CAFE compliance data for the baseline since it was the latest, most representative transparent data set that we had available. However, the agencies plan to use the MY 2010 data, if available, to develop an updated market forecast for use in the final rule. To the extent the MY 2010 data becomes available within the time frame of the comment period for this proposal the agencies will place a copy of this data into each agencies docket.

1.2.2 On what data is the baseline vehicle fleet based?

As part of the CAFE program, EPA measures vehicle CO_2 emissions and converts them to mpg, and generates and maintains the federal fuel economy database. See 49 U.S.C 32904 and 40 CFR Part 600. Most of the information about the vehicles that make up the 2008 fleet was gathered from EPA's emission certification and fuel economy database, most of which is available to the public. These data included, by individual vehicle model produced in MY 2008, vehicle production volume, fuel economy rating for CAFE certification (*i.e.*, on the 2-cycle city-highway test), carbon dioxide emissions (equivalent to fuel economy rating for CAFE certification), fuel type (gasoline, diesel, and/or alternative fuel), number of engine cylinders, displacement, valves per cylinder, engine cycle, transmission type, drive (rear-wheel, all-wheel, etc.), hybrid type (if applicable), and aspiration (naturally-aspirated, turbocharged, etc.). In addition to this information about each vehicle model produced in MY 2008, the agencies also need information about the fuel economy-improving/CO_2-reducing technologies already on those vehicle models in order to assess how much and which technologies to apply to determine a path toward future compliance. However, EPA's certification database does not include a detailed description of the types of fuel economy-improving/CO_2-reducing technologies considered in this NPRM because this level of information was not reported in MY 2008 for emission certification or fuel economy testing. Thus, the agencies augmented this description with publicly-available data which includes more complete technology descriptions from Ward's Automotive Group.[b,c] The agencies also need information about the footprints of MY 2008 vehicles in order to create potential target curves (as discussed in Chapter 2 of the TSD, vehicles are plotted as data points defined by (footprint, fuel economy) or (footprint, CO_2 emissions). In a few instances when relevant vehicle information (such as, for example, vehicle footprint) was not available from these two sources, the agencies obtained this information principally from publicly-accessible internet sites such as Motortrend.com or Edmunds.com, and occasionally from other sources (such as articles about specific vehicles revealed from internet search engine research).[d,e,f]

The baseline vehicle fleet for the analysis informing these proposed rules is highly similar to the baseline vehicle fleet used in the MYs 2012-2016 rulemaking, and like that baseline, is comprised of publicly-available data to the largest extent possible. Whereas some of the technology data included in the MYs 2012-2016 analysis' baseline fleet was based on confidential product plan information about MY 2008 vehicles, specifically, data about which vehicles already have low friction lubricants, electric power steering, improved accessories,

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[b] WardsAuto.com: Used as a source for engine specifications shown in Table 1-1.

[c] Note that WardsAuto.com, where this information was obtained, is a fee-based service, but all information is public to subscribers.

[d] Motortrend.com and Edmunds.com: Used as a source for footprint and vehicle weight data.

[e] Motortrend.com and Edmunds.com are free, no-fee internet sites.

[f] A small amount of footprint data from manufacturers' MY 2008 product plans submitted to the agencies was used in the development of the baseline.

and low rolling resistance tires applied, the agencies no longer consider that information as needing to be withheld, because by now all MY 2008 vehicle models are already in the on-road fleet. As a result, the agencies are able to make public the exact baseline used in this rulemaking analysis.

As explained in the MYs 2012-2016 TSD, creating the 2008 baseline fleet Excel file was an extremely labor-intensive process. EPA in consultation with NHTSA first considered using EPA's CAFE certification data, which contains most of the required information. However, since the deadline for manufacturers to report this data did not allow enough time, in the MYs 2012-2016 rulemaking, for early modeling review, the agencies began to create the baseline fleet file using an alternative data source.

The agencies ultimately relied on a combination of EPA's vehicle emissions certification data, data from a paid subscription to Ward's Automotive Group, and CAFE certification data. EPA's vehicle emissions certification data contains much of the information required for creating a baseline fleet file, but it lacked the production volumes that are necessary for the OMEGA and Volpe models, and also contains some vehicle models that manufacturers certified but did not produce in MY 2008. The data from Ward's contained production volumes (which were not ultimately used, because they did not have volumes for individual vehicles down to the resolution of the specific engine and transmission level) and vehicle specifications, and eliminated extraneous vehicles.

The EPA vehicle emissions certification dataset came in two parts, an engine file and a vehicle file, which the agencies combined into one spreadsheet using their common index. The more-specific Ward's data also came in two parts, an engine file and a vehicle file, and also required mapping, which was more difficult than combining the EPA vehicle emissions certification dataset files because there was no common index between the Ward's files. A new index was implanted in the engine file and a search equation in the vehicle file, which identified most of the vehicle and engine combinations. Each vehicle and engine combination was reviewed and corrections were made manually when the search routine failed to give the correct engine and vehicle combination. The combined Ward's data was then mapped to the EPA vehicle emissions certification data by creating a new index in the combined Ward's data and using the same process that was used to combine the Ward's engine and vehicle files.

In the next step, CAFE certification data had to be merged in order to fill out the needed production volumes. NHTSA and EPA reviewed the CAFE certification data for MY 2008 as it became available in the MYs 2012-2016 rulemaking. The CAFE certification set could have been used with the Ward's data without the EPA vehicle emission certification data set, but was instead appended to the combined Ward's and EPA vehicle emission certification dataset. That combined dataset was then mapped into the CAFE dataset using the same Excel mapping technique described above. Finally EPA and NHTSA obtained the remaining attribute and technology data, such as footprint, curb weight, and others (for a complete list of data with sources see Table 1-1 below) from other sources, thus completing the baseline dataset.

We note that, besides the use of updated AEO and CSM information, the baseline fleet for this rulemaking is different from the fleet used in the MYs 2012-2016 rulemaking in one fairly minor way. Specifically, in the MYs 2012-2016 the agencies aggregated full-size pickup data in the baseline by using average values to represent all variants of a given pickup line. While full-size pickups might be offered with various combinations of cab style (*e.g.*, regular, extended, crew) and box length (*e.g.*, 5 ½', 6 ½', 8'), and therefore multiple footprint sizes, CAFE compliance data for MY 2008 did not contain footprint information, and therefore could not reliably be used to identify which pickup entries correspond to footprint values estimable from public or commercial sources. Therefore, the agencies used the known production levels of average values to represent all variants of a given pickup line (*e.g.*, all variants of the F-150, or all variants of the Sierra/Silverado) in order to calculate the sales-weighted average footprint/fuel economy value for each pickup family. In retrospect, this may have affected how we fit the light truck target curve, among other things, so the agencies have since created an expanded version of the fleet to account for the variation in footprint/wheelbase for the large pickups of Chrysler, Ford, GM, Nissan and Toyota. In MY 2008, large pickups were available from Nissan with 2, Chrysler and Toyota with 3, and Ford and GM with 5 wheelbase/footprint combinations. The agencies got this footprint data from MY 2008 product plans submitted by the various manufacturers, which can be made public at this time because by now all MY 2008 vehicle models are already in production, which makes footprint data about them essentially public information.

The agencies created the expanded fleet by replicating original records from a single pickup footprint model into multiple pickup models with distinct footprint values, in order to reflect the additional pickup model footprints just noted. For example, an F-150 in the MY 2008 baseline used in the MYs 2012-2016 rulemaking analysis with a footprint value of 67 square feet, is disaggregated by replicating 2 times in all respects, except with footprint values of 58, 67, and 73 square feet. Sales volumes of these pickups from the original record were distributed to each of the "58 square feet" and "73 square feet" duplicates based on the distribution of MY 2008 sales by these pickups' wheelbase/footprint, which the agencies took from product plan data submitted by the manufacturers in 2008/2009 in response to requests to support the MYs 2012-2016 rulemaking analysis. The agencies were able to distribute the sales for each of the original pickups by wheelbase/footprint by matching each of the pickups in the baseline fleet with pickups in the product plans on the basis of drive type, transmission type, and engine displacement, cylinders/configuration and HP, and then sorting and summing the sales of the matched pickups in the product plans by wheelbase/footprint.

Both agencies used this fleet forecast to populate input files for the agencies' respective modeling systems. The structure of the market forecast input file used for DOT's CAFE Compliance and Effects Modeling System (a.k.a. "the Volpe model") is described the model documentation.[2] To help readers who wish to directly examine the baseline fleet file for EPA's OMEGA model, and to provide some idea of its contents for those readers who do not, Table 1-1 shows the columns of the complete fleet file, which includes the MY 2008 baseline data that was compiled. Each column has its name, definition (description) and source. Most elements shown in Table 1-1 also appear in the market forecast input file for

DOT's modeling system, which also accommodates some additional data elements discussed in the model documentation.

Table 1-1 Data, Definitions, and Sources

Data Item	Definition	Where The Data is From
Index	Index Used to link EPA and NHTSA baselines	Created
Manufacturer	Commnon name of company that manufactured vehicle. May include more name plates than Cert Manufacturer Name.	Certification data
CERT Manufacturer Name	Certification name of company that manufactured vehicle	Certification data
Name Plate	Name of Division	Certification data
Model	Name of Vehicle	Certification data
Reg Class	EPA Fuel Economy Class Name	Certification data
Our Class	If a car's Footprint<43 then "SubCmpctAuto" If a car's 43<=Footprint<46 then "CompactAuto" If a car's 46<=Footprint<53 then "MidSizeAuto" If a car's Footprint >=53 then "LargeAuto" If a S.U.V.'s Footprint < 43 then "SmallSuv" If a S.U.V.'s 43<=Footprint<46 then "MidSizeSuv" If a S.U.V's Footprint >=46 then "LargeSuv" If a Truck's Footprint < 50 then "SmallPickup" If a Truck's Footprint>=50 then "LargPickup" If a Van's Structure is Ladder then "CargoVan" If a Van's Structure is Unibody then "Minivan"	Derived From Certification data and Footprint
CSM Class	CSM Worldwide's class for the vehicle. Used to weight vehicles based on CSM data.	CSM Worldwide
Vehicle Type Number	Vehicle Type Number assigned to a vehicle based on its number of cylinders, valves per cylinder, and valve actuation technology	Defined by EPA staff
Vehicle Index From Sum Page	Number to be used as a cross reference with the Sum Pages.	NA
Traditional Car/Truck	Traditional Car Truck value for reference.	Certification data
NHTSA Defined New Car/Truck	New NHTSA Car Truck value as defined in 2011 Fuel economy regulations. Used in calculations.	NHTSA
Total Production Volume	Total number of vehicles produced for that model.	Certification data
Fuel Econ. (mpg)	EPA Unadjusted Fuel Economy	Certification data
CO2	CO2 calculated from MPG. CO2 weighted 1.15 times higher for diesel vehicles.	Certification data
Area (sf)	Average Track x Wheelbase	Calculated from track width and wheel base
Fuel	Gas or Diesel	Wards
Fuel Type	Gas or Diesel or Electric	Certification data
Disp (lit.)	Engine Cylinder Displacement Size in Liters	Wards/Certification data
Effective Cyl	Number of Cylinder + 2 if the engine has a turbo or super charger.	Derived From Certification data.
Actual Cylinders	Actual Number of Engine Cylinders	Certification data
Valves Per Cylinder	Number of Valves Per Actual Cylinder	Certification data

Valve Type	Type of valve actuation.	Wards (Note:Type E is from Cert Data)
Valve Actuation	Type of valve actuation with values compatible with the package file.	Wards
VVT	Type of valve timing with values compatible with the package file.	Wards
VVLT	Type of valve lift with values compatible with the package file.	Wards
Deac	Cylinder Deactivation with a value that is compatible with the package file.	Wards
Fuel injection system	Type of fuel injection.	Wards
Boost	Type of Boost if any.	Wards
Engine Cycle	As Defined by EPA Cert. Definition	Wards
Horsepower	Max. Horsepower of the Engine	Wards
Torque	Max. Torque of the Engine	Wards
Trans Type	A=Auto AMT=Automated Manual M=Manual CVT= Continuously Variable Transmission	Certification data
Trans	Type Code with number of Gears	Certification data
Num of Gears	Number of Gears	Certification data
Transmission	Transmisison definition. Matches the cost definition.	Certification data
Structure	Ladder or Unibody	General Internet Searches
Drive	Fwd, Rwd, 4wd	Certification data
Drive with AWD	Fwd, Rwd, Awd, 4wd	Certification data
Wheelbase	Length of Wheelbase	Some from Edmunds.com or Motortrend.com, Others from product plans with a subset verified with Edmunds.com or Motortrend.com for accuracy.
Track Width (front)	Length of Track Width in inches	Some from Edmunds.com or Motortrend.com, Others from product plans with a subset verified with Edmunds.com or Motortrend.com for accuracy.
Track Width (rear)	Length of Track Width in inches	Some from Edmunds.com or Motortrend.com, Others from product plans with a subset verified with Edmunds.com or Motortrend.com for accuracy.
Footprint: PU Average	Car and Large Truck Footprints are normal (Average Track x Wheelbase). Medium and Small Truck footprints are the production weighted average for each vehicle.	Derived from data from Edmunds.com or Motortrend.com. Production volumes or specific footprints from product plans.
Theshold FootPrint	Footprint valve that will be set to 41 for values less than 41, Will be set to 56 for car values > 56, and will be set to 74 for truck values >74	Derived from data from Edmunds.com or Motortrend.com. Production volumes or specific footprints from product plans.
Curb Weight	Curb Weight of the Vehicle	Some from Edmunds.com or Motortrend.com, Others from product plans with a subset verified with Edmunds.com or Motortrend.com for accuracy.
GVWR	Gross Vehicle Weight Rating of the Vehicle	Some from Edmunds.com or Motortrend.com, Others from product plans with a subset verified with Edmunds.com or Motortrend.com for accuracy.
Stop-Start/Hybrid/Full EV	Type of Electrification if any. Blank = None	Certification data
Import Car	Cars Imported	Certification data
Towing Capacity (Maximum)	Weight a vehicle is rated to tow.	Volpe Input File
Engine Oil	Ratio between the applied shear stress and the	Volpe Input File

Viscosity	rate of shear, which measures the resistance of flow of the engine oil (as per SAE Glossary of Automotive Terms)	
Volume 2009	Projected Production Volume for 2009	Calculated based on 2008 volume and Annual Energy Outlook and CSM adjustment factors.
Volume 2010	Projected Production Volume for 2010	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2011	Projected Production Volume for 2011	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2012	Projected Production Volume for 2012	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2013	Projected Production Volume for 2013	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2014	Projected Production Volume for 2014	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2015	Projected Production Volume for 2015	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2016	Projected Production Volume for 2016	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2017	Projected Production Volume for 2017	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2018	Projected Production Volume for 2018	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2019	Projected Production Volume for 2019	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2020	Projected Production Volume for 2020	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2021	Projected Production Volume for 2021	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2022	Projected Production Volume for 2022	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2023	Projected Production Volume for 2023	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2024	Projected Production Volume for 2024	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Volume 2025	Projected Production Volume for 2025	Calculated based on 2008 volume and AEO and CSM adjustment factors.
Low drag brakes	See Volpe Documentation	Volpe Input File
Electric Power steering	See Volpe Documentation	Volpe Input File
Volpe Index	Number used to reorder the vehicles in the EPA baseline in the same order as the Volpe input file.	Volpe Input File

Notes:

1. For engines not available in the WardsAuto.com engine file, an internet search was done to find this information.
2. These data were obtained from manufacturer's product plans. They were used to block (where possible) the model from adding technology that was already on a vehicle.
3. Ward's Automotive Group data obtained from "2008 Light Vehicle Engines."

The sales volumes for the MY 2008 baseline fleet are included in the section below on reference fleet under the MY 2008 columns. Table 1-2 displays the engine technologies present in the baseline fleet. Again, the engine technologies for the vehicles manufactured by these manufacturers in MY 2008 were largely obtained from Ward's Auto online.

Table 1-2 2008 Engine Technology Percentages

Manufacturer	Vehicle Type	Turbo Charged	Super Charged	Single Overhead Cam	Dual Overhead Cam	Overhead Cam	Variable Valve Timing Continuous	Variable Valve Timing Discrete	Variable Valve Timing Intake Only	Variable Valve Lift and Timing Continuous	Variable Valve Lift and Timing Discrete	Cylinder Deactivation	Direct Injection
All	Both	3%	0%	20%	63%	17%	8%	22%	30%	0%	12%	6%	5%
All	Cars	4%	0%	17%	73%	9%	9%	24%	35%	0%	13%	3%	7%
All	Trucks	1%	0%	24%	48%	29%	6%	19%	23%	0%	10%	11%	3%
Aston Martin	Cars	0%	0%	0%	100%	0%	0%	100%	0%	24%	0%	0%	0%
Aston Martin	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
BMW	Cars	33%	1%	14%	86%	0%	14%	86%	0%	0%	13%	0%	33%
BMW	Trucks	5%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	6%
Chrysler/Fiat	Cars	1%	0%	21%	72%	8%	0%	42%	0%	0%	0%	5%	0%
Chrysler/Fiat	Trucks	0%	0%	39%	4%	57%	0%	4%	0%	0%	0%	4%	0%
Daimler	Cars	2%	0%	55%	45%	0%	72%	4%	13%	0%	0%	0%	2%
Daimler	Trucks	16%	1%	36%	64%	0%	35%	17%	47%	0%	0%	0%	16%
Ferrari	Cars	0%	0%	0%	100%	0%	0%	100%	0%	29%	0%	0%	0%
Ferrari	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ford	Cars	0%	1%	15%	85%	0%	4%	0%	47%	0%	0%	0%	0%
Ford	Trucks	0%	0%	65%	32%	3%	28%	1%	9%	0%	0%	0%	0%
Geely/Volvo	Trucks	0%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
Geely/Volvo	Cars	49%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
GM	Trucks	0%	0%	0%	31%	69%	5%	17%	14%	0%	0%	40%	0%
GM	Cars	1%	0%	0%	56%	44%	29%	31%	1%	0%	0%	4%	6%
Honda	Cars	0%	0%	57%	43%	0%	0%	27%	20%	0%	100%	11%	0%
Honda	Trucks	4%	0%	64%	36%	0%	0%	4%	28%	0%	100%	0%	4%
Hyundai	Cars	0%	0%	0%	100%	0%	0%	0%	100%	0%	0%	0%	0%
Hyundai	Trucks	0%	0%	0%	100%	0%	0%	0%	100%	0%	0%	0%	0%
Kia	Cars	0%	0%	0%	100%	0%	0%	0%	10%	0%	0%	0%	0%
Kia	Trucks	0%	0%	0%	100%	0%	0%	0%	17%	0%	0%	0%	0%
Lotus	Cars	0%	77%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
Lotus	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mazda	Cars	11%	0%	0%	99%	0%	0%	7%	92%	0%	0%	0%	11%
Mazda	Trucks	24%	0%	1%	99%	0%	0%	13%	87%	0%	0%	0%	24%
Mitsubishi	Cars	6%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%	0%
Mitsubishi	Trucks	0%	0%	100%	0%	0%	38%	0%	0%	0%	0%	0%	0%

Nissan	Cars	0%	0%	0%	100%	0%	0%	4%	96%	0%	0%	0%	0%
Nissan	Trucks	0%	0%	0%	100%	0%	0%	0%	100%	0%	0%	0%	0%
Porsche	Cars	17%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	17%
Porsche	Trucks	12%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	100%
Spyker/Saab	Cars	100%	0%	0%	100%	0%	0%	17%	0%	0%	0%	0%	0%
Spyker/Saab	Trucks	0%	0%	0%	62%	38%	0%	0%	62%	0%	0%	28%	0%
Subaru	Cars	15%	0%	69%	31%	0%	0%	0%	31%	0%	1%	0%	0%
Subaru	Trucks	3%	0%	70%	30%	0%	0%	23%	7%	0%	27%	0%	0%
Suzuki	Cars	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%
Suzuki	Trucks	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%
Tata/JLR	Cars	0%	0%	0%	100%	0%	0%	76%	24%	0%	0%	0%	0%
Tata/JLR	Trucks	0%	20%	0%	100%	0%	0%	0%	100%	0%	0%	0%	0%
Tesla	Cars	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Tesla	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Toyota	Cars	0%	0%	0%	100%	0%	0%	29%	71%	0%	0%	0%	8%
Toyota	Trucks	0%	0%	0%	100%	0%	0%	61%	39%	0%	0%	0%	6%
Volkswagen	Cars	43%	0%	85%	15%	0%	0%	48%	0%	0%	1%	0%	89%
Volkswagen	Trucks	1%	0%	0%	100%	0%	0%	99%	0%	0%	79%	0%	100%

The data in Table 1-2 indicates that manufacturers had already begun implementing a number of fuel economy/GHG reduction technologies in the baseline (2008) fleet. For example, VW stands out as having a significant number of turbocharged direct injection engines, though it is uncertain whether their engines are also downsized. Some of the valve and cam technologies are quite common in the baseline fleet: for example, nearly half the baseline fleet already has dual cam phasing, while Honda and GM have considerable levels of engines with cylinder deactivation. Honda also has already implemented continuously variable valve lift on a majority of their engines. Part of the implication of these technologies already being present in the baseline is that if manufacturers have already implemented them, they are therefore not available in the rulemaking analysis for improving fuel economy and reducing CO_2 emissions further, requiring the agencies to look toward increasing penetration of these and other technologies and increasingly advanced technologies to project continued improvements in stringency over time.

The section below provides further detail on the conversion of the MY 2008 baseline into the MYs 2017-2025 reference fleet. It also describes more of the data contained in the baseline spreadsheet.

1.3 The MY 2017-2025 Reference Fleet

The reference fleet aims to reflect the current market conditions and expectations about conditions of the vehicle fleet during the model years to which the agencies' rules apply. Fundamentally, constructing this fleet involved projecting the MY 2008 baseline fleet into the MYs 2017-2025 model years. It also included the assumption that none of the vehicle models had changes during this period. Projecting this future fleet is a process that is necessarily uncertain. NHTSA and EPA therefore relied on many sources of reputable information to make these projections.

1.3.1 On what data is the reference vehicle fleet based?

EPA and NHTSA have based the projection of total car and light truck sales on the most recent projections available made by the Energy Information Administration (EIA). EIA publishes a projection of national energy use annually called the Annual Energy Outlook (AEO).[3] EIA published its Early Annual Energy Outlook for 2011 in December 2010. EIA released updated data to NHTSA in February (Interim AEO). The final release of AEO for 2011 came out in April 2011, but by that time EPA/NHTSA had already prepared modeling runs for potential 2017-2025 standards using the interim data release to NHTSA. EPA and NHTSA will use the newest version of AEO available in projecting the reference fleet for the final rule.

Similar to the analyses supporting the MYs 2012-2016 rulemaking, the agencies have used the Energy Information Administration's (EIA's) National Energy Modeling System (NEMS) to estimate the future relative market shares of passenger cars and light trucks. However, NEMS methodology includes shifting vehicle sales volume, starting after 2007, away from fleets with lower fuel economy (the light-truck fleet) towards vehicles with higher fuel economies (the passenger car fleet) in order to facilitate compliance with CAFE and GHG MYs 2012-2016 standards (the car and truck volumes based on this analysis are shown in Table 1-3). Because we use our market projection as a baseline relative to which we measure the effects of new standards, and we attempt to estimate the industry's ability to comply with new standards without changing product mix (*i.e.*, we analyze the effects of the proposed rules assuming manufacturers will not change fleet composition as a compliance strategy, as opposed to changes that might happen due to market forces), the Interim AEO 2011-projected shift in passenger car market share as a result of required fuel economy improvements creates a circularity. Therefore, for the current analysis, the agencies developed a new projection of passenger car and light truck sales shares by running scenarios from the Interim AEO 2011 reference case that first deactivate the above-mentioned sales-volume shifting methodology and then hold post-2017 CAFE standards constant at MY 2016 levels. Incorporating these changes reduced the projected passenger car share of the light vehicle market by an average of about 5% during 2017-2025. This case is referred to as the "Unforced Reference Case," and the values are shown below in Table 1-4.

Table 1-3 AEO 2011 Reference Case Values

Model Year	Cars	Trucks	Total Vehicles
2017	8,984,200	6,812,000	15,796,100
2018	8,998,200	6,552,200	15,550,400
2019	9,170,900	6,391,300	15,562,200
2020	9,553,600	6,336,200	15,889,800

2021	9,801,100	6,380,000	16,181,100
2022	10,056,600	6,384,600	16,441,200
2023	10,244,500	6,396,500	16,641,000
2024	10,483,400	6,407,700	16,891,100
2025	10,739,600	6,470,200	17,209,800

Table 1-4 AEO 2011 Interim Unforced Reference Case Values

Model Year	Cars	Trucks	Total Vehicles
2017	8,440,703	7,365,619	15,806,322
2018	8,376,192	7,200,218	15,576,410
2019	8,464,457	7,114,201	15,578,658
2020	8,725,709	7,170,230	15,895,939
2021	8,911,173	7,277,894	16,189,066
2022	9,123,436	7,316,337	16,439,772
2023	9,344,051	7,311,438	16,655,489
2024	9,580,693	7,353,394	16,934,087
2025	9,836,330	7,414,129	17,250,459

In 2017, car and light truck sales are projected to be 8.4 and 7.4 million units, respectively. While the total level of sales of 15.8 million units is similar to pre-2008 levels, the fraction of car sales in 2017 and beyond is projected to be higher than in the 2000-2007 time frame. Note that EIA's definition of cars and trucks follows that used by NHTSA prior to the MY 2011 CAFE final rule. The MY 2011 CAFE final rule reclassified approximately 1 million 2-wheel drive sport utility vehicles from the truck fleet to the car fleet. EIA's sales projections of cars and trucks for the 2017-2025 model years under the old NHTSA truck definition are shown above in Table 1-3 and Table 1-4.

In addition to a shift towards more car sales, sales of segments within both the car and truck markets have also been changing and are expected to continue to change in the future. Manufacturers are continuing to introduce more crossover models which offer much of the utility of SUVs but use more car-like designs and unibody structures. In order to reflect these changes in fleet makeup, EPA and NHTSA used a custom long range forecast purchased from CSM Worldwide (CSM). CSM Worldwide (CSM) [g] is a well-known industry analyst, that provided the forecast used by the agencies for the 2012-2016 final rule. NHTSA and EPA decided to use the forecast from CSM for several reasons. One, CSM uses a ground up

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[g] CSM World Wide, CSM World Wide is a paid service provider.

approach (*e.g.*, looking at the number of plants and capacity for specific engines, transmissions, and vehicles) for their forecast, which the agencies believe is a robust forecasting approach. Two, CSM agreed to allow us to publish their high level data, on which the forecast is based, in the public domain. Three, the CSM forecast covered all the timeframe of greatest relevance to this analysis (2017-2025 model years). Four, it provided projections of vehicle sales both by manufacturer and by market segment. And five, it utilized market segments similar to those used in the EPA emission certification program and fuel economy guide, such that the agencies could include only the vehicle types covered by the proposed standards.

CSM created a forecast that covered model years 2017-2025. Since the agencies used this forecast to generate the reference fleet (*i.e.*, the fleet expected to be sold absent any increases in the stringency regulations after the 2016 model year), it is important for the forecast to be independent of increases during 2017-2025 in the stringency of CAFE/ GHG standards. However, CSM assumed that CAFE and GHG standards would continue to increase in stringency after 2016, although CSM did not use specific future standards as quantitative inputs to its model. In its quantitative analysis, CSM used fuel price, industry demand, consumer demand and other economic factors to project the composition of the future fleet. In response to question by the agencies, CSM indicated that their assumption of future standards had a negligible (non-discernable) impact on their forecast since it was not a direct quantitative input to the model such that CSM's forecast would have been essentially the same had CSM assumed no stringency increases after 2016.

The agencies combined the CSM forecast with data from other sources to create the reference fleet projections. This process is discussed in sections that follow.

1.3.2 How do the agencies develop the reference vehicle fleet?

The process of producing the 2017-2025 reference fleet involved combining the baseline fleet with the projection data described above. This was a complex multistep procedure, which is described in this section.

1.3.3 How was the 2008 baseline data merged with the CSM data?

EPA and NHTSA employed the same methodology as in the 2012-16 rule for mapping certification vehicles to CSM vehicles. Merging the 2008 baseline data with the 2017-2025 CSM data required a thorough mapping of certification vehicles to CSM vehicles by individual make and model. One challenge that the agencies faced when determining a reference case fleet was that the sales data projected by CSM had different market segmentation than the data contained in EPA's internal database. In order to create a common segmentation between the two databases, the agencies performed a side-by-side comparison of each vehicle model in both datasets, and created an additional "CSM segment" modifier in the spreadsheet to map the two datasets. The reference fleet sales based on the "CSM segmentation" was then projected.

The baseline data and reference fleet volumes are available to the public. The baseline Excel spreadsheet in the docket is the result of the merged files.[4] The spreadsheet provides specific details on the sources and definitions for the data. The Excel file contains several tabs. They are: "Data", "Data Tech Definitions", "SUM", "SUM Tech Definitions", "Truck Vehicle Type Map", and "Car Vehicle Type Map". "Data" is the tab with the raw data. "Data Tech Definitions" is the tab where each column is defined and its data source named. "SUM" is the tab where the raw data is processed to be used in the OMEGA and Volpe models. The "SUM" tab minus columns A-F and minus the Generic vehicles is the input file for the models. The "Generic" manufacturer (shown in the "SUM" tab) is the sum of all manufacturers and is calculated as a reference, and for data verification purposes. It is used to validate the manufacturers' totals. It also gives an overview of the fleet. Table 1-5 shows the sum of the models chosen. The number of models is determined by the number of unique segment and vehicle type combinations. These combinations of segment and vehicle type (the vehicle type number is the same as the technology package number) are determined by the technology packages discussed in the EPA RIA. "SUM Tech Definitions" is the tab where the columns of the "SUM" tab are defined. The "Truck Vehicle Type Map" and "Car Vehicle Type Map" map the number of cylinder and valve actuation technology to the "tech package" vehicle type number.

Table 1-5 Models from the SUM Tab Model

Model
Car Like LargeSuv >=V8 Vehicle Type: 13
Car Like LargeSuv V6 Vehicle Type: 16
Car Like LargeSuv V6 Vehicle Type: 12
Car Like LargeSuv V6 Vehicle Type: 9
Car Like LargeSuv I4 and I5 Vehicle Type: 7

Car Like MidSizeSuv V6   Vehicle Type: 8
Car Like MidSizeSuv V6   Vehicle Type: 5
Car Like MidSizeSuv I4   Vehicle Type: 7
Car Like SmallSuv V6   Vehicle Type: 12
Car Like SmallSuv V6   Vehicle Type: 4
Car Like SmallSuv I4   Vehicle Type: 3
LargeAuto >=V8   Vehicle Type: 13
LargeAuto >=V8   Vehicle Type: 10
LargeAuto >=V8   Vehicle Type: 6
LargeAuto V6   Vehicle Type: 12
LargeAuto V6   Vehicle Type: 5
MidSizeAuto >=V8   Vehicle Type: 13
MidSizeAuto >=V8   Vehicle Type: 10
MidSizeAuto >=V8 (7 or >)   Vehicle Type: 6
MidSizeAuto V6   Vehicle Type: 12
MidSizeAuto V6   Vehicle Type: 8
MidSizeAuto V6   Vehicle Type: 5
MidSizeAuto I4   Vehicle Type: 3

In the combined EPA certification and CSM database, all 2008 vehicle models were assumed to continue out to 2025, though their volumes changed in proportion to CSM projections. Also, any new models expected to be introduced within the 2009-2025 timeframe are not included in the data. These volumes are reassigned to the existing models to keep the overall fleet volume the same. All MYs 2017-2025 vehicles are mapped to the existing vehicles by a process of mapping to manufacturer market share and overall segment distribution. The mappings are discussed in the next section. Further discussion of this limitation is discussed below in section 1.3.4. The statistics of this fleet will be presented below since further modifications were required to the volumes as the next section describes.

1.3.4 How were the CSM forecasts normalized to the AEO forecasts?

The next step in the agencies' generation of the reference fleet is one of the more complicated steps to explain. Here, the projected CSM forecasts for relative sales of cars and trucks by manufacturer and by market segment was normalized (set equal) to the total sales estimates of the Early Release of the 2011 Annual Energy Outlook (AEO). NHTSA and EPA used projected car and truck volumes for this period from Early AEO 2011. However, the AEO projects sales only at the car and truck level, not at the manufacturer and model-specific level, and the agencies' analysis requires this further level of detail. The CSM data provided year-by-year percentages of cars and trucks sold by each manufacturer as well as the percentages of each vehicle segment. Using these percentages normalized to the AEO-projected volumes then provided the manufacturer-specific market share and model-specific sales for model years 2017-2025 (it is worth clarifying that the agencies are not using the model-specific sales volumes from CSM, only the higher-level volumes by manufacturer and segment). This process is described in greater detail in the following paragraphs.

In order to determine future production volumes, the agencies developed multipliers by manufacturer and vehicle segment that could be applied to MY 2008 volumes. The process for developing the multipliers is complicated, but is easiest to explain as a three-step process, though the first step is combined with both the second and third step, so only one multiplier per manufacturer and vehicle segment is developed.

The three steps are:

1) Adjust total car and truck sales to match AEO projections.

2) Adjust car sales to match CSM market share projections for each manufacturer and car segment.

3) Adjust truck sales to match CSM market share projections for each manufacturer and truck segment.

The first step is the adjustment of total car and truck sales in 2008 to match AEO projections of total car and truck sales in 2017-2025. The volumes for all of the trucks in 2008 were added up (TruckSum2008), and so were the volumes of all the cars (CarSum2008). A multiplier was developed to scale the volumes in 2008 to the AEO projections. The example equation below shows the general form of how to calculate a car or truck multiplier. The AEO projections are shown above in Table 1-3.

Example Equation **:**

TruckMultiplier(Year X) = AEOProjectionforTrucks(Year X) / TruckSum2008

CarMultiplier(Year X) = AEOProjectionforCars(Year X) / CarSum2008

Where: Year X is the model year of the multiplier.

The AEO projection is different for each model year. Therefore, the multipliers are different for each model year. The multipliers can be applied to each 2008 vehicle as a first adjustment, but multipliers based solely on AEO have limited value since those multipliers can only give an adjustment that will give the correct total numbers of cars and trucks without the correct market share or vehicle mix. A correction factor based on the CSM data, which does contain market share and vehicle segment mix, is therefore necessary, so combining the AEO multiplier with CSM multipliers (one per manufacturer, segment, and model year) will give the best multipliers.

There were several steps in developing an adjustment for Cars based on the CSM data. CSM provided data on the market share and vehicle segment distribution. The first step in determining the adjustment for Cars was to total the number of Cars in each vehicle segment by manufacturer in MY 2008. A total for all manufacturers in each segment was also calculated. The next step was to multiply the volume of each segment for each manufacturer by the CSM market share. The AEO multiplier was also applied at this time. This gave projected volumes with AEO total volumes and market share correction for Cars. This is shown in the "Adjusted for 2017AEO and Manufacturer Market Share" column of Table 1-6.

The next step is to adjust the sales volumes for CSM vehicle segment distribution. The process for adjusting for vehicle segment is more complicated than a simple one step multiplication. In order to keep manufacturers' volumes constant and still have the correct vehicle segment distribution, vehicles need to move from segment to segment while maintaining constant manufacturers' totals. Six rules and one assumption were applied to accomplish the shift. The assumption (based on the shift in vehicle sales in 2008 and 2009) is that people are moving to smaller vehicles in the rulemaking time frame independently of regulatory requirements. A higher-level (less detailed) example of this procedure is provided in Section II of the preamble.

Vehicles from CSM's "Luxury Car," "Specialty Car," and "Other Car" segments, if reduced, will be equally distributed to the remaining four categories ("Full-Size Car," "Mid-Size Car," "Small Car," "Mini Car"). If these sales increased, they were taken from the remaining four categories so that the relative sales in these four categories remained constant.

Vehicles from CSM's "Luxury Car," "Specialty Car," and "Other Car" segments, if increased will take equally from the remaining categories ("Full-Size Car," "Mid-Size Car," "Small Car," "Mini Car").

All manufacturers have the same multiplier for a given segment shift based on moving all vehicles in that segment to achieve the CSM distribution. Table 1-6 shows how the 2017 vehicles moved and the multipliers that were created for each adjustment. This does not mean that new vehicle segments will be added (except for Generic Mini Car described in the next step) to manufacturers that do not produce them. Vehicles within each manufacturer will be shifted as close to the distribution as possible given the other rules. Table 1-7 has the percentages of Cars per CSM segment. These percentages are multiplied by the total number of vehicles in a given year to get the total sales in the segment. Table 1-6 shows the totals for 2017 in the "2017 AEO-CSM Sales Goal" column.

When "Full-Size Car," "Mid-Size Car," "Small Car" are processed, if vehicles need to move in or out of the segment, they will move into or out of the next smaller segment. So, if Mid-Size Cars are being processed they can only move to or be taken from Small Cars. Note: In order to accomplish this, a "Generic Mini Car" segment was added to manufacturers who did not have a Mini (type) Car in production in 2008, but needed to shift down vehicles from the Small Car segment.

The data must be processed in the following order: "Luxury Car," "Specialty Car," "Other Car," "Full-Size Car," "Mid-Size Car," "Small Car." The "Mini Car" does not need to be processed separately. By using this order, it works out that vehicles will always move toward the correct distribution. There are two exceptions, BMW and Porsche only have "Luxury Car," "Specialty Car," and "Other Car" vehicles, so their volumes were not changed or shifted since these rules did not apply to them.

When an individual manufacturer multiplier is applied for a segment, the vehicles move to or from the appropriate segments as specified in the previous rules and as shown in Table 1-6.

Table 1-6 2017 Model Year Volume Shift*

CSM Segment	2008 MY Sales	Adjusted for 2017 AEO and Manufacturer Market Share	Luxury, Specialty, Other Adjustment	Full Size Adjustment	Midsize Adjustment	Small Car Adjustment	2017 AEO-CSM Sales Goal
All Full-Size Car	829,896	830,832	818,226	347,034	347,034	347,034	347,034
All Luxury Car	1,048,341	1,408,104	1,423,691	1,423,691	1,423,691	1,423,691	1,423,691
All Mid-Size Car	2,103,108	2,500,723	2,475,267	2,946,459	2,431,715	2,431,715	2,431,715
All Mini Car	617,902	868,339	851,234	851,234	851,234	1,439,985	1,439,985

All Small Car	1,912,736	2,548,393	2,513,350	2,513,350	3,028,094	2,439,343	2,439,343
All Specialty Car	469,324	627,425	702,048	702,048	702,048	702,048	702,048
All Others	0	0	0	0	0	0	0
Number Vehicles that shift and Where							
All Full-Size Car			(12,606)	(471,192)	0	0	
All Luxury Car			15,587	0	0	0	
All Mid-Size Car			(25,456)	471,192	(514,744)	0	
All Mini Car			(17,105)	0	0	588,751	
All Small Car			(35,043)	0	514,744	(588,751)	
All Specialty Car			74,623	0	0	0	
All Others			0	0	0	0	
Individual Manufacturer Multiplier							
All Full-Size Car				0.42			
All Luxury Car			0.973				
All Mid-Size Car					0.97		
All Mini Car						1.55	
All Small Car						0.96	
All Specialty Car			0.963				
All Others			1				

Table 1-7 CSM – Percent of Cars per Segment*

CSM Segment	2017	2018	2019	2020	2021	2022	2023	2024	2025
Compact Car	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Full-Size Car	3.95%	3.56%	3.35%	4.10%	3.59%	3.03%	2.97%	2.46%	2.46%
Luxury Car	16.70%	16.87%	17.14%	17.23%	17.05%	17.02%	17.10%	17.40%	17.40%
Mid-Size Car	27.68%	27.77%	27.47%	26.94%	27.18%	27.82%	28.51%	28.11%	28.11%
Mini Car	15.33%	15.46%	15.45%	15.46%	15.59%	15.67%	15.47%	15.23%	15.23%
Small Car	27.77%	27.57%	27.74%	27.99%	28.29%	28.43%	28.18%	28.49%	28.49%
Specialty Car	8.56%	8.76%	8.84%	8.27%	8.29%	8.03%	7.77%	8.31%	8.31%
Others	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Mathematically, an individual manufacturer multiplier is calculated by making the segment the goal and dividing by the previous total for the segment (shown in Table 1-7). If the number is greater than 1, the vehicles are entering the segment, and if the number is less than 1, the vehicles are leaving the segment. So, for example, if Luxury Cars have an adjustment of 1.5, then for a specific manufacturer who has Luxury Cars, a multiplier of 1.5 is applied to its luxury car volume, and the total number of vehicles that shifted into the Luxury segment is subtracted from the remaining segments to maintain that company's market share. On the other hand, if Large Cars have an adjustment of 0.7, then for a specific manufacturer who has Large Cars, a multiplier of 0.7 is applied to its Large Cars, and the total number of vehicles leaving that segment is transferred into that manufacturer's Mid-Size Cars.

After the vehicle volumes are shifted using the above rules, a total for each manufacturer and vehicle segment is maintained. The total for each manufacturer segment for a specific model year (*e.g.*, 2017 General Motors Luxury Cars) divided by the MY 2008 total for that manufacturer segment (*e.g.*, 2008 General Motors Luxury Cars) is the new multiplier used to determine the future vehicle volume for each vehicle model. This is done by taking the multiplier (which is for a specific manufacturer and segment) times the MY 2008 volume for the specific vehicle model (*e.g.*, 2008 General Motors Luxury Car Cadillac CTS). This process is repeated for each model year (2017-2025).

The method used to adjust CSM Trucks to the AEO market share was different than the method used for Cars. The process for Cars is different than Trucks because it is not possible to predict how vehicles would shift between segments based on current market trends. This is because of the added utility of some trucks that makes their sales more insensitive to factors like fuel price. Again, CSM provided data on the market share and vehicle segment distribution. The process for having the fleet match CSM's market share and vehicle segment distribution was iterative.

The following totals were determined:

- The total number of trucks for each manufacturer in 2008 model year.
- The total number of trucks in each truck segment in 2008 model year.
- The total number of truck in each segment for each manufacturer in 2008 model year.
- The total number of trucks for each manufacturer in a specific future model year based on the AEO and CSM data. This is the goal for market share.
- The total number of trucks in each truck segment in a specific future model year based on the AEO and CSM data. This is the goal for vehicle segment distribution. Table 1-8 has the percentages of Trucks per CSM segment.

Table 1-8 CSM – Percent of Trucks per Segment

CSM Segment	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
Full-Size CUV	5.9%	6.3%	6.8%	7.5%	8.3%	8.8%	9.5%	9.2%	9.1%
Full-Size Pickup	16.8%	16.5%	15.9%	16.1%	15.4%	15.1%	14.3%	13.8%	13.5%

Full-Size SUV	1.9%	1.5%	1.3%	1.0%	0.9%	0.8%	0.5%	0.5%	0.6%
Full-Size Van	1.2%	1.2%	1.1%	1.4%	1.3%	1.3%	1.3%	1.2%	1.2%
Mid-Size CUV	18.0%	17.4%	17.6%	17.2%	16.9%	16.8%	16.8%	17.0%	17.0%
Mid-Size MAV	4.5%	4.6%	4.9%	5.4%	5.9%	6.2%	6.5%	7.1%	7.4%
Mid-Size Pickup	6.1%	6.1%	6.1%	5.6%	5.7%	5.7%	5.8%	5.9%	5.8%
Mid-Size SUV	4.1%	4.8%	4.8%	4.5%	4.7%	4.8%	4.8%	4.6%	4.6%
Mid-Size Van	11.6%	11.9%	11.9%	11.7%	11.6%	11.6%	11.6%	11.3%	11.3%
Small CUV	26.0%	25.9%	25.7%	25.6%	25.1%	24.9%	24.7%	25.3%	25.3%
Small MAV	2.5%	2.6%	2.8%	2.9%	3.0%	3.1%	3.1%	3.2%	3.2%
Small SUV	1.3%	1.2%	1.1%	1.2%	1.1%	1.1%	1.1%	1.0%	1.0%

To start, two different types of tables were created. One table had each manufacturer with its total sales for 2008 (similar to Table 1-10). This table will have the goal for each manufacturer, and a column added for each iteration with the current total. The second table has a truck segment total by manufacturer. The second table starts out with a "Generic" manufacturer (Table 1-10) which is the table where the goal resides. Each manufacturer (BMW for example is shown in Table 1-11) is then listed below the "Generic" manufacturer. With each iteration, a new total is added for each segment that is calculated and added to the table. This is not shown in the tables below. The agencies then engaged in a process of first adjusting the numbers in the tables to the goal for market share distribution. This was followed by adjusting to the goal for vehicle segment distribution. Each time an adjustment was done a new column was added. An adjustment was done by creating a multiplier (either segment distribution-based or manufacturer distribution-based) and applying it to each vehicle segment total in the current iteration. A manufacturer-based multiplier is calculated by taking the goal total for a manufacturer and dividing by the current total (starting with 2008 model year volumes) for a manufacturer. A segment distribution-based multiplier is calculated by taking the goal distribution volumes in the Generic manufacturer set and dividing them by the current volume. Table 1-9, Table 1-10, and Table 1-11 below illustrates two iterations using BMW as an example.

Table 1-9 Manufacturer Truck Totals

	2008 Model Year Sales	Manufacturer Distribution 2017 Volume Goal	Multiplier for Iteration 1
BMW	61,324	138.053	138,053/61324=2.25

Table 1-10 Segment Specific Truck Totals for All Manufacturers

Manufacturer	CSM Segment	2008 Model Year Sales	Segment Distribution 2017 Volume Goal	Multipliers
Generic**	Full-Size Pickup	1,332,335	1,240,844	0.931
Generic	Mid-Size Pickup	452,013	452,017	1.000
Generic	Full-Size Van	33,384	85,381	2.558
Generic	Mid-Size Van	719,529	855,022	1.188
Generic	Mid-Size MAV	110,353	331,829	3.007
Generic	Small MAV	231,265	186,637	0.807
Generic	Full-Size SUV	559,160	138,821	0.248
Generic	Mid-Size SUV	436,080	305,382	0.700
Generic	Small SUV	196,424	94,657	0.482
Generic	Full-Size CUV	264,717	433,683	1.638
Generic	Mid-Size CUV	923,165	1,327,905	1.438
Generic	Small CUV	1,612,029	1,913,439	1.187

** Generic means all manufacturers.

Table 1-11 Segment Specific Truck Totals for BMW

Manufacturer	CSM Segment	2008 Model Year Sales	Iteration 1 Adjust for Market Share	Iteration 2 Adjust for Segment Distribution
BMW	Full-Size Pickup			
BMW	Mid-Size Pickup			
BMW	Full-Size Van			
BMW	Mid-Size Van			
BMW	Mid-Size MAV	3,882	2.25*3,882=8,739	2.85*8,739=24,907
BMW	Small MAV			
BMW	Full-Size SUV			
BMW	Mid-Size SUV			
BMW	Small SUV			
BMW	Full-Size CUV			
BMW	Mid-Size CUV	36,409	2.25*36,409=81,964	1.1*81,964=90,134
BMW	Small CUV	21,033	2.25*21,033=47,350	1..02*47,350=48,306
Total BMW Vehicles		61,324	138,053	163,347

Using this process, the numbers will get closer to the goal of matching CSM's market share for each manufacturer and distribution for each vehicle segment after each of the iterations. The iterative process is carried out until the totals nearly match the goals.

After 19 iterations, all numbers were within 0.01% of CSM's distributions. The calculation iterations could have been stopped sooner, but they were continued to observe how the numbers would converge.

After the market share and segment distribution were complete, the totals need to be used to create multipliers that could be applied to the original individual 2008 model year vehicle volumes (each unique manufacture models volume). The total for each manufacturer segment divided by the 2008 model year total for each manufacturer segment gives a multiplier that can be applied to each vehicle based on its manufacturer and segment.

The above process is done for each model year needed (2017-2025). The multipliers are then applied to each vehicle in 2008 model year, which gives a volume for each vehicle in 2017 through 2025 model year.

1.3.5 What are the sales volumes and characteristics of the reference fleet?

Table 1-12 and Table 1-14 below contain the sales volumes that result from the process above for MY 2008 and 2017-2020. Table 1-13 and Table 1-15 below contain the sales volumes that result from the process above for MY 2021-2025.

Table 1-12 Vehicle Segment Volumes[a]

	Actual and Projected Sales Volume				
Reference Class Segment	2008	2017	2018	2019	2020
LargeAuto	562,240	376,107	356,768	353,609	394,864
MidSizeAuto	3,098,927	3,311,268	3,290,408	3,303,621	3,381,785
CompactAuto	1,979,461	2,347,980	2,325,393	2,369,301	2,448,021
SubCmpctAuto	1,365,833	2,458,222	2,454,112	2,489,208	2,553,350
LargePickup	1,582,226	1,514,619	1,443,766	1,383,190	1,386,195
SmallPickup	177,497	156,227	157,932	160,752	146,029
LargeSUV	2,783,949	3,194,489	3,150,101	3,177,868	3,203,244
MidSizeSUV	1,263,360	1,358,755	1,309,212	1,267,394	1,285,822
SmallSUV	285,355	148,251	149,933	154,675	162,677
MiniVan	642,055	754,562	739,551	717,065	714,323
CargoVan	110,858	185,841	199,234	201,974	219,628

[a] Volumes in this table are based on the pre-2011 NHTSA definition of Cars and Trucks.

Table 1-13 Vehicle Segment Volumes[a]

	Actual and Projected Sales Volume				
Reference Class Segment	2021	2022	2023	2024	2025
LargeAuto	380,192	358,295	362,672	356,173	368,843
MidSizeAuto	3,442,116	3,548,263	3,692,533	3,751,496	3,814,941
CompactAuto	2,520,977	2,592,199	2,632,926	2,744,634	2,843,069
SubCmpctAuto	2,626,364	2,687,167	2,721,102	2,796,061	2,878,288
LargePickup	1,368,301	1,349,421	1,301,293	1,271,751	1,260,389
SmallPickup	150,123	147,138	151,315	154,627	154,838
LargeSUV	3,312,914	3,362,608	3,412,753	3,475,873	3,520,992
MidSizeSUV	1,281,240	1,283,244	1,268,288	1,292,662	1,305,362
SmallSUV	167,223	169,643	170,239	173,191	175,713
MiniVan	729,078	738,982	740,785	720,720	726,256
CargoVan	210,539	202,812	201,585	196,900	201,768

[a] Volumes in this table are based on the pre-2011 NHTSA definition of Cars and Trucks.

Table 1-14 2011+ NHTSA Car and Truck Definition Based Volumes

Vehicle Type	Actual and Projected Sales Volume				
	2008	2017	2018	2019	2020
Trucks	5,621,193	5,818,655	5,671,046	5,582,962	5,604,377
Cars	8,230,568	9,987,667	9,905,364	9,995,696	10,291,562
Cars and Trucks	13,851,761	15,806,322	15,576,410	15,578,658	15,895,939

Table 1-15 2011+ NHTSA Car and Truck Definition Based Volumes

Vehicle Type	Actual and Projected Sales Volume				
	2021	2022	2023	2024	2025
Trucks	5,683,902	5,703,996	5,687,486	5,675,949	5,708,899
Cars	10,505,165	10,735,777	10,968,003	11,258,138	11,541,560
Cars and Trucks	16,189,066	16,439,772	16,655,489	16,934,087	17,250,459

Table 1-16 and Table 1-17 below contain the sales volumes by manufacturer and vehicle type for MY 2008 and 2017-2025.

Table 1-16 NHTSA Car and Truck Definition Manufacturer Volumes

Manufacturers	Vehicle Type	2008 Baseline Sales	2017 Projected Volume	2018 Projected Volume	2019 Projected Volume	2020 Projected Volume
All	Both	13,851,761	15,806,322	15,576,410	15,578,658	15,895,939
All	Cars	8,230,568	9,987,667	9,905,364	9,995,696	10,291,562
All	Trucks	5,621,193	5,818,655	5,671,046	5,582,962	5,604,377
Aston Martin	Cars	1,370	1,035	1,051	1,072	1,034
Aston Martin	Trucks	-	-	-	-	-
BMW	Cars	291,796	313,022	322,939	346,075	357,942
BMW	Trucks	61,324	138,053	131,942	131,373	128,339
Chrysler/Fiat	Cars	703,158	418,763	397,538	391,689	415,319
Chrysler/Fiat	Trucks	956,792	409,702	387,858	366,447	360,677
Daimler	Cars	208,195	284,847	276,409	281,425	290,989
Daimler	Trucks	79,135	86,913	83,651	88,188	92,919
Ferrari	Cars	1,450	6,676	6,700	6,794	6,916
Ferrari	Trucks	-	-	-	-	-
Ford	Cars	956,699	1,299,899	1,311,467	1,332,039	1,378,789
Ford	Trucks	814,194	763,549	748,829	717,773	717,037
Ford	Cars	956,699	1,299,899	1,311,467	1,332,039	1,378,789
Geely/Volvo	Trucks	32,748	41,887	42,187	43,125	42,615
Geely/Volvo	Cars	65,649	88,234	89,394	91,575	93,003
GM	Trucks	1,507,797	1,362,761	1,438,355	1,505,025	1,530,755
GM	Cars	1,587,391	1,462,204	1,474,076	1,493,511	1,544,983
HONDA	Cars	1,006,639	1,154,600	1,138,087	1,144,639	1,163,666
HONDA	Trucks	505,140	596,481	544,619	527,535	525,089
HYUNDAI	Cars	337,869	592,027	578,373	582,971	598,283
HYUNDAI	Trucks	53,158	152,885	151,461	155,642	154,173
Kia	Cars	221,980	322,044	312,370	314,879	323,676
Kia	Trucks	59,472	98,702	98,280	100,679	96,535
Lotus	Cars	252	240	243	250	266
Lotus	Trucks	-	-	-	-	-
Mazda	Cars	246,661	253,540	262,512	266,951	270,078
Mazda	Trucks	55,885	51,788	57,535	57,494	58,154
Mitsubishi	Cars	85,358	65,099	63,671	63,826	65,080
Mitsubishi	Trucks	15,371	37,632	36,300	35,454	35,215
Nissan	Cars	717,869	870,797	849,678	854,400	882,791
Nissan	Trucks	305,546	444,938	412,383	398,559	397,869
PORSCHE	Cars	18,909	35,093	35,444	36,116	35,963
PORSCHE	Trucks	18,797	13,233	12,001	11,469	11,141

Spyker/Saab	Cars	21,706	20,024	20,007	20,144	21,069
Spyker/Saab	Trucks	4,250	2,871	3,596	3,826	3,509
Subaru	Cars	116,035	224,112	216,598	217,095	223,466
Subaru	Trucks	82,546	78,242	75,152	72,832	72,458
Suzuki	Cars	79,339	90,708	89,932	90,568	93,548
Suzuki	Trucks	35,319	22,109	21,385	20,692	20,675
Tata/JLR	Cars	9,596	55,881	56,222	57,267	58,182
Tata/JLR	Trucks	55,584	57,579	56,606	57,854	56,213
Tesla	Cars	800	27,986	28,435	28,990	27,965
Tesla	Trucks	-	-	-	-	-
Toyota	Cars	1,260,364	1,849,196	1,834,181	1,836,306	1,883,734
Toyota	Trucks	951,136	1,330,511	1,223,415	1,142,104	1,154,304
Volkswagen	Cars	291,483	551,638	540,036	537,114	554,822
Volkswagen	Trucks	26,999	128,819	145,491	146,891	146,700

Table 1-17 NHTSA Car and Truck Definition Manufacturer Volumes

Manufacturers	Vehicle Type	2020 Projected Volume	2021 Projected Volume	2022 Projected Volume	2023 Projected Volume	2024 Projected Volume
All	Both	16,189,066	16,439,772	16,655,489	16,934,087	17,250,459
All	Cars	10,505,165	10,735,777	10,968,003	11,258,138	11,541,560
All	Trucks	5,683,902	5,703,996	5,687,486	5,675,949	5,708,899
Aston Martin	Cars	1,058	1,049	1,041	1,141	1,182
Aston Martin	Trucks	-	-	-	-	-
BMW	Cars	359,098	360,034	360,561	388,193	405,256
BMW	Trucks	128,724	128,899	127,521	146,525	145,409
Chrysler/Fiat	Cars	421,013	424,173	423,882	426,017	436,479
Chrysler/Fiat	Trucks	348,613	363,008	361,064	344,962	331,762
Daimler	Cars	300,378	304,738	312,507	332,337	340,719
Daimler	Trucks	99,449	100,935	105,315	107,084	101,067
Ferrari	Cars	7,059	7,138	7,227	7,441	7,658
Ferrari	Trucks	-	-	-	-	-
Ford	Cars	1,401,617	1,415,221	1,474,797	1,503,670	1,540,109
Ford	Trucks	714,181	714,266	700,005	688,854	684,476
Ford	Cars	1,401,617	1,415,221	1,474,797	1,503,670	1,540,109
Geely/JLR	Trucks	41,768	41,686	42,031	42,461	42,588
Geely/JLR	Cars	92,726	92,512	96,840	99,181	101,107
GM	Trucks	1,530,020	1,507,653	1,496,819	1,493,597	1,524,008
GM	Cars	1,564,277	1,578,556	1,606,495	1,636,805	1,673,936
HONDA	Cars	1,198,880	1,237,504	1,265,564	1,307,851	1,340,321
HONDA	Trucks	535,916	539,235	536,898	536,994	557,697
HYUNDAI	Cars	613,355	627,964	634,308	657,710	677,250
HYUNDAI	Trucks	156,466	157,493	161,189	166,092	168,136

Kia	Cars	331,319	339,102	342,746	351,882	362,783
Kia	Trucks	95,432	94,694	95,688	96,119	97,653
Lotus	Cars	278	290	299	308	316
Lotus	Trucks	-	-	-	-	-
Mazda	Cars	274,740	281,150	296,910	300,614	306,804
Mazda	Trucks	59,227	60,307	61,966	61,971	61,368
Mitsubishi	Cars	65,851	67,261	67,680	70,728	73,305
Mitsubishi	Trucks	35,309	35,227	35,469	36,001	36,387
Nissan	Cars	912,629	937,447	954,340	982,771	1,014,775
Nissan	Trucks	408,029	411,883	417,121	422,217	426,454
PORSCHE	Cars	36,475	36,607	36,993	39,504	40,696
PORSCHE	Trucks	11,242	11,385	11,370	11,409	11,219
Spyker/Saab	Cars	21,294	21,709	22,410	22,800	23,130
Spyker/Saab	Trucks	3,560	3,461	3,435	3,426	3,475
Subaru	Cars	230,780	238,613	241,612	248,283	256,970
Subaru	Trucks	72,773	72,736	73,022	74,142	74,722
Suzuki	Cars	95,725	97,599	99,263	100,447	103,154
Suzuki	Trucks	20,767	20,734	20,803	21,162	21,374
Tata/JLR	Cars	58,677	59,349	60,639	63,728	65,418
Tata/JLR	Trucks	58,153	58,590	58,865	57,981	56,805
Tesla	Cars	28,623	28,369	28,150	30,862	31,974
Tesla	Trucks	-	-	-	-	-
Toyota	Cars	1,903,706	1,986,077	2,036,992	2,080,528	2,108,053
Toyota	Trucks	1,215,539	1,235,052	1,224,980	1,208,013	1,210,016
Volkswagen	Cars	585,607	593,314	596,749	605,336	630,163
Volkswagen	Trucks	148,734	146,750	153,927	156,939	154,284

Table 1-18 also shows how the change in fleet make-up may affect the footprint distributions over time. The resulting data indicate that footprint will not change significantly between 2008 and 2025. There will be an increase in the number of cars sold, which will cause the average footprints for cars and trucks combined to be slightly smaller (about 2%). This is the result of AEO projecting an increased number of cars, and CSM predicting that most of that increase will be in the subcompact segment. Again, we note that in order to ensure that our baseline inputs were not influenced by the proposed regulations, agencies re-ran AEO to hold standards constant after 2016 (the reader will remember from the text above that CSM had indicated that its projections were not sensitive to assumptions about new standards).

Table 1-18 Production Foot Print Mean

Model Year	Average Footprint of all Vehicles	Average Footprint Cars	Average Footprint Trucks

2008	48.9	45.4	53.9
2017	48.2	44.9	53.8
2018	48.1	44.9	53.7
2019	48.0	44.9	53.6
2020	48.0	44.9	53.7
2021	48.0	44.9	53.6
2022	47.9	44.9	53.6
2023	47.9	44.9	53.5
2024	47.7	44.9	53.4
2025	47.7	44.9	53.3

Table 1-19 below shows the changes in engine cylinders over the model years. The current assumptions show that engines will be downsized over the model years to which these proposed rules apply. This shift is a projected consequence of the expected changes in class and segment mix as predicted by AEO and CSM, and does not represent engine downsizing attributable to the 2012-2016 light-duty CAFE and GHG standards.

Table 1-19 Percentages of 4, 6, 8 Cylinder Engines by Model Year

	Trucks			**Cars**		
Model Year	**4 Cylinders**	**6 Cylinders**	**8 Cylinders**	**4 Cylinders**	**6 Cylinders**	**8 Cylinders**
2008	10.3%	56.4%	33.3%	56.9%	37.8%	5.3%
2017	10.9%	63.7%	25.4%	60.6%	34.5%	5.0%
2018	10.6%	64.5%	24.8%	60.7%	34.4%	5.0%
2019	10.4%	65.5%	24.1%	60.7%	34.3%	5.0%
2020	10.3%	65.6%	24.1%	60.3%	34.7%	5.0%
2021	10.3%	66.3%	23.4%	60.6%	34.4%	4.9%
2022	10.3%	66.7%	23.0%	61.1%	34.2%	4.8%
2023	10.3%	67.7%	22.0%	60.9%	34.3%	4.8%
2024	10.5%	68.1%	21.4%	61.0%	34.1%	4.8%
2025	10.5%	68.2%	21.3%	61.1%	34.0%	4.8%

For the final rule, the agencies intend to use a more recent version of EIAs AEO, and we also will consider using MY 2010 for the baseline, and potentially an updated future market forecast.

References:

[1] EPA's Omega Model and input sheets are available at http://www.epa.gov/oms/climate/models.htm; DOT/NHTSA's CAFE Compliance and Effects Modeling System (commonly known as the "Volpe Model") and input and output sheets are available at http://www.nhtsa.gov/fuel-economy.

[2] http://www.nhtsa.gov/Laws+&+Regulations/CAFE+-+Fuel+Economy/CAFE+Compliance+and+Effects+Modeling+System:+The+Volpe+Model

[3] Department of Energy, Energy Information Administration, Annual Energy Outlook (AEO) 2011, Early Release. *Available at* http://www.eia.gov/forecasts/aeo/ (last accessed Aug. 15, 2011).

[4] The baseline Excel file ("2008-2025 Production Summary Data _Definitions Docket 08_27_2009") is available in the docket (Docket EPA-HQ-OAR-2010-0799).

Chapter 2: What are the Attribute-Based Curves the Agencies are Proposing, and How Were They Developed?

2.1 Why are standards attribute-based and defined by a mathematical function?

As in the MYs 2012-2016 CAFE/GHG rules, and as NHTSA did in the MY 2011 CAFE rule, NHTSA and EPA are proposing to set attribute-based CAFE and CO_2 standards that are defined by a mathematical function. EPCA, as amended by EISA, expressly requires that CAFE standards for passenger cars and light trucks be based on one or more vehicle attributes related to fuel economy, and be expressed in the form of a mathematical function.[1] The CAA has no such requirement, although such an approach is permissible under section 202 (a) and EPA has used the attribute-based approach in issuing standards under analogous provisions of the CAA (*e.g.*, criteria pollutant standards for non-road diesel engines using engine size as the attribute,[2] in the recent GHG standards for heavy duty pickups and vans using a work factor attribute,[3] and in the MYs 2012-2016 GHG rule itself which used vehicle footprint as the attribute). Public comments on the MYs 2012-2016 rulemaking widely supported attribute-based standards for both agencies' standards.

Under an attribute-based standard, every vehicle model has a performance target (fuel economy and CO_2 emissions for CAFE and CO_2 emissions standards, respectively), the level of which depends on the vehicle's attribute (for this proposal, footprint, as discussed below). The manufacturers' fleet average performance is determined by the production-weighted[a] average (for CAFE, harmonic average) of those targets.

The agencies believe that an attribute-based standard is preferable to a single-industry-wide average standard in the context of CAFE and CO_2 standards for several reasons. First, if the shape is chosen properly, every manufacturer is more likely to be required to continue adding more fuel efficient technology each year across their fleet, because the stringency of the compliance obligation will depend on the particular product mix of each manufacturer. Therefore a maximum feasible attribute-based standard will tend to require greater fuel savings and CO_2 emissions reductions overall than would a maximum feasible flat standard (that is, a single mpg or CO_2 level applicable to every manufacturer).

Second, depending on the attribute, attribute-based standards reduce the incentive for manufacturers to respond to CAFE and CO_2 standards in ways harmful to safety.[b] Because each vehicle model has its own target (based on the attribute chosen), properly fitted attribute-

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[a] Production for sale in the United States.

[b] The 2002 NAS Report described at length and quantified the potential safety problem with average fuel economy standards that specify a single numerical requirement for the entire industry. *See* 2002 NAS Report at 5, finding 12. Ensuing analyses, including by NHTSA, support the fundamental conclusion that standards structured to minimize incentives to downsize all but the largest vehicles will tend to produce better safety outcomes than flat standards.

based standards provide little, if any, incentive to build smaller vehicles simply to meet a fleet-wide average, because the smaller vehicles will be subject to more stringent compliance targets.[c]

Third, attribute-based standards provide a more equitable regulatory framework for different vehicle manufacturers.[d] A single industry-wide average standard imposes disproportionate cost burdens and compliance difficulties on the manufacturers that need to change their product plans to meet the standards, and puts no obligation on those manufacturers that have no need to change their plans. As discussed above, attribute-based standards help to spread the regulatory cost burden for fuel economy more broadly across all of the vehicle manufacturers within the industry.

Fourth, attribute-based standards better respect economic conditions and consumer choice, as compared to single-value standards. A flat, or single value standard, encourages a certain vehicle size fleet mix by creating incentives for manufacturers to use vehicle downsizing as a compliance strategy. Under a footprint-based standard, manufacturers are required to invest in technologies that improve the fuel economy of the vehicles they sell rather than shifting the product mix, because reducing the size of the vehicle is generally a less viable compliance strategy given that smaller vehicles have more stringent regulatory targets.

2.2 What attribute are the agencies proposing to use, and why?

As in the MYs 2012-2016 CAFE/GHG rules, and as NHTSA did in the MY 2011 CAFE rule, NHTSA and EPA are proposing to set CAFE and CO_2 standards that are based on vehicle footprint, which has an observable correlation to fuel economy and emissions. There are several policy and technical reasons why NHTSA and EPA believe that footprint is the most appropriate attribute on which to base the standards, even though some other vehicle attributes (notably curb weight) are better correlated to fuel economy and emissions.

First, in the agencies' judgment, from the standpoint of vehicle safety, it is important that the CAFE and CO_2 standards be set in a way that does not encourage manufacturers to respond by selling vehicles that are in any way less safe. While NHTSA's research of historical crash data also indicates that reductions in vehicle mass that are accompanied by reductions in vehicle footprint tend to compromise vehicle safety, footprint-based standards provide an incentive to use advanced lightweight materials and structures that would be discouraged by weight-based standards, because manufacturers can use them to improve a vehicle's fuel economy and CO_2 emissions without their use necessarily resulting in a change in the vehicle's fuel economy and emissions targets.

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[c] Assuming that the attribute is related to vehicle size.

[d] *Id.* at 4-5, finding 10.

Further, although we recognize that weight is better correlated with fuel economy and CO_2 emissions than is footprint, we continue to believe that there is less risk of "gaming" (changing the attribute(s) to achieve a more favorable target) by increasing footprint under footprint-based standards than by increasing vehicle mass under weight-based standards—it is relatively easy for a manufacturer to add enough weight to a vehicle to decrease its applicable fuel economy target a significant amount, as compared to increasing vehicle footprint. We also continue to agree with concerns raised in 2008 by some commenters on the MY 2011 CAFE rulemaking that there would be greater potential for gaming under multi-attribute standards, such as those that also depend on weight, torque, power, towing capability, and/or off-road capability. The agencies agree with the assessment first presented in NHTSA's MY 2011 CAFE final rule[4] that the possibility of gaming is lowest with footprint-based standards, as opposed to weight-based or multi-attribute-based standards. Specifically, standards that incorporate weight, torque, power, towing capability, and/or off-road capability in addition to footprint would not only be more complex, but by providing degrees of freedom with respect to more easily-adjusted attributes, they could make it less certain that the future fleet would actually achieve the average fuel economy and CO_2 reduction levels projected by the agencies.

The agencies recognize that based on economic and consumer demand factors that are external to this rule, the distribution of footprints in the future may be different (either smaller or larger) than what is projected in this rule. However, the agencies continue to believe that there will not be significant shifts in this distribution as a direct consequence of this proposed rule. The agencies also recognize that some international attribute-based standards use attributes other than footprint and that there could be benefits for a number of manufacturers if there was greater international harmonization of fuel economy and GHG standards for light-duty vehicles, but this is largely a question of how stringent standards are and how they are tested and enforced. It is entirely possible that footprint-based and weight-based systems can coexist internationally and not present an undue burden for manufacturers if they are carefully crafted. Different countries or regions may find different attributes appropriate for basing standards, depending on the particular challenges they face—from fuel prices, to family size and land use, to safety concerns, to fleet composition and consumer preference, to other environmental challenges besides climate change. The agencies anticipate working more closely with other countries and regions in the future to consider how to address these issues in a way that least burdens manufacturers while respecting each country's need to meet its own particular challenges.

The agencies continue to find that footprint is the most appropriate attribute upon which to base the proposed standards, but recognizing strong public interest in this issue, we seek comment on whether the agencies should consider setting standards for the final rule based on another attribute or another combination of attributes. If commenters suggest that the agencies should consider another attribute or another combination of attributes, the agencies specifically request that the commenters address the concerns raised in the paragraphs above regarding the use of other attributes, and explain how standards should be developed using the other attribute(s) in a way that contributes more to fuel savings and CO_2 reductions than the footprint-based standards, without compromising safety.

2.3 What mathematical functions have the agencies previously used, and why?

2.3.1 NHTSA in MY 2008 and MY 2011 CAFE (constrained logistic)

For the MY 2011 CAFE rule, NHTSA estimated fuel economy levels after normalization for differences in technology, but did not make adjustments to reflect other vehicle attributes (*e.g.*, power-to-weight ratios).[e] Starting with the technology adjusted passenger car and light truck fleets, NHTSA used minimum absolute deviation (MAD) regression without sales weighting to fit a logistic form as a starting point to develop mathematical functions defining the standards. NHTSA then identified footprints at which to apply minimum and maximum values (rather than letting the standards extend without limit) and transposed these functions vertically (*i.e.*, on a gpm basis, uniformly downward) to produce the promulgated standards. In the preceding rule, for MYs 2008-2011 light truck standards, NHTSA examined a range of potential functional forms, and concluded that, compared to other considered forms, the constrained logistic form provided the expected and appropriate trend (decreasing fuel economy as footprint increases), but avoided creating "kinks" the agency was concerned would provide distortionary incentives for vehicles with neighboring footprints.[f]

2.3.2 MYs 2012-2016 Light Duty GHG/CAFE (constrained/piecewise linear)

For the MYs 2012-2016 rules, NHTSA and EPA re-evaluated potential methods for specifying mathematical functions to define fuel economy and GHG standards. The agencies concluded that the constrained logistic form, if applied to post-MY 2011 standards, would likely contain a steep mid-section that would provide undue incentive to increase the footprint of midsize passenger cars.[5] The agencies judged that a range of methods to fit the curves would be reasonable, and used a minimum absolute deviation (MAD) regression without sales weighting on a technology-adjusted car and light truck fleet to fit a linear equation. This equation was used as a starting point to develop mathematical functions defining the standards as discussed above. The agencies then identified footprints at which to apply minimum and maximum values (rather than letting the standards extend without limit) and transposed these constrained/piecewise linear functions vertically (*i.e.*, on a gpm or CO_2 basis, uniformly downward) to produce the fleetwide fuel economy and CO_2 emission levels for cars and light trucks described in the final rule.[6]

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[e] *See* 74 FR 14196, 14363-14370 (Mar. 30, 2009) for NHTSA discussion of curve fitting in the MY 2011 CAFE final rule.

[f] *See* 71 FR 17556, 17609-17613 (Apr. 6, 2006) for NHTSA discussion of "kinks" in the MYs 2008-2011 light truck CAFE final rule (there described as "edge effects"). A "kink," as used here, is a portion of the curve where a small change in footprint results in a disproportionally large change in stringency.

2.3.3 How have the agencies changed the mathematical functions for the proposed MYs 2017-2025 standards, and why?

By requiring NHTSA to set CAFE standards that are attribute-based and defined by a mathematical function, Congress appears to have wanted the post-EISA standards to be data-driven – a mathematical function defining the standards, in order to be "attribute-based," should reflect the observed relationship in the data between the attribute chosen and fuel economy.[g] EPA is also proposing to set attribute-based CO_2 standards defined by similar mathematical functions, for the reasonable technical and policy grounds discussed below and in section II of the preamble to the proposed rule, and which supports a harmonization with the CAFE standards.

The relationship between fuel economy (and GHG emissions) and footprint, though directionally clear (*i.e.*, fuel economy tends to decrease and CO_2 emissions tend to increase with increasing footprint), is theoretically vague and quantitatively uncertain; in other words, not so precise as to *a priori* yield only a single possible curve.[h] There is thus a range of legitimate options open to the agencies in developing curve shapes. The agencies may of course consider statutory objectives in choosing among the many reasonable alternatives. For example, curve shapes that might have some theoretical basis could lead to perverse outcomes contrary to the intent of the statutes to conserve energy and protect human health and the environment.[i] Thus, the decision of how to set the target curves cannot always be just about most "clearly" using a mathematical function to define the relationship between fuel economy and the attribute; it often has to have a normative aspect, where the agencies adjust the function that would define the relationship in order to avoid perverse results, improve equity of burden across manufacturers, preserve consumer choice, etc. This is true both for the decisions that guide the mathematical function defining the sloped portion of the target curves, and for the separate decisions that guide the agencies' choice of "cutpoints" (if any) that define the fuel economy/CO_2 levels and footprints at each end of the curves where the curves become flat. Data informs these decisions, but how the agencies define and interpret the relevant data, and then the choice of methodology for fitting a curve to the data, must include a consideration of both technical data and policy goals.

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[g] A mathematical function can be defined, of course, that has nothing to do with the relationship between fuel economy and the chosen attribute – the most basic example is an industry-wide standard defined as the mathematical function *average required fuel economy* = *X*, where *X* is the single mpg level set by the agency. Yet a standard that is simply defined as a mathematical function that is not tied to the attribute(s) would not meet the requirement of EISA.

[h] In fact, numerous manufacturers have confidentially shared with the agencies what they describe as "physics based" curves, with each OEM showing significantly different shapes, and footprint relationships. The sheer variety of curves shown to the agencies further confirm the lack of an underlying principle of "fundamental physics" driving the relationship between CO_2 emission or fuel consumption and footprint, and the lack of an underlying principle to dictate any outcome of the agencies' establishment of footprint-based standards.

[i] For example, if the agencies set weight-based standards defined by a steep function, the standards might encourage manufacturers to keep adding weight to their vehicles to obtain less stringent targets.

The next sections examine the policy concerns that the agencies considered in developing the proposed target curves that define the proposed MYs 2017-2025 CAFE and CO_2 standards, new technical work (expanding on similar analyses performed by NHTSA when the agency proposed MY 2011-2015 standards, and by both agencies during consideration of options for MY 2012-2016 CAFE and GHG standards) that was completed in the process of reexamining potential mathematical functions, how the agencies have defined the data, and how the agencies explored statistical curve-fitting methodologies in order to arrive at proposed curves.

2.4 What are the agencies proposing for the MYs 2017-2025 curves?

The proposed mathematical functions for the proposed MYs 2017-2025 standards are somewhat changed from the functions for the MYs 2012-2016 standards, in response to comments received from stakeholders and in order to address technical concerns and policy goals that the agencies judge more significant in this 9-year rulemaking than in the prior one, which only included 5 years. This section (2.4) discusses the methodology the agencies selected as, at this time, best addressing those technical concerns and policy goals, given the various technical inputs to the agencies' current analyses. Section 2.5 discusses how the agencies determined the cutpoints and the flat portions of the MYs 2017-2025 target curves. We also note that both of these sections address only how the target curves were fit to fuel consumption and CO_2 emission values determined using the city and highway test procedures, and that in determining respective regulatory alternatives, the agencies made further adjustments to the resultant curves in order to account for adjustments for improvements to mobile air conditioners.

Thus, recognizing that there are many reasonable statistical methods for fitting curves to data points that define vehicles in terms of footprint and fuel economy, the agencies have chosen for this proposed rule to fit curves using an ordinary least-squares formulation, on sales-weighted data, using a fleet that has had technology applied, and after adjusting the data for the effects of weight-to-footprint, as described below. This represents a departure from the statistical approach for fitting the curves in MYs 2012-2016, as explained in the next section. The agencies considered a wide variety of reasonable statistical methods in order to better understand the range of uncertainty regarding the relationship between fuel consumption (the inverse of fuel economy), CO_2 emission rates, and footprint, thereby providing a range within which decisions about standards would be potentially supportable.

2.4.1 What concerns were the agencies looking to address that led them to change from the approach used for the MYs 2012-2016 curves?

During the year and a half since the MYs 2012-2016 final rule was issued, NHTSA and EPA have received a number of comments from stakeholders on how curves should be fitted to the passenger car and light truck fleets. Some limited-line manufacturers have argued that curves should generally be flatter in order to avoid discouraging small vehicles, because steeper curves tend to result in more stringent targets for smaller vehicles. Most full-line manufacturers have argued that a passenger car curve similar in slope to the MY 2016 passenger car curve would be appropriate for future model years, but that the light truck curve should be revised to be less difficult for manufacturers selling the largest full-size pickup trucks. These manufacturers argued that the MY 2016 light truck curve was not "physics-based," and that in order for future tightening of standards to be feasible for full-line manufacturers, the truck curve for later model years should be steeper and extended further (i.e., made less stringent) into the larger footprints. The agencies also do not agree that the MY 2016 light truck curve was somehow deficient in lacking a "physics basis," or that it was somehow overly stringent for manufacturers selling large pickups—manufacturers making these arguments presented no "physics-based" model to explain how fuel economy should depend on footprint.[j] The same manufacturers indicated that they believed that the light truck standard should be somewhat steeper after MY 2016, primarily because, after more than ten years of progressive increases in the stringency of applicable CAFE standards, large pickups would be less capable of achieving further improvements without compromising load carrying and towing capacity.

In developing the curve shapes for this proposed rule, the agencies were aware of the current and prior technical concerns raised by OEMs concerning the effects of the stringency on individual manufacturers and their ability to meet the standards with available technologies, while producing vehicles at a cost that allowed them to recover the additional costs of the technologies being applied. Although we continue to believe that the methodology for fitting curves for the MY2012-2016 standards was technically sound, we recognize manufacturers' technical concerns regarding their abilities to comply with a similarly shallow curve after MY2016 given the anticipated mix of light trucks in MYs 2017-2025. As in the MYs 2012-2016 rules, the agencies considered these concerns in the analysis of potential curve shapes. The agencies also considered safety concerns which could be raised by curve shapes creating an incentive for vehicle downsizing, as well as the potential loss to consumer welfare should vehicle upsizing be unduly disincentivized. In addition, the agencies sought to improve the balance of compliance burdens among manufacturers. Among the technical concerns and resultant policy trade-offs the agencies considered were the following:

- Flatter standards (*i.e.*, curves) increase the risk that both the weight and size of vehicles will be reduced, compromising highway safety.
- Flatter standards potentially impact the utility of vehicles by providing an incentive for vehicle downsizing.
- Steeper footprint-based standards may incentivize vehicle upsizing, thus increasing the risk that fuel economy and greenhouse gas reduction benefits will be less than expected.
- Given the same industry-wide average required fuel economy or CO_2 standard, flatter standards tend to place greater compliance burdens on full-line manufacturers

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[j] See footnote h.

- Given the same industry-wide average required fuel economy or CO_2 standard, steeper standards tend to place greater compliance burdens on limited-line manufacturers (depending of course, on which vehicles are being produced).
- If cutpoints are adopted, given the same industry-wide average required fuel economy, moving small-vehicle cutpoints to the left (*i.e.*, up in terms of fuel economy, down in terms of CO_2 emissions) discourages the introduction of small vehicles, and reduces the incentive to downsize small vehicles in ways that would compromise highway safety.
- If cutpoints are adopted, given the same industry-wide average required fuel economy, moving large-vehicle cutpoints to the right (*i.e.*, down in terms of fuel economy, up in terms of CO_2 emissions) better accommodates the unique design requirements of larger vehicles—especially large pickups—and extends the size range over which downsizing is discouraged.

All of these were policy goals that required trade-offs, and in determining the curves they also required balance against the comments from the OEM comments discussed in the introduction to this section. Ultimately, the agencies do not agree that the MY 2017 target curves for this proposal, on a relative basis, should be made significantly flatter than the MY 2016 curve,[k] as we believe that this would undo some of the safety-related incentives and balancing of compliance burdens among manufacturers—effects that attribute-based standards are intended to provide.

Nonetheless, the agencies recognize full-line OEM concerns and have tentatively concluded that further increases in the stringency of the light truck standards will be more feasible if the light truck curve is made steeper than the MY 2016 truck curve and the right (large footprint) cut-point is extended over time to larger footprints. This conclusion is supported by the agencies' technical analyses of regulatory alternatives defined using the curves developed in the manner described below.

2.4.2 What methodologies and data did the agencies consider in developing the 2017-2025 curves?

In considering how to address the various policy concerns discussed in the previous sections, the agencies revisited the data and performed a number of analyses using different combinations of the various statistical methods, weighting schemes, adjustments to the data and the addition of technologies to make the fleets less technologically heterogeneous. As discussed in 2.3.3, in the agencies' judgment, there is no single "correct" way to estimate the relationship between CO_2 or fuel consumption and footprint – rather, each statistical result is based on the underlying assumptions about the particular functional form, weightings and error structures embodied in the representational approach. These assumptions are the subject

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[k] While "significantly" flatter is subjective, the year over year change in curve shapes is discussed in greater detail in Section 2.5.3.1.

of the following discussion. This process of performing many analyses using combinations of statistical methods generates many possible outcomes, each embodying different potentially reasonable combinations of assumptions and each thus reflective of the data as viewed through a particular lens. The choice of a standard developed by a given combination of these statistical methods is consequently a decision based upon the agencies' determination of how, given the policy objectives for this rulemaking and the agencies' MY 2008-based forecast of the market through MY 2025, to appropriately reflect the current understanding of the evolution of automotive technology and costs, the future prospects for the vehicle market, and thereby establish curves (i.e., standards) for cars and light trucks.

2.4.2.1 What information did the agencies use to estimate a relationship between fuel economy, CO_2 and footprint?

For each fleet, the agencies began with the MY 2008-based market forecast developed to support this proposal (*i.e.*, the baseline fleet), with vehicles' fuel economy levels and technological characteristics at MY 2008 levels.[1] The development, scope, and content of this market forecast is discussed in detail in Chapter 1 of the joint Technical Support Document supporting this rulemaking.

Figure 2-1 shows the MY 2008 CO_2 by car and truck class as it exists in the EPA OMEGA and NHTSA CAFE model data files (for a gasoline-only fleet, fuel consumption—the inverse of fuel economy—is directly proportional to CO_2). This dataset is the base fleet which is the starting point for all analysis in this proposal.

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[1] While the agencies jointly conducted this analysis, the coefficients ultimately used in the slope setting analysis are from the CAFE model.

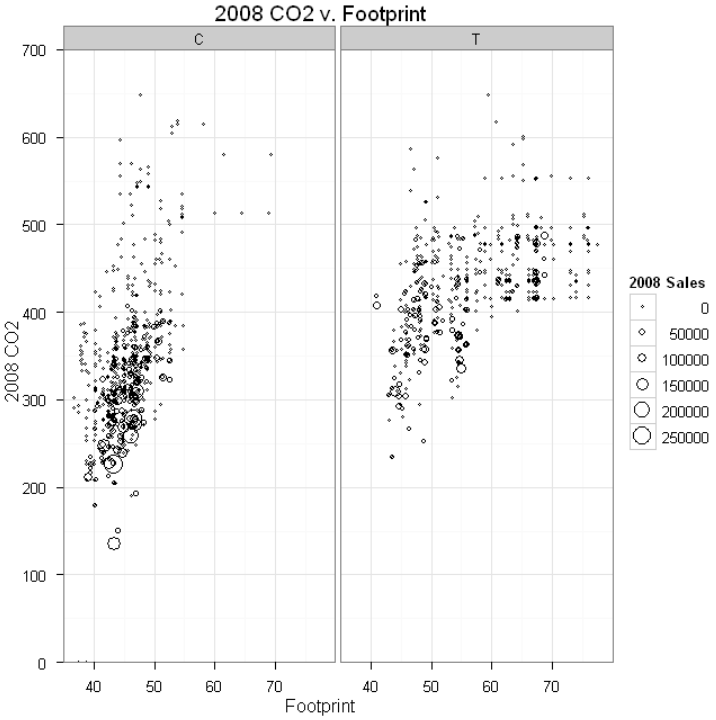

Figure 2-1 2008 CO2 vs. Footprint by Car and Truck

2.4.2.1 What adjustments did the agencies evaluate?

The agencies believe one possible approach is to fit curves to the minimally adjusted data shown above (the approach still includes sales mix adjustments, which influence results of sales-weighted regressions), much as DOT did when it first began evaluating potential attribute-based standards in 2003.[7] However, the agencies have found, as in prior rulemakings, that the data are so widely spread (*i.e.*, when graphed, they fall in a loose "cloud" rather than tightly around an obvious line) that they indicate a relationship between footprint and CO_2 and fuel consumption that is real but not particularly strong (Figure 2-1). Therefore, as discussed below, the agencies also explored possible adjustments that could help to explain and/or reduce the ambiguity of this relationship, or could help to produce policy outcomes the agencies judged to be more desirable.

2.4.2.1.1 Adjustment to reflect differences in technology

As in prior rulemakings, the agencies consider technology differences between vehicle models to be a significant factor producing uncertainty regarding the relationship between CO_2/fuel consumption and footprint. Noting that attribute-based standards are intended to encourage the application of additional technology to improve fuel efficiency and reduce CO_2

emissions, the agencies, in addition to considering approaches based on the unadjusted engineering characteristics of MY 2008 vehicle models, therefore also considered approaches in which, as for previous rulemakings, technology is added to vehicles for purposes of the curve fitting analysis in order to produce fleets that are less varied in technology content.

The agencies adjusted the baseline fleet for technology by adding all technologies considered, except for the most advanced high-BMEP (brake mean effective pressure) gasoline engines, diesel engines, strong HEVs, PHEVs, EVs, and FCVs. The agencies included 15 percent mass reduction on all vehicles. Figure 2-2 shows the same fleet, with technology adjustment and 2021 sales applied, and the baseline diesel fueled vehicles, HEV and EVs removed from the fleet. Of note, the fleet is now more closely clustered[m] (and lower in emissions), but the same basic pattern emerges; in both figures, the CO_2 emission rate (which, as mentioned above, is directly proportional to fuel consumption for a gasoline-only fleet) increases with increasing footprint, although the relationship is less pronounced for larger light trucks.

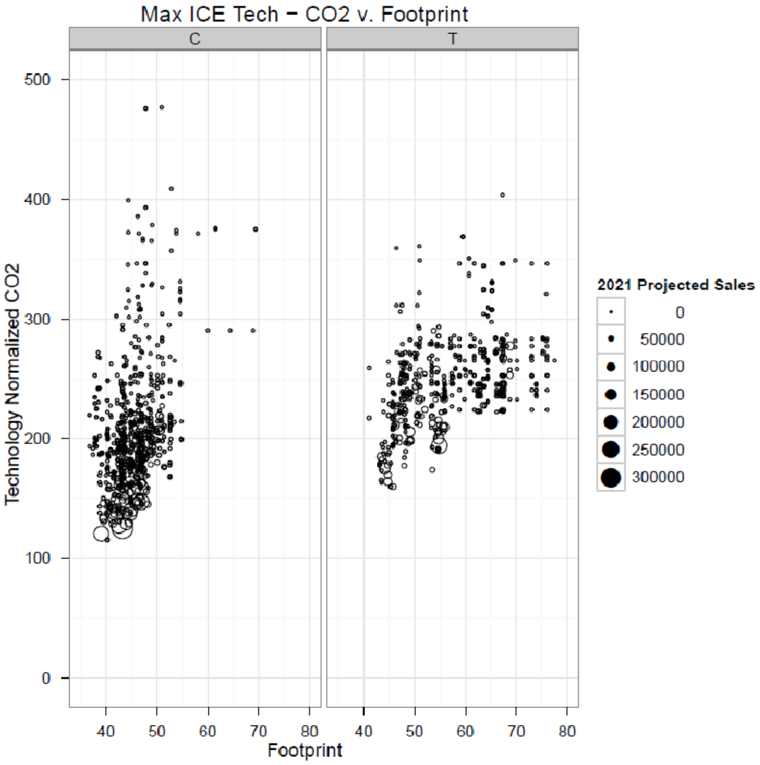

Figure 2-2 2008 CO2 vs. Footprint by Car and Truck, after Adjustment Reflecting Technology Differences, and removing diesel fueled vehicles, HEVs and EVs

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[m] For cars, the standard deviation of the CO_2 data is reduced from 81 to 54 through the technology normalization. For trucks, the standard deviation is reduced from 62 to 36.

2.4.2.2 Adjustments reflecting differences in performance and "density"

As discussed in Section 2.4.1, during stakeholder meetings the agencies held while developing this NPRM, some manufacturers indicated that they believed that the light truck standard should be somewhat steeper after MY 2016. As a means to produce a steeper light truck curve, the agencies considered adjustments for other differences between vehicle models (*i.e.*, inflating or deflating the fuel economy of each vehicle model based on the extent to which one of the vehicle's attributes, such as power, is higher or lower than average). Previously, NHTSA had rejected such adjustments because they imply that a multi-attribute standard may be necessary, and the agencies judged multi-attribute standard to be more subject to gaming than a footprint-only standard.[n,8] Having considered this issue again for purposes of this rulemaking, NHTSA and EPA conclude the need to accommodate in the target curves the challenges faced by manufacturers of large pickups currently outweighs these prior concerns. Therefore, the agencies also evaluated curve fitting approaches through which fuel consumption and CO_2 levels were adjusted with respect to weight-to-footprint alone, and in combination with power-to-weight. While the agencies examined these adjustments for purposes of fitting curves, the agencies are not proposing a multi-attribute standard; the proposed fuel economy and CO_2 targets for each vehicle are still functions of footprint alone. No adjustment would be used in the compliance process.

The agencies also examined some differences between the technology-adjusted car and truck fleets in order to better understand the relationship between footprint and CO_2/fuel consumption in the agencies' MY 2008 based forecast. More direct measures (such as coefficients of drag and rolling resistance), while useful for vehicle simulation, were not practical or readily available at the fleet level. Given this issue, and based on analysis published in the 2012-2016 rule,[9] the agencies investigated a sales-weighted (*i.e.*, treating every vehicle unit sold as a separate observation) regression equation involving power to weight ratio and vehicle weight (Equation 2-1).[o] This equation provides for a strong

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[n] For example, in comments on NHTSA's 2008 NPRM regarding MY 2011-2015 CAFE standards, Porsche recommended that standards be defined in terms of a "Summed Weighted Attribute", wherein the fuel economy target would calculated as follows: $target = f(SWA)$, where *target* is the fuel economy target applicable to a given vehicle model and $SWA = footprint + torque^{1/1.5} + weight^{1/2.5}$. (NHTSA-2008-0089-0174). While the standards the agencies are proposing for MY 2017-2025 are not multi-attribute standards, that is the target is only a function of footprint, we are proposing curve shapes that were developed considering more than one attribute.

[o] These parameters directly relate to the amount of energy required to move the vehicle. As compared to a lighter vehicle, more energy is required to move a heavier vehicle the same distance. Similarly, a more powerful engine, when technology adjusted, is less efficient than a less powerful engine.

correlation between HP/WT, weight and CO_2 emissions (R^2=0.78, Table 2-1) after accounting for technology adjustments.[p]

Equation 2-1 – Relationship between vehicle attributes and emissions or fuel consumption

$$\mathrm{CO2i\ or\ GPMi} = \beta_{hp/wt}\left(\frac{\mathrm{Horsepower}}{\mathrm{Weight}}\right)_i + \beta_{weight}\mathrm{Weight}_i + C$$

Where:

HP/Weight= the rated horsepower of the vehicle divided by the curb weight
Weight = the curb weight of the vehicle in pounds
C = a constant.

Table 2-1 – Physical Regression Coefficients against Technology Adjusted CO_2*

	Cars	Light Trucks
R^2	0.78	0.78
F-test p	<0.01	<0.01
$\beta_{hp/wt}$	$1.09*10^3$	$1.13*10^3$
β_{weight}	$3.29*10^{-2}$	$3.45*10^{-2}$
C	-3.29	2.73

*In this gasoline only fleet, these coefficients can be divided by 8887 (the amount of CO2 produced by the combustion of a gallon of the fuel used to certify the fuel economy and emissions of gasoline vehicles) to yield the corresponding fuel consumption coefficients.

The coefficients above show, for the agencies' MY 2008-based market forecast, strong correlation between these vehicle attributes and the fuel consumption and emissions of the vehicle, as well as strong similarity between car and truck coefficients. Given these very similar parameters, similar distributions of power and weight would be expected to produce similarly arrayed plots of CO_2 (or equivalently, fuel consumption) by footprint, regardless of car or truck class. Based on the differences seen in the technology-adjusted plot (Figure 2-2), the agencies further investigated these particular attributes and their relationship to footprint in the agencies' MY 2008-based market forecast, to examine the differences across the footprint distribution. Figure 2-3 shows vehicle curb weight charted against footprint, with sales weighted ordinary least squares sales fit (blue) and sales-weighted LOESS fit (red)

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[p] As R^2 does not equal 1, there are remaining unaccounted for differences beyond technology, power and weight. These may include gear ratios, axle ratios, aerodynamics, and other vehicle features not captured in this equation.

imposed. For cars, the LOESS fit, which weights nearby points more heavily, [q] is nearly identical to the linear fit in the data filled region between about 40 and 56 sq ft (with the gray bar showing standard error on the Loess fit). For this market forecast, average car curb weight is linearly proportional to car footprint between 40 and 56 sq ft, or in other words, cars progress in weight in a regular fashion as they get larger (Figure 2-3). By contrast, a linear fit does not overlap with the LOESS fit on the truck side, which indicates that for this market forecast, truck curb weight does not linearly increase with footprint, at least not across the entire truck fleet. The LOESS fit shows that larger trucks (those on the right side of the data bend in Figure 2-2) have a different trend than smaller trucks, and after about 55 sq ft, no longer proportionally increases in weight. The same pattern is seen in Figure 2-1 and Figure 2-2 above.

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[q]: "In a [LOESS] Fit, fitting is done locally. That is, for the fit at point *x*, the fit is made using points in a neighborhood of *x*, weighted by their distance from *x* (with differences in 'parametric' variables being ignored when computing the distance). The size of the neighborhood is controlled by *α* For *α* < *1*, the neighborhood includes proportion *α* of the points, and these have tricubic weighting (proportional to *(1 - (dist/maxdist)^3)^3*. For *α* > *1*, all points are used, with the 'maximum distance' assumed to be *α^1/p* times the actual maximum distance for *p* explanatory variables."
A span of 1 was used in these images. http://cran.r-project.org/doc/manuals/fullrefman.pdf

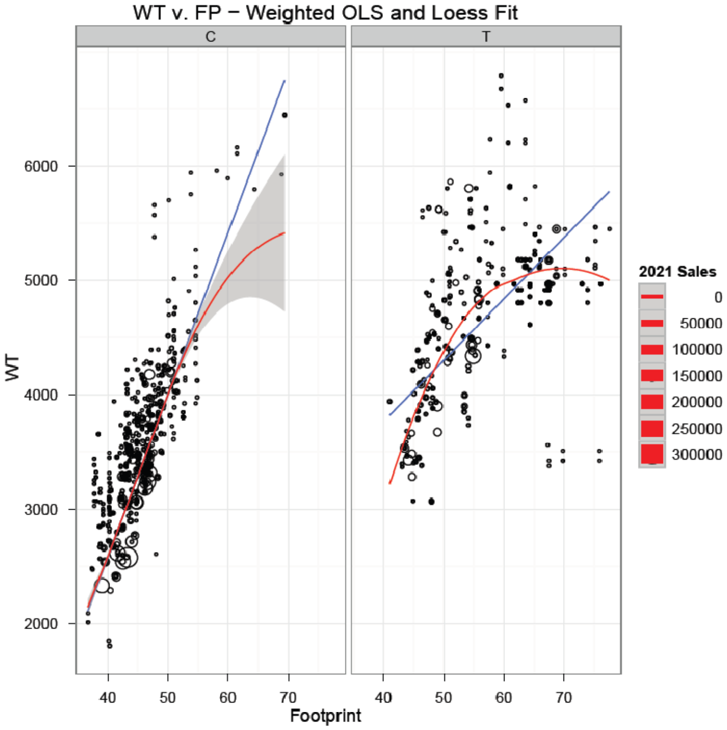

Figure 2-3 Relationship between Weight and Footprint in Agencies' MY2008-Based Market Forecast

To further pursue this topic, weight divided by footprint (WT/FP) can be thought of as a "density" of a vehicle (although dimensionally it has units of pressure). As seen in Figure 2-4, the trend in WT/FP in the agencies' MY2008-based market forecast is different in trucks than in cars. The linear trend on cars is an increase in WT/FP as footprint increases (Figure 2-4). In contrast, light trucks do not consistently increase in WT/FP ratio as the vehicles grow larger, but WT/FP actually decreases (Figure 2-4).

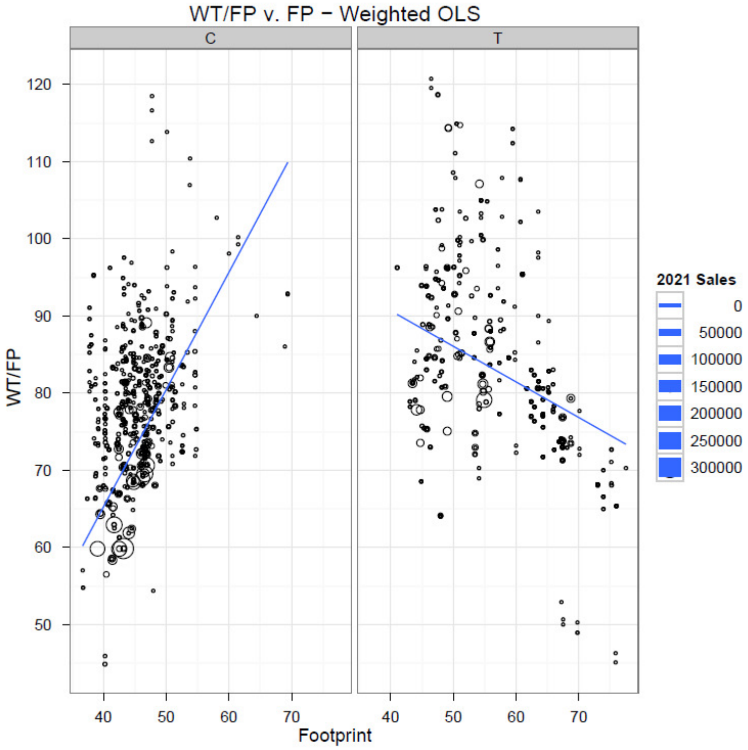

Figure 2-4 Relationship between Weight/FP and Footprint in Agencies' MY2008-Based Market Forecast

The heterogeneity of the truck fleet explains part of the WT/FP trend, where the pickup truck fleet is largest in footprint, but is also relatively light for its size due to the flat bed (Figure 2-5). Note that the two light truck classes with the smallest WT/FP ratios are small and large pickups. Further, as the only vehicle class with a sales-weighted average footprint above 60 square feet, the large pickup trucks have a strong influence on the slope of the truck curve. As the correlation between weight and CO_2 is strong (Table 2-1), having proportionally lighter vehicles at one extreme of the footprint distribution can bias a curve fit to these vehicles. If no adjustment is made to the curve fitted to the truck fleet, and no other compensating flexibilities or adjustments are made available, manufacturers selling significant numbers of vehicles at the large end of the truck distribution will face compliance burdens that are comparatively more challenging that those faced by manufacturers not serving this part of the light truck market. As noted further below, this consideration underlies the agencies' proposal to change the cutpoint for larger light trucks from 66 feet to 74 feet, and to steepen the slope of the light truck curve for larger light trucks.

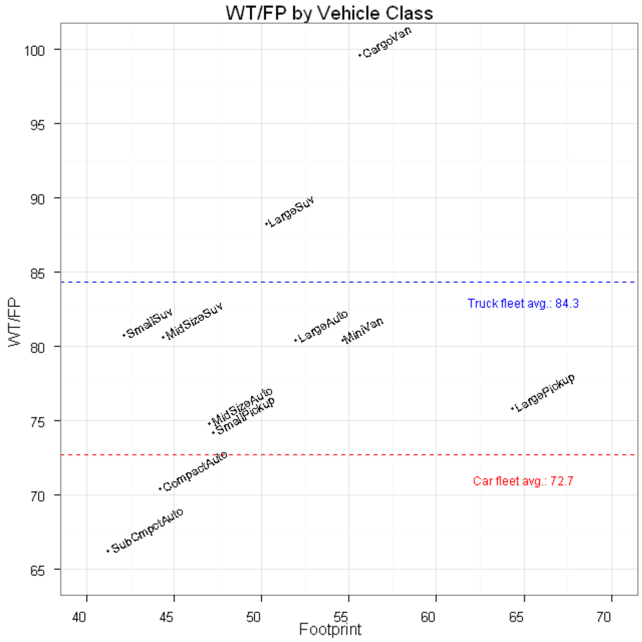

Figure 2-5 Class and the WT/FP distribution

The agencies also investigated the relationship between HP/WT and footprint in the agencies' MY2008-based market forecast (Figure 2-6). On a sales weighted basis, cars tend to become proportionally more powerful as they get larger. In contrast, there is a minimally positive relationship between HP/WT and footprint for light trucks, indicating that light trucks become only slightly more powerful as they get larger, but that the trend is not especially pronounced.

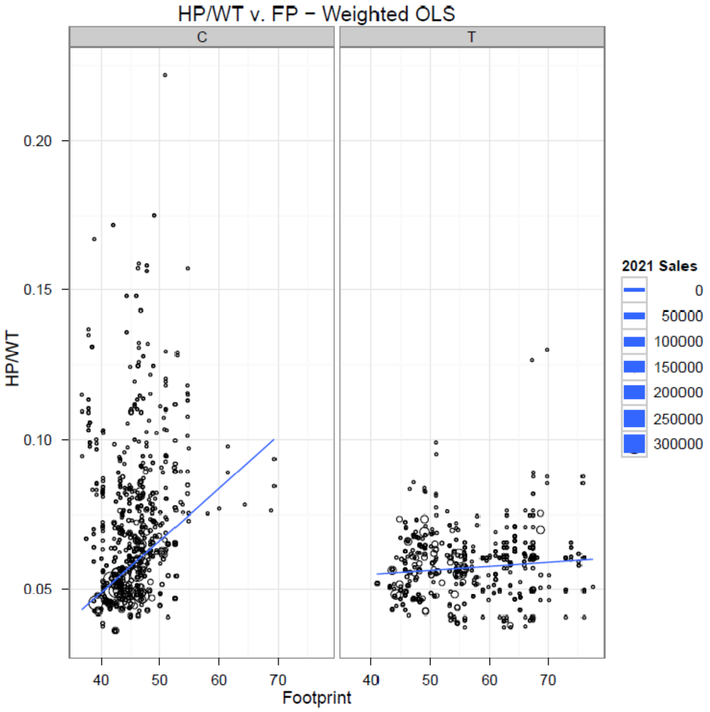

Figure 2-6 HP/WT v. FP

One factor influencing results of this analysis is the non-homogenous nature of the truck fleet; some vehicles at the smaller end of the footprint curve are different in design and utility from others at the larger end (leading to the observed bend in the LOESS fit, Figure 2-6). There are many high volume four-wheel drive vehicles with smaller footprint in the truck fleet (such as the Chevrolet Equinox, Dodge Nitro, Ford Escape, Honda CR-V, Hyundai Santa Fe, Jeep Liberty, Nissan Rogue, Toyota RAV4, and others) exhibit only select truck characteristics.[r] By contrast, the largest pickup trucks in the light truck fleet have unique aerodynamic and power characteristics that tend to increase CO_2 emissions and fuel consumption. These disparities contribute to the slopes of lines fitted to the light truck fleet.

The agencies technical analyses of regulatory alternatives developed using curves fitted as described below supported OEM comments that there will be significant compliance challenges for the manufacturers of large pickup trucks, and supported the agencies' policy goal of a steeper slope for the light truck curve. Consequently, the agencies considered options including fitting curves developed using results of the analysis described above.. Specifically, the agencies note that the WT/FP ratio of the light duty fleet potentially has a

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[r] In most cases, these vehicles have four wheel drive, but no significant towing capability, and no open-bed. Many of these vehicles are also offered without four wheel drive, and these two wheel drive versions are classified as passenger cars, not light trucks.

large impact on a sales weighted regression.[s] The increasing trend in WT/FP versus footprint for cars in the 2008 MY baseline would steepen the slope of the car curve, while the decreasing trend in WT/FP would flatten the truck slope, as compared to a WT/FP adjusted fleet. This result was reflected in the MYs 2012-2016 final rulemaking,[10] where the agencies noted the steep car curves resulting from a weighted least squares analysis.

Based on the above analysis, the agencies also considered adjustments for other differences between vehicle models. Therefore, utilizing the coefficients derived in Equation 2-1, the agencies also evaluated curve fitting approaches through which fuel consumption and CO_2 levels were adjusted with respect to weight-to-footprint alone, and in combination with power-to-weight. This adjustment procedure inflates or deflates the fuel economy or CO_2 emissions of each vehicle model based on the extent to which one of the vehicle's attributes, such as power, is higher or lower than average. As mentioned above, while the agencies considered this technique for purposes of fitting curves, the agencies are not proposing a multi-attribute standard, as the proposed fuel economy and CO_2 targets for each vehicle are still functions of footprint alone. No adjustment would be used in the compliance process.

The basis for the gallon-per-mile (GPM) adjustments is the sales-weighted linear regression discussed in 2.4 (Equation 2-1, Table 2-1). The coefficients to this equation give the impact of the various car attributes on CO_2 emissions and fuel consumption in the agencies' MY 2008-based market forecast. For example, β_{weight} gives the impact of weight while holding the ratio horsepower to weight constant. Importantly, this means that as weight changes, horsepower must change as well to keep the power/weight ratio constant. Similarly, $\beta_{\mathrm{hp/wt}}$ gives the CO_2 impact of changing the performance of the vehicle while keeping the weight constant. These coefficients were used to perform an adjustment of the gallons per mile measure for each vehicle to the respective car or truck—*i.e.,* in the case of a HP/WT adjustment, to deflate or inflate the fuel consumption of each vehicle model based on the extent to which the vehicle's power-to-weight ratio is above or below the regression-based value at that footprint.

The agencies performed this normalization to adjust for differences in vehicle weight per square foot observations in the data discussed in Section 2.4. This adjustment process requires two pieces of information: the weight coefficient from Equation 2-1 and the average weight per footprint (*i.e.*, pounds per square foot) for that vehicle's group. Two groups, passenger cars and light trucks, were used. For each group, the average weight per footprint was calculated as a weighted average with the weight being the same as in the above regression (projected sales by vehicle in 2021). The equation below indicates how this adjustment was carried out.

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[s] As mentioned above, the agencies also performed the same analysis without sales weighting, and found that the WT/FP ratio also had a directionally similar effect on the fitted car and truck curves.

Equation 2-2 WT/FP adjustment

$$\text{Weight per Footprint Adjusted GPM}_i \text{ or CO2i} = \text{GPM}_i - \left(\text{Weight}_i - \frac{\overline{\text{Weight}}}{\text{Footprint}} \times \text{Footprint}_i\right) \times \beta_{\text{weight}}$$

The term in parentheses represents the vehicle's deviation from an "expected weight." That is, multiplying the average weight per footprint for a group of vehicles (cars or trucks) by a specific vehicle's footprint gives an estimate of the weight of that specific vehicle if it's density were "average," based on the MY 2008 fleet. Put another way, this factor represents what the weight is "expected" to be, given the vehicle's footprint, and based on the MY 2008 fleet. This "expected weight" is then subtracted from the vehicle's actual weight. Vehicles that are heavier than their "expected weight" will receive a positive value (*i.e.*, a deflated fuel economy value) here, while vehicles that are lighter than their "expected weight" will receive a negative number (*i.e.*, an inflated fuel economy value).

This deviation from "expected weight" is then converted to a gallon value by the regression coefficient. The units on this coefficient are gallons per mile per pound, as can be deduced from equation 1. This value is then subtracted from the vehicle's actual gallons per mile measure. Note that the adjusted truck data no longer exhibits the bend seen in Figure 2-1 and Figure 2-2.

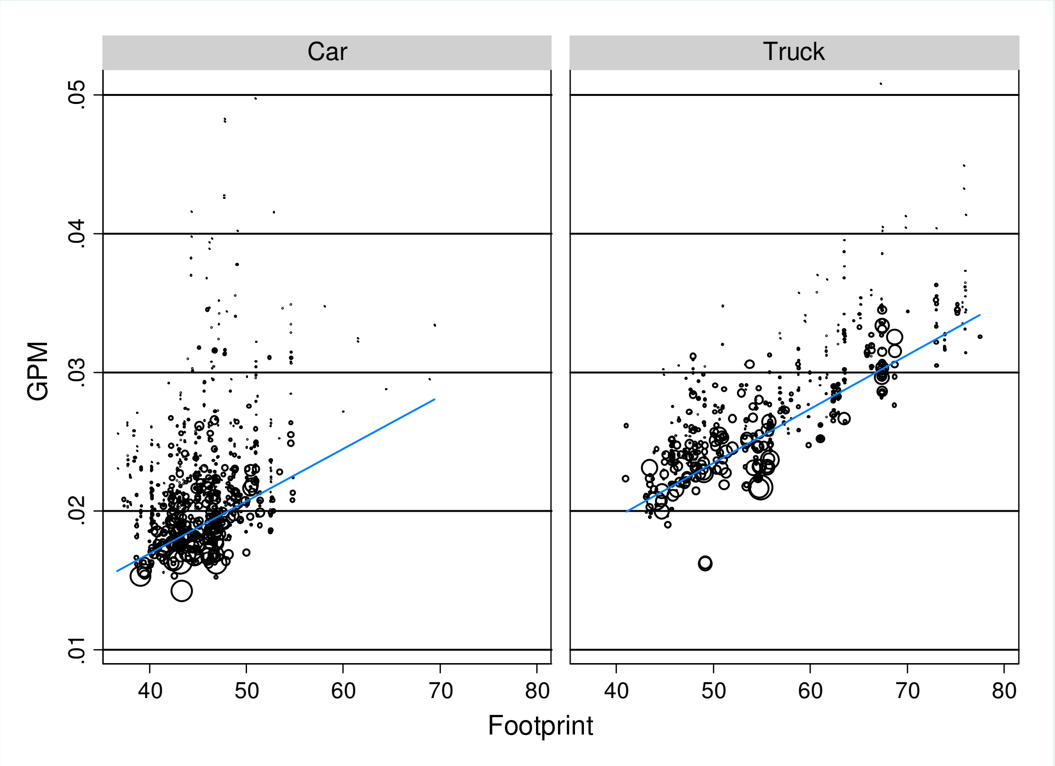

Figure 2-7 WT/FP Adjusted Fuel Consumption vs. Footprint

This adjustment serves to reduce the variation in gallons per mile measures caused by variation in weight in the agencies' MY 2008-based market forecast. Importantly, this adjustment serves to reduce the fuel consumption (*i.e.*, inflate fuel economy) for those vehicles which are heavier than their footprint would suggest while increasing the gallons per mile measure (*i.e.*, deflating fuel economy) for those vehicles which are lighter. For trucks, a linear trend is more evident in the data cloud.[t] The following table shows the degree of adjustment for several vehicle models:

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[t] Using EPA's dataset, R^2 for the sales weighted ordinary least squared linear fit between footprint and CO_2 improved from 0.38 (technology adjusted CO_2) to 0.64 (technology and weight / footprint adjusted CO_2)

Table 2-2 - Sample Adjustments for Weight to Footprint, Cars

Manufacturer	Model	Name Plate	Weight / Footprint	Footprint	GPM	MPG	Adjusted GPM	Adjusted MPG	GPM % Adjustment
HONDA	HONDA FIT	FIT	64.4	39.5	0.01	69.40	0.0157	63.73	8.9%
TOYOTA	TOYOTA COROLLA	COROLLA	61.3	42.5	0.01	69.94	0.0164	60.80	15.0%
FORD	FORD FOCUS	FOCUS FWD	62.9	41.7	0.02	61.94	0.0177	56.34	9.9%
GENERAL MOTORS	CHEVROLET MALIBU	MALIBU	73.5	46.9	0.02	53.70	0.0185	54.08	-0.7%
HONDA	HONDA ACCORD	ACCORD 4DR SEDAN	69.6	46.6	0.02	57.57	0.0179	55.73	3.3%
NISSAN	INFINITI G37	G37 COUPE	76.7	47.6	0.02	47.83	0.0200	50.08	-4.5%
GENERAL MOTORS	CHEVROLET CORVETTE	CORVETTE	69.3	46.3	0.02	40.84	0.0251	39.83	2.5%
FORD	FORD MUSTANG	MUSTANG	74.7	46.7	0.03	31.32	0.0316	31.67	-1.1%
TOYOTA	TOYOTA CAMRY	CAMRY SOLARA CONVERTIBLE	75.6	46.9	0.02	50.87	0.0191	52.27	-2.7%
VOLKSWAGEN	VOLKSWAGEN JETTA	JETTA	78.0	42.4	0.02	46.77	0.0211	47.47	-1.5%
FORD	FORD FUSION	FUSION FWD	72.2	46.1	0.02	59.96	0.0168	59.61	0.6%
HONDA	HONDA ACCORD	ACCORD 2DR COUPE	71.6	46.6	0.02	56.92	0.0178	56.26	1.2%
HYUNDAI	HYUNDAI SONATA	SONATA	70.7	46.0	0.02	61.72	0.0166	60.34	2.3%
HONDA	HONDA CIVIC	CIVIC	59.9	43.2	0.02	64.25	0.0177	56.38	14.0%

Table 2-3 – Sample Adjustments for Weight to Footprint, Trucks

Manufacturer	Model	Name Plate	Weight / Footprint	Footprint	GPM	MPG	Adjusted GPM	Adjusted MPG	GPM % Adjustment
FORD	FORD ESCAPE	ESCAPE FWD	80.1	65.2	0.02	51.00	0.0181	55.11	-7.5%
GENERAL MOTORS	CHEVROLET C15	C15 SILVERADO 2WD 119WB	85.9	55.9	0.03	39.76	0.0248	40.29	-1.3%
FIAT	JEEP GRAND CHEROKEE	GRAND CHEROKEE 4WD	103.7	47.1	0.02	41.45	0.0222	44.98	-7.9%
HONDA	HONDA PILOT	PILOT 4WD	85.2	51.3	0.02	40.95	0.0243	41.22	-0.6%
TOYOTA	TOYOTA HIGHLANDER	HIGHLANDER 4WD	79.6	49.0	0.02	45.90	0.0227	44.05	4.2%
FORD	FORD F150	F150 FFV 4WD 145 WB	73.8	67.4	0.03	32.70	0.0334	29.97	9.1%
FIAT	DODGE RAM	RAM 1500 PICKUP 4WD 140 WB	78.1	66.3	0.03	33.75	0.0316	31.65	6.6%
TOYOTA	TUNDRA	TOYOTA TUNDRA 4WD 145 WB	79.3	68.7	0.03	32.07	0.0325	30.73	4.3%
TATA	LAND ROVER RANGE ROVER SPORT	RANGE ROVER SPORT	118.6	47.5	0.03	33.17	0.0239	41.92	-20.9%
GENERAL MOTORS	CHEVROLET UPLANDER	UPLANDER FWD	114.4	49.2	0.02	45.46	0.0163	61.34	-25.9%
GENERAL MOTORS	HUMMER H3	H3 4WD	99.9	50.7	0.03	36.71	0.0242	41.30	-11.1%
GENERAL MOTORS	PONTIAC TORRENT	TORRENT FWD	84.2	48.2	0.02	46.64	0.0215	46.56	0.2%
TOYOTA	TACOMA	TOYOTA TACOMA 4WD	74.8	53.4	0.02	43.01	0.0252	39.63	8.5%

Based on Equation 2-1, the agencies also evaluated an adjustment of GPM and CO_2 based on HP/WT.

Equation 2-3 –Adjustment based on HP/WT

$$\frac{\mathrm{HP}}{\mathrm{WT}}\text{adjusted } \mathrm{GPM_i} \text{ or } \mathrm{CO2_i} = \mathrm{GPM_i} - \left(\frac{\mathrm{HP_i}}{\mathrm{WT_i}} - \overline{\frac{\mathrm{HP}}{\mathrm{WT}}}\right) \times \beta_{\mathrm{HP/WT}}$$

Figure 2-8 shows the adjusted data and the estimated relationship between the adjusted GPM values and footprint.

Table 2-4 shows the degree of adjustment for several vehicle models. Those vehicles which have more power than average for their actual curb weight are adjusted downward (*i.e.*, fuel economy ratings are inflated), while those that have less power than average are adjusted upward (*i.e.*, fuel economy ratings are deflated).

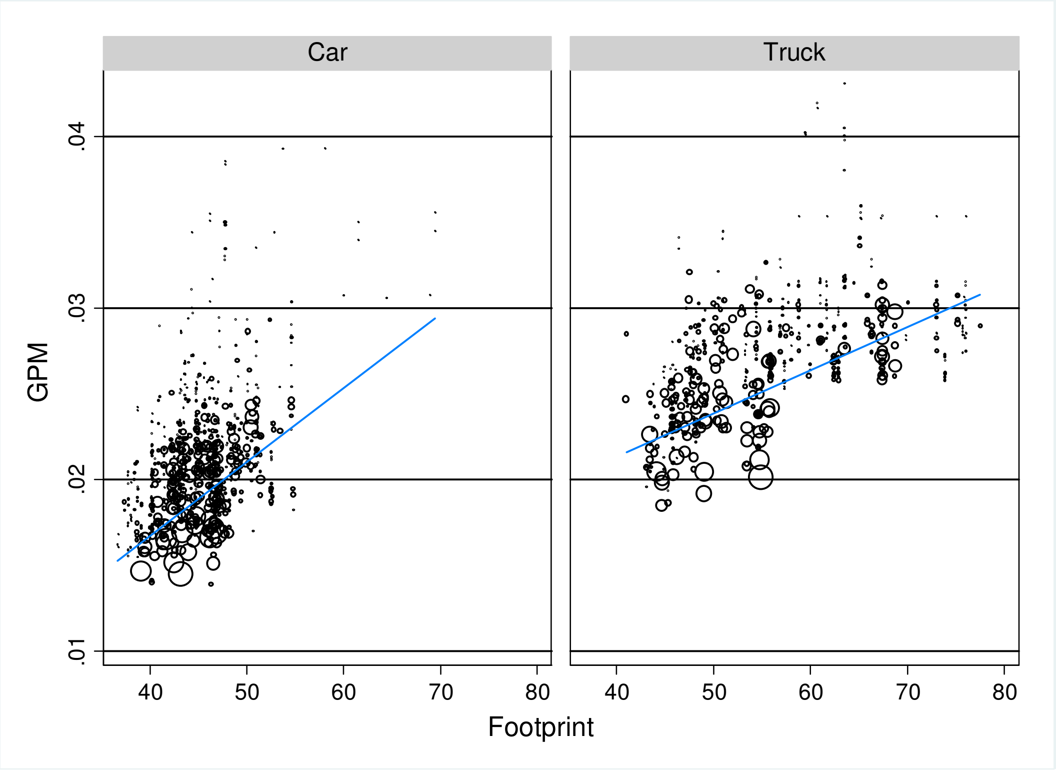

Figure 2-8 HP/WT Adjusted Fuel Consumption v. Footprint

Table 2-4 - Sample Adjustments for Horsepower to Weight, Cars

Manufacturer	Model	Name Plate	Horsepower	Footprint	GPM	MPG	Adjusted GPM	Adjusted MPG	GPM % Adjustment
HONDA	HONDA FIT	FIT	109	39.5	0.01	69.40	0.0157	63.73	8.9%
TOYOTA	TOYOTA COROLLA	COROLLA	126	42.5	0.01	69.94	0.0164	60.80	15.0%
FORD	FORD FOCUS	FOCUS FWD	140	41.7	0.02	61.94	0.0177	56.34	9.9%
GENERAL MOTORS	CHEVROLET MALIBU	MALIBU	169	46.9	0.02	53.70	0.0185	54.08	-0.7%
HONDA	HONDA ACCORD	ACCORD 4DR SEDAN	190	46.6	0.02	57.57	0.0179	55.73	3.3%
NISSAN	INFINITI G37	G37 COUPE	330	47.6	0.02	47.83	0.0200	50.08	-4.5%
GENERAL MOTORS	CHEVROLET CORVETTE	CORVETTE	400	46.3	0.02	40.84	0.0251	39.83	2.5%
FORD	FORD MUSTANG	MUSTANG	500	46.7	0.03	31.32	0.0316	31.67	-1.1%
TOYOTA	TOYOTA CAMRY	CAMRY SOLARA CONVERTIBLE	225	46.9	0.02	50.87	0.0191	52.27	-2.7%
VOLKSWAGEN	VOLKSWAGEN JETTA	JETTA	170	42.4	0.02	46.77	0.0211	47.47	-1.5%
FORD	FORD FUSION	FUSION FWD	160	46.1	0.02	59.96	0.0168	59.61	0.6%
HONDA	HONDA ACCORD	ACCORD 2DR COUPE	190	46.6	0.02	56.92	0.0178	56.26	1.2%
HYUNDAI	HYUNDAI SONATA	SONATA	162	46.0	0.02	61.72	0.0166	60.34	2.3%
HONDA	HONDA CIVIC	CIVIC	140	43.2	0.02	64.25	0.0177	56.38	14.0%

Table 2-5 - Sample Adjustments for Horsepower to Weight, Trucks

Manufacturer	Model	Name Plate	Horsepower	Footprint	GPM	MPG	Adjusted GPM	Adjusted MPG	GPM % Adjustment
FORD	FORD ESCAPE	ESCAPE FWD	153	65.2	0.02	51.00	0.0181	55.11	-7.5%
GENERAL MOTORS	CHEVROLET C15	C15 SILVERADO 2WD 119WB	195	55.9	0.03	39.76	0.0248	40.29	-1.3%
FIAT	JEEP GRAND CHEROKEE	GRAND CHEROKEE 4WD	210	47.1	0.02	41.45	0.0222	44.98	-7.9%
HONDA	HONDA PILOT	PILOT 4WD	244	51.3	0.02	40.95	0.0243	41.22	-0.6%
TOYOTA	TOYOTA HIGHLANDER	HIGHLANDER 4WD	270	49.0	0.02	45.90	0.0227	44.05	4.2%
FORD	FORD F150	F150 FFV 4WD 145 WB	300	67.4	0.03	32.70	0.0334	29.97	9.1%
FIAT	DODGE RAM	RAM 1500 PICKUP 4WD 140 WB	345	66.3	0.03	33.75	0.0316	31.65	6.6%
TOYOTA	TUNDRA	TOYOTA TUNDRA 4WD 145 WB	381	68.7	0.03	32.07	0.0325	30.73	4.3%
TATA	LAND ROVER RANGE ROVER SPORT	RANGE ROVER SPORT	300	47.5	0.03	33.17	0.0239	41.92	-20.9%
GENERAL MOTORS	CHEVROLET UPLANDER	UPLANDER FWD	240	49.2	0.02	45.46	0.0163	61.34	-25.9%
GENERAL MOTORS	HUMMER H3	H3 4WD	242	50.7	0.03	36.71	0.0242	41.30	-11.1%
GENERAL MOTORS	PONTIAC TORRENT	TORRENT FWD	185	48.2	0.02	46.64	0.0215	46.56	0.2%
TOYOTA	TACOMA	TOYOTA TACOMA 4WD	236	53.4	0.02	43.01	0.0252	39.63	8.5%

The agencies seek comment on the appropriateness of these adjustments, particularly regarding whether these adjustments suggest that standards should be defined in terms of other attributes in addition to footprint, and whether they may encourage changes other than encouraging the application of technology to improve fuel economy and reduce CO_2 emissions. The agencies also seek comment regarding whether these adjustments effectively “lock in” through MY 2025 relationships that were observed in MY 2008.

The above approaches resulted in three data sets each for (a) vehicles without added technology and (b) vehicles with technology added to reduce technology differences, any of which may provide a reasonable basis for fitting mathematical functions upon which to base the slope of the standard curves: (1) vehicles without any further adjustments; (2) vehicles with adjustments reflecting differences in “density” (weight/footprint); and (3) vehicles with adjustments reflecting differences in “density,” and adjustments reflecting differences in performance (power/weight).

2.4.2.3 What statistical methods did the agencies evaluate?

Using these data sets, the agencies tested a range of regression methodologies, each judged to be possibly reasonable for application to at least some of these data sets.

2.4.2.3.1 Regression Approach

In the MYs 2012-2016 final rules, the agencies employed a robust regression approach (minimum absolute deviation, or MAD), rather than an ordinary least squares (OLS) regression.[11] MAD is generally applied to mitigate the effect of outliers in a dataset, and thus was employed in that rulemaking as part of our interest in attempting to best represent the underlying technology. NHTSA had used OLS in early development of attribute-based CAFE standards, but NHTSA (and then NHTSA and EPA) subsequently chose MAD instead of OLS for both the MY 2011 and the MYs 2012-2016 rulemakings. These decisions on regression technique were made both because OLS gives additional emphasis to outliers[12] and because the MAD approach helped achieve the agencies' policy goals with regard to curve slope in those rulemakings.[13] In the interest of taking a fresh look at appropriate regression methodologies as promised in the 2012-2016 light duty rulemaking, in developing this proposal, the agencies gave full consideration to both OLS and MAD. The OLS representation, as described, uses squared errors, while MAD employs absolute errors and thus weights outliers less.

As noted, one of the reasons stated for choosing MAD over least square regression in the MYs 2012-2016 rulemaking was that MAD reduced the weight placed on outliers in the data. As seen in Figure 2-1, there clearly are some outliers in the data, mostly to the high CO_2 and fuel consumption side. However, the agencies have further considered whether it is appropriate to classify these vehicles as outliers. Unlike in traditional datasets, these vehicles' performance is not mischaracterized due to errors in their measurement, a common reason for outlier classification. Being certification data, the chances of large measurement errors should be near zero, particularly towards high CO_2 or fuel consumption. Thus, they can only be outliers in the sense that the vehicle designs are unlike those of other vehicles. These outlier vehicles may include performance vehicles, vehicles with high ground clearance, 4WD, or boxy designs. Given that these are equally legitimate on-road vehicle designs, the agencies concluded that it would appropriate to reconsider the treatment of these vehicles in the regression techniques.

Based on these considerations as well as the adjustments discussed above, the agencies concluded it was not meaningful to run MAD regressions on gpm data that had already been adjusted in the manner described above. Normalizing already reduced the variation in the data, and brought outliers towards average values. This was the intended effect, so the agencies deemed it unnecessary to apply an additional remedy to resolve an issue that had already been addressed, but we seek comment on the use of robust regression techniques under such circumstances.

2.4.2.3.2 Sales Weighting

Likewise, the agencies reconsidered employing sales-weighting to represent the data. As explained below, the decision to sales weight or not is ultimately based upon a choice about how to represent the data, and not by an underlying statistical concern. Sales weighting is used if the decision is made to treat each (mass produced) unit sold as a unique physical observation. Doing so thereby changes the extent to which different vehicle model types are emphasized as compared to a non-sales weighted regression. For example, while total General Motors Silverado (332,000) and Ford F-150 (322,000) sales differ by less than 10,000 in MY 2021 market forecast, 62 F-150s models and 38 Silverado models are reported in the agencies baselines. Without sales-weighting, the F-150 models, because there are more of them, are given 63 percent more weight in the regression despite comprising a similar portion of the marketplace and a relatively homogenous set of vehicle technologies.

The agencies did not use sales weighting in the 2012-2016 rulemaking analysis of the curve shapes. A decision to not perform sales weighting reflects judgment that each vehicle model provides an equal amount of information concerning the underlying relationship between footprint and fuel economy. Sales-weighted regression gives the highest sales vehicle model types vastly more emphasis than the lowest-sales vehicle model types thus driving the regression toward the sales-weighted fleet norm. For unweighted regression, vehicle sales do not matter. The agencies note that the light truck market forecast shows MY 2025 sales of 218,000 units for Toyota's 2WD Sienna, and shows 66 model configurations with MY 2025 sales of fewer than 100 units. Similarly, the agencies' market forecast shows MY 2025 sales of 267,000 for the Toyota Prius, and shows 40 model configurations with MY2025 sales of fewer than 100 units. Sales-weighted analysis would give the Toyota Sienna and Prius more than a thousand times the consideration of many vehicle model configurations. Sales-weighted analysis would, therefore, cause a large number of vehicle model configurations to be virtually ignored in the regressions.[14]

However, the agencies did note in the MYs 2012-2016 final rules that, "sales weighted regression would allow the difference between other vehicle attributes to be reflected in the analysis, and also would reflect consumer demand." [15] In reexamining the sales-weighting for this analysis, the agencies note that there are low-volume model types account for many of the passenger car model types (50 percent of passenger car model types account for 3.3 percent of sales), and it is unclear whether the engineering characteristics of these model types should equally determine the standard for the remainder of the market.

In the interest of taking a fresh look at appropriate methodologies as promised in the last final rule, in developing this proposal, the agencies gave full consideration to both sales-weighted and unweighted regressions.

2.4.2.3.3 Analyses Performed

We performed regressions describing the relationship between a vehicle's CO2/fuel consumption and its footprint, in terms of various combinations of factors: initial (raw) fleets with no technology, versus after technology is applied; sales-weighted versus non-sales weighted; and with and without two sets of normalizing factors applied to the observations. The agencies excluded diesels and dedicated AFVs because the agencies anticipate that advanced gasoline-fueled vehicles are likely to be dominant through MY2025.

These are depicted graphically in Figures 2-9 through 2-16, below.

Thus, the basic OLS regression on the initial data (with no technology applied) and no sales-weighting represents one perspective on the relation between footprint and fuel economy. Adding sales weighting changes the interpretation to include the influence of sales volumes, and thus steps away from representing vehicle technology alone. Likewise, MAD is an attempt to reduce the impact of outliers, but reducing the impact of outliers might perhaps be less representative of technical relationships between the variables, although that relationship may change over time in reality. Each combination of methods and data reflects a perspective, and the regression results simply reflect that perspective in a simple quantifiable manner, expressed as the coefficients determining the line through the average (for OLS) or the median (for MAD) of the data. It is left to policy makers to determine an appropriate perspective and to interpret the consequences of the various alternatives.

We invite comments on the application of the weights as described above, and the implications for interpreting the relationship between fuel efficiency and footprint.

2.4.2.4 What results did the agencies obtain?

Both agencies analyzed the same statistical approaches. For regressions against data including technology normalization, NHTSA used the CAFE modeling system, and EPA used EPA's OMEGA model. The agencies obtained similar regression results, and have based today's joint proposal on those obtained by NHTSA.

For illustrative purposes, the set of figures below show the range of curves determined by the possible combinations of regression technique, with and without sales weighting, with and without the application of technology, and with various adjustments to the gpm variable prior to running a regression. Again, from a statistical perspective, each of these regressions simply represents the assumptions employed. Since they are all univariate linear regressions, they describe the line that will result from minimizing the residuals or squared residuals. Figures show the results for passenger cars, then light trucks, for ordinary least squares (OLS) then similar results for MAD regressions for cars and light trucks, respectively. The various equations are represented by the string of attributes used to define the regression. See the table, Regression Descriptors, below, for the legend. Thus, for example, the line representing ols_LT_wt_ft_adj_init_w should be read as follows: an OLS regression, for light trucks, using data adjusted according to weight to footprint, no technology added, and weighted by sales.

Table 2-6 Regression Descriptors

Notation	Description
ols or mad	Ordinary least squares or mean absolute deviation
PC or LT	Passenger car or light truck
hp_wt_adj	Adjustment for horsepower to weight
wt_ft_adj	Adjustment for weight to footprint
wt_ft_hp_wt_adj	Adjustment for both horsepower to weight and weight to footprint
init or final	Vehicles with no technology (initial) or with technology added (final)
u or w	Unweighted or weighted by sales

Thus, the next figure, for example, represents a family of curves (lines) fit using ordinary least squares on data for passenger cars, not modified for technology, and which therefore permits comparisons of results in terms of the factors that change in each regression. These factors are whether the data are sales-weighted (denoted "w") or unweighted (denoted "u"), as well as the adjustments described above. Each of these adjustments has an influence on the regressions results, depicted in the figures below.

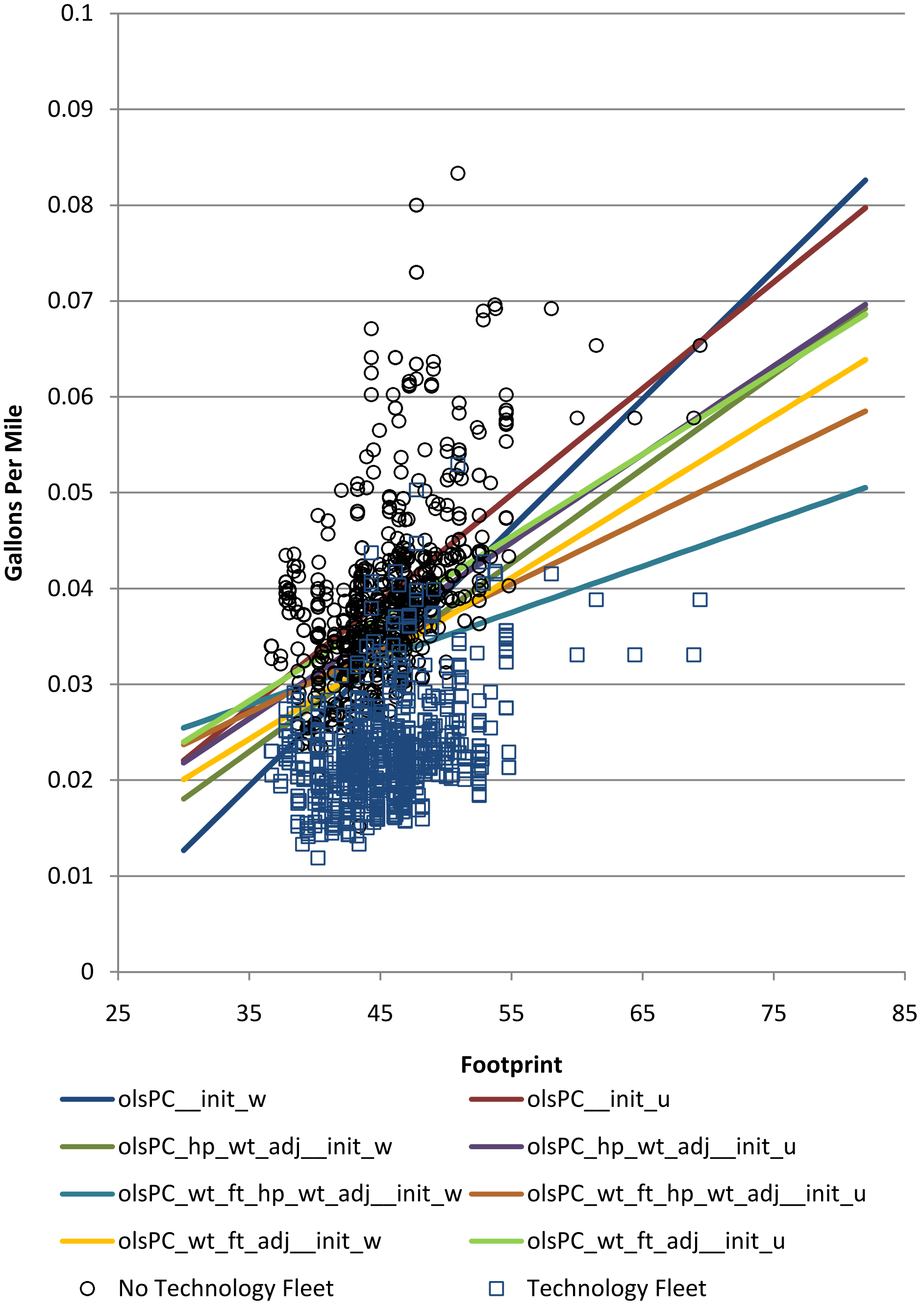

Figure 2-9 Best Fit Results for Various Regressions: Cars, No Added Technology, OLS

Figure 2-10, below, shows comparable results, this time with data representing the additional technology that has been added to reduce technological heterogeneity. Note that the data now pass through the relevant data "cloud" for the fleet with the technology adjustment applied. The slopes of the lines are somewhat more clustered (less divergent) in the chart depicting added technology (as discussed in footnote m)

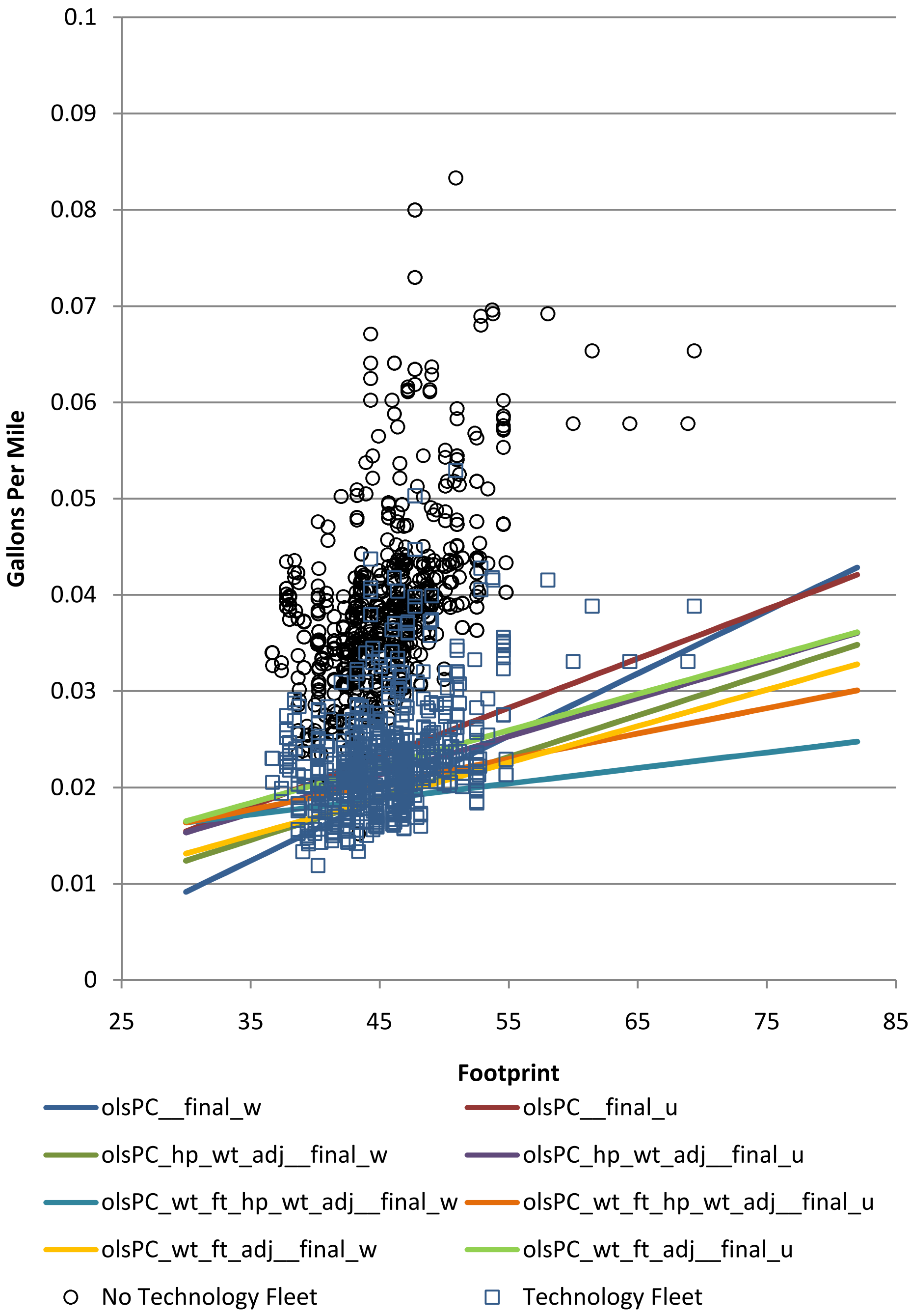

Figure 2-10 Best Fit Results for Various Regressions: Cars, with Added Technology, OLS

Similar to the figures displaying the results for passenger cars, the figures below display regression lines for trucks, first with no technology added, then subsequently, for the case where technology has been added. Slopes appear more similar to each other here than of passenger cars.

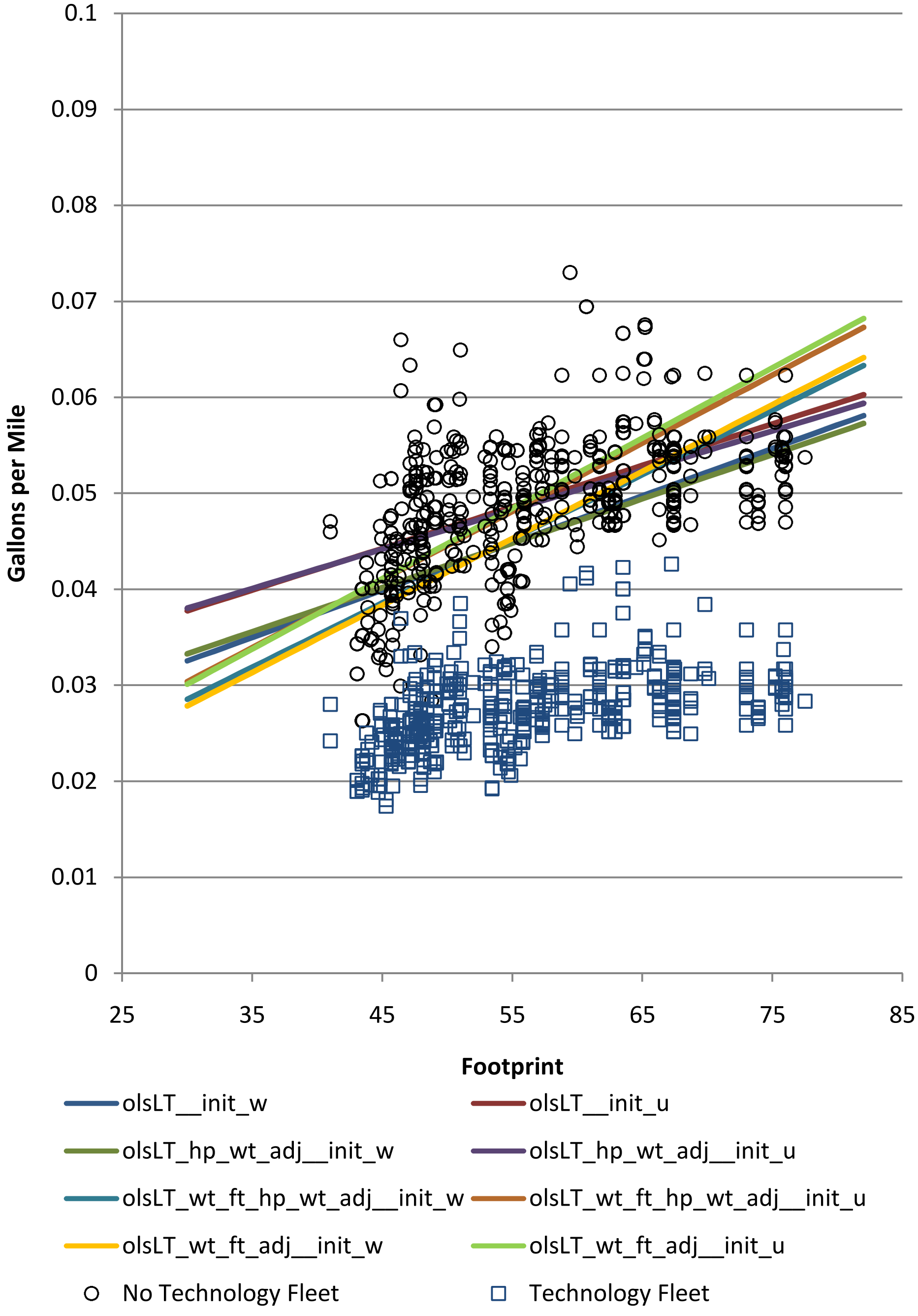

Figure 2-11 Best Fit Results for Various Regressions: Trucks, No Added Technology, OLS

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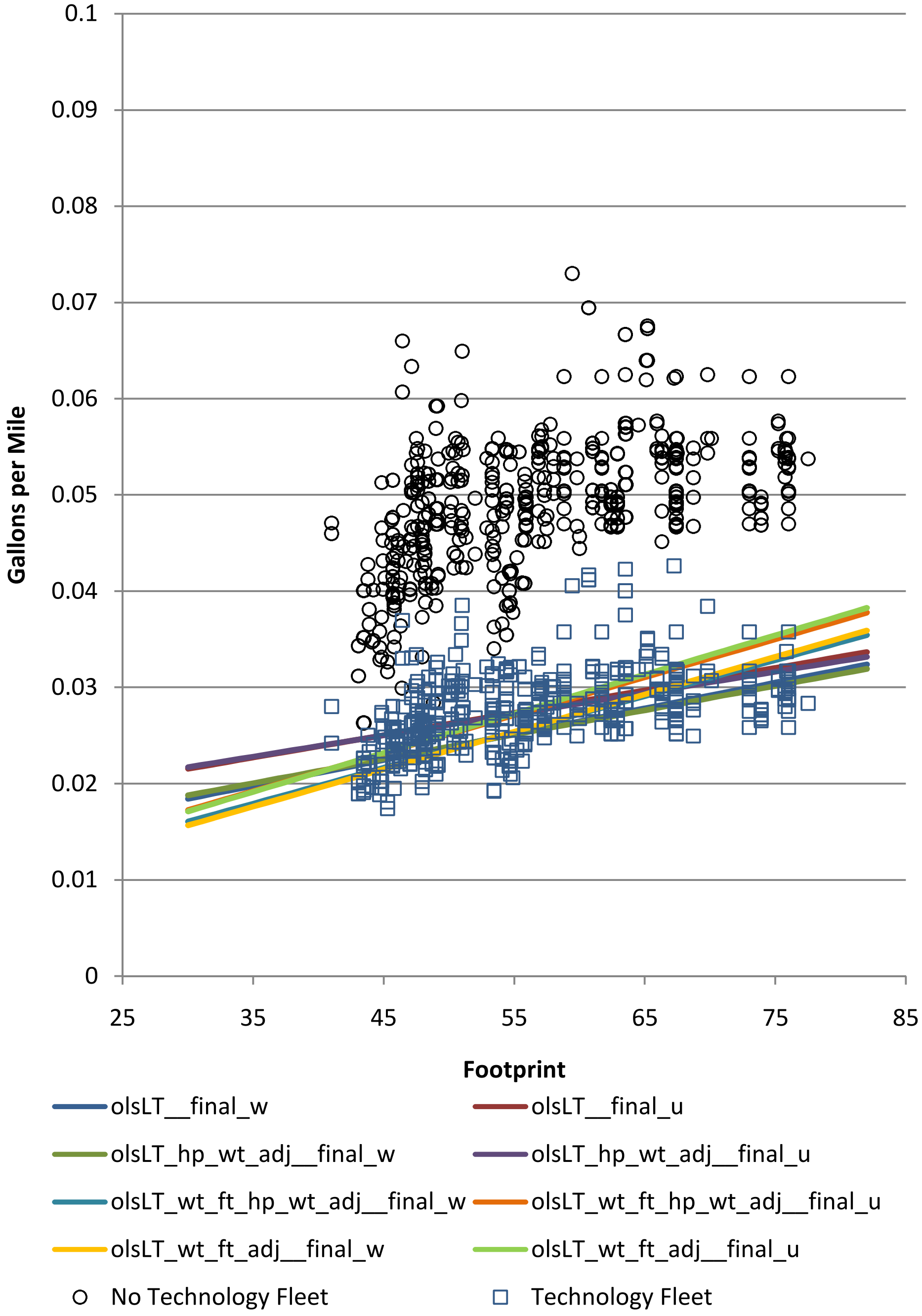

Figure 2-12 Best Fit Results for Various Regressions: Trucks, With Added Technology, OLS

Figure 2-13, below, displays regression results for the passenger car MAD fitted curves. The technology adjustment does not have, however, the same degree of impact in reducing the difference in the attained slopes (between those with and without the addition of technology) evidenced in the OLS regressions.

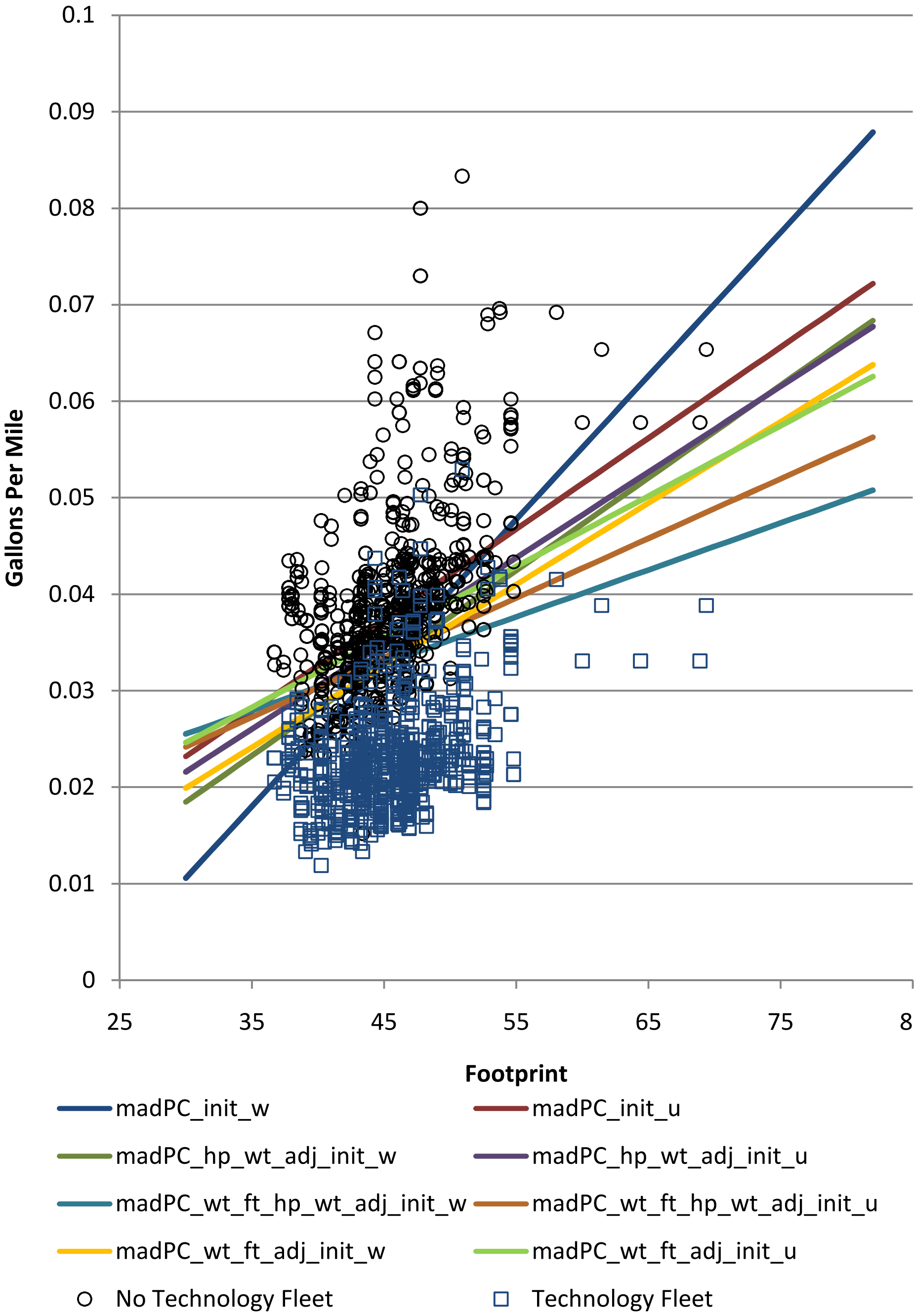

Figure 2-13 Best Fit Results for Various Regressions: Cars, No Added Technology, MAD

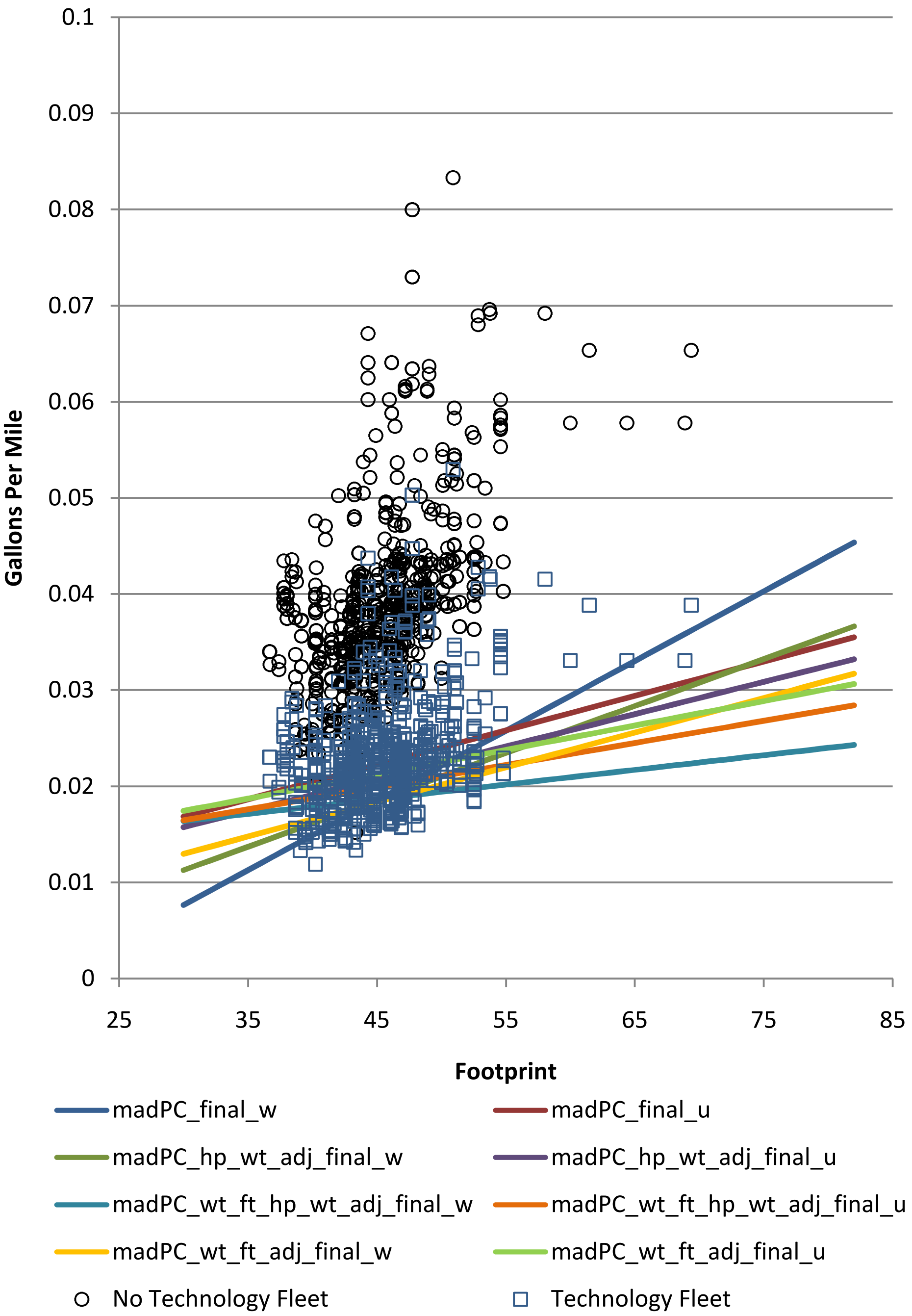

Figure 2-14 Best Fit Results for Various Regressions: Cars, Added Technology, MAD

The MAD regression results below in Figure 2-15 show a grouping of the fitted lines similar to that displayed in the OLS fits for trucks. As expected, an additional reduction in divergence is seen in the case where technology has been added, in Figure 2-15, which can be ascribed to the reduction in heterogeneity of the fleet brought about by the addition of the technology.

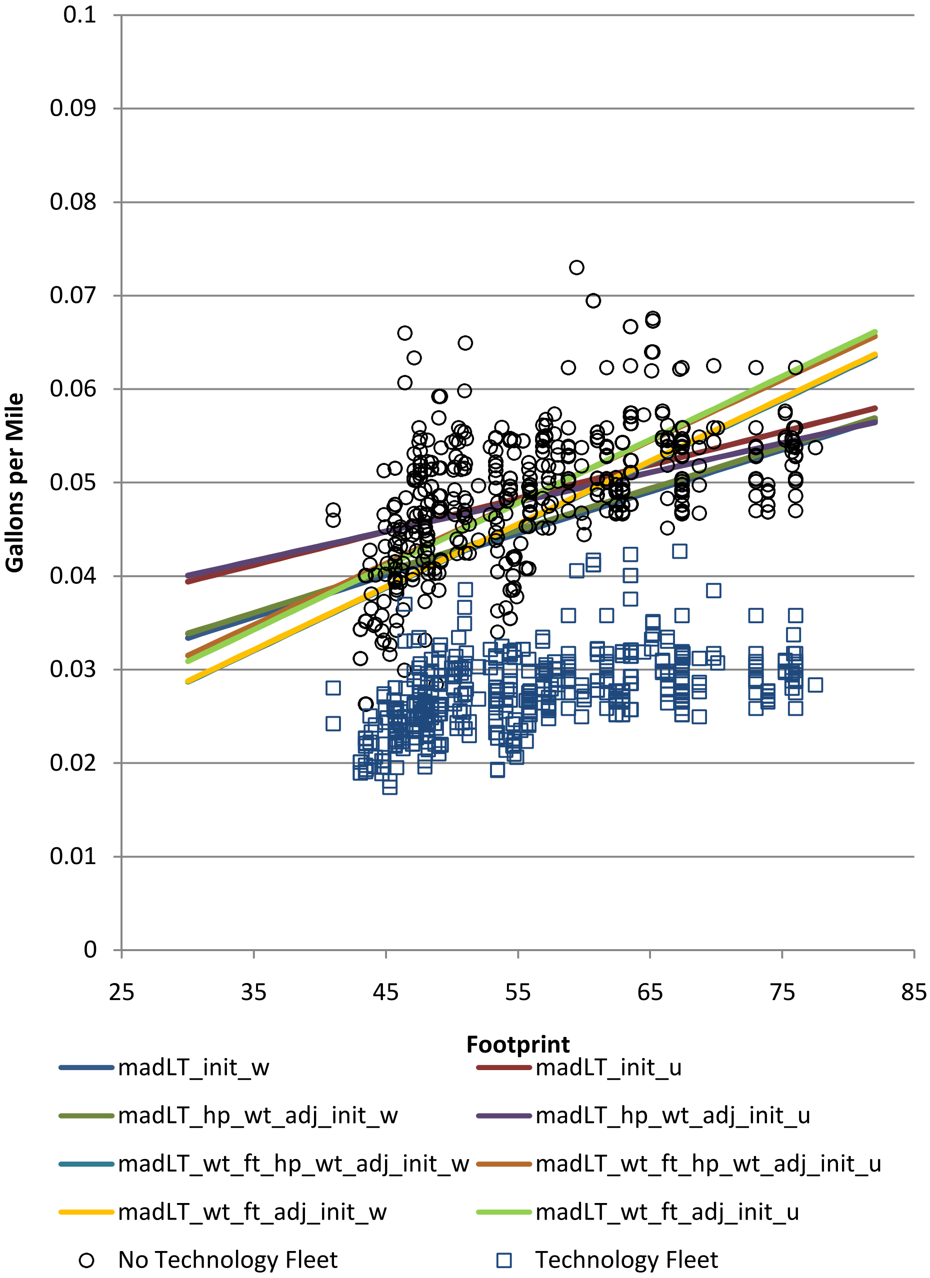

Figure 2-15 Best Fit Results for Various Regressions: Trucks, No Added Technology, MAD

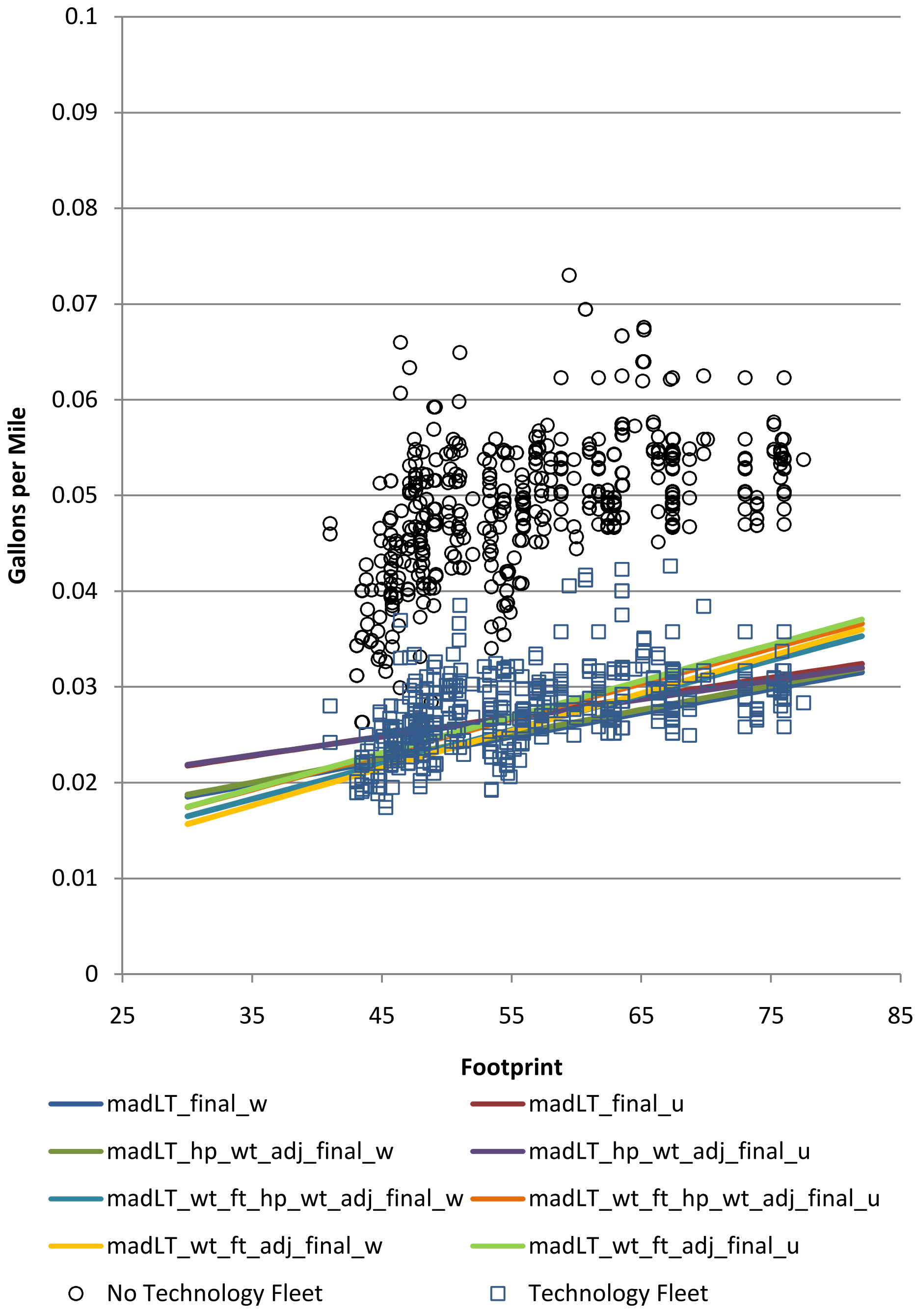

Figure 2-16 Best Fit Results for Various Regressions: Trucks, with Added Technology, MAD

2.4.2.5 Which methodology did the agencies choose for this proposal, and why is it reasonable?

The choice among the alternatives presented above was to use the OLS formulation, on sales-weighted data, using a fleet that has had technology applied, and after adjusting the data for the effect of weight-to-footprint, as described above. The agencies believe that this represents a technically reasonable approach for purposes of developing target curves to define the proposed standards, and that it represents a reasonable trade-off among various considerations balancing statistical, technical, and policy matters, which include the statistical representativeness of the curves considered and the steepness of the curve chosen. The agencies judge the application of technology prior to curve fitting to provide a reasonable means—one consistent with the rule's objective of encouraging manufacturers to add technology in order to increase fuel economy—of reducing variation in the data and thereby helping to estimate a relationship between fuel consumption/CO_2 and footprint.

Similarly, for the agencies' current MY 2008-based market-forecast and the agencies' current estimates of future technology effectiveness, the inclusion of the weight-to-footprint data adjustment prior to running the regression also helps to improve the fit of the curves by reducing the variation in the data, and the agencies believe that the benefits of this adjustment for this proposed rule likely outweigh the potential that resultant curves might somehow encourage reduced load carrying capability or vehicle performance (note that the we are not suggesting that we believe these adjustments will reduce load carrying capability or vehicle performance). In addition to reducing the variability, the truck curve is also steepened, and the car curve flattened compared to curves fitted to sales weighted data that do not include these normalizations. The agencies agree with manufacturers of full-size pick-up trucks that in order to maintain towing and hauling utility, the engines on pick-up trucks must be more powerful, than their low "density" nature would statistically suggest based on the agencies' current MY2008-based market forecast and the agencies' current estimates of the effectiveness of different fuel-saving technologies. Therefore, it may be more equitable (*i.e.*, in terms of relative compliance challenges faced by different light truck manufacturers) to adjust the slope of the curve defining fuel economy and CO_2 targets.

The results of the normalized regressions are displayed in Table, below.

Table 2-7 Regression Results

Vehicle	Slope (gallons/mile)	Constant (gallons/mile)
Passenger cars	0.000431	-0.00052489
Light trucks	0.0002526	0.01121968

As described above, however, other approaches are also technically reasonable, and also represent a way of expressing the underlying relationships. The agencies plan to revisit the analysis for the final rule, after updating the underlying market forecast and estimates of technology effectiveness, and based on relevant public comments received. In addition, the agencies intend to update the technology cost estimates, which could alter the NPRM analysis results and consequently alter the balance of the trade-offs being weighed to determine the final curves.

As shown in the figures below, the line represents the sales-weighted OLS regression fit of gallons per mile regressed on footprint, with the data first adjusted by weight to footprint, as described above. This introduces weight as an additional consideration into the slope of the footprint curve, although in a manner that adjusts the data as described above, and thus maintains a simple graphical interpretation of the curve in a two dimensional space (gallons per mile and footprint).

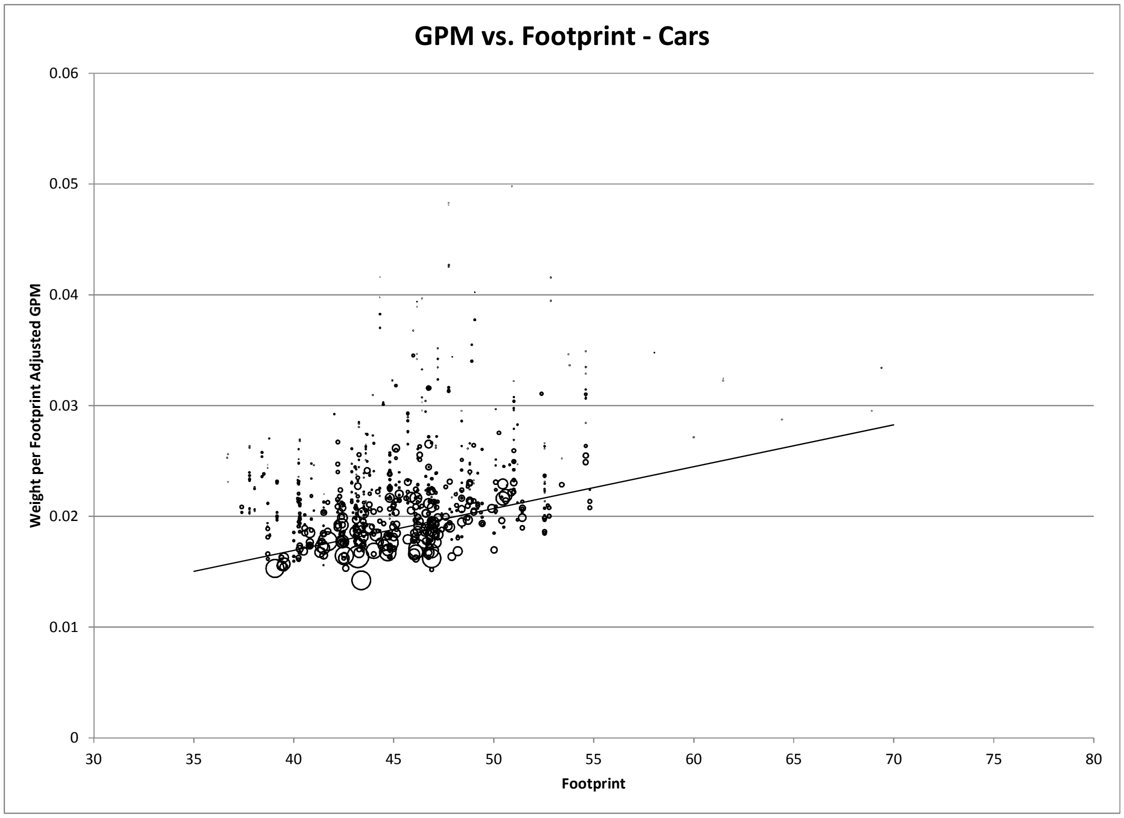

Figure 2-17 Gallons per Mile versus Footprint, Cars

(Data adjusted by weight to footprint).

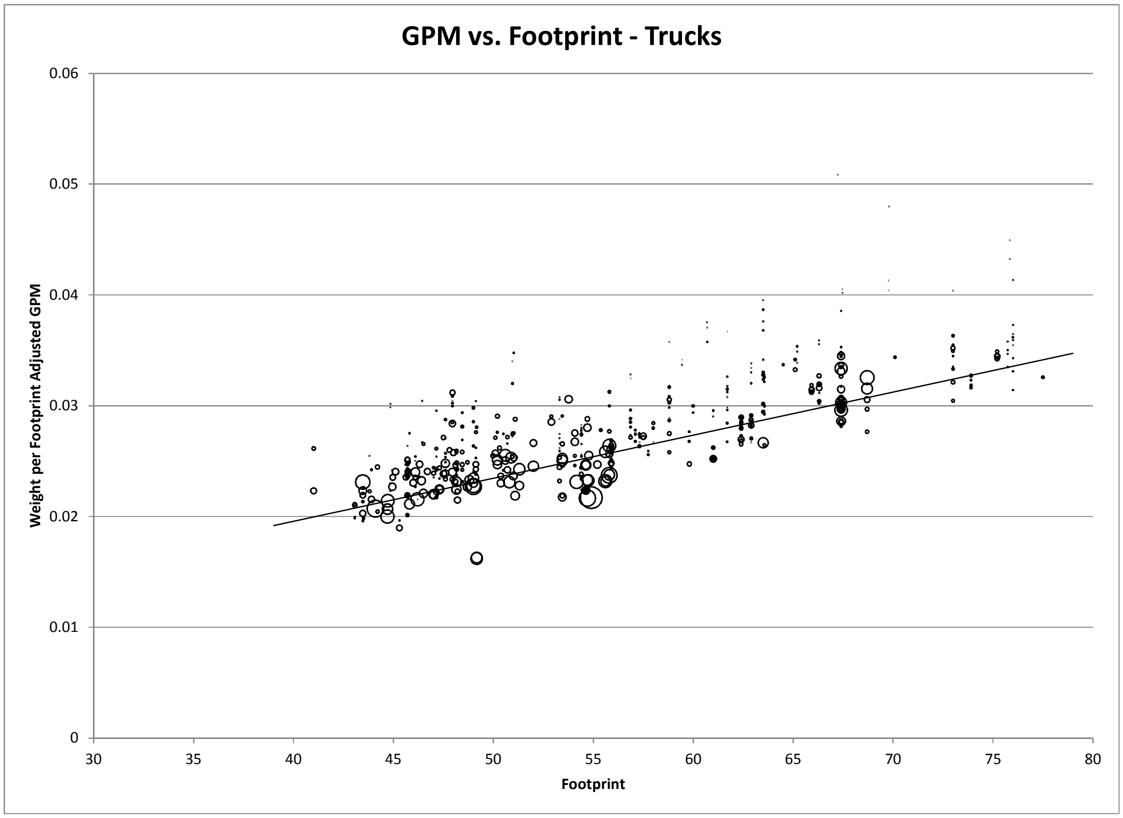

Figure 2-18 Gallons per Mile versus Footprint, Trucks (data adjusted by weight to footprint).

In the preceding two figures, passenger car and light truck data is represented for the specification chosen, with the size of the observation scaled to sales. The agencies note with regard to light trucks that for the MYs 2012-2016 analysis NPRM and final rule analyses, some models of pickups had been aggregated together, when, for example, the same pickup had been available in different cab configurations with different wheelbases.[16] For the current analysis, these models have been disaggregated and are represented individually, which leads to a slightly different outcome in the regression results than had they remained aggregated.

2.4.2.6 Implications of the proposed slope compared to MY 2012-2016

The proposed slope has several implications relative to the MY 2016 curves, with the majority of changes on the truck curve. With the agencies' current MY2008-based market forecast and the agencies' current estimates of technology effectiveness, the combination of sales weighting and WT/FP normalization produced a car curve slope similar to that finalized in the MY 2012-2016 final rulemaking (4.7 g/mile in MY 2016, vs. 4.5 g/mile proposed in MY 2017). By contrast, the truck curve is steeper in MY 2017 than in MY 2016 (4.0 g/mile in MY 2016 vs. 4.9 g/mile in MY 2017). As discussed previously, a steeper slope relaxes the stringency of targets for larger vehicles relative to those for smaller vehicles, thereby shifting relative compliance burdens among manufacturers based on their respective product mix.

2.5 Once the agencies determined the appropriate slope for the sloped part, how did the agencies determine the rest of the mathematical function?

The agencies continue to believe that without a limit at the smallest footprints, the function—whether logistic or linear—can reach values that would be unfairly burdensome for a manufacturer that elects to focus on the market for small vehicles; depending on the underlying data, an unconstrained form could result in stringency levels that are technologically infeasible and/or economically impracticable for those manufacturers that may elect to focus on the smallest vehicles. On the other side of the function, without a limit at the largest footprints, the function may provide no floor on required fuel economy. Also, the safety considerations that support the provision of a disincentive for downsizing as a compliance strategy apply weakly, if at all, to the very largest vehicles. Limiting the function's value for the largest vehicles thus leads to a function with an inherent absolute minimum level of performance, while remaining consistent with safety considerations.

Just as for slope, in determining the appropriate footprint and fuel economy values for the "cutpoints," the places along the curve where the sloped portion becomes flat, the agencies took a fresh look for purposes of this proposal, taking into account the updated market forecast and new assumptions about the availability of technologies. The next two sections discuss the agencies' approach to cutpoints for the passenger car and light truck curves separately, as the policy considerations for each vary somewhat.

2.5.1 Cutpoints for PC curve

The passenger car fleet upon which the agencies have based the target curves for MYs 2017-2025 is derived from MY 2008 data, as discussed above. In MY 2008, passenger car footprints ranged from 36.7 square feet, the Lotus Exige 5, to 69.3 square feet, the Daimler Maybach 62. In that fleet, several manufacturers offer small, sporty coupes below 41 square feet, such as the BMW Z4 and Mini, Honda S2000, Mazda MX-5 Miata, Porsche Carrera and 911, and Volkswagen New Beetle. Because such vehicles represent a small portion (less than 10 percent) of the passenger car market, yet often have performance, utility, and/or structural characteristics that could make it technologically infeasible and/or economically impracticable for manufacturers focusing on such vehicles to achieve the very challenging average requirements that could apply in the absence of a constraint, EPA and NHTSA are again proposing to cut off the sloped portion of the passenger car function at 41 square feet, consistent with the MYs 2012-2016 rulemaking. The agencies recognize that for manufacturers who make small vehicles in this size range, putting the cutpoint at 41 square feet creates some incentive to downsize (*i.e.*, further reduce the size, and/or increase the production of models currently smaller than 41 square feet) to make it easier to meet the target. Putting the cutpoint here may also create the incentive for manufacturers who do not currently offer such models to do so in the future. However, at the same time, the agencies believe that there is a limit to the market for cars smaller than 41 square feet -- most consumers likely have some minimum expectation about interior volume, among other things. The agencies thus believe that the number of consumers who will want vehicles smaller than 41 square feet (regardless of how they are priced) is small, and that the incentive to downsize to less than 41 square feet in response to this proposal, if present, will be at best minimal. On the other hand, the agencies note that some manufacturers are introducing mini cars not reflected in the agencies MY 2008-based market forecast, such as the Fiat 500, to the U.S. market, and that the footprint at which the curve is limited may affect the incentive for manufacturers to do so.

Above 56 square feet, the only passenger car models present in the MY 2008 fleet were four luxury vehicles with extremely low sales volumes—the Bentley Arnage and three versions of the Rolls Royce Phantom. As in the MYs 2012-2016 rulemaking, NHTSA and EPA therefore are proposing again to cut off the sloped portion of the passenger car function at 56 square feet.

While meeting with manufacturers prior to issuing the proposal, the agencies received comments from some manufacturers that, combined with slope and overall stringency, using 41 square feet as the footprint at which to cap the target for small cars would result in unduly challenging targets for small cars. The agencies do not agree. No specific vehicle need meet its target (because standards apply to fleet average performance), and maintaining a sloped function toward the smaller end of the passenger car market is important to discourage unsafe downsizing, the agencies are thus proposing to again “cut off” the passenger car curve at 41 square feet, notwithstanding these comments.

The agencies seek comment on setting cutpoints for the MYs 2017-2025 passenger car curves at 41 square feet and 56 square feet.

2.5.2 Cutpoints for LT curve

The light truck fleet upon which the agencies have based the target curves for MYs 2017-2025, like the passenger car fleet, is derived from MY 2008 data, as discussed in Section 2.4 above. In MY 2008, light truck footprints ranged from 41.0 square feet, the Jeep Wrangler, to 77.5 square feet, the Toyota Tundra. For consistency with the curve for passenger cars, the agencies are proposing to cut off the sloped portion of the light truck function at the same footprint, 41 square feet, although we recognize that no light trucks are currently offered below 41 square feet. With regard to the upper cutpoint, the agencies heard from a number of manufacturers during the discussions leading up to this proposal that the location of the cutpoint in the MYs 2012-2016 rules, 66 square feet, meant that the same standard applied to all light trucks with footprints of 66 square feet or greater, and that in fact the targets for the largest light trucks in the later years of that rulemaking were extremely challenging. Those manufacturers requested that the agencies extend the cutpoint to a larger footprint, to reduce targets for the largest light trucks which represent a significant percentage of those manufacturers light truck sales. At the same time, in re-examining the light truck fleet data, the agencies concluded that aggregating pickup truck models in the MYs 2012-2016 rule had led the agencies to underestimate the impact of the different pickup truck model configurations above 66 square feet on manufacturers' fleet average fuel economy and CO2 levels (as discussed immediately below). In disaggregating the pickup truck model data, the impact of setting the cutpoint at 66 square feet after model year 2016 became clearer to the agencies.

In the agencies' view, there is legitimate basis for these comments. The agencies' market forecast includes about 24 vehicle configurations above 74 square feet with a total volume of about 50,000 vehicles or less during any MY in the 2017-2025 time frame. While a relatively small portion of the overall truck fleet, for some manufacturers, these vehicles are non-trivial portion of sales. As noted above, the very largest light trucks have significant load-carrying and towing capabilities that make it particularly challenging for manufacturers to add fuel economy-improving/CO_2-reducing technologies in a way that maintains the full functionality of those capabilities.

Considering manufacturer CBI and our estimates of the impact of the 66 square foot cutpoint for future model years, the agencies have initially determined to adopt curves that transition to a different cut point. While noting that no specific vehicle need meet its target (because standards apply to fleet average performance), we believe that the information provided to us by manufacturers and our own analysis supports the gradual extension of the cutpoint for large light trucks in this proposal from 66 square feet in MY 2016 out to a larger footprint square feet before MY 2025.

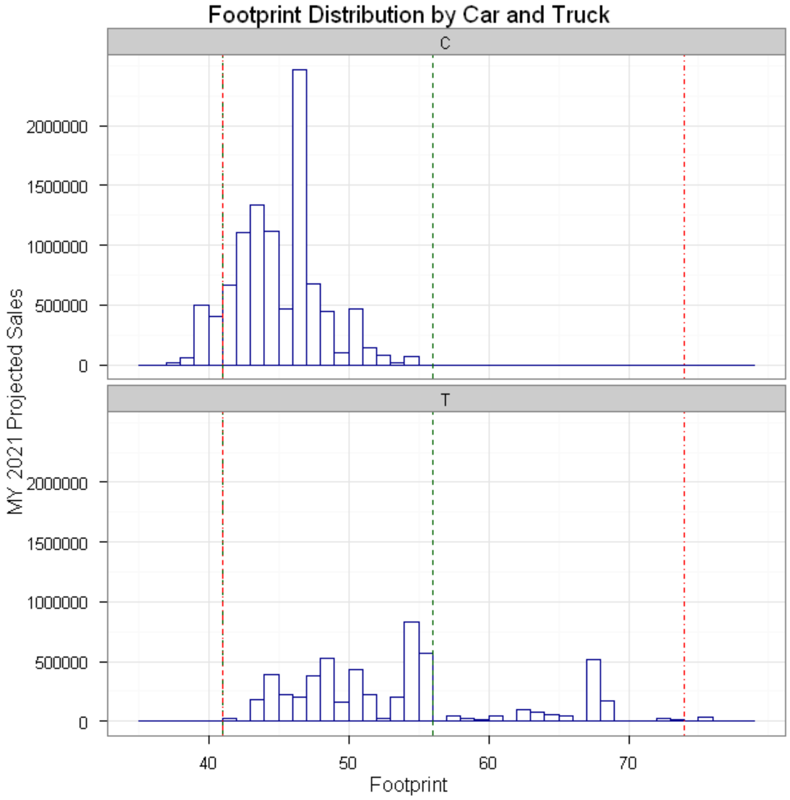

Figure 2-19 Footprint Distribution by Car and Truck*

*Proposed truck cutpoints for MY 2025 shown in red, car cutpoints shown in green

The agencies are proposing to phase in the higher cutpoint for the truck curve in order to avoid any backsliding from the MY 2016 standard. A target that is feasible in one model year should never become less feasible in a subsequent model year—manufacturers should have no reason to remove fuel economy-improving/CO_2-reducing technology from a vehicle once it has been applied. Put another way, the agencies are proposing to not allow "curve crossing" from one model year to the next. In proposing MYs 2011-2015 CAFE standards and promulgating MY 2011 standards, NHTSA proposed and requested comment on avoiding curve crossing, as an "anti-backsliding measure."[17] The MY 2016 2 cycle test curves are therefore a floor for the MYs 2017-2025 curves. For passenger cars, which have minimal change in slope from the MY 2012-2016 rulemakings and no change in cut points, there are no curve crossing issues in the proposed standards.

The minimum stringency determination was done using the two cycle curves. Stringency adjustments for air conditioning and other credits were calculated after curves that did not cross were determined in two cycle space. The year over year increase in these adjustments cause neither the GHG nor CAFE curves (with A/C) to contact the 2016 curves when charted.

2.5.3 Once the agencies determined the complete mathematical function shape, how did the agencies adjust the curves to develop the proposed standards and regulatory alternatives?

The curves discussed above all reflect the addition of technology to individual vehicle models to reduce technology differences between vehicle models before fitting curves. This application of technology was conducted not to directly determine the proposed standards, but rather for purposes of technology adjustments, and set aside considerations regarding potential rates of application (*i.e.*, phase-in caps), and considerations regarding economic implications of applying specific technologies to specific vehicle models. The following sections describe further adjustments to the curves discussed above, that affect both the shape of the curve (section 2.5.3.1), and the location of the curve (2.5.3.2), that helped the agencies determine curves that defined the proposed standards.

2.5.3.1 Adjusting for Year over Year Stringency

As in the MYs 2012-2016 rules, the agencies developed curves defining regulatory alternatives for consideration by "shifting" these curves. For the MYs 2012-2016 rules, the agencies did so on an absolute basis, offsetting the fitted curve by the same value (in gpm or g/mi) at all footprints. In developing this proposal, the agencies have reconsidered the use of this approach, and have concluded that after MY 2016, curves should be offset on a relative basis—that is, by adjusting the entire gpm-based curve (and, equivalently, the CO_2 curve) by the same percentage rather than the same absolute value. The agencies' estimates of the effectiveness of these technologies are all expressed in relative terms—that is, each technology (with the exception of A/C) is estimated to reduce fuel consumption (the inverse of fuel economy) and CO_2 emissions by a specific percentage of fuel consumption without the technology. It is, therefore, more consistent with the agencies' estimates of technology effectiveness to develop the proposed standards and regulatory alternatives by applying a proportional offset to curves expressing fuel consumption or emissions as a function of footprint. In addition, extended indefinitely (and without other compensating adjustments), an absolute offset would eventually (*i.e.*, at very high average stringencies) produce negative (gpm or g/mi) targets. Relative offsets avoid this potential outcome. Relative offsets do cause curves to become, on a fuel consumption and CO_2 basis, flatter at greater average stringencies; however, as discussed above, this outcome remains consistent with the agencies' estimates of technology effectiveness. In other words, given a relative decrease in average required fuel consumption or CO_2 emissions, a curve that is flatter by the same relative amount should be equally challenging in terms of the potential to achieve compliance through the addition of fuel-saving technology.

On this basis, and considering that the "flattening" occurs gradually for the regulatory alternatives the agencies have evaluated, the agencies tentatively conclude that this approach to offsetting the curves to develop year-by-year regulatory alternatives neither re-creates a situation in which manufacturers are likely to respond to standards in ways that compromise highway safety, nor undoes the attribute-based standard's more equitable balancing of compliance burdens among disparate manufacturers. The agencies invite comment on these conclusions, and on any other means that might avoid the potential outcomes—in particular, negative fuel consumption and CO_2 targets—discussed above.

2.5.3.2 Adjusting for anticipated improvements to mobile air conditioning systems

The fuel economy values in the agencies' market forecast are based on the 2-cycle (*i.e.*, city and highway) fuel economy test and calculation procedures that do not reflect potential improvements in air conditioning system efficiency, refrigerant leakage, or refrigerant Global Warming Potential (GWP). Recognizing that there are significant and cost effective potential air conditioning system improvements available in the rulemaking timeframe (discussed in detail in Chapter 5 of the draft joint TSD), the agencies are increasing the stringency of the target curves based on the agencies' assessment of the capability of manufacturers to implement these changes. For the proposed CAFE standards and alternatives, an offset is included based on air conditioning system efficiency improvements, as these improvements are the only improvements that effect vehicle fuel economy. For the proposed GHG standards and alternatives, a stringency increase is included based on air conditioning system efficiency, leakage and refrigerant improvements. As discussed above in Chapter 5 of the join TSD, the air conditioning system improvements affect a vehicle's fuel efficiency or CO_2 emissions performance as an additive stringency increase, as compared to other fuel efficiency improving technologies which are multiplicative. Therefore, in adjusting target curves for improvements in the air conditioning system performance, the agencies are adjusting the target curves by additive stringency increases (or vertical shifts) in the curves.

For the GHG target curves, the offset for air conditioning system performance is being handled in the same manner as for the MY 2012-2016 rules. For the CAFE target curves, NHTSA for the first time is proposing to account for potential improvements in air conditioning system performance. Using this methodology, the agencies first use a multiplicative stringency adjustment for the sloped portion of the curves to reflect the effectiveness on technologies other that air conditioning system technologies, creating a series of curve shapes that are "fanned" based on two-cycle performance. Then the curves are offset vertically by the air conditioning improvement by an equal amount at every point.

References:

[1] 49 U.S.C. 32902(a)(3)(A).

[2] 69 FR 38958 (June 29, 2004).

[3] 76 FR 57106, 57162-64, (Sept. 15, 2011).

[4] *See* 74 FR at 14359 (Mar. 30, 2009).

[5] 75 FR at 25362.

[6] *See generally* 74 FR at 49491-96; 75 FR at 25357-62.

[7] 68 FR 74920-74926.

[8] 74 FR 14359.

[9] See 75 FR at 25458

[10] 75 FR at 25363

[11] *See* 75 FR at 25359.

[12] *Id.* at 25362-63.

[13] *Id.* at 25363.

[14] 75 FR at 25362 and n. 64

[15] 75 FR at 25632/3.

[16] *See* 75 FR at 25354

[17] 74 Fed. Reg. at 14370 (Mar. 30, 2009).

Chapter 3: Technologies Considered in the Agencies' Analysis

This Chapter of the joint TSD describes the technologies NHTSA and EPA evaluated as potential inputs in their respective models and provides estimates of the technologies' costs, effectiveness and availability. This Chapter also describes, in general terms, how the agencies use these inputs in their respective models.

The agencies assume, in this analysis, that manufacturers will add a variety of technologies to each of their vehicle model platforms in order to improve their fuel economy and GHG performance. In order to evaluate proposed CAFE and GHG standards and regulatory alternatives, it is essential to understand what is feasible within the timeframe of the proposed rule. Determining the technological feasibility of proposed 2017-2025 standards requires a thorough study of the technologies available to the manufacturers during that timeframe. This chapter includes an assessment of the cost, effectiveness, and the availability, development time, and manufacturability of the technology within either the normal redesign periods of a vehicle line or in the design of a new vehicle. As we describe below, when a technology can be applied can affect the cost as well as the technology penetration rate (or phase-in caps) that are assumed in the analysis.

The agencies considered technologies in many categories that manufacturers could use to improve the fuel economy and reduce CO_2 emissions of their vehicles during the MYs 2017-2025 timeframe. Many of the technologies described in this chapter are available today, are well known, and could be incorporated into vehicles once product development decisions are made. These are "nearer-term" technologies and are identical or very similar to those considered in the MYs 2012-2016 final rule analysis (of course, many of these technologies will likely be applied to the light-duty fleet in order to achieve the 2012-2016 CAFE and GHG standards; such technologies would be part of the 2016 reference case for this analysis[a]). Other technologies considered, may not currently be in production, but are under development and are expected to be in production in the next five to ten years. Examples of these technologies are downsized and turbocharged engines operating at combustion pressures even higher than today's turbocharged engines, and an emerging hybrid architecture mated with an 8 speed transmission—a combination that is not available today. These are technologies which the agencies believe can, for the most part, be applied both to cars and trucks, and which are expected to achieve significant improvements in fuel economy and reductions in CO2 emissions at reasonable costs in the MYs 2017 to 2025 timeframe. The agencies note that we did not consider in our analysis technologies that are currently in an initial stage of research because of the uncertainties involved in estimating their costs and effectiveness and in assessing whether the technologies will be ready to implement at significant penetration rates during the timeframe of this proposal. Examples of such

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[a] The technologies in the 2016 reference fleet are projections made by EPA's OMEGA model and NHTSA's CAFE model respectively. Some technologies may be significantly represented in this reference fleet and these details can be found in each agency's respective RIAs.

technologies would be camless valve actuation and fuel cell vehicles.[b] The agencies acknowledge that due to the relatively long period between the date of this proposal and the rulemaking timeframe, the possibility exists that new and innovative technologies not considered in this analysis will make their way into the fleet (perhaps even in significant numbers). The agencies plan to re-assess these technologies, along with all of the technologies considered in this proposal, as part of our mid-term evaluation.

3.1 What Technologies did the agencies consider for the proposed 2017-2025 standards?

The technologies considered for this NPRM analysis by NHTSA and EPA are briefly described below. They fit generally into five broad categories: engine, transmission, vehicle, electrification/accessory, and hybrid technologies. A more detailed description of each technology, and the technology's costs and effectiveness, is described in greater detail in section 3.4 of this TSD.

Types of engine technologies applied in this NPRM analysis to improve fuel economy and reduce CO_2 emissions include the following:

- *Low-friction lubricants* – low viscosity and advanced low friction lubricants oils are now available with improved performance and better lubrication.
- *Reduction of engine friction losses* – can be achieved through low-tension piston rings, roller cam followers, improved material coatings, more optimal thermal management, piston surface treatments, and other improvements in the design of engine components and subsystems that improve engine operation.
- *Second level of low-friction lubricants and engine friction reduction* – As technologies advance between now and the rulemaking timeframe, there will further developments enabling lower viscosity and lower friction lubricants and more engine friction reduction technologies available.
- *Cylinder deactivation* – deactivates the intake and exhaust valves and prevents fuel injection into some cylinders during light-load operation. The engine runs temporarily as though it were a smaller engine which substantially reduces pumping losses
- *Variable valve timing* – alters the timing or phase of the intake valve, exhaust valve, or both, primarily to reduce pumping losses, increase specific power, and control residual gases.

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[b] Fuel cell vehicles may be especially useful in lieu of full battery electric technology for the larger trucks. We may consider this possibility for the final rule.

- *Discrete variable valve lift* – increases efficiency by optimizing air flow over a broader range of engine operation which reduces pumping losses. Accomplished by controlled switching between two or more cam profile lobe heights.

- *Continuous variable valve lift* – is an electromechanically controlled system in which cam period and phasing is changed as lift height is controlled. This yields a wide range of performance optimization and volumetric efficiency, including enabling the engine to be valve throttled.

- *Stoichiometric gasoline direct-injection technology* – injects fuel at high pressure directly into the combustion chamber to improve cooling of the air/fuel charge within the cylinder, which allows for higher compression ratios and increased thermodynamic efficiency.

- *Turbocharging and downsizing* – increases the available airflow and specific power level, allowing a reduced engine size while maintaining performance. This reduces pumping losses at lighter loads in comparison to a larger engine. In this NPRM, the agencies considered three levels of boosting, 18 bar brake mean effective pressure (BMEP), 24 bar BMEP and 27 bar BMEP, as well as four levels of downsizing, from I4 to smaller I4 or I3, from V6 to I4 and from V8 to V6 and I4. 18 bar BMEP is applied with 33 percent downsizing, 24 bar BMEP is applied with 50 percent downsizing and 27 bar BMEP is applied with 56 percent downsizing. To achieve the same level of torque when downsizing the displacement of an engine by 50 percent, approximately double the manifold absolute pressure (2 bar) is required. Accordingly, with 56 percent downsizing, the manifold absolute pressure range increases up to 2.3 bar. Ricardo states in their 2011 vehicle simulation project report that advanced engines in the 2020–2025 timeframe can be expected to have advanced boosting systems that increase the pressure of the intake charge up to 3 bar[1]. Refer to Section 3.3.1.2.22.2 for examples of Ricardo-modeled displacements used for turbocharged and downsized engines in each vehicle class.

- *Exhaust-gas recirculation boost* – increases the exhaust-gas recirculation used in the combustion process to increase thermal efficiency and reduce pumping losses. Levels of exhaust gas recirculation approach 25% by volume in the highly boosted engines modeled by Ricardo (this, in turn raises the boost requirement by approximately 25%). This technology is only applied to 24 bar and 27 bar BMEP engines in this NPRM.

- *Diesel engines* – have several characteristics that give superior fuel efficiency, including reduced pumping losses due to lack of (or greatly reduced) throttling, and a combustion cycle that operates at a higher compression ratio, with a very lean air/fuel mixture, than an equivalent-performance gasoline engine. This technology requires additional enablers, such as NO_x trap catalyst after-treatment or selective catalytic reduction NO_x after-treatment.

Types of transmission technologies applied in this NPRM include:

- *Improved automatic transmission controls* – optimizes shift schedule to maximize fuel efficiency under wide ranging conditions, and minimizes losses associated with torque converter slip through lock-up or modulation.
- *Six- and seven-speed automatic transmissions* – the gear ratio spacing and transmission ratio are optimized to enable the engine to operate in a more efficient operating range over a broader range of vehicle operating conditions.
- *Dual clutch transmission (DCT)* - are similar to a manual transmission, but the vehicle controls shifting and launch functions. A dual-clutch automated shift manual transmission uses separate clutches for even-numbered and odd-numbered gears, so the next expected gear is pre-selected, which allows for faster, smoother shifting.
- *Eight-speed automatic transmissions* – the gear transmission ratio are optimized to enable the engine to operate in a more efficient operating range over a broader range of vehicle operating conditions. This technology is applied after 2016.
- *Shift Optimization* – tries to keep the engine operating near its most efficient point for a give power demand. The shift controller emulates a traditional CVT by selecting the best gear ratio for fuel economy at a given required vehicle power level to take full advantage of high BMEP engines.
- *Manual 6-speed transmission* – offers an additional gear ratio, often with a higher overdrive gear ratio, than a 5-speed manual transmission.
- *High Efficiency Gearbox (automatic, DCT or manual)* – continuous improvement in seals, bearings and clutches, super finishing of gearbox parts, and development in the area of lubrication, all aimed at reducing frictional and other parasitic load in the system for an automatic, DCT or manual type transmission.

Types of vehicle technologies applied in this NPRM analysis include:

- *Low-rolling-resistance tires – have characteristics that* reduce frictional losses associated with the energy dissipated in the deformation of the tires under load, therefore reducing the energy needed to move the vehicle. There are two levels of rolling resistance reduction considered in this NRPM analysis targeting at 10 percent and 20 percent rolling resistance reduction respectively.
- *Low-drag brakes* – reduce the sliding friction of disc brake pads on rotors when the brakes are not engaged because the brake pads are pulled away from the rotors.
- *Front or secondary axle disconnect for four-wheel drive systems* – provides a torque distribution disconnect between front and rear axles when torque is not required for the non-driving axle. This results in the reduction of associated parasitic energy losses.

- *Aerodynamic drag reduction* – is achieved by changing vehicle shape or reducing frontal area, including skirts, air dams, underbody covers, and more aerodynamic side view mirrors. There are two levels of aerodynamic drag reduction considered in this NPRM analysis targeting 10 percent and 20 percent rolling resistance reduction respectively.
- *Mass reduction*– Mass reduction encompasses a variety of techniques ranging from improved design and better component integration to application of lighter and higher-strength materials. Mass reduction can lead to collateral fuel economy and GHG benefits due to downsized engines and/or ancillary systems (transmission, steering, brakes, suspension, etc.). The maximum mass reduction level considered in this NPRM is 20 percent.

Types of electrification/accessory and hybrid technologies applied in this NPRM include:

- *Electric power steering (EPS) and electro-hydraulic power steering (EHPS)* – is an electrically-assisted steering system that has advantages over traditional hydraulic power steering because it replaces a continuously operated hydraulic pump, thereby reducing parasitic losses from the accessory drive.
- *Improved accessories (IACC)* – may include high efficiency alternators, electrically driven (i.e., on-demand) water pumps and cooling and even regenerative braking. This excludes other electrical accessories such as electric oil pumps and electrically driven air conditioner compressors. There are two levels of IACC applied in this NPRM analysis. The second level of IACC includes alternator regenerative braking on top of what are included in the first level of IACC.
- *Air Conditioner Systems* – These technologies include improved hoses, connectors and seals for leakage control. They also include improved compressors, expansion valves, heat exchangers and the control of these components for the purposes of improving tailpipe CO_2 emissions and fuel economy when the A/C is operating. These technologies are covered separately in Chapter 5 of this draft joint TSD.
- *12-volt Stop-start* – also known as idle-stop or 12V micro hybrid and commonly implemented as a 12-volt belt-driven integrated starter-generator, this is the most basic hybrid system that facilitates idle-stop capability. Along with other enablers, this system replaces a common alternator with an enhanced power starter-alternator, both belt driven, and a revised accessory drive system.
- *P2 Hybrid* – P2 hybrid is a newly emerging hybrid technology that uses a transmission integrated electric motor placed between the engine and a gearbox or CVT, much like the IMA system described above except with a wet or dry separation clutch which is used to decouple the motor/transmission from the engine. In addition, a P2 Hybrid would typically be equipped with a larger electric machine. Engaging the clutch allows all-electric operation and more efficient

brake-energy recovery. Disengaging the clutch allows efficient coupling of the engine and electric motor and, when combined with a DCT transmission, reduces gear-train losses relative to power-split or 2-mode hybrid systems.

- *Plug-in hybrid electric vehicles (PHEV)* – are hybrid electric vehicles with the means to charge their battery packs from an outside source of electricity (usually the electric grid). These vehicles have larger battery packs with more energy storage and a greater capability to be discharged. They also use a control system that allows the battery pack to be substantially depleted under electric-only or blended mechanical/electric operation.

- *Electric vehicles (EV)* – are vehicles with all-electric drive and with vehicle systems powered by energy-optimized batteries charged primarily from grid electricity. EVs with 75 mile, 100 mile and 150 mile ranges have been included as potential technologies.

Types of accessory/hybridization/electrification technologies discussed but not applied in this NPRM analysis include:

- *Higher Voltage Stop-Start/Belt Integrated Starter Generator (BISG)* – sometimes referred to as a mild hybrid, BISG provides idle-stop capability and uses a high voltage battery with increased energy capacity over typical automotive batteries. The higher system voltage allows the use of a smaller, more powerful electric motor and reduces the weight of the motor, inverter, and battery wiring harnesses. This system replaces a standard alternator with an enhanced power, higher voltage, higher efficiency starter-alternator, that is belt driven and that can recover braking energy while the vehicle slows down (regenerative braking).

- *Integrated Motor Assist (IMA)/Crank integrated starter generator (CISG)* – provides idle-stop capability and uses a high voltage battery with increased energy capacity over typical automotive batteries. The higher system voltage allows the use of a smaller, more powerful electric motor and reduces the weight of the wiring harness. This system replaces a standard alternator with an enhanced power, higher voltage and higher efficiency starter-alternator that is crankshaft mounted and can recover braking energy while the vehicle slows down (regenerative braking). The IMA technology is not included as an enabling technology in this analysis, although it is included as a baseline technology because it exists in the 2008 baseline fleet.

- *Power-split Hybrid (PSHEV)* – is a hybrid electric drive system that replaces the traditional transmission with a single planetary gearset and a motor/generator. This motor/generator uses the engine to either charge the battery or supply additional power to the drive motor. A second, more powerful motor/generator is permanently connected to the vehicle's final drive and always turns with the wheels. The planetary gear splits engine power between the first motor/generator and the drive motor to either charge the battery or supply power to the wheels.

The power-split hybrid technology is not included as an enabling technology in this analysis, although it is included as a baseline technology because it exists in the 2008 baseline fleet.

- *2-Mode Hybrid (2MHEV)* – is a hybrid electric drive system that uses an adaptation of a conventional stepped-ratio automatic transmission by replacing some of the transmission clutches with two electric motors that control the ratio of engine speed to vehicle speed, while clutches allow the motors to be bypassed. This improves both the transmission torque capacity for heavy-duty applications and reduces fuel consumption and CO_2 emissions at highway speeds relative to other types of hybrid electric drive systems. The 2-mode hybrid technology is not included as an enabling technology in this analysis, although it is included as a baseline technology because it exists in the 2008 baseline fleet.

3.2 How did the agencies determine the costs of each of these technologies?

3.2.1 Direct Costs

3.2.1.1 Costs from Tear-down Studies

There are a number of technologies that have been costed using a rigorous tear-down method described in this section. As a general matter, the agencies believe that the best method to derive technology cost estimates is to conduct studies involving tear-down and analysis of actual vehicle components. A “tear-down” involves breaking down a technology into its fundamental parts and manufacturing processes by completely disassembling actual vehicles and vehicle subsystems and precisely determining what is required for its production. The result of the tear-down is a “bill of materials” for each and every part of the vehicle or vehicle subsystem. This tear-down method of costing technologies is often used by manufacturers to benchmark their products against competitive products. Historically, vehicle and vehicle component tear-down has not been done on a large scale by researchers and regulators due to the expense required for such studies. While tear-down studies are highly accurate at costing technologies for the year in which the study is intended, their accuracy, like that of all cost projections, may diminish over time as costs are extrapolated further into the future because of uncertainties in predicting commodities (and raw material) prices, labor rates, and manufacturing practices. The projected costs may be higher or lower than predicted.

Over the past several years, EPA has contracted with FEV, Inc. and its subcontractor Munro & Associates to conduct tear-down cost studies for a number of key technologies evaluated by the agencies in assessing the feasibility of future GHG and CAFE standards. The analysis methodology included procedures to scale the tear-down results to smaller and larger vehicles, and also to different technology configurations. FEV’s methodology was documented in a report published as part of the MY 2012-2016 rulemaking process, detailing the costing of the first tear-down conducted in this work (#1 in the below list).[2] This report was peer reviewed by experts in the industry and revised by FEV in response to the peer review comments.[3] Subsequent tear-down studies (#2-5 in the below list) were documented in follow-up FEV reports made available in the public docket for the MY 2012-2016 rulemaking.[4]

Since then, FEV's work under this contract work assignment has continued. Additional cost studies have been completed and are available for public review.[5] The most extensive study, performed after the MY 2012-2016 Final Rule, involved whole-vehicle tear-downs of a 2010 Ford Fusion power-split hybrid and a conventional 2010 Ford Fusion. (The latter served as a baseline vehicle for comparison.) In addition to providing power-split HEV costs, the results for individual components in these vehicles were subsequently used to cost another hybrid technology, the P2 hybrid, which employs similar hardware. This approach to costing P2 hybrids was undertaken because P2 HEVs were not yet in volume production at the time of hardware procurement for tear-down. Finally, an automotive lithium-polymer battery was torn down and costed to provide supplemental battery costing information to that associated with the NiMH battery in the Fusion. This HEV cost work, including the extension of results to P2 HEVs, has been extensively documented in a new report prepared by FEV.[6] Because of the complexity and comprehensive scope of this HEV analysis, EPA commissioned a separate peer review focused exclusively on it. Reviewer comments generally supported FEV's methodology and results, while including a number of suggestions for improvement which were subsequently incorporated into FEV's analysis and final report. The peer review comments and responses are available in the rulemaking docket.[7] [8]

Over the course of this work assignment, teardown-based studies were performed on the technologies listed below. These completed studies provide a thorough evaluation of the new technologies' costs relative to their baseline (or replaced) technologies.

1. Stoichiometric gasoline direct injection (SGDI) and turbocharging with engine downsizing (T-DS) on a DOHC (dual overhead cam) I4 engine, replacing a conventional DOHC I4 engine.
2. SGDI and T-DS on a SOHC (single overhead cam) on a V6 engine, replacing a conventional 3-valve/cylinder SOHC V8 engine.
3. SGDI and T-DS on a DOHC I4 engine, replacing a DOHC V6 engine.
4. 6-speed automatic transmission (AT), replacing a 5-speed AT.
5. 6-speed wet dual clutch transmission (DCT) replacing a 6-speed AT.
6. 8-speed AT replacing a 6-speed AT.
7. 8-speed DCT replacing a 6-speed DCT.
8. Power-split hybrid (Ford Fusion with I4 engine) compared to a conventional vehicle (Ford Fusion with V6). The results from this tear-down were extended to address P2 hybrids. In addition, costs from individual components in this tear-down study were used by the agencies in developing cost estimates for PHEVs and EVs.
9. Mild hybrid with stop-start technology (Saturn Vue with I4 engine), replacing a conventional I4 engine.

10. Fiat Multi-Air engine technology. (Although results from this cost study are included in the rulemaking docket, they were not used by the agencies in this rulemaking's technical analyses.)

In addition, FEV and EPA extrapolated the engine downsizing costs for the following scenarios that were based on the above study cases:

1. Downsizing a SOHC 2 valve/cylinder V8 engine to a DOHC V6.
2. Downsizing a DOHC V8 to a DOHC V6.
3. Downsizing a SOHC V6 engine to a DOHC 4 cylinder engine.
4. Downsizing a DOHC 4 cylinder engine to a DOHC 3 cylinder engine.

The agencies have relied on the findings of FEV for estimating the cost of the technologies covered by the tear-down studies. However, we note that FEV based their costs on the assumption that these technologies would be mature when produced in large volumes (450,000 units or more for each component or subsystem). If manufacturers are not able to employ the technology at the volumes assumed in the FEV analysis with fully learned costs, then the costs for each of these technologies would be expected to be higher. There is also the potential for stranded capital[c] if technologies are introduced too rapidly for some indirect costs to be fully recovered. While the agencies consider the FEV tear-down analysis results to be generally valid for the 2017-2025 timeframe for fully mature, high sales volumes, we have had FEV perform supplemental analysis to consider potential stranded capital costs, and have included these in our cost estimates. The issue of stranded capital is discussed in detail in Section 3.2.2.3 of this draft TSD.

3.2.1.2 Costs of HEV, PHEV, EV, and FCEVs

The agencies have also reconsidered the costs for HEVs, PHEVs, EVs, and FCEVs since the MY 2012-2016 rulemaking and the TAR as the result of two issues. The first issue is that electrified vehicle technologies are developing rapidly and we sought to capture the results from the most recent analyses. The second issue is that the analysis for the MYs 2012-2016 final rule employed a single $/kWhr estimate, and did not consider the specific vehicle and technology application for the battery when we estimated the cost of the battery.[d] Specifically, batteries used in HEVs (high power density applications) versus EVs (high energy density applications) need to be considered appropriately to reflect the design differences, the chemical material usage differences, and the differences in cost per kW-hr as the power to energy ratio of the battery changes for different applications. To address these issues for this proposal, the agencies have used a battery cost model developed by Argonne National Laboratory (ANL) for the Vehicle Technologies Program of the U.S. Department of

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[c] The potential for stranded capital occurs when manufacturing equipment and facilities cannot be used in the production of a new technology.

[d] However, we believe that this had little impact on the results of the cost analyses in support of the MYs 2012-2016 final rule, as the agencies projected that the standards could be met with an increase of less than 2 percent penetration of hybrid technology and no increase in plug-in or full electric vehicle technology.

Energy (DoE) Office of Energy Efficiency and Renewable Energy.[9] The model developed by ANL allows users to estimate unique battery pack cost using user customized input sets for different types of electrified powertrains, such as strong hybrid, PHEV and EV. Since the publication of the TAR, ANL's battery cost model has been peer-reviewed and ANL has updated the model to incorporate suggestions from peer-reviewers.[10] This newly updated model is used in this NPRM analysis and we discuss our updated battery costs in section in Section 3.4.3.9. The agencies also added new configurations of HEV, PHEV and EV to the analysis that include the P2 HEV configuration, two different all-electric mileage ranges for PHEVs (20 and 40 in-use miles) and three different mileage ranges for EVs (75, 100 and 150 in-use miles). Details regarding these vehicle technologies are discussed in sections 3.4.3.6.4 and 3.4.3.6.5.

3.2.1.3 Direct Manufacturing Costs

Building on the MYs 2012-2016 final rule, the agencies took a fresh look at technology cost and effectiveness values for purposes of this joint NPRM. For costs, the agencies reconsidered both the direct or "piece" costs and indirect costs of individual components of technologies. For the direct costs that were not developed through the FEV tear-down studies, the agencies generally followed a bill of materials (BOM) approach. A bill of materials, in a general sense, is a list of components that make up a system—in this case, an item of fuel economy-improving technology. In order to determine what a system costs, one of the first steps is to determine its components and what they cost.

NHTSA and EPA estimated these components and their costs based on a number of sources for cost-related information. The objective was to use those sources of information considered to be most credible for projecting the costs of individual vehicle technologies. For those cost estimates that are fundamentally unchanged since the 2012-2016 final rule and/or the 2010 TAR (we make note of these in Section 3.4, below), we have a full description of the sources used in Chapter 3 of the final joint TSD supporting that rule.[11,12] For those costs that have been updated since those analyses (e.g., battery pack cost, costs based on more recent tear down analyses, etc.), we note their sources in Section 3.4, below. We have also considered input from manufacturers and suppliers gathered either through meetings following the 2010 TAR or in comment submitted in response to the 2010 TAR, some of which cannot be shared publicly in detailed form but, where used, we make note of it without violating its confidentiality. Note that a summary of comments on the 2010 TAR, with the agencies' responses, was published as a "Supplemental Notice of Intent" in December of 2010.[13] As discussed throughout this chapter, the agencies have reviewed, revalidated or updated cost estimates for individual components based on the latest information available.

Once costs were determined, they were adjusted to ensure that they were all expressed in 2009 dollars using the GDP price deflator as described in section 3.2.4. Indirect costs were accounted for using the ICM approach developed by EPA and explained below. NHTSA and EPA also considered how costs should be adjusted to reflect manufacturer learning as discussed below. Additionally, costs were adjusted by modifying or scaling content assumptions to account for differences across the range of vehicle sizes and functional requirements, and adjusted the associated material cost impacts to account for the revised content, although these adjustments were different for each agency due to the different vehicle subclasses used in their respective models.

3.2.2 Indirect Costs

3.2.2.1 Indirect Cost Multiplier Changes

As discussed in greater detail below, the agencies have revised the markups used to estimate indirect costs. The first change was to normalize the ICM values to be consistent with the historical average retail price equivalent (RPE) of 1.5, rather than the single year that the RTI study examined. This was done by applying a factor of .5/.46 to all indirect cost elements. The second change was to re-consider the markup factors and the data used to generate them. The result on this new thinking is to increase the markup in all cases. The final change is the way in which the ICM factors are applied. In previous analyses ICMs were applied to the learned value of direct costs. However, since learning influences direct costs only, the agencies were concerned that this could overstate the impact of learning on total costs. Indirect costs are thus now established based on the initial value of direct costs and held constant until the long-term ICM is applied. This is done for all ICM factors except warranties, which are influenced by the learned value of direct costs.

3.2.2.2 Cost markups to account for indirect costs

To produce a unit of output, auto manufacturers incur direct and indirect costs. Direct costs include the cost of materials and labor costs. Indirect costs may be related to production (such as research and development [R&D]), corporate operations (such as salaries, pensions, and health care costs for corporate staff), or selling (such as transportation, dealer support, and marketing). Indirect costs are generally recovered by allocating a share of the costs to each unit of goods sold. Although it is possible to account for direct costs allocated to each unit of goods sold, it is more challenging to account for indirect costs allocated to a unit of goods sold. To make a cost analysis process more feasible, markup factors, which relate total indirect costs to total direct costs, have been developed. These factors are often referred to as retail price equivalent (RPE) multipliers.

Cost analysts and regulatory agencies including EPA and NHTSA have frequently used these multipliers to estimate the resultant impact on costs associated with manufacturers' responses to regulatory requirements. The best approach to determining the impact of changes in direct manufacturing costs on a manufacturer's indirect costs would be to actually estimate the cost impact on each indirect cost element. However, doing this within the constraints of an agency's time or budget is not always feasible, and the technical, financial, and accounting information to carry out such an analysis may simply be unavailable.

RPE multipliers provide, at an aggregate level, the relative shares of revenues (Revenue = Direct Costs + Indirect Costs + Net Income) to direct manufacturing costs. Using RPE multipliers implicitly assumes that incremental changes in direct manufacturing costs produce common incremental changes in all indirect cost contributors as well as net income. A concern in using the RPE multiplier in cost analysis for new technologies added in response to regulatory requirements is that the indirect costs of vehicle modifications are not likely to be the same for different technologies. For example, less complex technologies could require fewer R&D efforts or less warranty coverage than more complex technologies. In addition, some simple technological adjustments may, for example, have no effect on the number of corporate personnel and the indirect costs attributable to those personnel. The use of RPEs, with their assumption that all technologies have the same proportion of indirect costs, is likely to overestimate the costs of less complex technologies and underestimate the costs of more complex technologies.

To address this concern, the agencies have developed modified multipliers. These multipliers are referred to as indirect cost multipliers (ICMs). In contrast to RPE multipliers, ICMs assign unique incremental changes to each indirect cost contributor

$$\text{ICM} = (\text{direct cost} + \text{adjusted indirect cost} + \text{profit})/(\text{direct cost})$$

Developing the ICMs from the RPE multipliers requires developing adjustment factors based on the complexity of the technology and the time frame under consideration. This methodology was used in the cost estimation for the MYs 2012-2016 final rule. The ICMs were developed in a peer-reviewed report from RTI International and were subsequently discussed in a peer-reviewed journal article.[14] Note that the cost of capital (reflected in profit) is included because of the assumption implicit in ICMs (and RPEs) that capital costs are proportional to direct costs, and businesses need to be able to earn returns on their investments. The capital costs are those associated with the incremental costs of the new technologies.

As noted above, for the analysis supporting this proposed rulemaking, the agencies are again using the ICM approach but have made some changes to both the ICM factors and to the method of applying those factors to arrive at a final cost estimate. The first of these changes was done in response to continued thinking among the EPA-NHTSA team about how past ICMs have been developed and what are the most appropriate data sources to rely upon in determining the appropriate ICMs. The second change has been done both due to staff concerns and public feedback suggesting that the agencies were inappropriately applying learning effects to indirect costs via the multiplicative approach to applying the ICMs.

Regarding the first change – to the ICM factors themselves – a little background must first be provided. In the original work done under contract to EPA by RTI International,[15] EPA experts had undertaken a consensus approach to determining the impact of specific technology changes on the indirect costs of a company. Subsequent to that effort, EPA experts conducted a blind survey to make this determination on a different set of technology changes. This subsequent effort, referred to by EPA as a modified-Delphi approach, resulted in slightly different ICM determinations. This effort is detailed in a memorandum contained in the docket for this rule.[16] Upon completing this effort, the EPA team determined that the original RTI values should be averaged with the modified-Delphi values to arrive at the final ICMs for low and medium complexity technologies and that the original RTI values would be used for high complexity level 1 while the modified-Delphi values would be used for high complexity level 2. These final ICMs as described were used in the MYs 2012-2016 light-duty GHG/CAFE rulemaking.

More recently, EPA and NHTSA decided that the original light-duty RTI values, because of the technologies considered for low and medium complexity, should no longer be used and that we should rely solely on the modified-Delphi values for these complexity levels. The original light-duty RTI study used low rolling resistance tires as a low complexity technology example and a dual clutch transmission as a medium complexity technology. Upon further thought, the technologies considered for the modified Delphi values (passive aerodynamic improvements for low complexity and turbocharging with downsizing for medium complexity) were considered to better represent the example technologies. As a result, the modified-Delphi values became the working ICMs for low and medium complexity rather than averaging those values with the original RTI report values. NHTSA and EPA staff also re-examined the technology complexity categories that were assigned to each light-duty technology and modified these assignments to better reflect the technologies that are now used as proxies to determine each category's ICM value.

A secondary-level change was also made as part of this ICM recalculation to the light-duty ICMs. That change was to revise upward the RPE level reported in the original RTI report from an original value of 1.46 to 1.5 to reflect the long term average RPE. The original RTI study was based on 2007 data. However, an analysis of historical RPE data indicates that, although there is year to year variation, the average RPE has remained roughly 1.5. ICMs will be applied to future year's data and therefore NHTSA and EPA staff believe that it would be appropriate to base ICMs on the historical average rather than a single year's result. Therefore, ICMs in this proposed rulemaking were adjusted to reflect this average level. As a result, the High 1 and High 2 ICMs have also changed.

Table 3-1 shows both the ICM values used in the MYs 2012-2016 final rule and the new ICM values used for the analysis supporting these proposed rules. Near term values account for differences in the levels of R&D, tooling, and other indirect costs that will be incurred. Once the program has been fully implemented, some of the indirect costs will no longer be attributable to the standards and, as such, a lower ICM factor is applied to direct costs.

Table 3-1 Indirect Cost Multipliers Used in this Analysis[a]

	2012-2016 Rule		This Proposal	
Complexity	Near term	Long term	Near term	Long term
Low	1.17	1.13	1.24	1.19
Medium	1.31	1.19	1.39	1.29
High1	1.51	1.32	1.56	1.35
High2	1.70	1.45	1.77	1.50

[a] Rogozhin, A., et. al., "Using indirect cost multipliers to estimate the total cost of

The second change made to the ICMs has to do with the way in which they are applied. To date, we have applied the ICMs, as done in any analysis that relied on RPEs, as a pure multiplicative factor. This way, a direct manufacturing cost of, say, $100 would be multiplied by an ICM of 1.24 to arrive at a marked up technology cost of $124. However, as learning effects (discussed below) are applied to the direct manufacturing cost, the indirect costs are also reduced accordingly. Therefore, in year two the $100 direct manufacturing cost might reduce to $97, and the marked up cost would become $120 ($97 x 1.24). As a result, indirect costs would be reduced from $24 to $20. Given that indirect costs cover many things such as facility-related costs, electricity, etc., it is perhaps not appropriate to apply the ICM to the learned direct costs, at least not for those indirect cost elements unlikely to change with learning. The EPA-NHTSA team believes that it is appropriate to allow only warranty costs to decrease with learning, since warranty costs are tied to direct manufacturing costs (since warranty typically involves replacement of actual parts which should be less costly with learning). The remaining elements of the indirect costs should remain constant year-over-year, at least until some of those indirect costs are no longer attributable to the rulemaking effort that imposed them (such as R&D).

As a result, the ICM calculation has become more complex with the analysis supporting this proposal. We must first establish the year in which the direct manufacturing costs are considered "valid." For example, a cost estimate might be considered valid today, or perhaps not until high volume production is reached—which will not occur until MY 2015 or later. That year is known as the base year for the estimated cost. That cost is the cost used to determine the "non-warranty" portion of the indirect costs. For example, the non-warranty portion of the medium complexity ICM in the short-term is 0.343 (the warranty versus non-warranty portions of the ICMs are shown in Table 3-2). For the dual cam phasing (DCP) technology on an I4 engine we have estimated a direct manufacturing cost of $70 in MY 2015. So the non-warranty portion of the indirect costs would be $24.01 ($70 x 0.343). This value would be added to the learned direct manufacturing cost for each year through 2018, the last year of short term indirect costs. Beginning in 2019, when long-term indirect costs begin, the additive factor would become $18.13 ($70 x 0.259). Additionally, the $70 cost in 2015 would become $67.90 in MY 2016 due to learning ($70 x (1-3%)). So, while the warranty portion of the indirect costs would be $3.15 ($70 x 0.045) in 2015, indirect costs would decrease to $3.06 ($67.90 x 0.045) in 2016 as warranty costs decrease with learning. The resultant indirect costs for the DCP-I4 technology would be $27.16 ($24.01+$3.15) in MY 2015 and $27.07 ($24.01+$3.06) in MY2016, and so on for subsequent years.

Table 3-2 Warranty and Non-Warranty Portions of ICMs

	Near term	Long term

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adding new technology in the automobile industry," International Journal of Production Economics (2009); "Documentation of the Development of Indirect Cost Multipliers for Three Automotive Technologies," Helfand, G., and Sherwood, T., Memorandum dated August 2009; "Heavy Duty Truck Retail Price Equivalent and Indirect Cost Multipliers," Draft Report prepared by RTI International and Transportation Research Institute, University of Michigan, July 2010

Complexity	Warranty	Non-warranty	Warranty	Non-warranty
Low	0.012	0.230	0.005	0.187
Medium	0.045	0.343	0.031	0.259
High1	0.065	0.499	0.032	0.314
High2	0.074	0.696	0.049	0.448

There is some level of uncertainty surrounding both the ICM and RPE markup factors. The ICM estimates used in this proposal group all technologies into three broad categories and treat them as if individual technologies within each of the three categories (low, medium, and high complexity) will have exactly the same ratio of indirect costs to direct costs. This simplification means it is likely that the direct cost for some technologies within a category will be higher and some lower than the estimate for the category in general. Additionally, the ICM estimates were developed using adjustment factors developed in two separate occasions: the first, a consensus process, was reported in the RTI report; the second, a modified Delphi method, was conducted separately and reported in an EPA memorandum. Both these panels were composed of EPA staff members with previous background in the automobile industry; the memberships of the two panels overlapped but were not the same. The panels evaluated each element of the industry's RPE estimates and estimated the degree to which those elements would be expected to change in proportion to changes in direct manufacturing costs. The method and the estimates in the RTI report were peer reviewed by three industry experts and subsequently by reviewers for the International Journal of Production Economics.[17] However, the ICM estimates have not yet been validated through a direct accounting of actual indirect costs for individual technologies. RPEs themselves are also inherently difficult to estimate because the accounting statements of manufacturers do not neatly categorize all cost elements as either direct or indirect costs. Hence, each researcher developing an RPE estimate must apply a certain amount of judgment to the allocation of the costs. Since empirical estimates of ICMs are ultimately derived from the same data used to measure RPEs, this affects both measures. However, the value of RPE has not been measured for specific technologies, or for groups of specific technologies. Thus applying a single average RPE to any given technology by definition overstates costs for very simple technologies, or understates them for advanced technologies.

3.2.2.3 Stranded capital

Because the production of automotive components is capital-intensive, it is possible for substantial capital investments in manufacturing equipment and facilities to become "stranded" (where their value is lost, or diminished). This would occur when the capital is rendered useless (or less useful) by some factor that forces a major change in vehicle design, plant operations, or manufacturer's product mix, such as a shift in consumer demand for certain vehicle types. It can also be caused by new standards that phase-in at a rate too rapid to accommodate planned replacement or redisposition of existing capital to other activities. The lost value of capital equipment is then amortized in some way over production of the new technology components.

It is difficult to quantify accurately any capital stranding associated with new technology phase-ins under the proposed standards because of the iterative dynamic involved – that is, the new technology phase-in rate strongly affects the potential for additional cost due to stranded capital, but that additional cost in turn affects the degree and rate of phase-in for the same or other individual competing technologies. In addition, such an analysis is very company-, factory-, and manufacturing process-specific, particularly in regard to finding alternative uses for equipment and facilities. Nevertheless, in order to account for the possibility of stranded capital costs, the agencies asked FEV to perform an analysis, using conservative assumptions, of the potential stranded capital costs associated with rapid phase-in of technologies due to new standards, using data from FEV's primary teardown-based cost analyses.[18]

The assumptions made in FEV's stranded capital analysis with potential for major impacts on results are:

- All manufacturing equipment was bought brand new when the old technology started production (no carryover of equipment used to make the previous components that the old technology itself replaced).
- 10-year normal production runs: Manufacturing equipment used to make old technology components is straight-line depreciated over a 10-year life.
- Factory managers do not optimize capital equipment phase-outs (that is, they are assumed to routinely repair and replace equipment without regard to whether or not it will soon be scrapped due to adoption of new vehicle technology).
- Estimated stranded capital is amortized over 5 years of annual production at 450,000 units (of the new technology components). This annual production is identical to that assumed in FEV's primary teardown-based cost analyses. The 5-year recovery period is chosen to help ensure a conservative analysis; the actual recovery would of course vary greatly with market conditions.

FEV assembled a team of manufacturing experts to perform the analysis, using a methodology with the following key steps for each vehicle technology scenario:

1) Identify all of the old technology components that are no longer used or that are modified in the new technology vehicles (from the comparison bills of materials developed in the primary teardown-based analyses).

2) For each of these components identify the manufacturing equipment and tooling needed to make it.

3) Estimate the new-purchase $ value of each item identified in step 2.

4) Assign an "Investment Category" to each equipment item identified in step 2, based on an assessment by FEV's experts of recoverable value:

    - Flexible: Equipment can be used to manufacture new technology or other parts (0% stranded)

- Re-Useable: Equipment can be used in alternative industries, sold at 50% of its remaining value (50% stranded)
- Semi-Dedicated: Estimate that 50% of equipment is flexible (50% stranded)
- Dedicated: Custom manufacturing equipment (100% stranded)

5) Assign an "Investment Category" to each tooling item identified in step 2, based on an assessment by FEV's experts of recoverable value:

   - Flexible: Can be used for manufacturing new technology parts (0% stranded)
   - Perishable: Frequent replacement of tooling (0% stranded)
   - Semi-Dedicated Tooling: Estimate that 50% of tooling is dedicated (50% stranded)
   - Dedicated: Commodity-specific (100% stranded)

6) Multiply the % stranding values from steps 4 and 5 by the $ values from step 3.

7) Multiply the results in step 6 by 70%, 50%, and 20% for 3-, 5-, and 8-year stranding scenarios, respectively. That is, an old technology, for which production is truncated prematurely after only 8 years, will experience the stranding of 20% (the last 2 years of its 10-year normal production run) of its associated remaining capital value.

8) Sum the results in step 7 to obtain overall stranded capital costs.

9) Divide the results in step 8 by 2,250,000 (5 years x 450,000 units/year) to obtain $/vehicle values, applicable to new technology vehicles for the 1st 5 years of their production due to the assumed 5-year recovery period.

The stranded capital analysis was performed for three transmission technology scenarios, two engine technology scenarios, and one hybrid technology scenario, as shown in Table 3-3. The methodology used by EPA in applying these results to the technology costs is described in Chapter 3 of EPA's draft RIA. The methodology used by NHTSA in applying these results to the technology costs is described in NHTSA's preliminary RIA section V.

Table 3-3 Stranded Capital Analysis Results (2009 dollars/vehicle)

Replaced technology	New technology	Stranded capital cost per vehicle when replaced technology's production is ended after:		
		3 years	5 years	8 years
6-speed AT	6-speed DCT	$55	$39	$16
6-speed AT	8-speed AT	$48	$34	$14
6-speed DCT	8-speed DCT	$28	$20	$8
Conventional V6	DSTGDI I4	$56	$40	$16
Conventional V8	DSTGDI V6	$60	$43	$17
Conventional V6	Power-split HEV	$111	$79	$32

DSTGDI=Downsized, turbocharged engine with stoichiometric gasoline direct injection.

3.2.3 Cost reduction through manufacturer learning

For this proposal, we have not changed our estimates of learning and how learning will impact costs going forward from what was employed in the analysis for the MYs 2012-2016 light-duty vehicle rule. However, we have updated our terminology in an effort to clarify that we consider there to be one learning effect—learning by doing—which results in cost reductions occurring with every doubling of production.[e] In the past, we have referred to volume-based and time-based learning. Our terms were meant only to denote where on the volume learning curve a certain technology was—“volume-based learning” meant the steep portion of the curve where learning effects are greatest, while “time-based learning” meant the flatter portion of the curve where learning effects are less pronounced. Unfortunately, our terminology led some to believe that we were implementing two completely different types of learning—one based on volume of production and the other based on time in production. Our new terminology—steep portion of the curve and flat portion of curve—is simply meant to make more clear that there is one learning curve and some technologies can be considered to be on the steep portion while others are well into the flatter portion of the curve. These two portions of the volume learning curve are shown in Figure 3-1.

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[e] Note that this new terminology was described in the recent heavy-duty GHG final rule (see 76 FR 57320). The learning approach used in this analysis is entirely consistent with that used and described for that analysis.

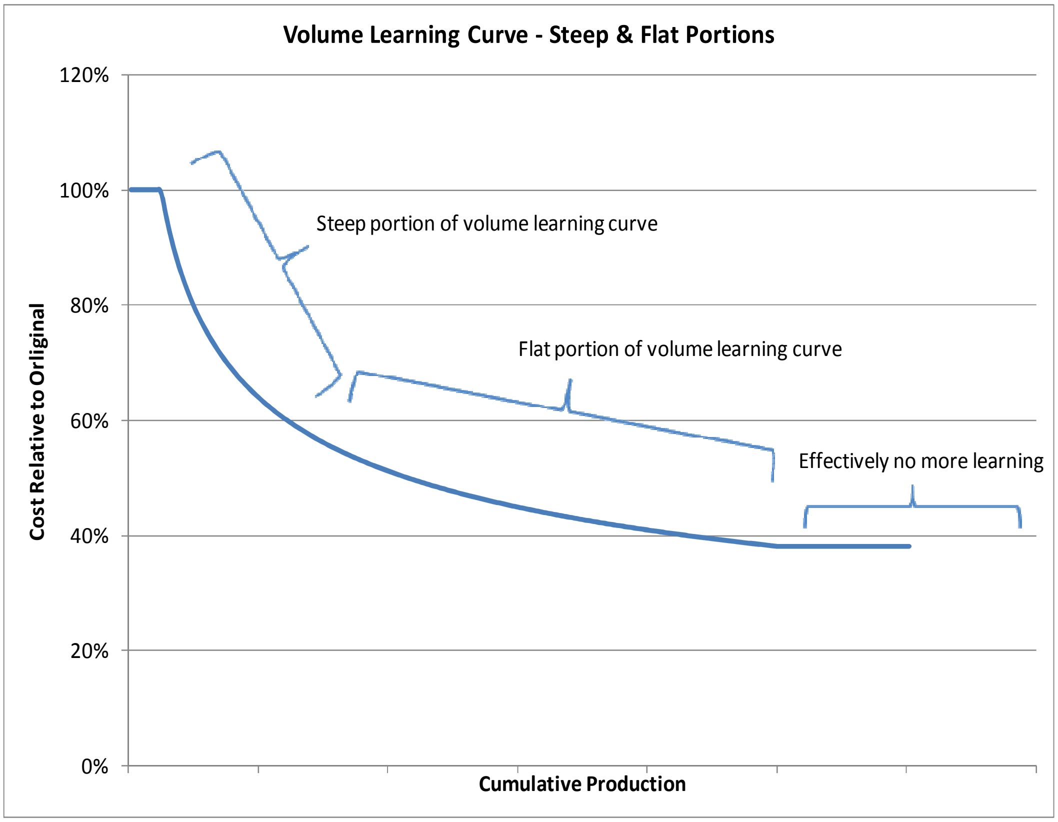

Figure 3-1 Steep & Flat Portions of the Volume Learning Curve

For some of the technologies considered in this analysis, manufacturer learning effects would be expected to play a role in the actual end costs. The “learning curve” or “experience curve” describes the reduction in unit production costs as a function of accumulated production volume. In theory, the cost behavior it describes applies to cumulative production volume measured at the level of an individual manufacturer, although it is often assumed—as both agencies have done in past regulatory analyses—to apply at the industry-wide level, particularly in industries like the light duty vehicle production industry that utilize many common technologies and component supply sources. Both agencies believe there are indeed many factors that cause costs to decrease over time. Research in the costs of manufacturing has consistently shown that, as manufacturers gain experience in production, they are able to apply innovations to simplify machining and assembly operations, use lower cost materials, and reduce the number or complexity of component parts. All of these factors allow manufacturers to lower the per-unit cost of production. We refer to this phenomenon as the manufacturing learning curve.

NHTSA and EPA included a detailed description of the learning effect in the MYs 2012-2016 light-duty rule and the more recent heavy-duty rule.[19] Most studies of the effect of experience or learning on production costs appear to assume that cost reductions begin only after some initial volume threshold has been reached, but not all of these studies specify this threshold volume. The rate at which costs decline beyond the initial threshold is usually expressed as the percent reduction in average unit cost that results from each successive doubling of cumulative production volume, sometimes referred to as the learning rate. Many estimates of experience curves do not specify a cumulative production volume beyond which cost reductions would no longer occur, instead depending on the asymptotic behavior of the effect for learning rates below 100 percent to establish a floor on costs.

In past rulemaking analyses, as noted above, both agencies have used a learning curve algorithm that applied a learning factor of 20 percent for each doubling of production volume. NHTSA has used this approach in analyses supporting recent CAFE rules. In its analyses, EPA has simplified the approach by using an "every two years" based learning progression rather than a pure production volume progression (i.e., after two years of production it was assumed that production volumes would have doubled and, therefore, costs would be reduced by 20 percent).[f]

In the MYs 2012-2016 light-duty rule and the recent heavy-duty GHG final rule, the agencies employed an additional learning algorithm to reflect the volume-based learning cost reductions that occur further along on the learning curve. This additional learning algorithm was termed "time-based" learning in the 2012-2016 rule simply as a means of distinguishing this algorithm from the volume-based algorithm mentioned above, although both of the algorithms reflect the volume-based learning curve supported in the literature. As described above, we are now referring to this learning algorithm as the "flat portion" of the learning curve. This way, we maintain the clarity that all learning is, in fact, volume-based learning, and that the level of cost reductions depend only on where on the learning curve a technology's learning progression is. We distinguish the flat portion of the curve from the steep portion of the curve to indicate the level of learning taking place in the years following implementation of the technology (see Figure 3-1). The agencies have applied learning effects on the steep portion of the learning curve for those technologies considered to be newer technologies likely to experience rapid cost reductions through manufacturer learning, and learning effects on the flat portion learning curve for those technologies considered to be more mature technologies likely to experience only minor cost reductions through manufacturer learning. As noted above, the steep portion learning algorithm results in 20

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[f] To clarify, EPA has simplified the steep portion of the volume learning curve by assuming that production volumes of a given technology will have doubled within two years time. This has been done largely to allow for a presentation of estimated costs during the years of implementation, without the need to conduct a feedback loop that ensures that production volumes have indeed doubled. If we were to attempt such a feedback loop, we would need to estimate first year costs, feed those into OMEGA, review the resultant technology penetration rate and volume increase, calculate the learned costs, feed those into OMEGA (since lower costs would result in higher penetration rates, review the resultant technology penetration rate and volume increase, etc., until an equilibrium was reached. To do this for all of the technologies considered in our analysis is simply not feasible. Instead, we have estimated the effects of learning on costs, fed those costs into OMEGA, and reviewed the resultant penetration rates. The assumption that volumes have doubled after two years is based solely on the assumption that year two sales are of equal or greater number than year one sales and, therefore, have resulted in a doubling of production. This could be done on a daily basis, a monthly basis, or, as we have done, a yearly basis.

percent lower costs after two full years of implementation (*i.e.*, the MY 2016 costs would be 20 percent lower than the MYs 2014 and 2015 costs). Once two steep portion learning steps have occurred, flat portion learning at 3 percent per year becomes effective for 5 years. Beyond 5 years of learning at 3 percent per year, 5 years of learning at 2 percent per year, then 5 at 1 percent per year become effective.

Learning effects are applied to most but not all technologies because some of the expected technologies are already used rather widely in the industry and we therefore assume that learning impacts have already occurred. The steep portion learning algorithm was applied for only a handful of technologies that are considered to be new or emerging technologies. Most technologies have been considered to be more established given their current use in the fleet and, hence, the lower flat portion learning algorithm has been applied. The learning algorithms applied to each technology and the applicable timeframes are summarized in Table 3-4.

Table 3-4 Learning Effect Algorithms Applied to Technologies Used in this Analysis

Technology	Steep learning	Flat learning	No learning
Engine modifications to accommodate low friction lubes			2012-2025
Engine friction reduction – level 1 & 2			2012-2025
Lower rolling resistance tires – level 1			2012-2025
Low drag brakes			2012-2025
Secondary axle disconnect		2012-2025	
Electric/Plug-in vehicle battery charger installation labor			2012-2025
Variable valve timing		2012-2025	
Variable valve lift		2012-2025	
Cylinder deactivation		2012-2025	
Stoichiometric gasoline direct injection		2012-2025	
Aggressive shift logic – level 1 & 2		2012-2025	
Early torque converter lockup		2012-2025	
5/6/7/8 speed auto transmission		2012-2025	
6/8 speed dual clutch transmission		2012-2025	
High efficiency gearbox		2012-2025	
Improved accessories – level 1 & 2		2012-2025	
Electronic/electro-hydraulic power steering		2012-2025	
Aero improvements – level 1 & 2		2012-2025	
Conversion to DOHC without reducing # of cylinders		2012-2025	
Air conditioner related hardware		2012-20205	
Air conditioner alternative refrigerant	2016-2020	2021-2025	
Cooled EGR		2012-2025	
Conversion to Atkinson cycle		2012-2025	
Turbocharging & downsizing		2012-2025	

Mass reduction		2012-2025	
Advanced diesel		2012-2025	
Hybrid/Electric/Plug-in vehicle non-battery components		2012-2025	
P2 Hybrid vehicle battery-pack components	2012-2016	2017-2025	
Electric/Plug-in vehicle battery-pack components	2012-2025[a]		
Electric/Plug-in vehicle battery charger components	2012-2025[a]		
Stop-start	2012-2015	2016-2025	
Lower rolling resistance tires – level 2	2017-2021	2022-2025	

[a] Note that the steep learning effects have for EV and PHEV battery packs and charger components have been carried through 5 learning cycles but at a decelerated pace as described in the text.

The learning effects discussed here impact the technology costs in that those technology costs for which learning effects are considered applicable are changing throughout the period of implementation and the period following implementation. For example, some of the technology costs considered in this analysis are taken from the MY 2012-2016 light-duty rule. Many of the costs in the 2012-2016 light-duty rule were considered “applicable” for the 2012 model year. If flat-portion learning were applied to those technologies, the 2013 cost would be 3 percent lower than the 2012 cost, and the 2014 model year cost 3 percent lower than the 2013 cost, etc. As a result, the 2017-2025 costs for a given technology used in this analysis reflect those years of flat learning and would not be identical to the 2012 model year cost for that same technology presented in the 2012-2016 light-duty rule.

Because of the nature of battery pack development (i.e., we are arguably still in the research phase for the types of batteries considered in this proposal, and cost reduction through manufacturer-based learning has only just begun, if it has begun at all), the agencies have carried the learning curve through five steep based learning steps although at a somewhat slower pace than every two years. This has been done in an effort to maintain the shape of a traditional learning curve. This curve was developed by using the ANL BatPaC model costs as direct manufacturing costs applicable in the 2025 MY. We have then unlearned those costs back to 2012 using the curve shown in Figure 3-2. This is the same curve used in the 2010 TAR (see 2010 TAR at page B-22). This allows the agencies to estimate costs in MYs 2017 through 2025, as well as those costs in each year back to MY 2012, if desired. As noted, this learning curve consists of 5 full learning steps on the steep portion of the learning curve, each of which results in costs being reduced 20 percent relative to the prior step. These learning steps are shown occurring every two years beginning in 2012 until 2020, at which time a 5 year gap is imposed until 2025 when the fifth steep learning step occurs. Beyond 2025, learning on the flat portion of the curve begins at 3 percent per year cost reductions. The smooth line shows a logarithmic curve fit applied to the learning curve as the agencies’ cost model would apply learning.

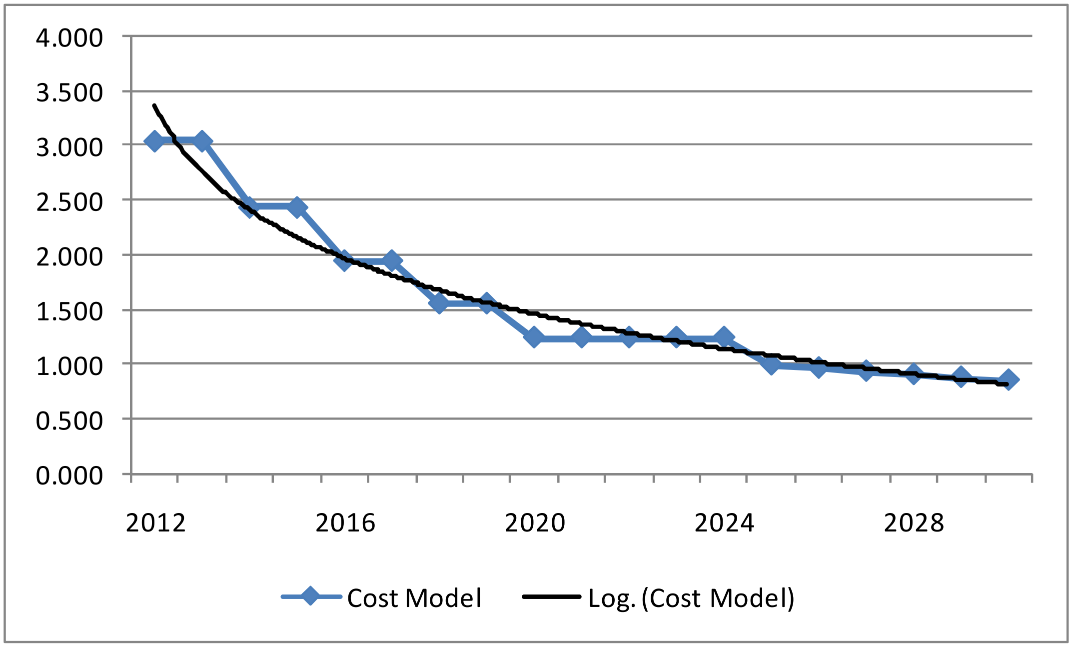

Figure 3-2 Learning Curve used for EV & PHEV Battery-Packs and In-Home Charger Costs

3.2.4 Costs Updated to 2009 Dollars

This change is simply to update any costs presented in earlier analyses to 2009 dollars using the GDP price deflator as reported by the Bureau of Economic Analysis on January 27, 2011. The factors used to update costs from 2007 and 2008 dollars to 2009 dollars are shown below. For the final rule, we may move to 2010 dollars but, for this analysis, given the timing of conducting modeling runs and developing inputs to those runs, the factors for converting to 2010 dollars were not yet available.

	2007	2008	2009
Price Index for Gross Domestic Product	106.3	108.6	109.6
Factor applied to convert to 2009 dollars	1.031	1.009	1.00

Source: Bureau of Economic Analysis, Table 1.1.4. Price Indexes for Gross Domestic Product, downloaded 1/27/2011, last revised 12/22/2010.

3.3 How did the agencies determine effectiveness of each of these technologies?

The agencies determined the effectiveness of each individual technology with a process similar to the one used for the 2012-2016 light duty vehicle GHG and CAFE standards. The individual effectiveness of several technologies discussed in this rule that were present in the earlier rule were left largely unchanged while others were updated. EPA and NHTSA reviewed recent confidential manufacturer estimates of technology effectiveness and found them to be generally consistent with our estimates. Additionally, EPA used vehicle simulation modeling to gain further insight on existing and new technologies for this rulemaking. EPA conducted a vehicle simulation project (described in 3.3.1) that included a majority of the proposed technologies, the results of which:

- informed existing individual technology effectiveness values,
- provided data for newly introduced technologies, and
- most importantly, provided an interactive data source with which to update and calibrate the new LP model

The lumped parameter model then served as the primary tool in evaluating the individual technology effectiveness estimates, the combined effectiveness of groups of technologies (or packages) and synergy factors, as described in 3.3.2. The effectiveness values, in conjunction with costs, were then applied to vehicles across the fleet for use in the Agencies' respective compliance models.

3.3.1 Vehicle simulation modeling

3.3.1.1 Background

For regulatory purposes, the fuel economy of any given vehicle is determined by placing the vehicle on a chassis dynamometer (akin to a large treadmill that puts the vehicle's wheels in contact with one or more rollers, rather than with a belt stretched between rollers) in a controlled environment, driving the vehicle over a specific driving cycle (in which driving speed is specified for each second of operation), measuring the amount of carbon dioxide emitted from the vehicle's tailpipe, and calculating fuel consumption based on the density and carbon content of the fuel.

One means of determining the effectiveness of a given technology as applied to a given vehicle model would be to measure the vehicle's fuel economy on a chassis dynamometer, install the new technology, and then re-measure the vehicle's fuel economy. However, most technologies cannot simply be "swapped out," and even for those that can, simply doing so without additional engineering work may change other vehicle characteristics (*e.g.*, ride, handling, performance, etc.), producing an "apples to oranges" comparison.

Some technologies can also be more narrowly characterized through bench or engine dynamometer (*i.e.*, in which the engine drives a generator that is, in turn, used to apply a controlled load to the engine) testing. For example, engine dynamometer testing could be used to evaluate the brake-specific fuel consumption (*e.g.*, grams per kilowatt-hour) of a given engine before and after replacing the engine oil with a less viscous oil. However, such testing does not provide a direct measure of overall vehicle fuel economy or changes in overall vehicle fuel economy.

For a vehicle that does not yet exist, as in the agencies' analyses of CAFE and GHG standards applicable to future model years, even physical testing can provide only an estimate of the vehicle's eventual fuel economy. Among the alternatives to physical testing, automotive engineers involved in vehicle design make use of computer-based analysis tools, including a powerful class of tools commonly referred to as "full vehicle simulation." Given highly detailed inputs regarding vehicle engineering characteristics, full vehicle simulation provides a means of estimating vehicle fuel consumption over a given drive cycle, based on the explicit representation of the physical laws governing vehicle propulsion and dynamics. Some vehicle simulation tools also incorporate combustion simulation tools that represent the combustion cycle in terms of governing physical and chemical processes. Although these tools are computationally intensive and required a great deal of input data, they provide engineers involved in vehicle development and design with an alternative that can be considerably faster and less expensive than physical experimentation and testing.

Properly executed, methods such as physical testing and full vehicle simulation can provide reasonably (though not absolutely) certain estimates of the vehicle fuel economy of specific vehicles to be produced in the future. However, when analyzing potential CAFE and GHG standards, the agencies are not actually designing specific vehicles. The agencies are considering implications of new standards that will apply to the average performance of manufacturers' entire production lines. For this type of analysis, precision in the estimation of the fuel economy of individual vehicle models is not essential; although it is important that the agency avoid systematic upward or downward bias, uncertainty at the level of individual models is mitigated by the fact that compliance with CAFE and GHG standards is based on average fleet performance.

DOT's CAFE model and EPA's OMEGA are not full vehicle simulation models. Both models use higher-level estimates of the efficacy of different technologies or technology packages. Both models apply methods to avoid potential double-counting of efficacy addressing specific energy loss mechanisms (*e.g.*, pumping losses), and for this NPRM, both agencies applied estimates using EPA's lumped parameter model, which was updated using results of full vehicle simulation performed by Ricardo, PLC. Although full vehicle simulation could, in principle, be fully integrated into the agencies' model-by-model analyses of the entire fleet to be projected to be produced in future model years, this level of integration would be infeasible considering the size and complexity of the fleet. Also, considering the forward-looking nature of the agencies' analyses, and the amount of information required to perform full vehicle simulation, this level of integration would involve misleadingly precise estimates of fuel consumption and CO_2 emissions.

Still, while the agencies have used results of full vehicle simulation to inform the development of model inputs for performing fleet-level analysis, information from other sources (*e.g.*, vehicle testing) could be considered when developing such model inputs. Before performing analysis to support the evaluation and finalization of post-2016 CAFE and GHG standards, the agencies will revisit estimates of technology efficacy for use DOT's CAFE model and EPA's OMEGA model, and invite comment on the use of information from full vehicle simulation and other sources. Related, DOT has, as discussed above, contracted with Argonne National Laboratory (ANL) to provide additional full vehicle simulation modeling support for this MYs 2017-2025 rulemaking, and anticipates that results will be available for use in developing inputs for the final rule.

3.3.1.2 2011 Ricardo Simulation Study

For this rule EPA built upon its 2008 vehicle simulation project[20] used to support the 2012-2016 light duty vehicle GHG and CAFE standards (reference). As in the initial project, the technical work was conducted by the global engineering consulting firm, Ricardo, Inc. (under subcontract to SRA Corporation), using its MSC.EASY5 dynamic vehicle simulation model. This section is intended to supplement the main report which (has been) recently published and peer-reviewed1. While this project represents a new round of full-scale vehicle simulation of advanced technologies, the scope has also been expanded in several ways to broaden the range of vehicle classes and technologies considered, consistent with a longer-term outlook through model years 2017-2025. The expanded scope also includes a new analytical tool (complex systems analysis tool) to assist in interpolating the response surface modeling (RSM) data and visualizing technology effectiveness. This tool was especially useful in isolating effectiveness trends during development of the updated Lumped Parameter model.

The agencies try to use publicly available information as the basis for technical assessments whenever possible. Because this rulemaking extends to MY 2025, and includes some technologies that are not currently in production and for which there is limited information available in the literature, some of the technology inputs used to estimate effectiveness are based on confidential business information. This includes the inputs related to the technologies listed below which were based on confidential business information belonging to Ricardo, Inc, and their expert judgment that contributed to projecting how these technologies might improve in the future. The agencies have also considered information which is in the public domain, in particular for turbo-charged, downsized GDI engines as discussed in Section 3.4.1.8, as well as confidential information on engine and transmission technologies from automotive suppliers which directionally was in line with the information considered by Ricardo. The agencies encourage commenters to submit technical information, preferably that may be released publicly, related to these technologies, particularly on their effectiveness and ability to be implemented in a way that maintains utility. The agencies welcome data and information on the technologies individually or in combinations.

- Advanced turbocharged and downsized, Atkinson, advanced diesel (*e.g.* projected BSFC maps)Hybrid powertrain control strategies
- Optimized transmission shift control strategies
- Transmission efficiency improvement.

Below is a summary of the significant content changes from the 2008 simulation project to the 2011 simulation project that supports the proposed rule:

3.3.1.2.1 More Vehicle Classes

Two additional vehicle classes were considered, for a total of seven classes: a small car (subcompact) and a medium/heavy duty truck class. The inclusion of the small car class increased the fidelity of the results by capturing engineering differences unique to the smallest vehicles in the market. The inclusion of the medium/heavy duty truck was meant primarily to support EPA's analysis for the Heavy Duty GHG Rule[21]. It is worth noting that these vehicle classes are for simulation purposes only and are not be confused with regulatory classes or NHTSA's technology subclasses.

3.3.1.2.2 More engine and vehicle technologies

The original 2008 project modeled several engine and transmission technologies that were expected to become commercially available within the 2012-2016 time frame. These technologies included advanced valvetrain technologies (such as variable valve timing and lift, cylinder deactivation), turbocharged and downsized engines, as well as 6 speed automatic transmissions, CVTs[g] and dual-clutch transmissions. The current project built on top of this effort with the inclusion of several new engine and vehicle technologies. Highlighted examples included:

- Advanced, highly downsized, high BMEP[h] turbocharged engines
- High efficiency transmissions with 8 speeds and optimized shift strategies to maximize vehicle system efficiency
- Atkinson-cycle engines for hybrids
- Stop-start (or idle-off) technology

A discussion of these technologies is included Section 3.3.3, and also in the 2011 vehicle simulation report1.

3.3.1.2.3 Includes hybrid architectures

For the first time, this new work includes modeling of hybrid architectures for all vehicle classes. Two main classes of hybrids were considered:

- Input powersplit hybrids. Examples of input powersplits in the market today include the Ford Fusion HEV and the Toyota Prius.
- P2 hybrids. An example of the P2 hybrid is the Hyundai Sonata Hybrid.

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[g] Continuously variable transmissions

[h] BMEP refers to brake mean effective pressure, a common engineering metric which describes the specific torque of an engine, as a way of comparing engines of different sizes. It is usually expressed in units of bar, or kPa, Current naturally aspirated production engines typically average 10-12 bar BMEP, while modern turbocharged engines are now exceeding 20 bar BMEP with regularity. Simply put, a 20 bar BMEP turbocharged engine will provide twice the torque of an equivalent sized engine that achieves 10 bar BMEP.

While input powersplit hybrids remain a very likely hybrid architecture choice for some manufacturers, the agencies focused solely on P2 hybrids compared to powersplit hybrids due to their apparent cost-effectiveness advantage in future years.

Ricardo proprietary methodology was used to develop the control strategies were developed for each architecture, the details of which can be found in section 6.8 of the 2011 project report[1].

3.3.1.2.4 Complex systems tool for data analysis

In the original 2008 project, EPA staff selected unique technology packages, based on engineering judgment, to cover a representative subset of possible vehicle options ending in MY 2016. The expanded project time horizon (through MY 2025) and increased complexity of potential vehicle technology interactions (including hybrids) made package selection much more difficult. To account for unforeseen results and trends which might exist, EPA and Ricardo adopted a complex systems approach, which is a rigorous computational strategy designed to mathematically account for multiple input variables and determine the significance of each (the complex systems approach is described in further detail in the 2011 Ricardo report). As a comparison, in the 2008 study, twenty-six unique technology packages spanning five vehicle classes were selected by EPA staff and then modeled. For this project a set of core technology packages were chosen for each vehicle class, constituting a total of 107 unique vehicle packages ("nominal runs"), which are shown as Table 3-3 and Table 3-6 in 3.3.1.2.8. A neural network Complex Systems approach to design of experiments (DOE) was then applied to generate a set of response surface models (RSM), in which several input parameters were varied independently over a specified range to identify the complex relationship between these inputs and the vehicle performance. Using these methods, the vehicle simulation was run for a set of discrete input variables chosen based on a full factorial analysis, using a computationally efficient algorithm to select each input variable within the design space, allowing for subsequent statistical regression of the output variables. This approach resulted in an average of approximately two thousand independent simulation runs for each of the 100+ vehicle packages, the outputs of which were interpolated in the data analysis tool developed for this modeling activity. For each of these nominal and DOE runs Ricardo provided detailed 10-hz output data csv files for review[i].

An interactive Complex Systems analysis and visualization tool was developed to interpret the vast arrays of RSM data generated as part of the project. It was created to sample a selected portion of the design space populated using the DOE approach described above, and then interpret the RSM data set in a form that could be used to calibrate the lumped

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[i] Stakeholders wishing to obtain this data may contact EPA to arrange for transfer of the data. Due to the considerable size of the files (2 terabytes), stakeholders must supply their own storage media.

parameter model (reference the equivalent-performance results in Section 3.3.1.2.16). For more detail on the use of the RSM tool, refer to the 2011 Ricardo report[1].

3.3.1.2.5 Process

The core technical work, completed in February 2011, consisted of the following steps:

- Definition of project scope
- Selection of vehicle classes and baseline vehicle characteristics
- Selection of vehicle architectures and individual technologies
- Selection of swept variables for use in the RSM matrix
- Selection of vehicle performance metrics
- Review and revision of the input assumptions and modeling process
- Build and run the baseline EASY5 vehicle models
- Review of baseline runs and checking for errors
- Build and run the nominal technology package EASY5 vehicle models
- Review results and debug
- Run complete DOE matrix for each technology package
- Incorporation of DOE results into RSM tool

3.3.1.2.6 Definition of project scope

At project initiation, an advisory committee was formed and led by EPA to help guide the analysis. The advisory committee consisted of technical experts from CARB and The ICCT, the latter of which co-founded the project. A complete list of advisory committee members is found in the vehicle simulation project report[1]. The committee agreed upon the underlying ground rules, reviewed modeling assumptions and identified the desired vehicle architectures and selected technologies for review. The boundaries for the project are highlighted (quoted) below:

- A total of seven vehicle classes will be included: small car, standard car, large car, small and large MPVs (multi-purpose vehicles), truck and HD truck

- LDV technologies must have the potential to be commercially deployed in the 2020-2025 timeframe

- Vehicle sizes (footprint and interior space) for each class will be largely unchanged from 2010 to 2020-2025

- Hybrid vehicles will use an advanced hybrid control strategy, focusing on battery state-of-charge management, but will not compromise vehicle drivability

- Vehicles will use fuels equivalent to 87 octane pump gasoline and 40 cetane pump diesel
- It is assumed that 2020-2025 vehicles will meet future California LEV III requirements for criteria pollutants, approximately equivalent to current SULEV II (or EPA Tier 2 Bin 2) emissions levels
- Changes in vehicle road loads including mass, aerodynamic drag, and rolling resistance, will not be accounted for in any of the modeled technologies. Instead, changes in vehicle road loads may be addressed through user-specified continuous input variables in the Complex Systems tool.

The committee also decided that the following technologies fell outside the scope of the project, either due to project resource limitations, lack of sufficient input data, or a low potential to be commercially deployed in the timeframe considered:

- Charge-depleting powertrains (e.g. plug-in hybrids and electric range-extended vehicles) and electric vehicles
- Fuel cell-powered vehicles
- Non-reciprocating internal combustion engines or external combustion engines
- Manual transmissions and single-clutch automated manual transmissions (AMTs)
- Kinetic energy recovery systems other than battery systems
- Intelligent vehicle-to-vehicle (V2V) and vehicle-to-infrastructure optimization technology
- Bottoming cycles (such as organic Rankine cycles) for energy recovery
- Vehicle safety systems or structures will not be explicitly modeled for vehicles, as it is beyond the scope of the study

The committee also selected a set of swept input variables (vehicle parameters) which were considered most important to vehicle fuel economy and performance (swept variables are continuously variable input values that affect vehicle output efficiency in a smooth function for the response surface model). These variables consisted of engine displacement, final drive ratio, electric drive motor size (for hybrids), as well as road load factors (vehicle mass, aerodynamic drag, and rolling resistance). All of these input variables were randomized in each vehicle design of experiment matrix and then incorporated into the post-processing RSM data visualization tool.

3.3.1.2.7 Selection of vehicle classes and baseline vehicle characteristics

In order to estimate both technology costs and CO2 reduction estimates, it is necessary to describe the baseline vehicle characteristics as the basis from which comparisons may be drawn. In the 2012-2016 light-duty vehicle rule the vehicle baseline was defined as having a naturally aspirated gasoline engine with a port-fuel injection system, two intake and two exhaust valves and fixed valve timing and lift; the baseline transmission was a conventional 4-speed automatic, with no hybrid systems. These vehicles are referred to throughout this section as the 2008 baselines. For the present study, EPA and Ricardo elected to include a set of 2010 "baseline" technology vehicles, which reflect MY2010 trends in engine and vehicle technology as well as some technologies that are expected to be widespread within a few years. It is important to note that the 2010 baseline vehicles in the Ricardo study do not reflect the technology content of the baseline fleet vehicles used by each agency in their respective compliance modeling. The Ricardo 2010 baseline vehicles are only used in the analysis required to establish effectiveness and synergies in the lumped parameter model. The 2010 baseline vehicles all include an engine with dual overhead camshaft and dual-independent intake/exhaust valve timing, a six-speed automatic transmission, 12-volt idle off (stop-start) functionality and an alternator with partial energy regeneration capability. There is no change in the engine displacement or vehicle road load coefficients between the 2008 baseline and the 2010 baseline vehicles. For a table showing the 2010 baseline vehicle characteristics refer to Appendix 3 of the 2011 Ricardo report[1].

In the Ricardo study, seven vehicle classes were selected for the analysis, in order to more fully represent the broad groupings of a wide variety of products offered in the US passenger car and light-duty truck market. The seven vehicle categories chosen were as follows:

- Small car: a subcompact car typically powered by a small 4 cylinder engine.
- Standard car: a midsize car typically powered by a small 6 cylinder engine.
- Large car: a large passenger car typically powered by a large 6 cylinder engine.
- Small MPV: a small multi-purpose vehicle (MPV) or "crossover" vehicle typically powered by a 4 cylinder engine
- Large MPV: a minivan or large MPV or "crossover" unibody constructed vehicle with a large frontal area, typically powered by a 6 cylinder engine, capable of carrying ~ 6 or more passengers.
- Large truck (1/2 ton): large sports-utility vehicles and large pickup trucks, typically a ladder-on-frame construction, and typically powered by an 8 cylinder engine.
- Class 2b/3 truck (3/4 ton): a large pickup truck (although with a GVW no greater than 8.500 pounds) with a heavier frame intended to provide additional utility (a.k.a. "work" truck), typically powered by a larger 8 cylinder gasoline or diesel engine

3.3.1.2.8 Technology selection

Ricardo presented the committee with an array of potential technologies that might become commercially viable and present in the light-duty market by 2025. EPA and the Advisory Committee suggested additional other technologies, *e.g.* Atkinson engines for hybrids, fast engine warm-up strategies, etc, to consider in the selection process. The complete set of potential technologies can be found in Appendix 2 of the 2011 Ricardo report[1]. After further deliberation within the committee and by Ricardo, a subset of technologies considered most promising (from a technical feasibility and cost effectiveness standpoint) was selected by the committee and Ricardo for inclusion in the project test matrix. The technologies were distributed among four distinct vehicle architectures. These architectures represented unique EASY5 model structures, and are listed below:

- 2010 Baseline vehicles: intended to represent physical replicas of existing vehicle models, although some minor additional content was included (as described in Section 3.3.1.2.7)

- Conventional stop-start: vehicles for the 2020-2025 timeframe that included advanced engines but did not incorporate an electric drive or braking energy recovery. These vehicles all contained a 12 volt stop-start (or idle-off) capability, along with the following technologies further detailed in the 2011 Ricardo simulation study[j]:

    - higher efficiency gearbox (2020 timeframe)
    - optimized shift strategy (best BSFC)
    - alternator regeneration (during braking)
    - high-efficiency alternator
    - advanced engine warmup technologies
    - engine friction reduction (+3.5% fuel consumption reduction over 2008 baseline)
- P2 hybrid: represent a class of hybrids in which the electric drive motor is coupled via a clutch directly to the transmission input shaft. An existing vehicle in the market which most closely represents this architecture is the 2011 Hyundai Sonata Hybrid except that Ricardo recommended a P2 hybrid with a more efficient and cost effective dual clutch transmission in lieu of a planetary gear transmission. Additional examples of a P2 hybrid approach are the 2011 Volkswagen Touareg Hybrid, the 2011 Porsche S Hybrid, and the 2012 Infiniti M35 Hybrid. Each of these are examples of “first generation” P2 systems, as compared to for example the powersplit hybrid systems offered by Ford, Toyota and or the IMA systems from Honda which are in their second, third or even fourth generation. The

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[j] The technologies included in all of the conventional stop-start packages were expected to be widespread by years 2017-2025. Some “anytime technologies” such as aerodynamic drag and rolling resistance reduction were excluded from the nominal runs, but were incorporated in the complex systems portion of this project.

agencies are aware of some articles in trade journals, newspapers and other reviews that some first generation P2 hybrid vehicles with planetary gear transmissions have trade-offs in NVH and drivability – though these reviews do not cover all of the P2 systems available today, [and a number of reviews are very positive with respect to NVH and drivability]. For this analysis we are projecting that these issues with some first generation P2 systems can be addressed with no hardware cost increase or reduction in efficiency for future generations of P2 systems developed for the 2017-2025 time frame. The agencies seek comment on our assumptions in this regard, and we request comment on the applicability of DCTs to P2 hybrid applications, including any challenges associated with NVH or drivability. Key technology assumptions included:

  - Lithium-ion battery
  - DCT transmission
  - Electric drive motor which provides, when combined with a less powerful engine, equivalent 0-60 performance to the baseline vehicle.
  - Engine displacement for the P2 hybrids were assumed to be 20% less than their conventional stop-start equivalents

- Input powersplit hybrid: represent a class of hybrids with both an electric drive motor and a separate generator linked to a planetary gearset which effectively controls the overall gear ratio and distribution of tractive and electrical power. Example vehicles in the market include the Toyota Prius and the Ford Fusion hybrid. Key technology assumptions are consistent with those for the P2 hybrid, with the exception of the power split device, which functions as a CVT-type transmission (as is the case in real world examples), and replaces the DCT transmission in the P2 design. As stated previously while this technology was simulated it was not used in this NPRM analysis.

Some architectures that seemed less appropriate for certain vehicle classes were omitted. For example, in the Ricardo modeling of the medium/heavy duty truck (a Class 3 vehicle with a GVWR >10,000 pounds, and thus not subject to the proposed standards in this rulemaking), no P2 or input powersplit hybrids were included. Other technologies that did not seem reasonable for some vehicle classes (such as dry-clutch DCTs for Large MPVs and Trucks) were also excluded in the Ricardo simulations.

In summary, 4 distinct vehicle architectures (including the baselines as an “architecture”), across 7 vehicle classes, and a number of engine and transmission combinations, represented the complete set of vehicle combinations. The test matrices[k] can

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[k] For each vehicle class, each advanced engine option is combined with each advanced transmission. Baseline runs are not combined with other transmissions.

be found below in Table 3-5 (for 2010 baselines and conventional stop-start vehicles) and Table 3-6 (for hybrids).

Table 3-5: Nominal Package Matrix for Non-Hybrids

			Advanced Engine				Advanced Transmission				
Vehicle Class	**Baseline Engine & 2010 6-Speed Automatic**	**2010 Diesel & 2010 6-Speed Automatic Transmission**	**Stoich DI Turbo with CPS**	**Lean DI Turbo with CPS**	**EGR DI Turbo with DVA**	**2020 Diesel**	**6-Speed Automatic**	**6-Speed Dry DCT**	**8-Speed Automatic**	**8-Speed Dry DCT**	**8-Speed Wet DCT**
Small Car	X		X	X	X	X	X	X			
Standard Car	X		X	X	X				X	X	
Small MPV	X		X	X	X				X	X	
Full Size Car	X		X	X	X	X			X	X	
Large MPV	X		X	X	X	X			X		X
LDT	X		X	X	X	X			X		X
LHDT	X	X	X	X	X	X			X		X

Table 3-6: Nominal package matrix for P2 and Input Powersplit hybrids

	Hybrid Architecture		Advanced Engine				
Vehicle Class	**P2 Hybrid with 2020 DCT**	**Input Powersplit**	**Stoich DI Turbo with CPS**	**Lean DI Turbo with CPS**	**EGR DI Turbo with CPS**	**Atkinson with CPS**	**Atkinson with DVA**
Small Car	X	X	X	X	X	X	X
Standard Car	X	X	X	X	X	X	X
Small MPV	X	X	X	X	X	X	X
Full Size Car	X	X	X	X	X	X	X
Large MPV	X	X	X	X	X	X	X
LDT	X		X	X	X	X	X
LHDT							

3.3.1.2.9 Selection of the swept input variables and their ranges

The advisory committee agreed upon a set of continuous input variables to be swept in each vehicle package response surface. These variables consisted of both powertrain characteristics (engine displacement, final drive ratio, and electric machine size for hybrids) and road load parameters (rolling resistance coefficient, aerodynamic drag force, and vehicle mass). They were included in the DOE matrix for each vehicle architecture and powertrain configuration, and also serve as inputs to the complex systems visualization tool. Table 3-7 and Table 3-8 show the swept variables used (and their ranges) for the conventional stop-start and hybrid packages, respectively. The ranges represent a percentage of the default value used in the nominal runs.

Table 3-7: Continuous input parameter sweep ranges for conventional stop-start vehicle

Parameter	DoE Range (%)	
Engine Displacement	50	125
Final Drive Ratio	75	125
Rolling Resistance	70	100
Aerodynamic Drag	70	100
Mass	60	120

Table 3-8: Continuous input parameter sweep ranges for P2 and Powersplit hybrid vehicles

	DoE Range (%)			
Parameter	P2 Hybrid		Powersplit	
Engine Displacement	50	150	50	125
Final Drive Ratio	75	125	75	125
Rolling Resistance	70	100	70	100
Aerodynamic Drag	70	100	70	100
Mass	60	120	60	120
Electric Machine Size	50	300	50	150

The ranges were intended to include both the (unknown) optimal value for each technology case, but also wide enough to capture the range of values as they depart from the optimal value (in engineering parlance this is often referred to as finding the “knee” in the curve).

From these variables, a user can determine the sensitivity of each input variable to the vehicle fuel economy and performance. For example, the effect of engine displacement on fuel economy was evaluated for several packages. A more elaborate discussion of engine displacement effects is provided in Section 3.3.1.2.22.2.

3.3.1.2.10 Selection of vehicle performance metrics

For both effectiveness and cost estimates in these rulemakings, the agencies are assuming that vehicles will maintain utility (performance) comparable to the models in the baseline fleet[1]. It was therefore important to maintain equivalent performance in the vehicle simulation modeling of future vehicle technology. The resulting effectiveness estimates were in the context of equivalent performance, which carried over into the lumped parameter model and into the OMEGA and Volpe packages.

Consistent with the 2008 simulation project, a set of vehicle (acceleration) performance metrics were selected by the advisory committee as a way of measuring "equivalent" vehicle performance. When quantifying vehicle efficiency, it is important that certain other vehicle performance metrics are maintained, such that there are no other competing factors contributing or detracting from the vehicle efficiency. Other vehicle characteristics that could impact or detract from vehicle efficiency (*e.g.,* noise, vibration and harshness (NVH), drivability, durability, etc) were also considered during the generation of model inputs. However, they were not analyzed explicitly, with the expectation that manufacturers would ultimately be able to meet vehicle refinement levels necessary for commercial acceptability of these new technologies. These metrics, shown below in Table 3-9, include time at full load to reach given speeds (0-10 mph, 0-30 mph, etc), maximum grade capability, and distance traveled at a given time (e.g., after 3 seconds). Ultimately, the measure of equivalent performance is up to the reader or user of the Complex Systems tool. For EPA's analysis baseline vehicle 0-30 mph and 0-60 mph acceleration times were used as a benchmark for equivalent performance for the advanced vehicle packages. These estimated acceleration times are included in Table 3-11 through Table 3-18. Detailed results that include all performance metrics including those for baseline vehicles are provided in the full 2011 simulation report[1].

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[1] The only exception to this is a subset of hybrids explicitly listed as "non-towing" vehicles. For further details and background, reference Section 1.3 of EPA's RIA.

Table 3-9: Vehicle performance metrics produced by the EASY5 model

Launch (WOT)	Passing (WOT)	Gradeability/ torque reserve
0-10 mph	30-50 mph	Max Speed @ 5% grade
0-30 mph	50-70 mph	Max Speed @ 10% grade
0-50 mph		Max Grade @ 70 mph (non-towing)
0-60 mph		Max Grade @ 60 mph (towing)
0-70 mph		
Distance @ 1.3 sec		
Distance @ 3 sec		
Speed @ 1.3 sec		
Speed @ 3 sec		

3.3.1.2.11 Review and revision of inputs

For any system modeling in which the results extend beyond the bounds of known physical examples (and therefore direct data validation is impossible), it is imperative that the inputs be carefully constructed and thoroughly examined to minimize the potential for uncertainty-related errors. Prior to coding of the models, Ricardo presented the following inputs for review and approval to EPA. For each topic, EPA reviewed the material considering the rationale of Ricardo's technical experts, the appropriateness of the inputs in relation to the assumed time horizon, the required emissions levels, and the known literature in the field today. Listed below are several of the model inputs that were jointly reviewed by Ricardo and EPA:

- Engine maps
    - Stoichiometric GDI turbo
    - Lean-burn GDI turbo
    - Cooled EGR turbo
    - Advanced diesel maps
- Transmission efficiency tables (by gear) including torque converter efficiency
- Engine warm-up strategy (cold start modifiers)
- Alternator regeneration strategy
- Transmission shift optimizer

- Engine friction reduction level
- P2 hybrid controls
- Input powersplit hybrid controls
- Hybrid battery assumptions
- Hybrid motor/generator efficiency maps

EPA technical experts recommended several changes and iterated with Ricardo to establish a consensus set of inputs that were plausible and met the ground rules of the project. Some of these changes resulted in higher efficiencies, while others lowered efficiency. Highlighted below are a few key examples, starting with development of the engine maps:

Engine maps carry perhaps the most significance of any of the sets of inputs needed to build vehicle simulation models. They provide the brake specific fuel consumption, or BSFC (typically in g/kWh) for a given engine speed and load. Typically these maps show an optimum speed and load band (or minimum BSFC "island") that is the most efficient condition in which to operate the engine. Ricardo generated engine maps for both the baseline vehicles (through benchmarking data) and proposed future engine maps for the various turbocharged and diesel engines. Figure 3-3 shows an example engine map for a baseline vehicle. It was constructed from EPA's analysis of a baseline vehicle model run output file. The contours represent lines of equivalent brake-specific fuel consumption.[m]

3.3.1.2.11.1 **Engine Technologies**

Ricardo developed the engines for the 2012-2025 timeframe in two ways. The first was to take current boosted SI research engines and project these would represent the level of performance which could be achieved by production engines in the 2020-2025 timeframe. The second method took current production Atkinson cycle SI and diesel engines and then included 2020-2025 timeframe technology improvements. Both methods extrapolated current engine design and development trend to the 2020-2025 timeframe. These current trends include engine friction reduction, improved fuel injection systems (e.g., spray guided for the SI, and higher injection pressures for the diesels), more advanced engine controls, and improved engine design for faster engine warm-up. EPA reviewed the engine maps recommended by Ricardo and generally concurred they were appropriate for the study time frame based on EPA's review of maps for current production engines and for research engines described in the literature.

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[m] BSFC is measured in units of grams of fuel per kw-hour of energy and is an indicator of engine efficiency. Lower numbers indicate more efficient operating regions. As in this case, an engine typically has an "island' or region of best efficiency, in this case between 2000-3000 RPM and 150-180 Nm of torque. This island becomes much larger with the advent of advanced technologies such as boosting and downsizing, as well as advanced valvetrain technologies.

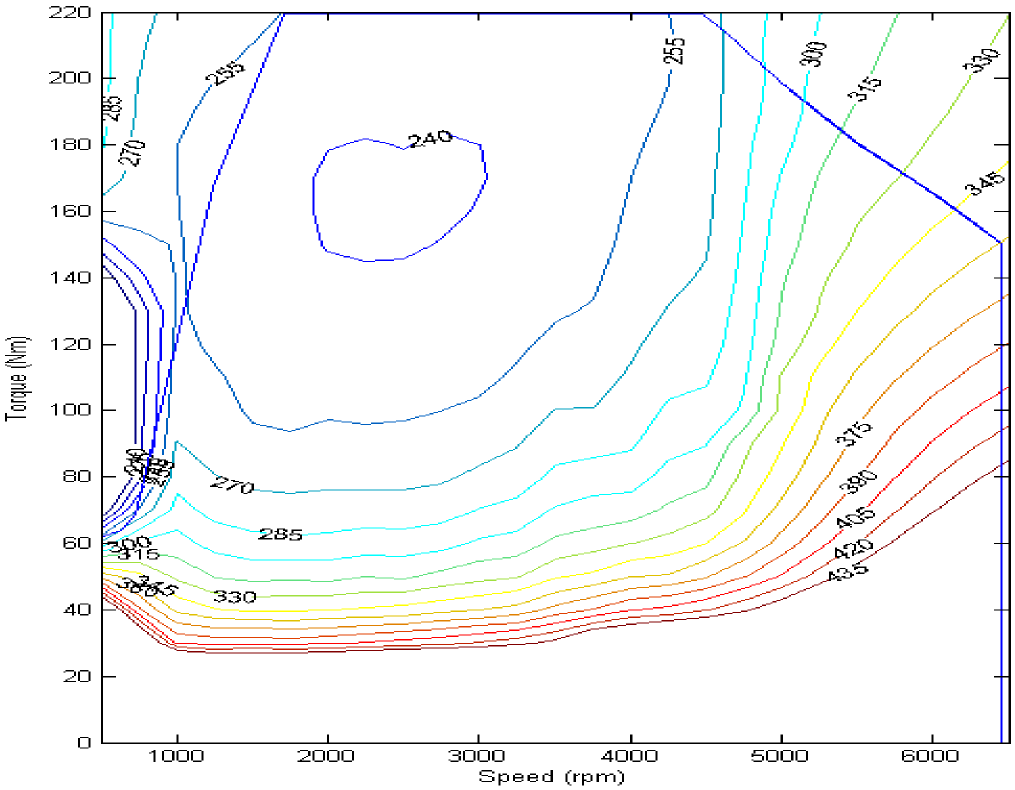


Figure 3-3: Example baseline engine BSFC map

3.3.1.2.11.2 Stoichiometric GDI

The original stoichiometric GDI map that Ricardo proposed was based on laboratory data they had published in 2007, showing a peak brake-specific load of just under 20 bar BMEP and a minimum BSFC of approximately 235 g/kWhr, obtained using a compression ratio of 10.5:1.[22] However, based on input from manufacturers and from other, more recent published data on developmental and research engines, EPA asked Ricardo to raise the load capability of the engine to approximately 27 bar BMEP.[23,24,25,26] This allowed a greater degree of engine downsizing, which resulted in a downsizing of a 1.5 liter engine to a 0.74 liter engine for the nominal small car and a 5.4 liter to a 1.94 liter engine for the nominal large truck. A compression ratio of 10.5:1 was maintained for improved efficiency. At the same time, EPA asked that Ricardo eliminate the use of high-load enrichment, since water-cooled exhaust manifolds, in some cases integrated into the cylinder head, can be incorporated in next-generation designs to mitigate the need for fuel enrichment in lowering turbine inlet temperatures to 950 degrees C and thus avoid the added costs of high-temperature materials in the turbocharger.[27,28] By reducing the need for fuel enrichment fuel consumption is reduced over the more aggressive portions of the drive cycle, and PM emissions control at high load is improved.

3.3.1.2.11.3 **Lean-burn GDI**

Ricardo's initial lean-burn GDI map was based on their single-cylinder research engine data, in which they operated in lean stratified charge mode at all speeds and loads, without due consideration of the potential limitations in lean exhaust NOx aftertreatment systems. To address concerns in this area, EPA examined the boundaries of operation of lean-NOx catalysts, assuming that manufacturers would adopt either LNTs or metal-zeolite urea SCR systems. EPA therefore asked Ricardo to place a constraint on the maximum allowable catalyst space velocity (at high engine power) and exhaust gas temperature entering the catalyst (at high load, low engine speed conditions) to maintain catalyst efficiency at high load and to reduce thermal sintering of PGM under high-temperature, lean operating conditions. More specifically, EPA recommended that engine operation switch away from lean operation (at air/fuel equivalence ratios up to approximately $\lambda=1.5$) to stoichiometric operation at turbine outlet temperatures above 600C, and at total exhaust flows corresponding to space velocities of 60,000/hour, assuming a catalyst volume of 2.5 times engine displacement. This marginally diminished the engine brake thermal efficiency to stoichiometric GDI levels over this region of the map, but it provided more certainty that the engine would be able to adhere to the emissions levels as assumed in the project ground rules by the Advisory Committee. Figure 3-4 shows the engine speed and load region EPA proposed as suitable for lean stratified operation.

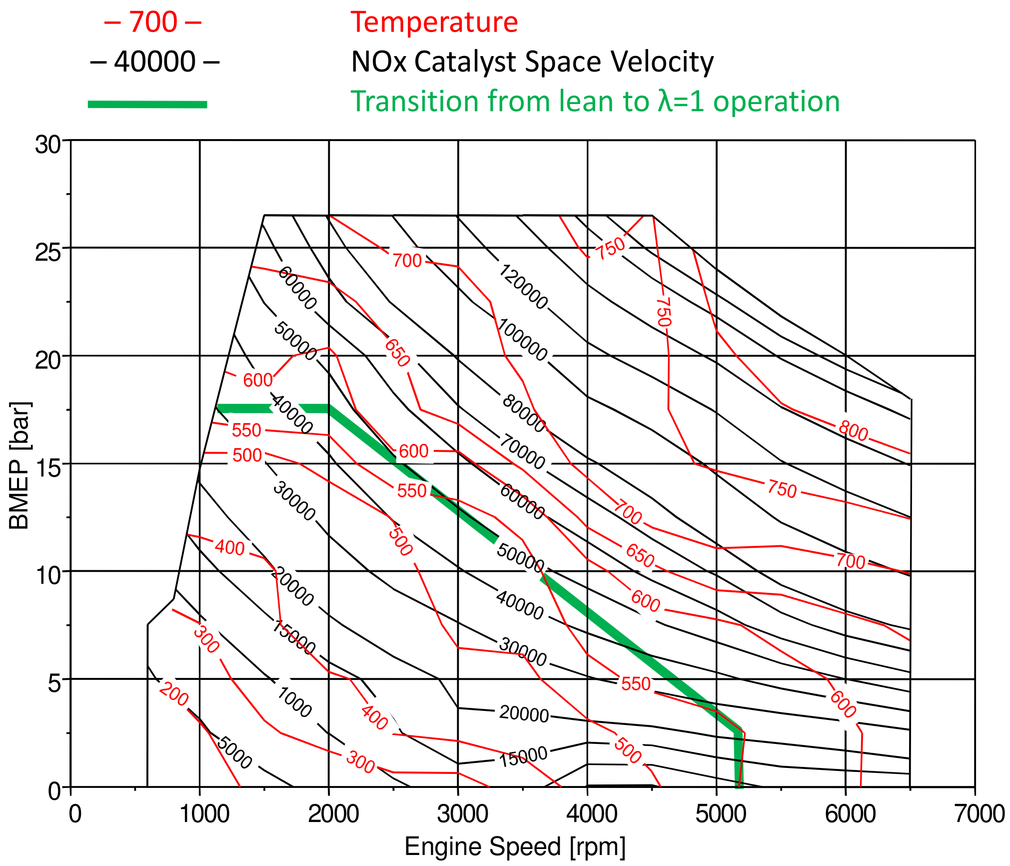


Figure 3-4 Proposed lean/stoichiometric operating threshold for lean-burn GDI engines

3.3.1.2.11.4 **Cooled EGR GDI**

EPA provided technical information from the literature which enabled Ricardo to assume a dual loop (both low pressure and high pressure EGR loops), cooled EGR system in addition to the stoichiometric turbocharged engine. The development of engine maps for this engine configuration was heavily informed by recently published data.[26,27,28,29]. Cooled EGR allowed the use of "λ=1" operation at the same compression ratio with more aggressive spark timing at high load and reduced pumping losses at part load while maintaining acceptable turbocharger inlet temperatures.

3.3.1.2.11.5 Motor/generator and power inverter efficiency maps

EPA recommended that Ricardo update the efficiency maps of the motor and generator (referred to as “electric machines” throughout the project), which they had proposed based on current best-in-class technology. The baseline motor/generator+inverter efficiency map is taken from a 2007 Camry and shown in Figure 3-5 below.

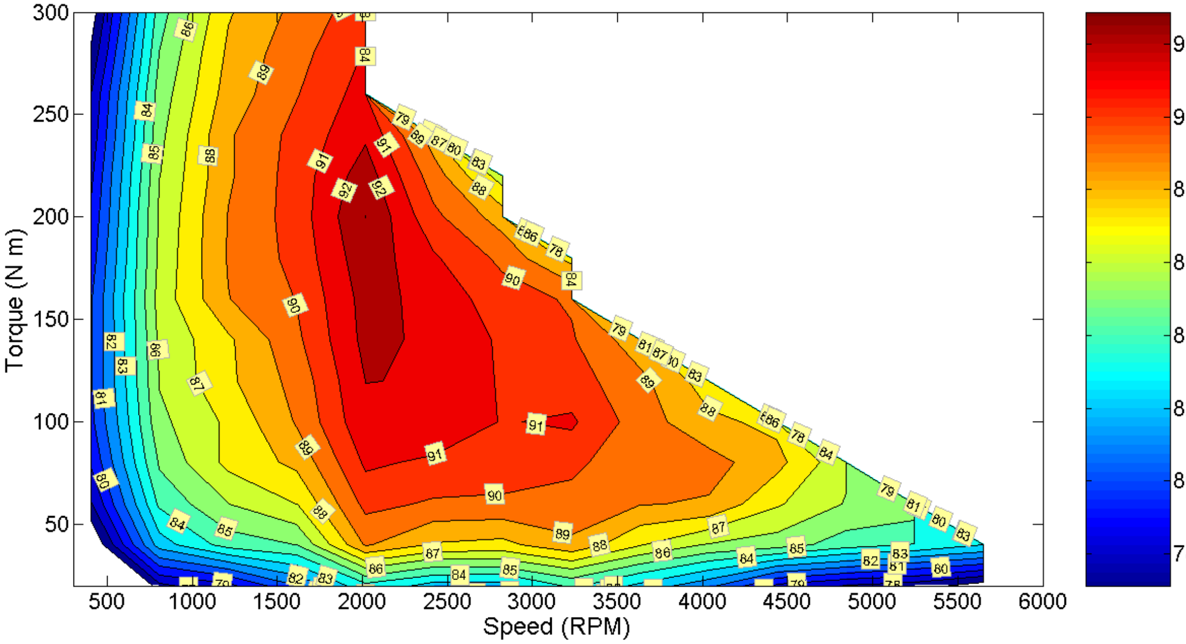


Figure 3-5: 2007 Camry Hybrid motor-inverter efficiency map (Burress, et al, 2008[30])

EPA requested that Ricardo provide their assessment of where they believed efficiency improvements might be made, based upon trends in research and development for both electric machines and power electronics. Ricardo and EPA generally agreed that these efficiency improvements were likely to be modest, particularly given the competitive pressures on manufacturers to reduce the cost of hybrid components. However, EPA and Ricardo assumed that today’s best-in-class efficiency would likely be marginally improved through continuous incremental reductions in parasitic losses. To account for this, EPA and Ricardo agreed to reduce the losses in the motor/generator by 10% (in other words, raising the efficiency of a 90% efficient motor to 91%) and to reduce the losses in the power electronics by 25% (mainly through continued improvements in inverter development and electronic control systems).

3.3.1.2.11.6 Battery

Battery packs were assumed to consist of spinel LiMnO2 cathode chemistry, which is consistent with the current state of technology. EPA recommended a maximum usable state of charge of 40% (from 30% charge to 70% charge) be incorporated as an operating window in

Ricardo's hybrid control logic. This range may increase in subsequent real world examples as manufacturers gain more field experience with long term battery durability. Additionally there will likely be more advances in battery construction and chemistry by 2025, so EPA considers these assumptions as conservative in view of the long term research currently underway in many battery research companies.

3.3.1.2.12 Additional Technologies Modeled by Ricardo for 2011 Report

The previous section discusses in detail those areas of the Ricardo simulation inputs which EPA provided recommendations to Ricardo on and which Ricardo agreed and made modifications to their initial suggestions. EPA did review modeling inputs for many other technologies modeled by Ricardo, but for which we generally agreed with the reasonableness of Ricardo's approach and did not request any changes. This section summarizes at a high level some of the additional technologies considered by Ricardo. Additional detail on these technologies is contained in the 2011 Ricardo final report.

Diesel engines - Ricardo started with existing production engines and identified technology advances that would lead to further advances in fuel consumption. These included many of the same technologies considered for advanced gasoline engines, such as engine friction reduction, improved fuel injection systems with higher injection pressures and more advanced controls, and better engine design to improve engine warm-up rate.

Transmission Technologies - Taking a systems approach in the vehicle simulation modeling, Ricardo also introduced additional transmission and driveline oriented technologies that may be pathways to increased efficiency. Some of these key technological enablers include: shift optimization schedules, advanced clutches, torque converter design and lockup schedules.

Automatic and Dual Clutch Transmissions - For the study timeframe, Ricardo assumed that eight-speed automatic transmissions will be in common use, as this supports more efficient operation, except for small cars, with energy losses expected to be about 20–33% lower than in current automatic transmissions. Energy losses in both wet clutch and dry clutch DCTs are expected to be 40–50% lower than in current automatic transmissions.

Transmission Shift Optimization - This advanced transmission shift optimization strategy tries to keep the engine operating near its most efficient point for a given power demand in effort to emulate a CVT. To protect against operating conditions out of normal range, several key parameters were identified, such as maximum engine speed, minimum lugging speed, and minimum delay between shifts. During development of this strategy, Ricardo estimated that fuel economy benefits of up to 5% can be obtained when compared to typical MY 2010 shift maps.

Torque Converter Technology – Ricardo utilized a lockup clutch model with a multi-damper system to provide earlier torque converter clutch engagement. The advanced automatic transmission applications allow torque converter lockup in any gear except first gear, up to sixth for the Small Car or eighth for the other LDV classes.

Shifting Clutch Technology - Shift clutch technology improves the thermal capacity of the shifting clutch to reduce plate count and lower clutch losses during shifting. Reducing the number of plates for the shifting process and reducing the hydraulic cooling requirements will increase the overall transmission efficiency for similar drivability characteristics.

Dry Sump Technology – A dry sump lubrication system provides benefits by keeping the rotating members out of oil, which reduces losses due to windage and churning. This approach will provide a GHG emissions benefit across all vehicle classes, with the best benefits at higher speed.

3.3.1.2.13 Baseline models built and run

Once all of the inputs were established, Ricardo built the baseline models: For these new (2010) baseline models Ricardo added a group of minor technologies, most of which already exist today in the market. The technologies included 12V stop-start, 6-speed automatic transmission, a high efficiency (70% efficient) alternator, and a strategy – "alternator regen" – that charges the 12V battery more aggressively by increasing the alternator field upon vehicle deceleration .

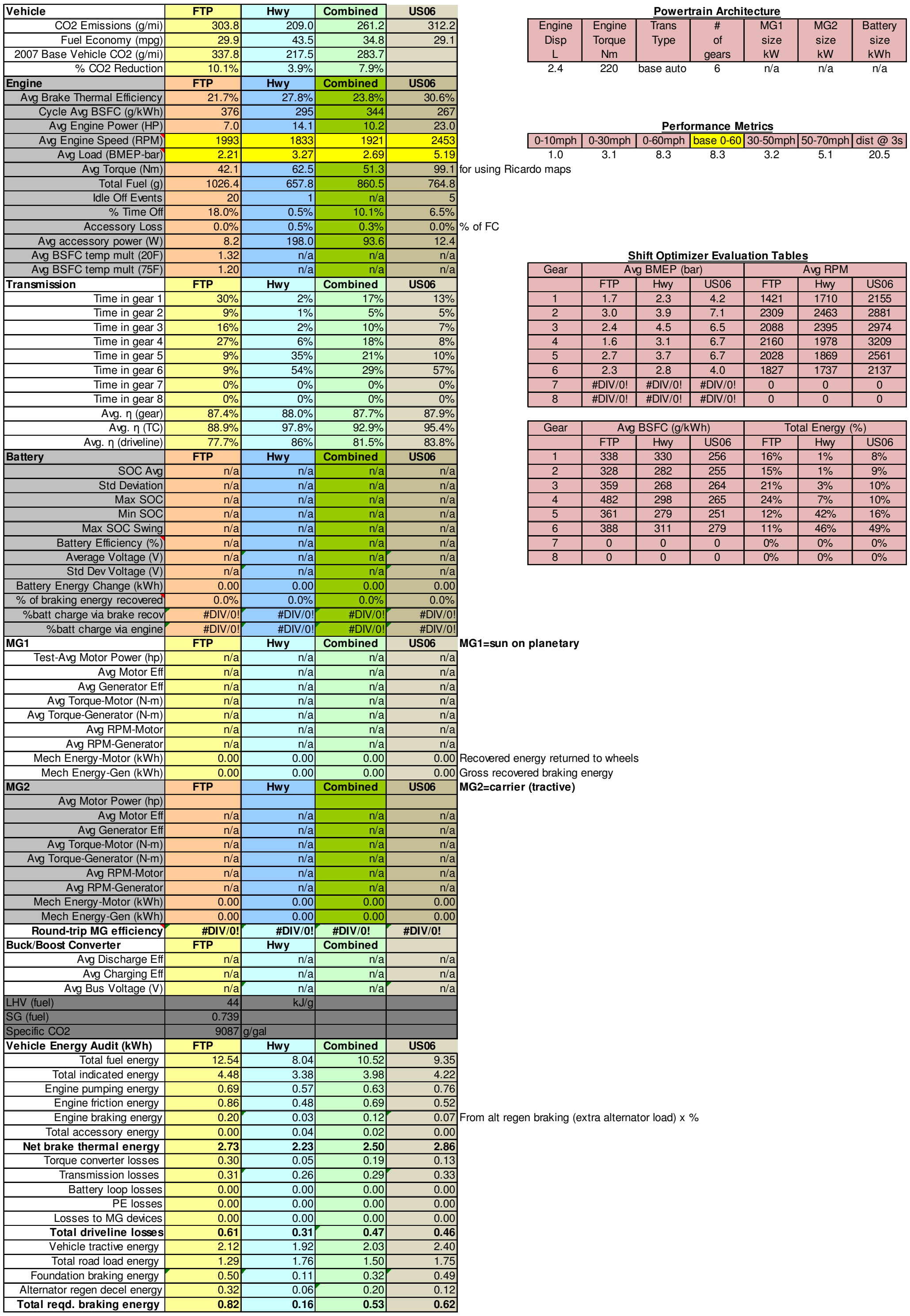
In the 2008 study Ricardo validated their baseline models with 2008 MY certification data. Ricardo's 2010 baseline model results provided effectiveness data for EPA to calibrate the lumped parameter model for some of the newly applied technologies. These technologies included alternator regeneration, high efficiency alternator, and stop-start.

For all model runs – the baselines and each of the advanced package nominal runs – EPA reviewed an extensive set of detailed intermediate output data for each model run. The parameters that were reviewed are shown in **Table 3-10**.

Table 3-10: Vehicle simulation output data reviewed

Ricardo outputs	**EPA-calculated outputs**
vehicle speed	engine operating point distribution
throttle position	engine load (BMEP)
engine torque	total accessory energy
engine power	round-trip battery loop losses
transmission input shaft torque	torque converter lockup time
wheel torque	total road load
transmission gear	total engine brake thermal energy
torque converter slip ratio	
current engine BSFC	**EPA-calculated metrics**
accessory power	cycle-average BSFC
engine speed	average brake thermal efficiency
road load	average engine power
N/V	average engine speed
electric power of motor generator	average engine torque
mechanical power of motor generator	# of idle-off events
motor generator speed	% of engine time off
motor generator torque	average accessory power
motor generator current	time in each gear
motor generator voltage	average gear efficiency
power flow through battery	average torque converter efficiency
battery state of charge	battery state-of-charge statistics
battery voltage	battery efficiency
regenerative braking power	% of vehicle braking energy recovered
vehicle foundation braking power	average motor efficiency
driver braking force	average generator efficiency
fuel mass flow rate	average motor and generator operating speeds
transmission mechanical loss power	average motor and generator operating torque
idle off status	total vehicle tractive energy

From this data, a set of summary statistics was generated to compare each baseline and nominal package run as a quality check. This information was used as the starting point in the dialogue between EPA and Ricardo to identify technical issues with the models. An example summary table (or “snapshot”) for the 2010 Standard Car baseline is provided in Figure 3-6.



Vehicle	FTP	Hwy	Combined	US06	
CO2 Emissions (g/mi)	303.8	209.0	261.2	312.2	
Fuel Economy (mpg)	29.9	43.5	34.8	29.1	
2007 Base Vehicle CO2 (g/mi)	337.8	217.5	283.7		
% CO2 Reduction	10.1%	3.9%	7.9%		
Engine	**FTP**	**Hwy**	**Combined**	**US06**	
Avg Brake Thermal Efficiency	21.7%	27.8%	23.8%	30.6%	
Cycle Avg BSFC (g/kWh)	376	295	344	267	
Avg Engine Power (HP)	7.0	14.1	10.2	23.0	
Avg Engine Speed (RPM)	1993	1833	1921	2453	
Avg Load (BMEP-bar)	2.21	3.27	2.69	5.19	
Avg Torque (Nm)	42.1	62.5	51.3	99.1	for using Ricardo maps
Total Fuel (g)	1026.4	657.8	860.5	764.8	
Idle Off Events	20	1	n/a	5	
% Time Off	18.0%	0.5%	10.1%	6.5%	
Accessory Loss	0.0%	0.5%	0.3%	0.0%	% of FC
Avg accessory power (W)	8.2	198.0	93.6	12.4	
Avg BSFC temp mult (20F)	1.32	n/a	n/a	n/a	
Avg BSFC temp mult (75F)	1.20	n/a	n/a	n/a	
Transmission	**FTP**	**Hwy**	**Combined**	**US06**	
Time in gear 1	30%	2%	17%	13%	
Time in gear 2	9%	1%	5%	5%	
Time in gear 3	16%	2%	10%	7%	
Time in gear 4	27%	6%	18%	8%	
Time in gear 5	9%	35%	21%	10%	
Time in gear 6	9%	54%	29%	57%	
Time in gear 7	0%	0%	0%	0%	
Time in gear 8	0%	0%	0%	0%	
Avg. η (gear)	87.4%	88.0%	87.7%	87.9%	
Avg. η (TC)	88.9%	97.8%	92.9%	95.4%	
Avg. η (driveline)	77.7%	86%	81.5%	83.8%	
Battery	**FTP**	**Hwy**	**Combined**	**US06**	
SOC Avg	n/a	n/a	n/a	n/a	
Std Deviation	n/a	n/a	n/a	n/a	
Max SOC	n/a	n/a	n/a	n/a	
Min SOC	n/a	n/a	n/a	n/a	
Max SOC Swing	n/a	n/a	n/a	n/a	
Battery Efficiency (%)	n/a	n/a	n/a	n/a	
Average Voltage (V)	n/a	n/a	n/a	n/a	
Std Dev Voltage (V)	n/a	n/a	n/a	n/a	
Battery Energy Change (kWh)	0.00	0.00	0.00	0.00	
% of braking energy recovered	0.0%	0.0%	0.0%	0.0%	
%batt charge via brake recov	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	
%batt charge via engine	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	
MG1	**FTP**	**Hwy**	**Combined**	**US06**	**MG1=sun on planetary**
Test-Avg Motor Power (hp)	n/a	n/a	n/a	n/a	
Avg Motor Eff	n/a	n/a	n/a	n/a	
Avg Generator Eff	n/a	n/a	n/a	n/a	
Avg Torque-Motor (N-m)	n/a	n/a	n/a	n/a	
Avg Torque-Generator (N-m)	n/a	n/a	n/a	n/a	
Avg RPM-Motor	n/a	n/a	n/a	n/a	
Avg RPM-Generator	n/a	n/a	n/a	n/a	
Mech Energy-Motor (kWh)	0.00	0.00	0.00	0.00	Recovered energy returned to wheels
Mech Energy-Gen (kWh)	0.00	0.00	0.00	0.00	Gross recovered braking energy
MG2	**FTP**	**Hwy**	**Combined**	**US06**	**MG2=carrier (tractive)**
Avg Motor Power (hp)					
Avg Motor Eff	n/a	n/a	n/a	n/a	
Avg Generator Eff	n/a	n/a	n/a	n/a	
Avg Torque-Motor (N-m)	n/a	n/a	n/a	n/a	
Avg Torque-Generator (N-m)	n/a	n/a	n/a	n/a	
Avg RPM-Motor	n/a	n/a	n/a	n/a	
Avg RPM-Generator	n/a	n/a	n/a	n/a	
Mech Energy-Motor (kWh)	0.00	0.00	0.00	0.00	
Mech Energy-Gen (kWh)	0.00	0.00	0.00	0.00	
Round-trip MG efficiency	**#DIV/0!**	**#DIV/0!**	**#DIV/0!**	**#DIV/0!**	
Buck/Boost Converter	**FTP**	**Hwy**	**Combined**		
Avg Discharge Eff	n/a	n/a	n/a	n/a	
Avg Charging Eff	n/a	n/a	n/a	n/a	
Avg Bus Voltage (V)	n/a	n/a	n/a	n/a	
LHV (fuel)	44	kJ/g			
SG (fuel)	0.739				
Specific CO2	9087	g/gal			
Vehicle Energy Audit (kWh)	**FTP**	**Hwy**	**Combined**	**US06**	
Total fuel energy	12.54	8.04	10.52	9.35	
Total indicated energy	4.48	3.38	3.98	4.22	
Engine pumping energy	0.69	0.57	0.63	0.76	
Engine friction energy	0.86	0.48	0.69	0.52	
Engine braking energy	0.20	0.03	0.12	0.07	From alt regen braking (extra alternator load) x %
Total accessory energy	0.00	0.04	0.02	0.00	
Net brake thermal energy	**2.73**	**2.23**	**2.50**	**2.86**	
Torque converter losses	0.30	0.05	0.19	0.13	
Transmission losses	0.31	0.26	0.29	0.33	
Battery loop losses	0.00	0.00	0.00	0.00	
PE losses	0.00	0.00	0.00	0.00	
Losses to MG devices	0.00	0.00	0.00	0.00	
Total driveline losses	**0.61**	**0.31**	**0.47**	**0.46**	
Vehicle tractive energy	2.12	1.92	2.03	2.40	
Total road load energy	1.29	1.76	1.50	1.75	
Foundation braking energy	0.50	0.11	0.32	0.49	
Alternator regen decel energy	0.32	0.06	0.20	0.12	
Total reqd. braking energy	**0.82**	**0.16**	**0.53**	**0.62**	

Powertrain Architecture

Engine Disp L	Engine Torque Nm	Trans Type	# of gears	MG1 size kW	MG2 size kW	Battery size kWh
2.4	220	base auto	6	n/a	n/a	n/a

Performance Metrics

0-10mph	0-30mph	0-60mph	base 0-60	30-50mph	50-70mph	dist @ 3s
1.0	3.1	8.3	8.3	3.2	5.1	20.5

Shift Optimizer Evaluation Tables

Gear	Avg BMEP (bar)			Avg RPM		
	FTP	Hwy	US06	FTP	Hwy	US06
1	1.7	2.3	4.2	1421	1710	2155
2	3.0	3.9	7.1	2309	2463	2881
3	2.4	4.5	6.5	2088	2395	2974
4	1.6	3.1	6.7	2160	1978	3209
5	2.7	3.7	6.7	2028	1869	2561
6	2.3	2.8	4.0	1827	1737	2137
7	#DIV/0!	#DIV/0!	#DIV/0!	0	0	0
8	#DIV/0!	#DIV/0!	#DIV/0!	0	0	0

Gear	Avg BSFC (g/kWh)			Total Energy (%)		
	FTP	Hwy	US06	FTP	Hwy	US06
1	338	330	256	16%	1%	8%
2	328	282	255	15%	1%	9%
3	359	268	264	21%	3%	10%
4	482	298	265	24%	7%	10%
5	361	279	251	12%	42%	16%
6	388	311	279	11%	46%	49%
7	0	0	0	0%	0%	0%
8	0	0	0	0%	0%	0%

Figure 3-6 Sample output summary sheet for Standard Car (Camry) baseline

Summary statistics were used as a first-order quality check on the model. Sample checks included:

- were average engine speed and load within or close to the best BSFC region for the vehicle's engine map?
- was transmission gear distribution reasonable and consistent between engine types?

3.3.1.2.14 Nominal runs

The Ricardo "nominal" runs refer to the initial set of vehicle simulation models built for each vehicle architecture and vehicle class. These runs were used by EPA to assess the validity of the detailed model outputs (and hence the models themselves) prior to proceeding with the full design of experiment runs. Table 3-11 shows the summary results from the raw nominal runs for the conventional stop-start vehicles (including 12V stop-start, 70% efficient alternator, shift optimizer and alternator regen, as well as a 3.5% improvement due to engine friction reduction). Conventional automatic transmissions are assumed in all nominal runs. No road load reductions are included in these results. GHG reductions are in reference to the 2008 baseline vehicles.

Table 3-11: Nominal Conventional Stop-Start modeling results

Vehicle Class	Engine Type	Displ. L	Torque Nm	Trans Type	FTP mpg	HW mpg	**Comb mpg**	0-30mph s	0-60mph s	**% GHG Reduction**
Small Car	STDI	0.74	157	AT6	53.2	55.1	**54.0**	4.0	10.0	**20%**
	LBDI	0.74	157	AT6	55.1	56.0	**55.5**	4.0	10.0	**22%**
	EGRB	0.74	157	AT6	55.1	57.4	**56.1**	4.0	10.0	**23%**
	2020 Diesel	1.23	221	AT6	55.8	59.4	**57.4**	3.7	9.8	**16%**
Std Car	STDI	1.04	220	AT8	44.8	54.5	**48.7**	3.1	8.5	**28%**
	LBDI	1.04	220	AT8	46.6	55.5	**50.2**	3.1	8.5	**31%**
	EGRB	1.04	220	AT8	46.4	56.7	**50.5**	3.1	8.5	**31%**
Large Car	STDI	1.41	298	AT8	37.1	43.2	**39.6**	3.0	7.4	**31%**
	LBDI	1.41	298	AT8	38.8	44.0	**41.0**	3.0	7.4	**33%**
	EGRB	1.41	298	AT8	38.6	44.9	**41.2**	3.0	7.4	**33%**
	2020 Diesel	2.85	503	AT8	38.2	46.5	**41.5**	2.9	7.5	**27%**
Small MPV	STDI	1.13	239	AT8	38.8	42.6	**40.4**	3.3	8.9	**25%**
	LBDI	1.13	239	AT8	40.3	43.1	**41.5**	3.3	8.9	**27%**
	EGRB	1.13	239	AT8	40.3	44.4	**42.0**	3.3	8.9	**28%**
Large MPV	STDI	1.31	277	AT8	34.8	39.2	**36.7**	3.2	8.6	**31%**
	LBDI	1.31	277	AT8	36.0	39.8	**37.6**	3.2	8.6	**33%**
	EGRB	1.31	277	AT8	36.2	40.9	**38.2**	3.2	8.6	**34%**
	2020 Diesel	2.61	460	AT8	37.3	43.3	**39.8**	3.0	8.6	**30%**
Truck	STDI	1.94	410	AT8	23.8	26.6	**25.0**	3.0	8.1	**26%**
	LBDI	1.94	410	AT8	24.6	27.0	**25.6**	3.0	8.1	**28%**
	EGRB	1.94	410	AT8	24.8	27.7	**26.0**	3.0	8.1	**29%**
	2020 Diesel	4.28	694	AT8	26.4	30.4	**28.1**	2.9	8.0	**26%**
HD Truck	STDI	2.3	486	AT8	16.5	18.3	**17.3**	3.2	9.8	**27%**
	LBDI	2.3	486	AT8	16.8	18.4	**17.5**	3.2	9.8	**28%**
	EGRB	2.3	486	AT8	17.2	19.1	**18.0**	3.2	9.8	**30%**
	2020 Diesel	6.6	895	AT8	19.8	21.5	**20.5**	2.9	8.8	**31%**

Table 3-12 shows the results from the nominal runs for the P2 hybrid vehicles. Dual-clutch transmissions are assumed in all nominal runs. No road load reductions are included in these results. GHG reductions are in reference to the 2008 baseline vehicles.

Table 3-12: Nominal P2 Hybrid modeling results

Vehicle Class	Engine Type	Displ. L	Torque Nm	EM size kW	Batt size kWh	Trans Type	FTP mpg	HW mpg	**Comb mpg**	0-30mph s	0-60mph s	**% GHG Reduction**
Small Car	STDI	0.59	124	14	0.70	DCT6	68.2	57.3	**62.8**	3.8	9.6	**31%**
	LBDI	0.59	124	14	0.70	DCT6	68.4	57.7	**63.2**	3.8	9.6	**31%**
	EGRB	0.59	124	14	0.70	DCT6	70.2	59.9	**65.2**	3.8	9.6	**33%**
	ATKCS	1.66	138	14	0.70	DCT6	70.8	59.0	**64.9**	3.7	10.0	**33%**
	ATKDVA	1.66	138	14	0.70	DCT6	71.7	60.5	**66.2**	3.7	10.0	**35%**
Std Car	STDI	0.83	176	24	1.00	DCT8	61.9	57.2	**59.7**	3.6	8.6	**42%**
	LBDI	0.83	176	24	1.00	DCT8	62.9	58.0	**60.6**	3.6	8.6	**42%**
	EGRB	0.83	176	24	1.00	DCT8	65.1	59.7	**62.5**	3.6	8.6	**44%**
	ATKCS	2.4	200	24	1.00	DCT8	64.6	59.7	**62.3**	3.4	8.6	**44%**
	ATKDVA	2.4	200	24	1.00	DCT8	65.9	61.0	**63.6**	3.4	8.6	**45%**
Large Car	STDI	1.13	238	28	1.10	DCT8	49.8	46.5	**48.2**	3.4	7.7	**43%**
	LBDI	1.13	238	28	1.10	DCT8	50.4	46.8	**48.7**	3.4	7.7	**44%**
	EGRB	1.13	238	28	1.10	DCT8	51.7	48.3	**50.1**	3.4	7.7	**45%**
	ATKCS	3.8	317	28	1.10	DCT8	49.9	46.2	**48.1**	3.0	7.1	**43%**
	ATKDVA	3.8	317	28	1.10	DCT8	51.1	47.4	**49.4**	3.0	7.1	**44%**
Small MPV	STDI	0.9	190	20	1.10	DCT8	50.1	44.2	**47.2**	3.9	9.4	**36%**
	LBDI	0.9	190	20	1.10	DCT8	50.8	44.5	**47.8**	3.9	9.4	**36%**
	EGRB	0.9	190	20	1.10	DCT8	52.0	46.1	**49.2**	3.9	9.4	**38%**
	ATKCS	2.6	217	20	1.10	DCT8	52.9	45.5	**49.3**	3.7	9.3	**38%**
	ATKDVA	2.6	217	20	1.10	DCT8	54.1	46.8	**50.5**	3.7	9.3	**40%**
Large MPV	STDI	1.05	221	25	1.15	DCT8	47.7	42.2	**45.0**	3.8	9.1	**44%**
	LBDI	1.05	221	25	1.15	DCT8	47.4	42.6	**45.1**	3.8	9.1	**44%**
	EGRB	1.05	221	25	1.15	DCT8	47.6	43.0	**45.4**	3.8	9.1	**44%**
	ATKCS	3.15	263	25	1.15	DCT8	48.3	42.4	**45.4**	3.6	8.8	**45%**
	ATKDVA	3.15	263	25	1.15	DCT8	48.8	43.5	**46.2**	3.6	8.8	**45%**
Truck	STDI	1.55	327	50	1.50	DCT8	32.5	28.4	**30.5**	3.3	7.9	**39%**
	LBDI	1.55	327	50	1.50	DCT8	33.0	28.6	**30.9**	3.3	7.9	**40%**
	EGRB	1.55	327	50	1.50	DCT8	33.8	29.6	**31.8**	3.3	7.9	**42%**
	ATKCS	4.6	384	50	1.50	DCT8	33.2	29.0	**31.2**	3.1	7.8	**40%**
	ATKDVA	4.6	384	50	1.50	DCT8	33.9	29.7	**31.8**	3.1	7.8	**42%**

Table 3-13 shows the results from the nominal runs for the input powersplit vehicles[n]. No road load reductions are included in these results. GHG reductions are in reference to the 2008 baseline vehicles.

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[n] While input powersplit hybrids remain a very likely hybrid architecture choice for some manufacturers, the Agencies focused on P2 hybrids compared to powersplits due to their apparent cost-effectiveness advantage in

Table 3-13: Nominal Powersplit hybrid modeling results

Vehicle Class	Engine Type	Displ. L	Torque Nm	EM size kW	Batt size kWh	Trans Type	FTP mpg	HW mpg	Comb mpg	0-30mph s	0-60mph s	% GHG Reduction
Small Car	STDI	0.59	124	14	0.70	PS	64.7	57.2	**61.1**	4.8	10.4	**29%**
	LBDI	0.59	124	14	0.70	PS	65.8	57.4	**61.7**	4.8	10.4	**30%**
	EGRB	0.59	124	14	0.70	PS	67.7	60.1	**64.0**	4.8	10.4	**32%**
	ATKCS	1.66	138	14	0.70	PS	64.2	59.5	**62.0**	4.7	9.8	**30%**
	ATKDVA	1.66	138	14	0.70	PS	67.3	60.0	**63.8**	4.7	9.8	**32%**
Std Car	STDI	0.83	176	80	1.00	PS	55.6	51.7	**53.8**	3.7	8.7	**35%**
	LBDI	0.83	176	80	1.00	PS	57.9	53.5	**55.8**	3.7	8.7	**38%**
	EGRB	0.83	176	80	1.00	PS	58.0	54.8	**56.5**	3.7	8.7	**38%**
	ATKCS	2.4	200	80	1.00	PS	53.3	51.7	**52.6**	3.6	8.0	**34%**
	ATKDVA	2.4	200	80	1.00	PS	56.4	53.3	**55.0**	3.6	8.0	**37%**
Large Car	STDI	1.13	238	28	1.10	PS	46.6	42.0	**44.4**	3.2	7.8	**38%**
	LBDI	1.13	238	28	1.10	PS	48.0	41.8	**45.0**	3.2	7.8	**39%**
	EGRB	1.13	238	28	1.10	PS	47.9	43.6	**45.9**	3.2	7.8	**40%**
	ATKCS	3.8	317	28	1.10	PS	40.3	38.7	**39.6**	3.2	7.1	**31%**
	ATKDVA	3.8	317	28	1.10	PS	43.0	40.8	**42.0**	3.2	7.1	**35%**
Small MPV	STDI	0.9	190	20	1.10	PS	49.1	42.2	**45.8**	4.7	10.3	**33%**
	LBDI	0.9	190	20	1.10	PS	50.8	42.7	**46.8**	4.7	10.3	**35%**
	EGRB	0.9	190	20	1.10	PS	51.3	44.9	**48.2**	4.7	10.3	**37%**
	ATKCS	2.6	217	20	1.10	PS	44.3	39.6	**42.1**	4.6	9.1	**28%**
	ATKDVA	2.6	217	20	1.10	PS	49.3	42.3	**45.9**	4.6	9.1	**34%**
Large MPV	STDI	1.05	221	25	1.15	PS	44.8	39.3	**42.1**	4.3	9.7	**40%**
	LBDI	1.05	221	25	1.15	PS	45.7	40.6	**43.3**	4.3	9.7	**42%**
	EGRB	1.05	221	25	1.15	PS	47.0	41.5	**44.4**	4.3	9.7	**43%**
	ATKCS	3.15	263	25	1.15	PS	41.7	38.6	**40.3**	4.2	8.8	**37%**
	ATKDVA	3.15	263	25	1.15	PS	44.3	39.6	**42.0**	4.2	8.8	**40%**

3.3.1.2.15 Response Surface Model matrix runs

After the nominal runs were completed according to the agreed-upon methodology, Ricardo set up a design of experiment matrix for each vehicle architecture. The continuously swept variables were randomized in a Latin hypercube fashion to achieve a representative sample within each matrix (reference the Ricardo report for more details on the complex systems modeling approach used). After a data review and removal of runs with errors[o] (as needed) Ricardo then generated Response Surface Models (RSM) for use in the complex systems tool. EPA used the tool to evaluate a range of potential engine displacements, final drive ratios and electric motor sizes (hybrids only) for each vehicle package, in an effort to

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future years. As a result the powersplit nominal runs did not receive the same level of engineering scrutiny as the P2 hybrid nominal runs.

[o] e.g., model runs in which the vehicles were underpowered to the point where they could not follow the prescribed vehicle speed trace, rendering an invalid test or "error". These configurations were then excluded from the data sets.

find the combination that would provide the greatest effectiveness while meeting EPA's definition of "equivalent performance".

3.3.1.2.16 Equivalent performance definition

The Ricardo output data provides several performance metrics, as discussed in 3.3.1.2.10. For simplicity, EPA assumed that a range of acceleration times for both a 0-60 mph test and also a 0-30 mph test (emphasizing launch character) would provide a simple yet representative measure of a vehicle's equivalent performance. A range was chosen rather than assuming a single point value equal to the baseline. This provided more acceptable data points and reduced error due to "noise" in the datasets. The acceptable acceleration times were as follows with respect to the baseline:

0-60 mph: 5 percent slower to 15 percent faster as compared to baseline
0-30 mph: 10 percent slower to 20 percent faster as compared to baseline

The range above reflects a deviation from the actual baseline value that is well within the normal variation of acceleration times for different vehicle models within a given vehicle class.

3.3.1.2.17 Treatment of "turbo lag" in performance runs for turbocharged engines

A common critique of comparisons of the modeled performance of highly turbocharged engines with naturally-aspirated engines is that consideration must be given to the delay in producing full engine load associated with the turbocharger, commonly referred to as "turbo lag". In technical discussions, Ricardo's engine experts assured EPA that the dual-sequential designs of the turbocharger systems in the engines in this study should mitigate most of this phenomenon often seen on older-model vehicles. However, due to the heavy reliance on turbocharged engines as a significant source of motive force for the high BMEP engines evaluated in this project, EPA took this sensitivity further into account.

Ricardo's initial model of WOT operation was based on a steady-state model of engine torque, assuming that the engine would be able to instantaneously reach a desired level of output torque, without consideration of the intake manifold filling dynamics or the mechanical inertia of the engine. EPA raised this as an issue, more in terms of properly representing vehicle performance than for effectiveness differences. EPA reviewed its own engine development data and proposed a somewhat conservative time constant for both the naturally aspirated engines (0.3 s) and the turbocharged engines (1.5 s), to apply to the engine torque response in the vehicle performance runs (these are shown below in Figure 3-7). In turn, Ricardo recalculated the acceleration times for the 0-30 and 0-60 mph runs to reflect the slower time constants. As a result, EPA used these two performance metrics exclusively in determining "equivalent performance". A transient engine/turbo model would have improved the accuracy of the model somewhat; however, it was beyond the scope of this project.

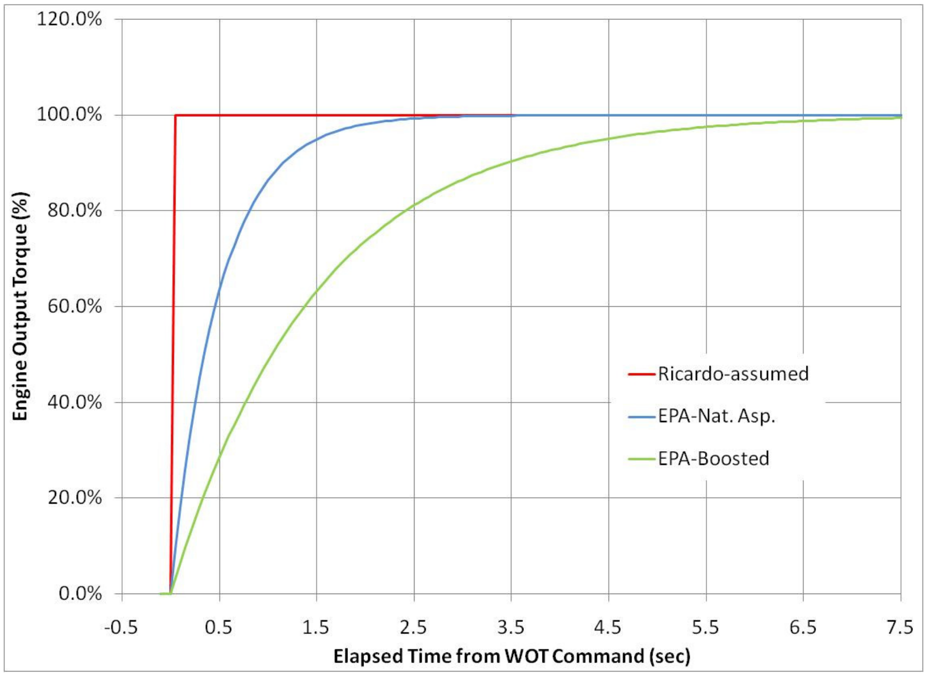

Figure 3-7: EPA proposed time constants and resulting effect on torque rise time for turbocharging

3.3.1.2.18 Treatment of engine response and "turbo lag" in cycle simulations and control logic algorithms

The EASY5 model used in the Ricardo simulations included engine and driveline inertia effects which account for some of the real-world transient torque delays. However, the simulation modeling did not include an adjustment to account for transient engine response delays (e.g. inclusion of time constant offsets), to simulate naturally aspirated and turbocharged engine response delays associated with intake manifold gas dynamics and turbocharger response delay. Consideration of engine response delay might affect how transmission shift optimization control logic and advanced HEV control logic is structured, and potentially affect GHG and fuel economy projections, particularly for boosted and downsized engines. EPA and Ricardo believe that the impact is small over the city and highway fuel economy test cycles. However, the agencies seek comment on the fuel economy impact of transient delays over the test cycles not accounted for in the Ricardo modeling.

3.3.1.2.19 "Equivalent performance" results for conventional stop-start vehicles

The following tables show the results from the complex systems tool, when displacement, final drive ratio and electric motor size are varied to optimize GHG and fuel consumption reduction effectiveness at equivalent performance for conventional stop-start, P2 and powersplit hybrids. Most of the vehicles show little change in performance between the nominal runs and the equivalent performance results from the complex systems tool. Table 3-14 through Table 3-18 illustrate the various effects of changing road loads on the various vehicle package configurations. Table 3-14, Table 3-16, and Table 3-16, respectively, show the equivalent performance results for the conventional stop-start (for both automatic transmissions and DCTs) and the P2 hybrid vehicles (modeled only as DCTs). No road load reductions are included in Table 3-14 through Table 3-16. For comparison, a second set of tables (Table 3-17 and Table 3-18) give equivalent performance results for conventional stop-start vehicles and P2 hybrids, each including example road load reductions[p] of 20% mass reduction, 20% aerodynamic drag reduction and 10% rolling resistance reduction.

The package effectiveness results from the equivalent performance runs were used in the datasets to calibrate the individual technology effectiveness values within the lumped parameter model. The development of the lumped parameter model is described in detail in Section 1.5 of EPA’s RIA.

Table 3-14: Equivalent performance results for conventional-stop start vehicles (no road load reductions)

Vehicle Class	Engine Type	Displ. L	Torque Nm	Trans Type	FTP mpg	HW mpg	**Comb mpg**	0-30mph s	0-60mph s	**% GHG Reduction**
Small Car	STDI	0.86	183	AT6	53.1	56.5	**54.6**	4.1	9.1	**21%**
	LBDI	0.90	190	AT6	56.3	57.5	**56.9**	4.1	8.9	**24%**
	EGRB	0.72	154	AT6	55.2	59.1	**56.9**	4.1	10.1	**24%**
	2020 Diesel	1.19	213	AT6	57.3	64.2	**60.2**	3.8	10.0	**20%**
Std Car	STDI	1.13	240	AT8	44.4	54.5	**48.5**	2.9	7.9	**28%**
	LBDI	1.26	266	AT8	47.0	56.0	**50.6**	2.8	7.2	**31%**
	EGRB	1.09	230	AT8	46.2	57.0	**50.5**	3.1	8.3	**31%**
Large Car	STDI	1.48	314	AT8	37.0	43.4	**39.6**	3.0	7.2	**31%**
	LBDI	1.50	317	AT8	39.2	44.3	**41.3**	2.9	7.1	**34%**
	EGRB	1.56	330	AT8	38.6	45.0	**41.2**	3.0	7.0	**34%**
	2020 Diesel	2.57	454	AT8	39.1	47.1	**42.3**	3.0	8.1	**28%**
Small MPV	STDI	1.32	280	AT8	38.9	42.4	**40.4**	3.2	8.0	**25%**
	LBDI	1.41	297	AT8	41.1	43.9	**42.3**	3.2	7.7	**28%**
	EGRB	1.40	296	AT8	40.0	45.1	**42.1**	3.2	7.7	**28%**
Large MPV	STDI	1.57	332	AT8	34.8	39.5	**36.8**	2.9	7.4	**31%**
	LBDI	1.51	319	AT8	36.2	40.6	**38.0**	3.0	7.7	**34%**
	EGRB	1.47	312	AT8	36.4	40.9	**38.3**	2.9	7.6	**34%**
	2020 Diesel	2.74	483	AT8	36.7	44.0	**39.7**	3.0	8.4	**29%**
Truck	STDI	2.30	486	AT8	24.0	26.8	**25.2**	2.8	7.0	**26%**
	LBDI	2.06	435	AT8	25.0	26.9	**25.8**	2.9	7.6	**28%**
	EGRB	2.28	482	AT8	24.8	28.1	**26.2**	2.9	7.2	**29%**
	2020 Diesel	4.12	669	AT8	26.8	31.2	**28.6**	2.9	8.3	**28%**
HD Truck	STDI	2.72	575	AT8	16.6	18.6	**17.4**	3.0	8.4	**27%**
	LBDI	2.69	568	AT8	17.2	18.8	**17.9**	2.9	8.4	**29%**
	EGRB	2.71	573	AT8	17.3	19.4	**18.2**	2.9	8.4	**30%**
	2020 Diesel	5.64	764	AT8	21.0	24.6	**22.5**	3.2	10.3	**37%**

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[p] Note that in the regulatory fleet analysis, levels of road load reduction technologies (e.g., mass reduction) will vary by vehicle class. These tables are illustrative in nature.

Table 3-15: Equivalent performance results for conventional-stop start vehicles with DCT transmissions (no road load reductions)

Vehicle Class	Engine Type	Displ. L	Torque Nm	Trans Type	FTP mpg	HW mpg	**Comb mpg**	0-30mph s	0-60mph s	**% GHG Reduction**
Small Car	STDI	0.91	193	dry DCT6	55.0	58.8	**56.7**	3.9	8.6	**23%**
	LBDI	0.92	196	dry DCT6	58.0	59.8	**58.8**	3.9	8.5	**26%**
	EGRB	0.89	188	dry DCT6	57.2	61.3	**59.0**	3.9	8.7	**27%**
	2020 Diesel	1.13	204	dry DCT6	61.4	69.4	**64.8**	3.9	10.4	**26%**
Std Car	STDI	1.08	229	dry DCT8	46.4	55.0	**49.9**	3.1	8.0	**30%**
	LBDI	1.29	273	dry DCT8	48.7	57.5	**52.3**	3.0	7.1	**33%**
	EGRB	1.17	248	dry DCT8	48.1	57.6	**51.9**	3.0	7.6	**33%**
Large Car	STDI	1.53	324	dry DCT8	38.4	44.0	**40.7**	2.9	6.8	**33%**
	LBDI	1.66	352	dry DCT8	40.5	45.4	**42.6**	2.9	6.5	**36%**
	EGRB	1.48	313	dry DCT8	40.0	45.6	**42.3**	3.0	7.0	**35%**
	2020 Diesel	2.44	431	dry DCT8	41.0	48.4	**44.0**	3.0	8.1	**31%**
Small MPV	STDI	1.30	276	dry DCT8	40.1	43.6	**41.6**	3.1	7.7	**27%**
	LBDI	1.32	280	dry DCT8	42.1	44.7	**43.2**	3.2	7.7	**30%**
	EGRB	1.33	282	dry DCT8	41.7	45.6	**43.3**	3.1	7.6	**30%**
Large MPV	STDI	1.53	324	wet DCT8	36.0	40.2	**37.8**	3.1	7.4	**33%**
	LBDI	1.56	330	wet DCT8	38.0	41.1	**39.4**	3.0	7.3	**36%**
	EGRB	1.56	330	wet DCT8	37.6	41.8	**39.4**	3.0	7.3	**36%**
	2020 Diesel	2.42	427	wet DCT8	39.2	45.2	**41.7**	3.1	9.0	**33%**
Truck	STDI	2.23	472	wet DCT8	24.8	27.1	**25.8**	3.0	7.1	**28%**
	LBDI	2.26	478	wet DCT8	25.9	27.7	**26.7**	3.0	7.0	**31%**
	EGRB	2.25	475	wet DCT8	25.8	28.1	**26.8**	3.0	7.0	**31%**
	2020 Diesel	3.78	613	wet DCT8	28.1	32.1	**29.8**	3.0	8.6	**31%**
HD Truck	STDI	2.55	538	wet DCT8	17.3	18.1	**17.6**	3.1	8.5	**28%**
	LBDI	2.62	554	wet DCT8	17.8	18.7	**18.2**	3.1	8.4	**30%**
	EGRB	2.58	544	wet DCT8	18.0	19.0	**18.4**	3.1	8.5	**31%**
	2020 Diesel	5.45	739	wet DCT8	21.8	24.2	**22.8**	3.3	10.3	**38%**

Table 3-16: Equivalent performance results for P2 hybrids (no road load reductions)

Vehicle Class	Engine Type	Displ. L	Torque Nm	EM size kW	Batt size kWh	Trans Type	FTP mpg	HW mpg	**Comb mpg**	0-30mph s	0-60mph s	**% GHG Reduction**
Small Car	STDI	0.68	144	21	0.70	DCT6	68.9	58.7	**63.9**	3.7	8.5	**32%**
	LBDI	0.68	144	21	0.70	DCT6	70.1	59.2	**64.7**	3.7	8.5	**33%**
	EGRB	0.67	142	21	0.70	DCT6	72.0	61.2	**66.7**	3.7	8.5	**35%**
	ATKCS	1.72	143	17	0.70	DCT6	72.0	60.8	**66.5**	3.9	9.6	**35%**
	ATKDVA	1.68	140	19	0.70	DCT6	74.4	62.0	**68.2**	3.8	9.6	**36%**
Std Car	STDI	1.00	213	26	1.00	DCT8	62.2	57.7	**60.1**	3.4	7.9	**42%**
	LBDI	0.95	202	27	1.00	DCT8	63.2	58.3	**60.9**	3.4	8.0	**43%**
	EGRB	1.04	219	26	1.00	DCT8	64.8	60.4	**62.7**	3.4	7.8	**44%**
	ATKCS	2.54	212	27	1.00	DCT8	64.6	59.5	**62.2**	3.4	8.6	**44%**
	ATKDVA	2.31	193	28	1.00	DCT8	65.7	60.7	**63.4**	3.4	8.7	**45%**
Large Car	STDI	1.39	292	29	1.10	DCT8	50.6	47.3	**49.1**	3.3	7.2	**44%**
	LBDI	1.37	289	29	1.10	DCT8	51.3	47.9	**49.7**	3.4	7.3	**45%**
	EGRB	1.38	291	29	1.10	DCT8	52.6	49.0	**50.9**	3.4	7.2	**46%**
	ATKCS	3.73	311	30	1.10	DCT8	48.6	46.1	**47.5**	3.2	7.5	**42%**
	ATKDVA	3.33	278	30	1.10	DCT8	50.7	47.7	**49.3**	3.3	8.0	**44%**
Small MPV	STDI	1.40	295	34	1.10	DCT8	52.3	45.5	**49.0**	3.6	8.1	**38%**
	LBDI	1.39	293	37	1.10	DCT8	53.0	45.9	**49.6**	3.5	8.0	**39%**
	EGRB	1.41	297	38	1.10	DCT8	54.4	47.2	**50.9**	3.4	7.9	**40%**
	ATKCS	3.87	322	38	1.10	DCT8	53.6	46.2	**50.0**	3.6	9.0	**39%**
	ATKDVA	3.59	299	39	1.10	DCT8	55.2	47.4	**51.4**	3.7	9.3	**41%**
Large MPV	STDI	1.31	276	30	1.15	DCT8	48.5	42.3	**45.5**	3.2	7.4	**45%**
	LBDI	1.30	274	31	1.15	DCT8	49.0	42.6	**45.9**	3.2	7.4	**45%**
	EGRB	1.29	272	32	1.15	DCT8	49.2	42.7	**46.0**	3.2	7.5	**45%**
	ATKCS	3.13	262	34	1.15	DCT8	48.0	42.3	**45.3**	3.2	8.2	**44%**
	ATKDVA	3.00	250	34	1.15	DCT8	48.5	43.0	**45.9**	3.2	8.3	**45%**
Truck	STDI	1.87	394	50	1.50	DCT8	33.3	29.0	**31.2**	3.3	7.3	**40%**
	LBDI	1.92	404	48	1.50	DCT8	33.6	29.3	**31.5**	3.4	7.2	**41%**
	EGRB	1.92	405	48	1.50	DCT8	34.6	30.2	**32.4**	3.3	7.2	**43%**
	ATKCS	5.34	445	53	1.50	DCT8	32.3	28.8	**30.6**	3.1	7.2	**39%**
	ATKDVA	5.34	445	56	1.50	DCT8	32.7	29.4	**31.1**	3.0	7.1	**40%**

Table 3-17 Equivalent performance results for conventional-stop start vehicles (with 20% mass, 20% aerodynamic drag and 10% rolling resistance reductions)

Vehicle Class	Engine Type	Displ. L	Torque Nm	Trans Type	FTP mpg	HW mpg	Comb mpg	0-30mph s	0-60mph s	% GHG Reduction
Small Car	STDI	0.68	145	AT6	65.0	70.0	67.2	4.1	9.2	35%
	LBDI	0.89	189	AT6	68.9	72.4	70.4	4.2	8.4	38%
	EGRB	0.69	146	AT6	67.6	73.1	70.0	4.1	9.2	38%
	2020 Diesel	0.91	164	AT6	71.8	83.2	76.5	3.7	10.4	37%
Std Car	STDI	1.04	220	AT8	53.9	67.6	59.3	2.9	7.2	41%
	LBDI	1.27	268	AT8	57.3	70.6	62.6	2.8	6.4	44%
	EGRB	0.98	207	AT8	56.2	70.1	61.7	3.0	7.6	43%
Large Car	STDI	1.00	212	AT8	46.5	53.8	49.5	3.1	8.1	45%
	LBDI	1.49	315	AT8	48.4	55.0	51.2	3.0	6.5	46%
	EGRB	1.00	212	AT8	48.5	55.9	51.6	3.1	8.1	47%
	2020 Diesel	2.05	362	AT8	48.5	59.7	53.0	3.0	8.1	42%
Small MPV	STDI	1.20	253	AT8	46.3	51.8	48.6	3.2	7.4	37%
	LBDI	1.40	296	AT8	49.1	53.5	51.0	3.3	6.9	40%
	EGRB	1.13	238	AT8	48.4	53.6	50.6	3.2	7.7	40%
Large MPV	STDI	1.00	212	AT8	42.4	46.8	44.3	3.2	8.8	43%
	LBDI	1.26	266	AT8	44.2	48.1	45.9	2.9	7.3	45%
	EGRB	1.02	216	AT8	44.2	48.7	46.2	3.2	8.7	45%
	2020 Diesel	1.98	349	AT8	46.4	54.0	49.6	3.0	9.0	43%
Truck	STDI	1.44	303	AT8	29.4	32.1	30.6	3.1	8.6	39%
	LBDI	1.89	399	AT8	30.2	32.9	31.3	2.8	7.0	41%
	EGRB	1.44	305	AT8	30.5	33.6	31.8	3.1	8.6	42%
	2020 Diesel	3.20	518	AT8	32.8	38.8	35.3	3.0	8.6	41%
HD Truck	STDI	2.21	466	AT8	20.0	22.2	20.9	3.0	8.4	39%
	LBDI	2.24	473	AT8	20.5	22.6	21.4	3.0	8.4	41%
	EGRB	2.19	463	AT8	20.9	23.1	21.8	3.0	8.4	42%
	2020 Diesel	4.45	603	AT8	25.3	30.1	27.3	3.2	10.3	48%

Table 3-18: Equivalent performance results for P2 hybrids (with 20% mass, 20% aerodynamic drag and 10% rolling resistance reductions)

Vehicle Class	Engine Type	Displ. L	Torque Nm	EM size kW	Batt size kWh	Trans Type	FTP mpg	HW mpg	**Comb mpg**	0-30mph s	0-60mph s	**% GHG Reduction**
Small Car	STDI	0.68	143	11	0.70	DCT6	85.8	72.2	**79.1**	3.7	7.9	**45%**
	LBDI	0.68	144	11	0.70	DCT6	87.6	73.1	**80.4**	3.7	7.9	**46%**
	EGRB	0.68	143	11	0.70	DCT6	89.5	75.4	**82.5**	3.7	8.0	**47%**
	ATKCS	1.60	133	11	0.70	DCT6	89.4	74.9	**82.2**	3.8	8.9	**47%**
	ATKDVA	1.52	127	11	0.70	DCT6	93.9	76.9	**85.4**	3.8	9.0	**49%**
Std Car	STDI	0.90	191	18	1.00	DCT8	78.1	71.1	**74.8**	3.2	7.2	**53%**
	LBDI	0.91	194	18	1.00	DCT8	79.7	72.2	**76.2**	3.3	7.2	**54%**
	EGRB	0.92	194	18	1.00	DCT8	81.4	74.2	**78.0**	3.2	7.1	**55%**
	ATKCS	2.36	197	18	1.00	DCT8	82.2	73.8	**78.2**	3.1	7.5	**55%**
	ATKDVA	2.03	169	18	1.00	DCT8	83.5	76.2	**80.0**	3.3	8.3	**56%**
Large Car	STDI	1.21	254	22	1.10	DCT8	63.2	57.3	**60.4**	3.1	6.6	**55%**
	LBDI	1.25	263	21	1.10	DCT8	64.9	58.5	**61.9**	3.1	6.5	**56%**
	EGRB	1.25	263	21	1.10	DCT8	65.7	59.8	**62.9**	3.1	6.6	**56%**
	ATKCS	3.52	293	21	1.10	DCT8	61.1	57.0	**59.2**	3.0	6.7	**54%**
	ATKDVA	3.29	274	21	1.10	DCT8	63.9	59.3	**61.7**	3.0	6.8	**56%**
Small MPV	STDI	1.25	265	21	1.10	DCT8	63.9	53.4	**58.7**	3.5	7.7	**48%**
	LBDI	1.22	257	22	1.10	DCT8	65.2	53.9	**59.5**	3.5	7.7	**49%**
	EGRB	1.24	262	21	1.10	DCT8	66.5	55.7	**61.1**	3.5	7.8	**50%**
	ATKCS	3.71	309	21	1.10	DCT8	65.0	55.1	**60.1**	3.4	8.2	**49%**
	ATKDVA	3.44	287	21	1.10	DCT8	67.5	56.7	**62.1**	3.6	8.7	**51%**
Large MPV	STDI	1.01	213	28	1.15	DCT8	59.5	50.2	**54.9**	3.2	7.4	**54%**
	LBDI	1.04	219	28	1.15	DCT8	61.0	50.9	**56.0**	3.2	7.3	**55%**
	EGRB	1.02	215	26	1.15	DCT8	60.6	51.6	**56.2**	3.2	7.3	**55%**
	ATKCS	2.91	243	21	1.15	DCT8	58.9	51.1	**55.1**	3.2	7.5	**54%**
	ATKDVA	2.84	237	22	1.15	DCT8	60.1	52.4	**56.3**	3.2	7.7	**55%**
Truck	STDI	1.57	330	41	1.50	DCT8	39.4	34.4	**37.0**	3.2	7.0	**50%**
	LBDI	1.60	337	38	1.50	DCT8	40.3	35.0	**37.7**	3.3	7.0	**51%**
	EGRB	1.58	334	40	1.50	DCT8	41.0	36.0	**38.6**	3.2	7.0	**52%**
	ATKCS	4.16	347	38	1.50	DCT8	39.9	34.9	**37.5**	3.0	7.1	**50%**
	ATKDVA	4.15	346	39	1.50	DCT8	41.4	35.9	**38.7**	3.0	7.2	**52%**

3.3.1.2.20 Validation of vehicle simulation results

Ricardo described the process used to validate the baseline vehicles in its report[1]. Ideally it would be desirable to validate the simulation results with actual vehicle certification test data. However, due to the nature and intended time frame (10+ years into the future) of the technologies modeled within the vehicle classes, it is difficult to find many real-world examples of specific technologies at the level of development reflected within the latest simulation models. Furthermore, there are no current vehicles in production that contain all (or even a majority) of the multiple advanced technologies embedded within the models so it is difficult to make meaningful direct comparisons between actual vehicles and model results. Finally, there is no direct way to disaggregate the various advanced technologies and isolate only the relevant pieces for evaluation (e.g., an advanced turbocharged engine at an interim BMEP level with a baseline-level transmission without stop-start): the lumped parameter model was developed for this very analytical capability. A full description of the lumped parameter model (including example comparisons of existing vehicle models to lumped parameter estimates) is provided in 3.3.2.

3.3.1.2.21 The "efficient frontier" capability in Complex Systems tool

A powerful feature of the Complex Systems tool is the "efficient frontier" function, which provides a graphical representation of the RSM data for the vehicle configuration of interest. The user can identify the combination of various attributes (engine displacement, final drive ratio, motor size, etc) which project the best model effectiveness. Figure 3-8 below is an example of the efficient frontier for a Standard Car with a cooled EGR turbocharged engine and a dry clutch DCT. The light red line along the top of the data set represents the best fuel economy at each 0-60 mph acceleration time within the desired window. The solid dark blue points represent the combinations that achieve both the desired 0-60 and 0-30 mph criteria for equivalent performance. In this way, it is easy to quantify the best effectiveness for a given technology package.

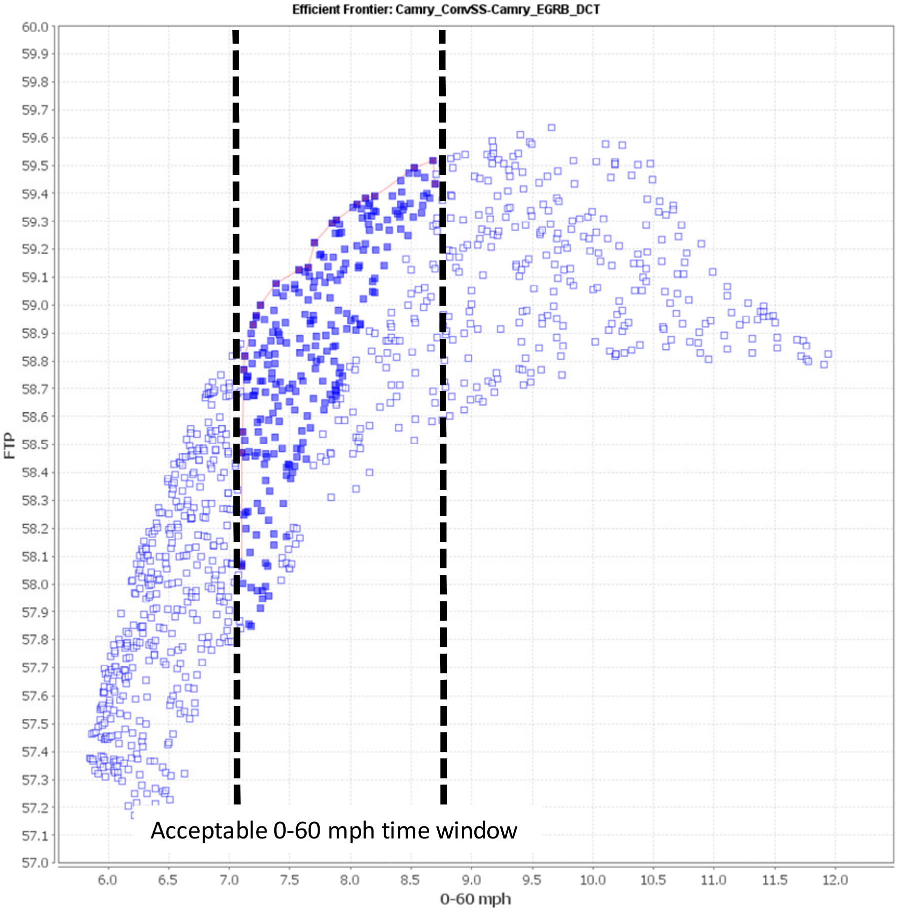

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Figure 3-8: "Efficient Frontier" function in complex systems tool

3.3.1.2.22 Significance of the Complex Systems tool

The complex systems tool was used not only to identify the optimal combination of input variables for each vehicle architecture, but also to analyze trends in the input variables for quality assurance (i.e., to make sure the response surface models made engineering sense), and to establish numerical relationships between these variables for the lumped parameter model calibration. Shown below are a few examples of the types of inquiries made via the complex systems tool:

3.3.1.2.22.1 Effects of motor size (HEVs)

EPA reviewed the effects of motor size on hybrids. As motor size is increased, there is more opportunity to recapture energy during braking (because more powerful motors can recover all of the energy in more severe braking events). However, oversized motors also experience reduced efficiency as they operate in a less efficient operating region. This is shown in Figure 3-9 below, which shows a sweep of motor size vs. fuel economy for both the FTP/HWFE combined and also the high speed/load US06 cycle. Note that the optimum motor size increases with respect to the US06 cycle due to more severe braking and acceleration rates.

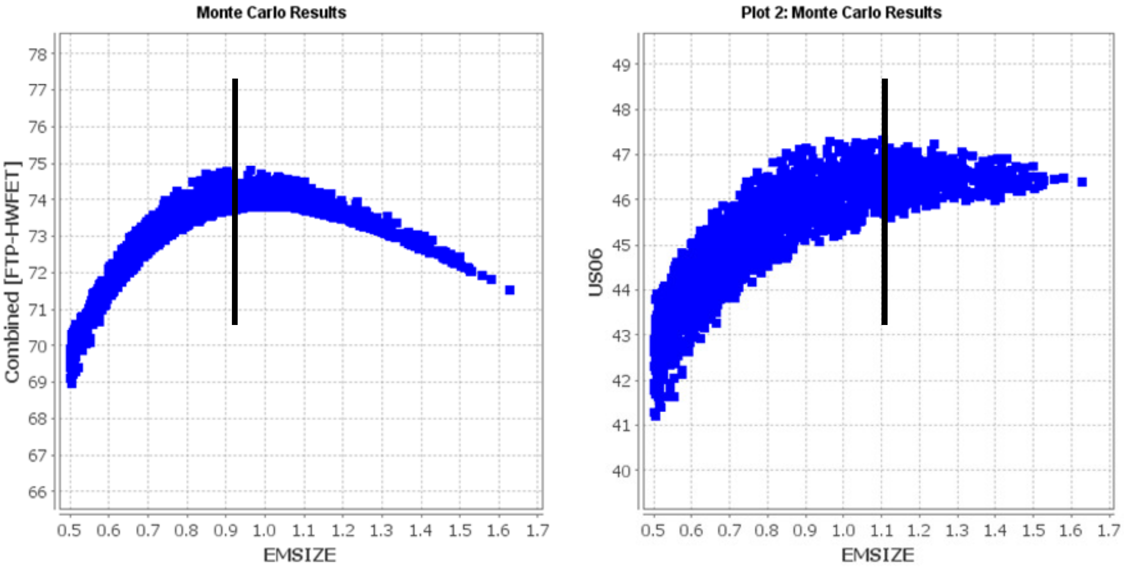


Figure 3-9: Electric motor sweeps for Standard Car class, P2 hybrid with stoichiometric GDI engine (left = FTP/HWFE test; right = US06 test)

3.3.1.2.22.2 Effects of engine displacement

EPA reviewed the effects of engine displacement at equivalent performance to determine if there would be an “optimal” range of downsizing for best effectiveness. Surprisingly, there was little benefit beyond downsizing the engine past a minimal point. Shown in Figure 3-10 is an example complex systems tool graph with fuel economy plotted against engine displacement multiplier (compared to the “nominal” engine displacement) for the Truck class for three gasoline turbocharged engine packages and one diesel engine package (note all packages included 20% weight reduction, 20% aerodynamic drag reduction, and 10% rolling resistance reduction):

- The diesel engine result shows that the nominal engine in this case was originally oversized because it was scaled on engine power not more accurately on engine torque and continued displacement reduction would improve fuel economy. For this package, the displacement for optimal fuel economy is smaller than 50% of the nominal value, however; when considering equivalent vehicle performance, the minimum diesel displacement increases to roughly 70% of the nominal value.

- In contrast, the gasoline turbo engine results shown reflect a relative insensitivity of displacement to fuel economy for these advanced vehicles.

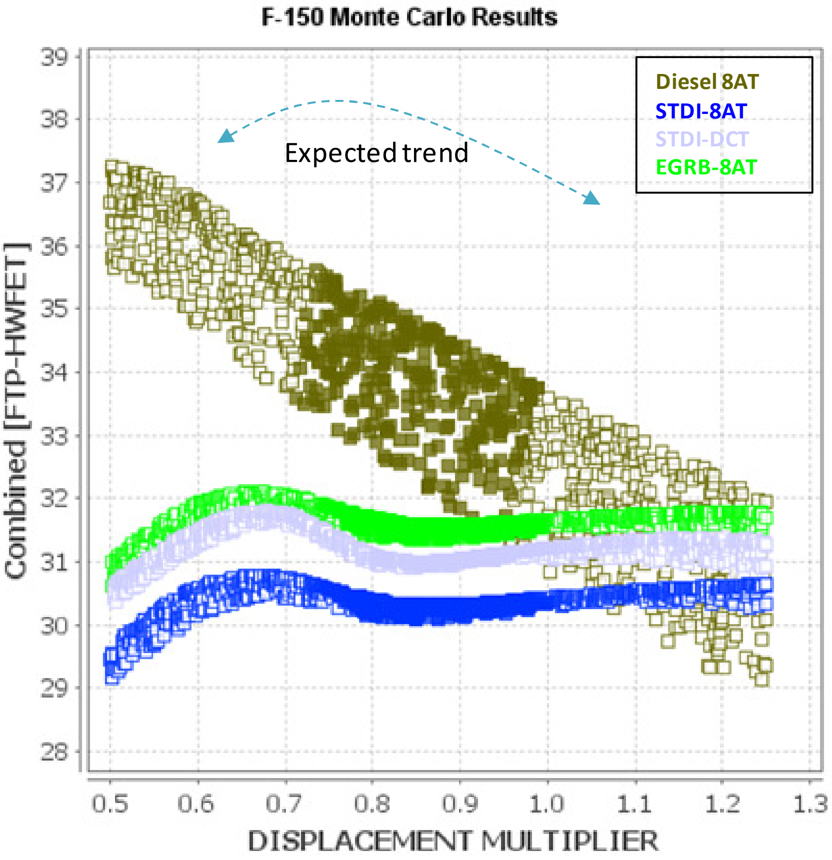


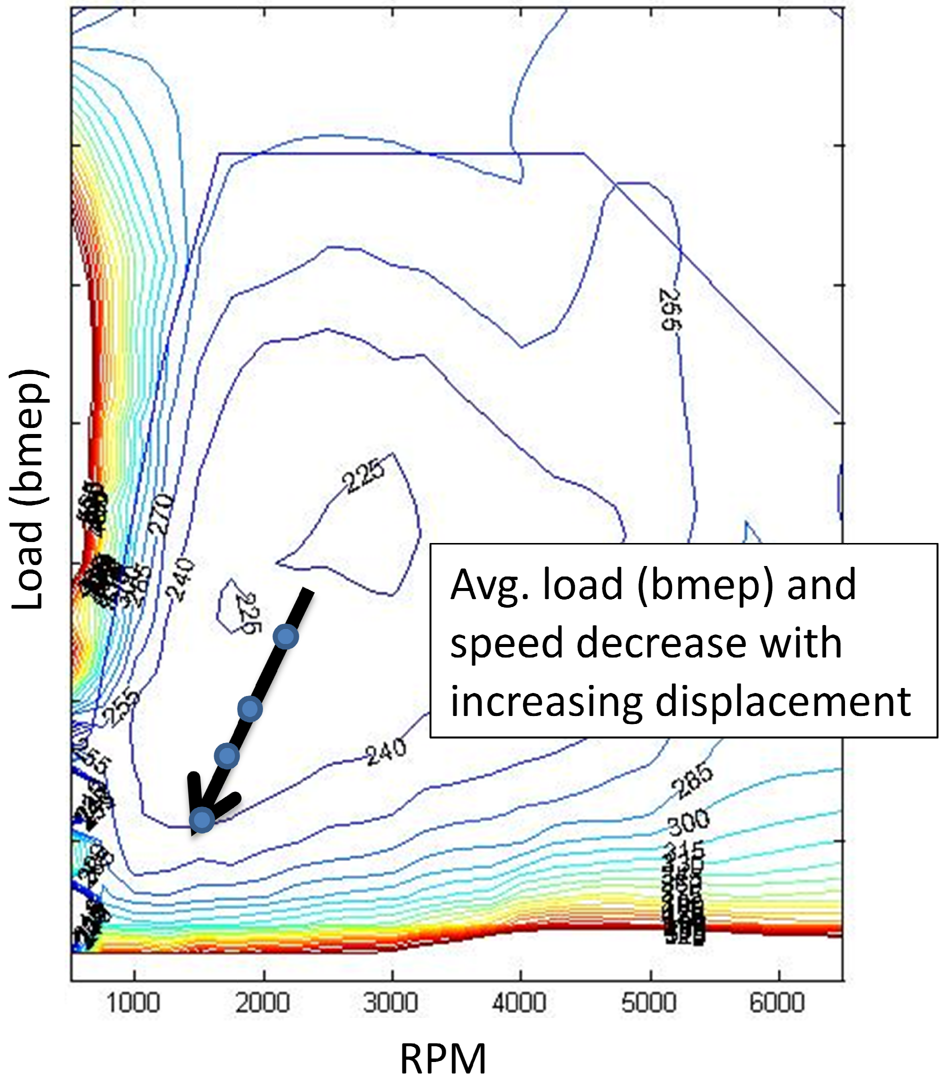
Figure 3-10: Example displacement sweep for Truck class in complex systems tool

Figure 3-10 shows that as modeled, the swept displacement range is not large enough for the advanced gasoline turbocharged engines. The displacement multiplier for these engines must be greater than 1.3x the nominal displacement before the fuel economy would degrade substantially. As the displacement drops below about 65% of the nominal (already downsized) value, the efficiency decreases, as the engine load must be much higher to provide the same required power. Regardless, the total fuel efficiency decrease from optimal is rather small compared to today's engines. A 27-bar cooled EGR turbocharged GDI engine map for a large car[q] was reverse-engineered from the Ricardo 10 hz output data, and is provided in Figure 3-11. The efficiency of this family of engines is very robust to changes in engine displacement because the highlighted BSFC region of interest (the second one out from the minimum BSFC "island") spans a large speed and load range. As a result, significant changes in displacement do not greatly reduce fuel efficiency. As displacement increases, the average operating points for the engine over a given test cycle will trend towards the lower left (lower speed, lower load[r]) portion of the map. In this case the points on the plot exist within the same BSFC contour, so there is little degradation in engine efficiency with increasing displacement (and drivetrain efficiency may improve at higher gears, potentially resulting in a fuel economy increase). Were the displacement to be increased much further, the operating region would cross the contour and fuel efficiency would begin to drop much more dramatically.

---

[q] The 27 bar, cooled EGR turbocharged engine maps are similar for all classes as they originated from a common reference map and scaled according to engine displacement, as described in Section 6.3 of the 2011 Ricardo report.

[r] Load decreases as it is reflective of a % of the maximum achievable torque and torque is increasing with increased displacement. Speed decreases because of the greater torque available combined with the shift optimizer algorithm (allowing for a greater propensity to operate in higher gears).



Avg. load (bmep) and speed decrease with increasing displacement

Figure 3-11: Advanced engine BSFC map (27-bar cooled EGR turbocharged GDI engine for large car)

3.3.1.2.23 Effects of mass reduction

With the complex systems tool EPA isolated the effectiveness of mass reduction on advanced vehicle technology packages. Figure 3-12 below shows a mass reduction sweep plot of the Large MPV class for a conventional STDI and P2 hybrid vehicle with an Atkinson engine.

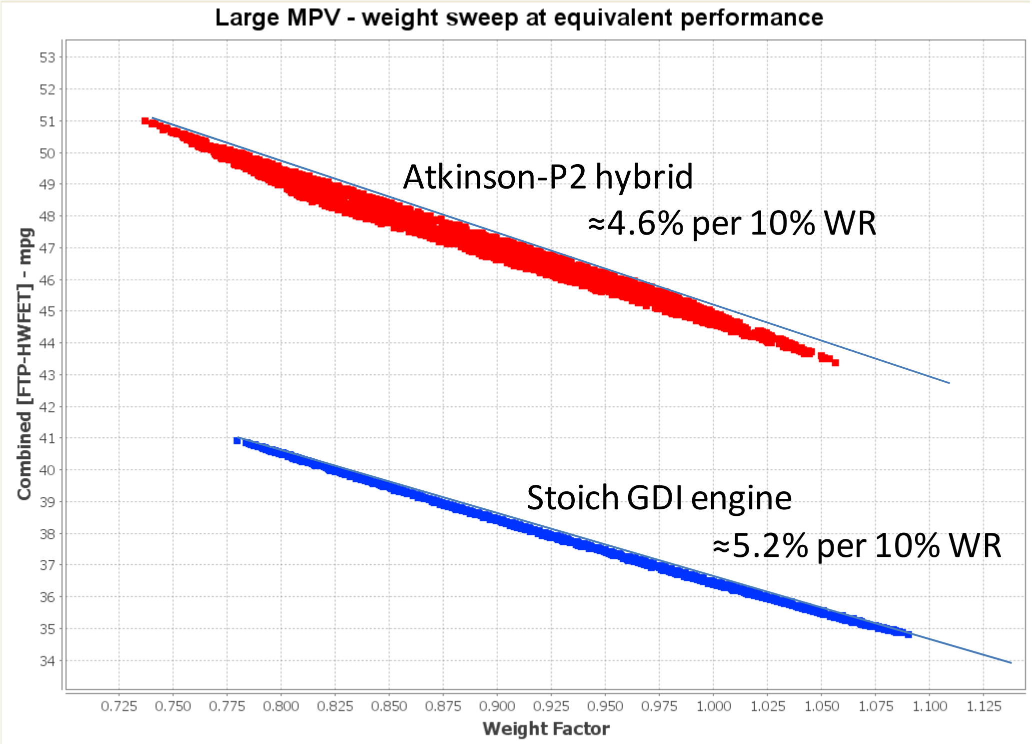


Figure 3-12: Mass reduction sweep for Large MPV class at baseline equivalent performance. Engine displacement and motor size (hybrids) held constant.

The mass reduction effectiveness, originally estimated at roughly 6% GHG reduction for a 10% reduction in mass, has been revised to reflect data such as that shown above. Isolated from benefits due to engine downsizing opportunities, the effectiveness of weight reduction for the non-hybrid packages is on the order of 5% per 10% weight reduction, while mass reduction for the P2 hybrid (or any hybrid) is reduced, on the order of 4.5% per 10% reduction due to the synergies with brake energy recovery (less braking energy is recoverable because the vehicle weighs less). The lumped parameter tool was also revised to incorporate the synergies of weight reduction and hybrids.

3.3.1.2.24 Vehicle simulation report peer review process

As previously discussed, vehicle simulation modeling is a very detailed, mathematically intensive approach which relies heavily on numerical engineering inputs. These inputs (e.g., engine maps, transmission efficiency, control logic, etc.) are the heart of the model and are derived directly from proprietary engineering knowledge of components and subsystems. To simulate advanced engine and vehicle concepts, state-of-the-art knowledge must be applied and converted into modeling inputs. Public domain information is rarely at the forefront of technology, and of little use in modeling vehicles in the 2017-2025 time frame.

Engineering details on advanced vehicle technologies are closely guarded in industry, and engineering services companies which develop and generate this confidential information rely on it to remain competitive in the marketplace. Therefore, it is difficult, if not impossible, to be completely transparent with an advanced vehicle simulation model and make all of the inputs available for public review. EPA commissioned an external peer review of the 2011 Ricardo simulation project and report. The peer reviewers selected were highly respected members of academia and industry, all with substantial backgrounds in automotive technology. The list of peer reviewers and their credentials is provided in the associated peer review report[31].

EPA charged the peer reviewers to thoroughly evaluate the body of work with respect to the following topics:

- Adequacy of the numerical inputs (engine technology selection, battery inputs, accessory load assumptions, etc) and highlight any caveats or limitations that would affect the final results.
- Validity and applicability of the simulation methodology, and if it adequately addresses synergies
- The results, and their validity and applicability to the light-duty vehicle fleet in the 2020-2025 timeframe.
- Completeness of the report (does it offer enough detail of the modeling process)
- The overall adequacy of the report for predicting the effectiveness of these technologies, and suggest recommendations for improvement

The first round of comments was reflective of the reviewer's lack of access to model inputs. Because the confidential inputs were initially withheld (for reasons described above), "lack of transparency" was a consistent theme amongst the reviewers, so much that they expressed frustration with their ability to evaluate the model methodology and the quality of the inputs. Additionally, due to the lack of access to Ricardo proprietary input data the peer reviewers expressed concern that they could not adequately judge the validity or accuracy of the input information or the simulation results. EPA worked with Ricardo to provide the peer reviewers with access to all of the detailed confidential modeling inputs under non disclosure agreements. With this necessary information, 3 of the 5 peer reviewers submitted a second round of comments which were generally more specific. In turn, Ricardo modified the report to address some of the comments, and they developed a response to comments document which covered the comments from the peer review. One common theme called for increased detail in how the inputs were generated. To address these requests, Ricardo provided the detailed case studies that were used in the development of the engine maps for the cooled EGR boosted engines and the Atkinson engines for hybrids. Ricardo also elaborated on the hybrid control strategy, complete with state flow diagrams of operating modes, as well as a discussion of how hybrid control strategy was optimized. Additional transmission input details were provided, including an overview of the development of advanced gear efficiencies and how the optimized shift strategy was applied.

The docket to this proposal contains Ricardo's response to comment document (which includes the first version of the Ricardo report that was peer reviewed and both rounds of peer review comments), and Ricardo's final report.[3233] The agencies seek comment on the all of these references and on the responsiveness of the final report to the peer review comments.

3.3.1.3 Future Argonne National Laboratory Simulation Study

The U.S. D.O.T. Volpe Center has entered into a contract with Argonne National Laboratory (ANL) to provide full vehicle simulation modeling support for this MYs 2017-2025 rulemaking. While modeling was not completed in time for use in this NPRM, NHTSA intends to use this modeling to validate/update technology effectiveness estimates and synergy factors for the final rulemaking analysis. This simulation modeling will be accomplished using ANL's full vehicle simulation tool called "Autonomie," which is the successor to ANL's Powertrain System Analysis Toolkit (PSAT) simulation tool, and ANL's expertise with advanced vehicle technologies.

3.3.2 Lumped parameter Modeling

3.3.2.1 Overview of the lumped parameter model

As a more practical alternative to full vehicle simulation, EPA developed a "lumped parameter model" that estimates the effectiveness of various technology combinations or "packages," in a manner that accounts for synergies between technologies. In the analysis supporting the MYs 2012-2016 light duty vehicle GHG and CAFE rule, EPA built over 140 packages for use in its OMEGA model, which spanned 19 vehicle classes and over 1100 vehicle models. Vehicle simulation modeling performed for EPA by Ricardo, PLC, was used to calibrate the lumped parameter model. Although DOT's analysis supporting the MYs 2012-2016 CAFE rule applied technologies incrementally, rather than specifying packages in advance, DOT calibrated CAFE model inputs, using EPA's lumped parameter model, to harmonize as fully as practical with estimates produced by EPA's lumped parameter model.

To support this rulemaking, EPA has updated its lumped parameter model and calibrated it with updated vehicle simulation work performed for EPA by Ricardo, PLC. As in the MYs 2012-2016 rulemaking, DOT has calibrated inputs including synergy factors, to the CAFE model to as fully as practical align with estimates produced by EPA's lumped parameter model.

Both agencies are continuing to conduct and sponsor vehicle simulation efforts to improve inputs to the agencies' respective modeling systems, and both agencies expect that the final rules will be informed by this ongoing work.

The basis for EPA's lumped parameter analysis is a first-principles energy balance that estimates the manner in which the chemical energy of the fuel is converted into various forms of thermal and mechanical energy on the vehicle. The analysis accounts for the dissipation of energy into the different categories of energy losses, including each of the following:

- Second law losses (thermodynamic losses inherent in the combustion of fuel),
- Heat lost from the combustion process to the exhaust and coolant,
- Pumping losses, i.e., work performed by the engine during the intake and exhaust strokes,
- Friction losses in the engine,
- Transmission losses, associated with friction and other parasitic losses of the gearbox, torque converter (when applicable) and driveline
- Accessory losses, related directly to the parasitics associated with the engine accessories,
- Vehicle road load (tire and aerodynamic) losses;
- Inertial losses (energy dissipated as heat in the brakes)

The remaining energy is available to propel the vehicle. It is assumed that the baseline vehicle has a fixed percentage of fuel lost to each category. Each technology is grouped into the major types of engine loss categories it reduces. In this way, interactions between multiple technologies that are applied to the vehicle may be determined. When a technology is applied, the lumped parameter model estimates its effects by modifying the appropriate loss categories by a given percentage. Then, each subsequent technology that reduces the losses in an already improved category has less of a potential impact than it would if applied on its own.

Using a lumped parameter approach for calculating package effectiveness provides necessary grounding to physical principles. Due to the mathematical structure of the model, it naturally limits the maximum effectiveness achievable for a family of similar technologies[s]. This can prove useful when computer-simulated packages are compared to a "theoretical limit" as a plausibility check. Additionally, the reduction of certain energy loss categories directly impacts the effects on others. For example, as mass is reduced the benefits of brake energy recovery decreases because there is not as much inertia energy to recapture.

Figure 3-13 is an example spreadsheet used by EPA to estimate the package effectiveness and the synergistic impacts of a technology package for a standard-size car.

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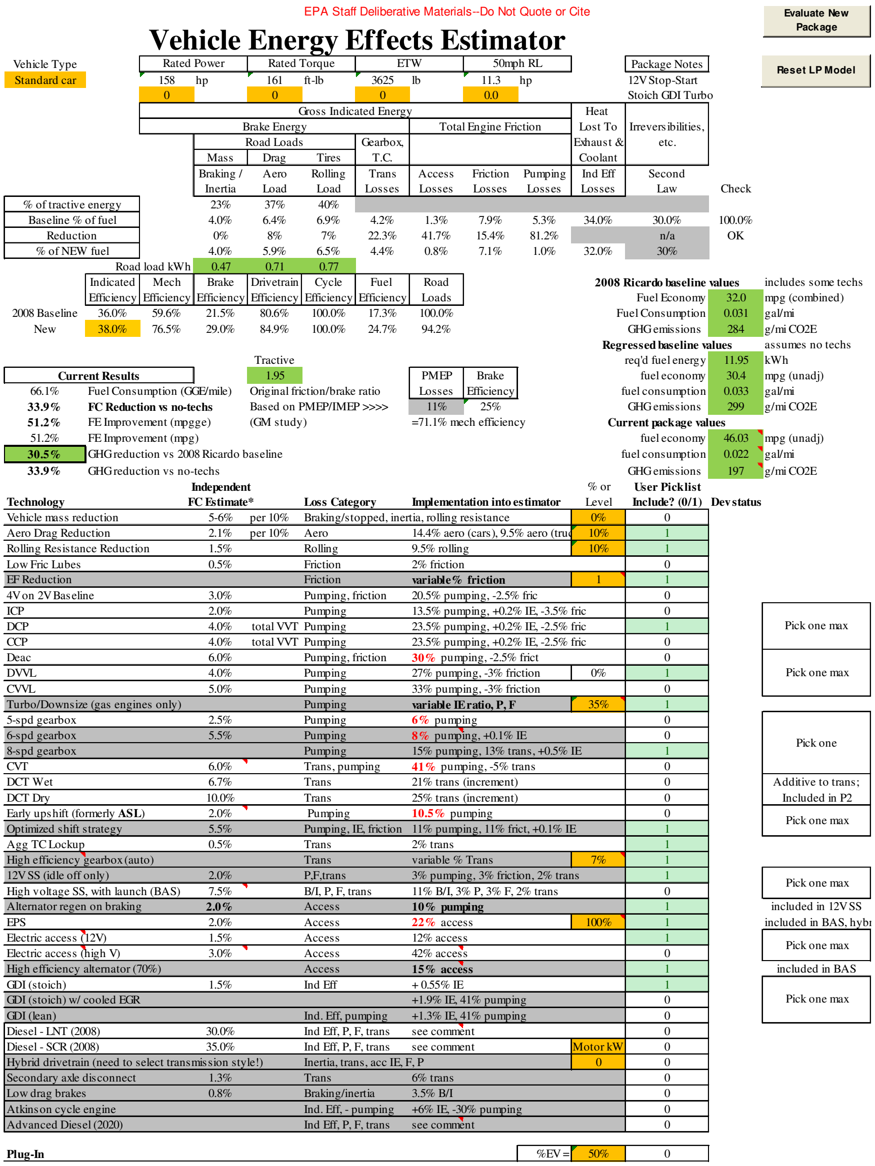
[s] For example, if only 4% of fuel energy is lost (in a baseline engine) to pumping work, leveraging multiple technologies to theoretically eliminate all pumping losses would yield an aggregate reduction of no more than 15% in fuel consumption.



EPA Staff Deliberative Materials--Do Not Quote or Cite

Evaluate New Package

Vehicle Energy Effects Estimator

Reset LP Model

Vehicle Type	Rated Power		Rated Torque		ETW		50mph RL		Package Notes
Standard car	158	hp	161	ft-lb	3625	lb	11.3	hp	12V Stop-Start
	0		0		0		0.0		Stoich GDI Turbo

	Gross Indicated Energy							Heat Lost To Exhaust & Coolant	Irreversibilities, etc.	
	Brake Energy				Total Engine Friction					
	Road Loads			Gearbox, T.C.						
	Mass	Drag	Tires							
	Braking / Inertia	Aero Load	Rolling Load	Trans Losses	Access Losses	Friction Losses	Pumping Losses	Ind Eff Losses	Second Law	Check
% of tractive energy	23%	37%	40%							
Baseline % of fuel	4.0%	6.4%	6.9%	4.2%	1.3%	7.9%	5.3%	34.0%	30.0%	100.0%
Reduction	0%	8%	7%	22.3%	41.7%	15.4%	81.2%		n/a	OK
% of NEW fuel	4.0%	5.9%	6.5%	4.4%	0.8%	7.1%	1.0%	32.0%	30%	
Road load kWh	0.47	0.71	0.77							

	Indicated Efficiency	Mech Efficiency	Brake Efficiency	Drivetrain Efficiency	Cycle Efficiency	Fuel Efficiency	Road Loads
2008 Baseline	36.0%	59.6%	21.5%	80.6%	100.0%	17.3%	100.0%
New	38.0%	76.5%	29.0%	84.9%	100.0%	24.7%	94.2%

2008 Ricardo baseline values		includes some techs
Fuel Economy	32.0	mpg (combined)
Fuel Consumption	0.031	gal/mi
GHG emissions	284	g/mi CO2E
Regressed baseline values		assumes no techs
req'd fuel energy	11.95	kWh
fuel economy	30.4	mpg (unadj)
fuel consumption	0.033	gal/mi
GHG emissions	299	g/mi CO2E
Current package values		
fuel economy	46.03	mpg (unadj)
fuel consumption	0.022	gal/mi
GHG emissions	197	g/mi CO2E

Tractive

1.95

Original friction/brake ratio

Based on PMEP/IMEP >>>>

(GM study)

PMEP Losses	Brake Efficiency
11%	25%

=71.1% mech efficiency

Current Results	
66.1%	Fuel Consumption (GGE/mile)
33.9%	**FC Reduction vs no-techs**
51.2%	FE Improvement (mpgge)
51.2%	FE Improvement (mpg)
30.5%	GHG reduction vs 2008 Ricardo baseline
33.9%	GHG reduction vs no-techs

Technology	**Independent FC Estimate***		**Loss Category**	**Implementation into estimator**	% or Level	**User Picklist Include? (0/1)**	**Dev status**	
Vehicle mass reduction	5-6%	per 10%	Braking/stopped, inertia, rolling resistance		0%	0		
Aero Drag Reduction	2.1%	per 10%	Aero	14.4% aero (cars), 9.5% aero (truc	10%	1		
Rolling Resistance Reduction	1.5%		Rolling	9.5% rolling	10%	1		
Low Fric Lubes	0.5%		Friction	2% friction		0		
EF Reduction			Friction	**variable % friction**	1	1		
4V on 2V Baseline	3.0%		Pumping, friction	20.5% pumping, -2.5% fric		0		
ICP	2.0%		Pumping	13.5% pumping, +0.2% IE, -3.5% fric		0		Pick one max
DCP	4.0%	total VVT	Pumping	23.5% pumping, +0.2% IE, -2.5% fric		1		
CCP	4.0%	total VVT	Pumping	23.5% pumping, +0.2% IE, -2.5% fric		0		
Deac	6.0%		Pumping, friction	**30%** pumping, -2.5% frict		0		Pick one max
DVVL	4.0%		Pumping	27% pumping, -3% friction	0%	1		
CVVL	5.0%		Pumping	33% pumping, -3% friction		0		
Turbo/Downsize (gas engines only)			Pumping	**variable IE ratio, P, F**	35%	1		
5-spd gearbox	2.5%		Pumping	**6%** pumping		0		Pick one
6-spd gearbox	5.5%		Pumping	**8%** pumping, +0.1% IE		0		
8-spd gearbox			Pumping	15% pumping, 13% trans, +0.5% IE		1		
CVT	6.0%		Trans, pumping	**41%** pumping, -5% trans		0		
DCT Wet	6.7%		Trans	21% trans (increment)		0		Additive to trans; Included in P2
DCT Dry	10.0%		Trans	25% trans (increment)		0		
Early upshift (formerly **ASL**)	2.0%		Pumping	**10.5%** pumping		0		Pick one max
Optimized shift strategy	5.5%		Pumping, IE, friction	11% pumping, 11% frict, +0.1% IE		1		
Agg TC Lockup	0.5%		Trans	2% trans		1		
High efficiency gearbox (auto)			Trans	variable % Trans	7%	1		
12V SS (idle off only)	2.0%		P,F,trans	3% pumping, 3% friction, 2% trans		1		Pick one max
High voltage SS, with launch (BAS)	7.5%		B/I, P, F, trans	11% B/I, 3% P, 3% F, 2% trans		0		
Alternator regen on braking	**2.0%**		Access	**10% pumping**		1		included in 12V SS
EPS	2.0%		Access	**22%** access	100%	1		included in BAS, hybr
Electric access (12V)	1.5%		Access	12% access		1		Pick one max
Electric access (high V)	3.0%		Access	42% access		0		
High efficiency alternator (70%)			Access	**15% access**		1		included in BAS
GDI (stoich)	1.5%		Ind Eff	+ 0.55% IE		1		Pick one max
GDI (stoich) w/ cooled EGR				+1.9% IE, 41% pumping		0		
GDI (lean)			Ind. Eff, pumping	+1.3% IE, 41% pumping		0		
Diesel - LNT (2008)	30.0%		Ind Eff, P, F, trans	see comment		0		
Diesel - SCR (2008)	35.0%		Ind Eff, P, F, trans	see comment	Motor kW	0		
Hybrid drivetrain (need to select transmission style!)			Inertia, trans, acc IE, F, P		0	0		
Secondary axle disconnect	1.3%		Trans	6% trans		0		
Low drag brakes	0.8%		Braking/inertia	3.5% B/I		0		
Atkinson cycle engine			Ind. Eff, - pumping	+6% IE, -30% pumping		0		
Advanced Diesel (2020)			Ind Eff, P, F, trans	see comment		0		
Plug-In				%EV =	50%	0		

Figure 3-13 Sample lumped parameter model spreadsheet

The LP model has been updated from the MYs 2012-2016 final rule to support the MYs 2017-2025 proposed standards. Changes were made to include new technologies for 2017 and beyond, improve fidelity for baseline attributes and technologies, and better represent hybrids based on more comprehensive vehicle simulation modeling. EPA RIA Chapter 1 provides details of the methodology used to update and refine the model.

3.3.2.2 Calibration of Lumped Parameter model to vehicle simulation data

The LP model includes a majority of the new technologies being considered as part of this proposed rulemaking. The results from the Ricardo vehicle simulation project (3.3.1) were used to successfully calibrate the predictive accuracy and the synergy calculations that occur within the LP model. When the vehicle packages Ricardo modeled are estimated in the lumped parameter model, the results are comparable. All of the baselines for each vehicle class, as predicted by the LP model, fall within 3% of the Ricardo-modeled baseline results. With a few exceptions (discussed in Chapter 1 of EPA's draft RIA the lumped parameter results for the 2020-2025 "nominal" technology packages are within 5% of the vehicle simulation results. Shown below in Figures x-y are Ricardo's vehicle simulation package results (for conventional stop-start and P2 hybrid packages[t]) compared to the lumped parameter estimates.

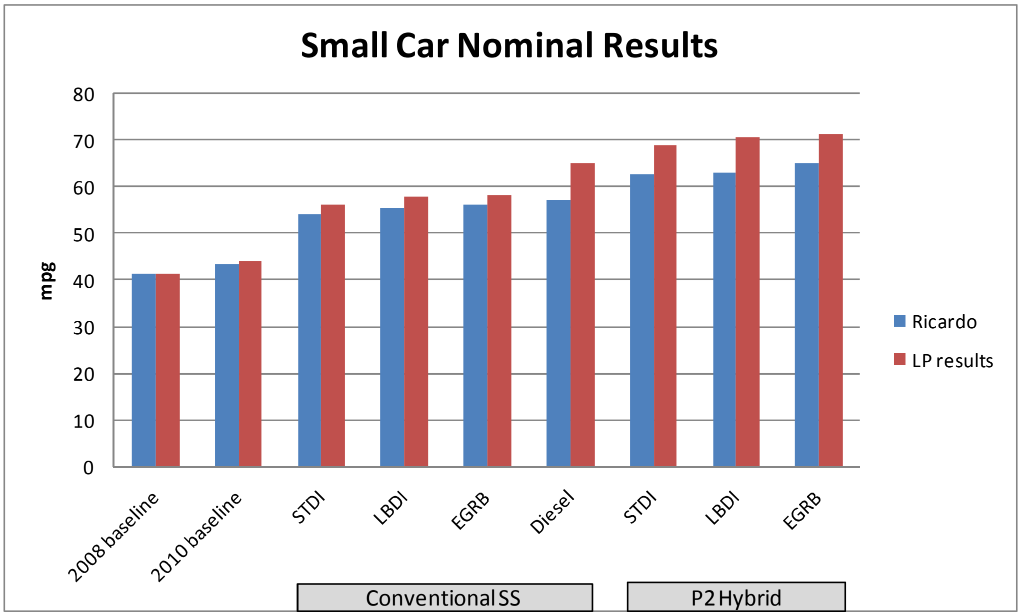


Figure 3-14: Comparison of LP to simulation results for Small Car class

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[t] Refer to 3.3.1for definitions of the baselines, "conventional stop-start" and "P2 hybrid" vehicle architectures.

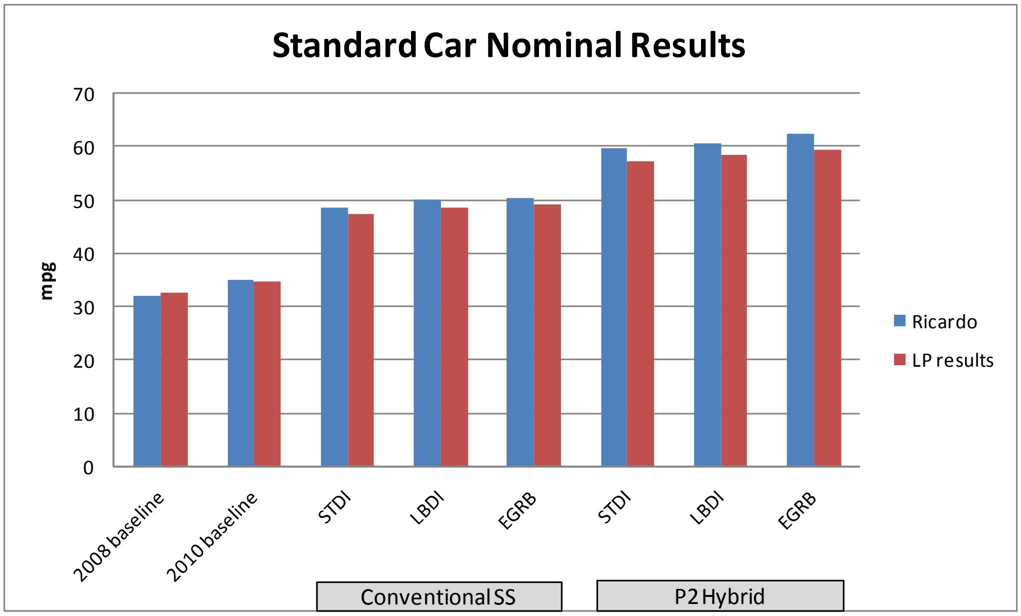

Figure 3-15: Comparison of LP to simulation results for Standard Car class

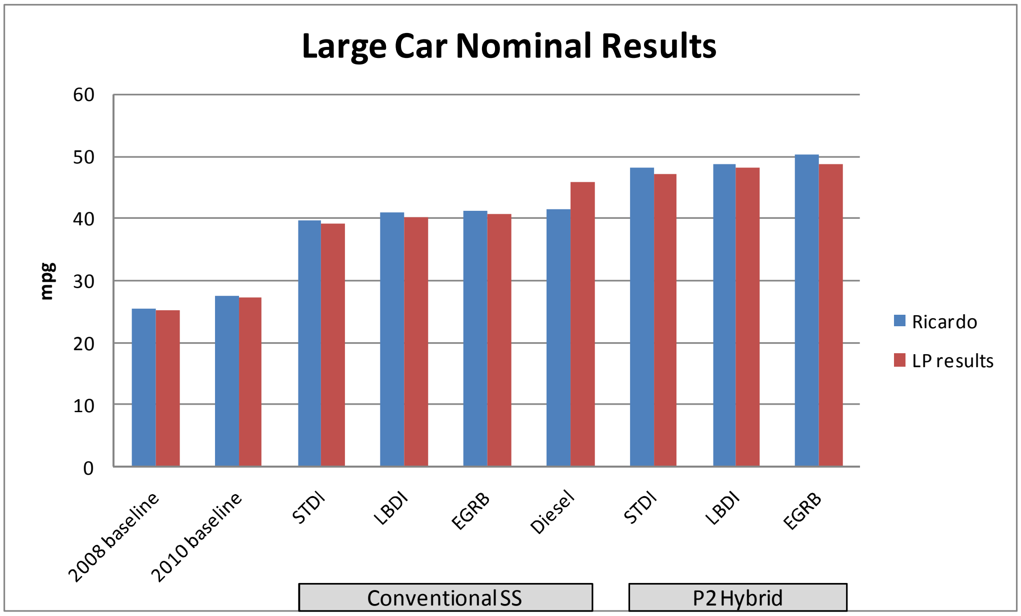

Figure 3-16: Comparison of LP to simulation results for Large Car class

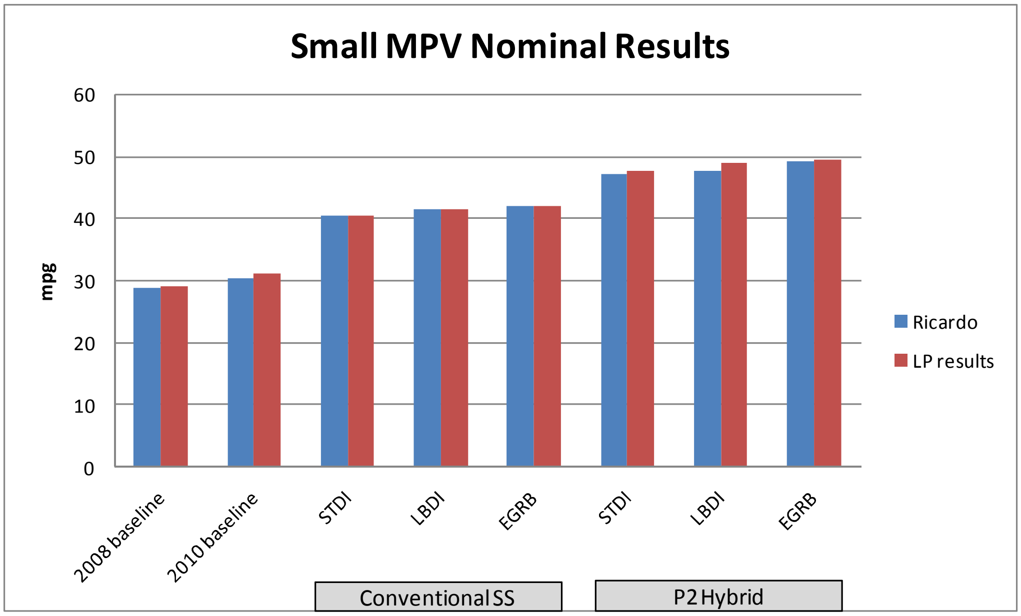

Figure 3-17: Comparison of LP to simulation results for Small MPV class

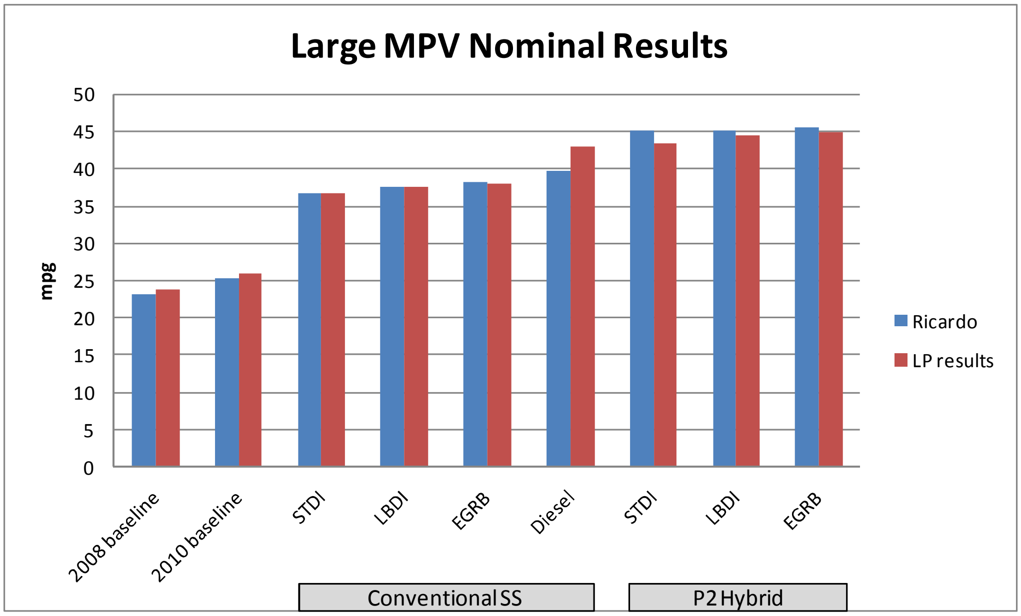

Figure 3-18: Comparison of LP to simulation results for Large MPV class

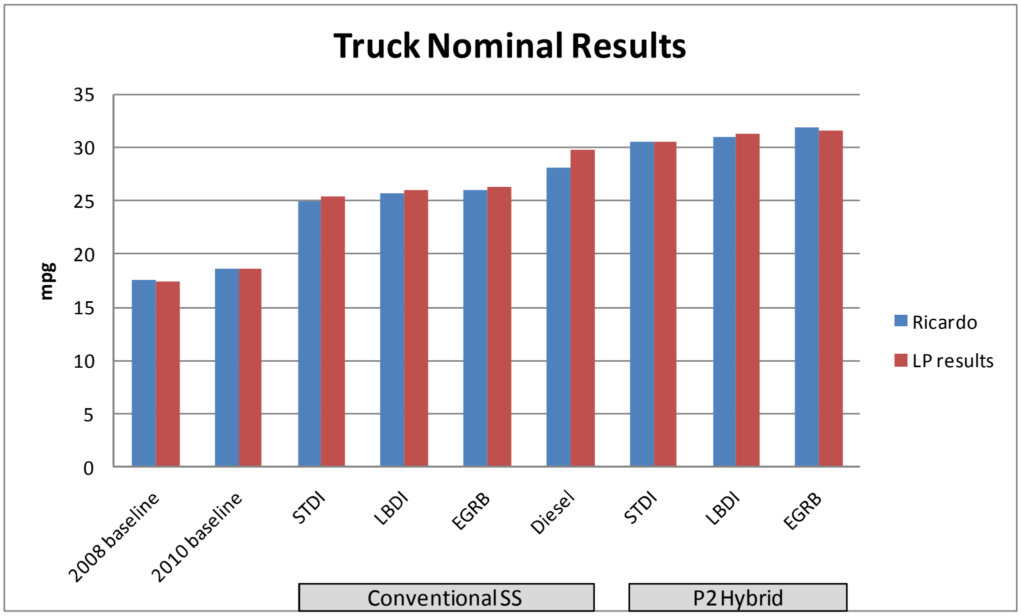

Figure 3-19: Comparison of LP to simulation results for Truck class

3.3.2.3 Comparison of results to real-world examples

To validate the lumped parameter model, representations of actual late-model production vehicles exhibiting advanced technologies were created. Shown below in Table 3-19 are a set of select vehicle models containing a diverse array of technologies: included are the pertinent technologies and vehicle specifications, along with actual vehicle certification fuel economy test data compared to the lumped parameter fuel economy estimates. For the vehicles and technologies shown, the predicted fuel economy is within about 3% of the actual data.

Table 3-19: Production vehicle certification data compared to lumped parameter predictions

Vehicle	2011 Chevy Cruze ECO	2011 Sonata Hybrid	2011 Escape Hybrid	2011 F-150 Ecoboost
Vehicle class	Small Car	Standard Car	Small MPV	Truck
Engine	1.4L I4 turbo GDI	2.4L I4 Atkinson	2.5L I4 Atkinson	3.5L V6 turbo GDI
Transmission	6 speed auto	6 speed DCT	CVT	6 speed auto
HEV motor (kW)	n/a	30	67	n/a
ETW (lbs)	3375	3750	4000	6000
City/HW FE (mpg)	**40.3**	**52.2**	**43.9**	**22.6**
LP estimate (mpg)	**40.2**	**51.7**	**44.0**	**21.9**
Key technologies applied in LP model	GDI (stoich.) turbo (30% downsize) ultra low R tires active grill shutters	P2 hybrid aero improvements	Powersplit hybrid	GDI (stoich) turbo (37% downsize)

3.4 What cost and effectiveness estimates have the agencies used for each technology?

As discussed in the previous sections, many the effectiveness estimates for this proposal, including the estimates for the technologies carried over from the MYs 2012-2016 final rule, been derived from the 2011 Ricardo study and corresponding updated version of the lumped-parameter model. It is important to note that when referencing the effectiveness estimates from the MYs 2012-2016 the final rule the agencies used the average of the range presented. If for example, the effectiveness range for technology X was determined to be 1 to 2 percent then the agencies used a value of 1.5 percent in their respective analyses. However, the effectiveness ranges that are presented for the MYs 2017-2025 analysis, as informed by the Ricardo 2011 study, define the range of estimates used by the agencies for the different vehicle types. Again using technology X as an example, if the range is now defined as 2.0 to 2.5 percent then for small passenger cars (subcompact or compact) the estimated effectiveness might be 2.0 percent but for large cars an estimate of 2.5 percent might be used.

3.4.1 Engine technologies

One thing that is immediately clear from the cost tables that follow is that we have updated our costing approach for some technologies in an effort to provide better granularity in our estimates. This is easily seen in Table 3-21, among others, where we list costs for technologies by engine configuration—in-line or "I" versus "V"—and/or by number of cylinders. In the 2012-2016 final rule, we showed costs for a small car, large car, large truck, etc. The problem with that approach is that different vehicle classes can have many different sized engines. This will be especially true going forward as more turbocharged and downsized engines enter the fleet. For example, we project that many vehicles in the large car class some of which, today, have V8 engines would have highly turbocharged I4 engines under the proposal. As such, we would not want to estimate the large car costs of engine friction reduction—which have always and continue to be based on the number of cylinders—assuming that all large cars have V8 engines.

3.4.1.1 Low Friction Lubricants

One of the most basic methods of reducing fuel consumption in gasoline engines is the use of lower viscosity engine lubricants. More advanced multi-viscosity engine oils are available today with improved performance in a wider temperature band and with better lubricating properties. This can be accomplished by changes to the oil base stock (*e.g.*, switching engine lubricants from a Group I base oils to lower-friction, lower viscosity Group III synthetic) and through changes to lubricant additive packages (*e.g.*, friction modifiers and viscosity improvers). The use of 5W-30 motor oil is now widespread and auto manufacturers are introducing the use of even lower viscosity oils, such as 5W-20 and 0W-20, to improve cold-flow properties and reduce cold start friction. However, in some cases, changes to the crankshaft, rod and main bearings and changes to the mechanical tolerances of engine components may be required. In all cases, durability testing would be required to ensure that durability is not compromised. The shift to lower viscosity and lower friction lubricants will also improve the effectiveness of valvetrain technologies such as cylinder deactivation, which rely on a minimum oil temperature (viscosity) for operation.

Several manufacturers have previously commented confidentially, that low friction lubricants could have an effectiveness value between 0 to 1 percent. The agencies used the average effectiveness of 0.5 in the MYs 2012-2016 final rule. For purposes of this proposal, the agencies relied on the lump parameter model and the range for the effectiveness of low friction lubricant is 0.5 to 0.8 percent.

In the 2012-2016 rule, the 2010 TAR and the recent HD GHG rule, EPA and NHTSA used a direct manufacturing cost (DMC) of \$3 (2007\$) and considered that cost to be independent of vehicle class since the engineering work required should apply to any engine size. The agencies continue to believe that this cost is appropriate and have updated it to \$3 (2009\$) for this analysis. No learning is applied to this technology so the DMC remains \$3 year-over-year. The agencies have used a low complexity ICM of 1.24 for this technology through 2018 and 1.19 thereafter. The resultant costs are shown in Table 3-20[u] Note that low friction lubes are expected to exceed 85 percent penetration by the 2017 MY.

Table 3-20 Costs for Engine Modifications to Accommodate Low Friction Lubes (2009$)

Cost type	Engine type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	All	\$3	\$3	\$3	\$3	\$3	\$3	\$3	\$3	\$3
IC	All	\$1	\$1	\$1	\$1	\$1	\$1	\$1	\$1	\$1
TC	All	\$4	\$4	\$4	\$4	\$4	\$4	\$4	\$4	\$4

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; all costs are incremental to the baseline.

3.4.1.2 Engine Friction Reduction

In addition to low friction lubricants, manufacturers can also reduce friction and improve fuel consumption by improving the design of engine components and subsystems. Approximately 10 percent of the energy consumed by a vehicle is lost to friction, and just over half is due to frictional losses within the engine.[34] Examples include improvements in low-tension piston rings, piston skirt design, roller cam followers, improved crankshaft design and bearings, material coatings, material substitution, more optimal thermal management, and piston and cylinder surface treatments. Additionally, as computer-aided modeling software

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[u] Note that the costs developed for low friction lubes for this analysis reflect the costs associated with any engine changes that would be required as well as any durability testing that may be required.

continues to improve, more opportunities for evolutionary friction reductions may become available.

All reciprocating and rotating components in the engine are potential candidates for friction reduction, and minute improvements in several components can add up to a measurable fuel economy improvement. In MYs 2012-2016 final rule, the agencies relied on the 2002 NAS, NESCCAF and EEA reports as well as confidential manufacturer data that suggested a range of effectiveness for engine friction reduction to be between 1 to 3 percent. Because of the incremental nature of the CAFE model, NHTSA used the narrower range of 1 to 2 percent, which resulted in an average effectiveness of 1.5 percent. Based on the 2011 Ricardo study the effectiveness for engine friction reduction range has been changed to 2.0 to 2.7 percent.. For this proposal the agencies have added a second level of incremental improvements in engine friction reduction over multiple vehicle redesign cycles. This second level of engine friction reduction includes some additional improvements to low friction lubricant, relative to the low friction lubricant technology discussed above. The technologies for this second level of engine friction reduction and low friction lubricants is considered to be mature only after MY 2017. The effectiveness for this second level, relative to the base engine, is 3.4 to 4.8 percent based on the lump parameter model. Because of the incremental nature of the CAFE model, NHTSA used the effectiveness range of 0.83 to 1.37 percent incremental to the first level of engine friction reduction and low friction lubricants.

In the 2012-2016 rule, the 2010 TAR and the HD GHG final rule, NHTSA and EPA used a cost estimate of $11 (2007$) per cylinder direct manufacturing cost, or $12 (2009$) per cylinder in this analysis. No learning is applied to this technology so the DMC remains $12 (2009$) year-over-year. The agencies have used a low complexity ICM of 1.24 for this technology through 2018 and 1.19 thereafter. The resultant costs are shown in Table 3-21. Note that the first level of engine friction reduction is expected to exceed 85 percent penetration by the 2017 MY.

Table 3-21 Costs for Engine Friction Reduction – Level 1 (2009$)

Cost type	Engine type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	I3	$35	$35	$35	$35	$35	$35	$35	$35	$35
DMC	I4	$47	$47	$47	$47	$47	$47	$47	$47	$47
DMC	V6	$70	$70	$70	$70	$70	$70	$70	$70	$70
DMC	V8	$93	$93	$93	$93	$93	$93	$93	$93	$93
IC	I3	$8	$8	$7	$7	$7	$7	$7	$7	$7
IC	I4	$11	$11	$9	$9	$9	$9	$9	$9	$9
IC	V6	$17	$17	$13	$13	$13	$13	$13	$13	$13
IC	V8	$23	$23	$18	$18	$18	$18	$18	$18	$18
TC	I3	$44	$44	$42	$42	$42	$42	$42	$42	$42
TC	I4	$58	$58	$56	$56	$56	$56	$56	$56	$56
TC	V6	$87	$87	$84	$84	$84	$84	$84	$84	$84
TC	V8	$116	$116	$111	$111	$111	$111	$111	$111	$111

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; all costs are incremental to the baseline.

The agencies have estimated the DMC of this technology—a second level of friction reduction with a second level of low friction lube—at double the combined DMCs of the first level of engine friction reduction and first level of low friction lube (double the DMC relative to the baseline). As a result, the costs of the second level of engine friction reduction are as shown in Table 3-22. For EFR2 the agencies have used a low complexity ICM of 1.24 through 2024 and 1.19 thereafter

Table 3-22 Costs for Engine Friction Reduction – Level 2 (2009$)

Cost type	Engine type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	I3	$76	$76	$76	$76	$76	$76	$76	$76	$76
DMC	I4	$100	$100	$100	$100	$100	$100	$100	$100	$100
DMC	V6	$146	$146	$146	$146	$146	$146	$146	$146	$146
DMC	V8	$193	$193	$193	$193	$193	$193	$193	$193	$193
IC	I3	$18	$18	$18	$18	$18	$18	$18	$18	$15
IC	I4	$24	$24	$24	$24	$24	$24	$24	$24	$19
IC	V6	$35	$35	$35	$35	$35	$35	$35	$35	$28
IC	V8	$47	$47	$47	$47	$47	$47	$47	$47	$37
TC	I3	$95	$95	$95	$95	$95	$95	$95	$95	$91
TC	I4	$124	$124	$124	$124	$124	$124	$124	$124	$119
TC	V6	$182	$182	$182	$182	$182	$182	$182	$182	$175
TC	V8	$240	$240	$240	$240	$240	$240	$240	$240	$230

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; all costs are incremental to the baseline.

3.4.1.3 Cylinder Deactivation

In conventional spark-ignited engines throttling the airflow controls engine torque output. At partial loads, efficiency can be improved by using cylinder deactivation instead of throttling. Cylinder deactivation (DEAC) can improve engine efficiency by disabling or deactivating (usually) half of the cylinders when the load is less than half of the engine's total torque capability – the valves are kept closed, and no fuel is injected – as a result, the trapped air within the deactivated cylinders is simply compressed and expanded as an air spring, with reduced friction and heat losses. The active cylinders combust at almost double the load required if all of the cylinders were operating. Pumping losses are significantly reduced as long as the engine is operated in this "part-cylinder" mode.

Cylinder deactivation control strategy relies on setting maximum manifold absolute pressures or predicted torque within which it can deactivate the cylinders. Noise and vibration issues reduce the operating range to which cylinder deactivation is allowed, although manufacturers continue exploring vehicle changes that enable increasing the amount of time that cylinder deactivation might be suitable. Some manufacturers may choose to adopt active engine mounts and/or active noise cancellations systems to address NVH concerns and to allow a greater operating range of activation (and the agencies have estimated the costs for doing so, as noted below). Manufacturers have legitimately stated that use of

DEAC on 4 cylinder engines would cause unacceptable NVH; therefore, as in the 2012-2016 rule and the TAR, the agencies are not applying cylinder deactivation to 4-cylinder engines in evaluating potential emission reductions/fuel economy improvements and attendant costs.

Cylinder deactivation has seen a recent resurgence thanks to better valvetrain designs and engine controls. General Motors and Chrysler Group have incorporated cylinder deactivation across a substantial portion of their V8-powered lineups. Honda (Odyssey, Pilot) offers V6 models with cylinder deactivation.

Effectiveness improvements scale roughly with engine displacement-to-vehicle weight ratio: the higher displacement-to-weight vehicles, operating at lower relative loads for normal driving, have the potential to operate in part-cylinder mode more frequently.

NHTSA and EPA reviewed estimates from the 2012-2016 final rule, TAR, the RIA for the heavy-duty GHG and fuel consumption rule. The OMEGA model, which is based on packages, applied a 6 percent reduction in CO_2 emissions depending on vehicle class. The CAFE model, due to its incremental nature, used a range depending on the engine valvetrain configuration. For example, for DOHC engines which are already equipped with DCP and DVVLD, there is little benefit that can be achieved from adding cylinder deactivation since the pumping work has already been minimized and internal Exhaust Gas Recirculation (EGR) rates are maximized, so the effectiveness is only up to 0.5 percent for DEACD. For SOHC engines which have CCP and DVVLS applied, effectiveness ranged from 2.5 to 3 percent for DEACS. For OHV engines, without VVT or VVL technologies, the effectiveness for DEACO ranged from 3.9 to 5.5 percent.

For this proposal the agencies, taking into account the additional review and the work performed for the Ricardo study, have revised the estimates for cylinder deactivation. The effectiveness for relative to the base engine is 4.7 to 6.5 percent based on the lump parameter model. Because of the incremental nature of the CAFE model, NHTSA used the effectiveness range of 0.44 to 0.66 percent incremental for SOHC and DOHC applications. For OHV applications, the effectiveness was increased slightly with a range of 4.66 to 6.30 percent.

In the 2012-2016 rule and the 2010 TAR, the agencies used a DMC estimate of $140 (2007$) and $157 (2007$) for cylinder deactivation technology on V6 and V8 engines, respectively. The DMC's become $144 (2009$) and $162 (2009$) for this analysis and are considered applicable in the 2015 MY. This technology is considered to be on the flat-portion of the learning curve. The agencies have applied a low complexity ICM of 1.24 to this technology through 2018 and 1.19 thereafter. The resultant costs are shown in Table 3-23.

Table 3-23 Costs for Cylinder Deactivation (2009$)

Cost type	Engine type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	V6	$137	$134	$131	$129	$126	$124	$121	$119	$116
DMC	V8	$154	$151	$148	$145	$142	$139	$136	$134	$131
IC	V6	$55	$55	$41	$41	$41	$41	$41	$41	$41

IC	V8	$62	$62	$46	$46	$46	$46	$46	$46	$46
TC	V6	$192	$189	$173	$170	$167	$165	$162	$160	$157
TC	V8	$216	$213	$194	$191	$188	$185	$182	$180	$177

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; all costs are incremental to the baseline.

If lost motion devices are on the engine, the cost of DEAC as applied to SOHC and DOHC engines could be as low as $32 in MY 2017. This $32 accounts for the potential additional application of active engine mounts on SOHC and DOHC engines and can only be applied on 50 percent of the vehicles. Further, this SOHC and DOHC engine estimate is relevant to the CAFE model only because the OMEGA model does not apply technologies in the same incremental fashion as the CAFE model.

3.4.1.4 Variable Valve Timing (VVT)

Variable valve timing (VVT) encompasses a family of valve-train designs that alter the timing of the intake valve, exhaust valve, or both, primarily to reduce pumping losses, increase specific power, and control the level of residual gases in the cylinder. VVT reduces pumping losses when the engine is lightly loaded by controlling valve timing closer to an optimum needed to sustain horsepower and torque. VVT can also improve volumetric efficiency at higher engine speeds and loads. Additionally, VVT can be used to alter (and optimize) the effective compression ratio where it is advantageous for certain engine operating modes (*e.g.*, in the Atkinson Cycle).

VVT has now become a widely adopted technology: in MY 2010, approximately 86 percent of all new cars and light trucks had engines with some method of variable valve timing.[35] Manufacturers are currently using many different types of variable valve timing, which have a variety of different names and methods. Manufacturers are currently using many different types of variable valve timing, which have a variety of different names and methods. Therefore, the degree of further improvement across the fleet is limited by the level of valvetrain technology already implemented on the vehicles. Information found in the 2008 baseline vehicle fleet file is used to determine the degree to which VVT technologies have already been applied to particular vehicles to ensure the proper level of VVT technology, if any, is applied. The three major types of VVT are listed below.

Each of the three implementations of VVT uses a cam phaser to adjust the camshaft angular position relative to the crankshaft position, referred to as “camshaft phasing.” The phase adjustment results in changes to the pumping work required by the engine to accomplish the gas exchange process. The majority of current cam phaser applications use hydraulically-actuated units, powered by engine oil pressure and managed by a solenoid that controls the oil pressure supplied to the phaser.

3.4.1.4.1 Intake Cam Phasing (ICP)

Valvetrains with ICP, which is the simplest of the cam phasing technologies, can modify the timing of the inlet valves by phasing the intake camshaft while the exhaust valve timing remains fixed. This requires the addition of a cam phaser on each bank of intake valves on the engine. An in-line 4-cylinder engine has one bank of intake valves, while V-configured engines have two banks of intake valves.

In the MYs 2012-2016 final rule and TAR, NHTSA and EPA assumed an effectiveness range of 2 to 3 percent for ICP. Based on the 2011 Ricardo study and updated lumped-parameter model the agencies have fined tuned the range to be 2.1 to 2.7 percent.

In the 2012-2016 rule and the 2010 TAR, the agencies estimated the DMC of a cam phaser needed for VVT-intake at $37 (2007$). This DMC becomes $38 (2009$) for this analysis and is considered applicable in the 2015 MY. This cost would be required for each cam shaft controlling intake valves, as such an overhead cam I4 would need one phaser, an overhead cam V6 or V8 would need two phasers, and an overhead valve V6 or V8 would need just one. This technology is considered to be on the flat-portion of the learning curve. The agencies have applied a low complexity ICM of 1.24 to this technology through 2018 and 1.19 thereafter. The resultant costs are shown in Table 3-24.

Table 3-24 Costs for VVT-Intake (2009$)

Cost type	Engine type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	OHC-I4	$36	$36	$35	$34	$34	$33	$32	$32	$31
DMC	OHC-V6/V8	$73	$71	$70	$68	$67	$66	$64	$63	$62
DMC	OHV-V6/V8	$36	$36	$35	$34	$34	$33	$32	$32	$31
IC	OHC-I4	$9	$9	$7	$7	$7	$7	$7	$7	$7
IC	OHC-V6/V8	$18	$18	$15	$15	$15	$15	$15	$15	$15
IC	OHV-V6/V8	$9	$9	$7	$7	$7	$7	$7	$7	$7
TC	OHC-I4	$46	$45	$42	$42	$41	$40	$40	$39	$38
TC	OHC-V6/V8	$91	$90	$84	$83	$82	$80	$79	$78	$76
TC	OHV-V6/V8	$46	$45	$42	$42	$41	$40	$40	$39	$38

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; OHC=overhead cam; OHV=overhead valve; all costs are incremental to the baseline.

3.4.1.4.2 Coupled Cam Phasing (CCP)

Valvetrains with coupled (or coordinated) cam phasing can modify the timing of both the inlet valves and the exhaust valves an equal amount by phasing the camshaft of a single overhead cam (SOHC) engine or an overhead valve (OHV) engine. For overhead cam engines, this requires the addition of a cam phaser on each bank of the engine. Thus, an in-line 4-cylinder engine has one cam phaser, while SOHC V-engines have two cam phasers. For overhead valve (OHV) engines, which have only one camshaft to actuate both inlet and exhaust valves, CCP is the only VVT implementation option available and requires only one cam phaser.[v]

The agencies' MYs 2012-2016 final rule estimated the effectiveness of CCP to be between 1 to 4 percent. Due to the incremental nature and decision tree logic of the Volpe model, NHTSA estimated the effectiveness for coupled cam phasing on a SOHC engine to be 1 to 3 percent and 1 to 1.5 percent for coupled cam phasing on an overhead valve engine.

For this proposal the agencies, taking into account the additional review and the work performed for the 2011 Ricardo study, have revised the estimates for cylinder deactivation. The effectiveness relative to the base engine is 4.1 to 5.5 percent based on the lump parameter model. Because of the incremental nature of the CAFE model, NHTSA used the incremental effectiveness range of 4.14 to 5.36 percent for SOHC applications; an increase over the 2012-16 final rule and 2010 TAR. For OHV applications, CCP was paired with discrete variable valve lift (DVVL) to form a new technology descriptor called variable valve actuation (VVA). VVA will be discussed later in Chapter 3.

The same cam phaser has been assumed for intake cam phasing as for coupled cam phasing, thus CCPs are identical to those presented in Table 3-24.

3.4.1.4.3 Dual Cam Phasing (DCP)

The most flexible VVT design is dual (independent) cam phasing, where the intake and exhaust valve opening and closing events are controlled independently. This allows the option of controlling valve overlap, which can be used as an internal EGR strategy. At low engine loads, DCP creates a reduction in pumping losses, resulting in improved fuel consumption/reduced CO_2 emissions. Increased internal EGR also results in lower engine-out NO_X emissions. The amount by which fuel consumption is improved and CO_2 emissions are reduced depends on the residual tolerance of the combustion system. Additional improvements are observed at idle, where low valve overlap could result in improved combustion stability, potentially reducing idle fuel consumption.

For the 2012-2016 final rule and TAR the EPA and NHTSA assumed an effectiveness range for DCP to be between 3 to 5 percent relative to a base engine or 2 to 3 relative to an engine with ICP. The agencies have updated this range, based on the updated lumped-parameter model to be 4.1 to 5.5 percent relative to a base engine or 2.0 to 2.7 percent relative to an engine with ICP.

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[v] It is also noted that coaxial camshaft developments would allow other VVT options to be applied to OHV engines. However, since they would potentially be adopted on a limited number of OHV engines NHTSA did not include them in the decision tree.

The costs for VVT-dual cam phasing are the same per phaser as described above for VVT-intake. However, for DCP, an additional cam phaser is required for each camshaft controlling exhaust valves. As a result, an overhead cam I4 would need two phasers, an overhead cam V6 or V8 would need four phasers, and an overhead valve V6 or V8 would need two. This technology is considered to be on the flat-portion of the learning curve. The agencies have applied a medium complexity ICM of 1.39 to this technology through 2018 and 1.29 thereafter. The resultant costs are shown in Table 3-25.

Table 3-25 Costs for VVT-Dual Cam Phasing (2009$)

Cost type	Engine type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	OHC-I4	$67	$65	$64	$63	$61	$60	$59	$58	$57
DMC	OHC-V6/V8	$143	$140	$138	$135	$132	$130	$127	$124	$122
DMC	OHV-V6/V8	$73	$71	$70	$68	$67	$66	$64	$63	$62
IC	OHC-I4	$27	$27	$20	$20	$20	$20	$20	$20	$20
IC	OHC-V6/V8	$58	$58	$43	$43	$43	$43	$43	$43	$43
IC	OHV-V6/V8	$29	$29	$22	$22	$22	$22	$22	$22	$22
TC	OHC-I4	$94	$92	$84	$83	$81	$80	$79	$78	$77
TC	OHC-V6/V8	$201	$198	$181	$178	$175	$173	$170	$167	$165
TC	OHV-V6/V8	$102	$101	$92	$90	$89	$87	$86	$85	$84

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; OHC=overhead cam; OHV=overhead valve; all costs are incremental to the baseline.

3.4.1.5 Variable Valve Lift (VVL)

Controlling the lift of the valves provides a potential for further efficiency improvements. By optimizing the valve-lift profile for specific engine operating regions, the pumping losses can be reduced by reducing the amount of throttling required to produce the desired engine power output. By moving the throttling losses further downstream of the throttle valve, the heat transfer losses that occur from the throttling process are directed into the fresh charge-air mixture just prior to compression, delaying the onset of knock-limited combustion processes. Variable valve lift control can also be used to induce in-cylinder mixture motion, which improves fuel-air mixing and can result in improved thermodynamic efficiency. Variable valve lift control can also potentially reduce overall valvetrain friction. At the same time, such systems may also incur increased parasitic losses associated with their actuation mechanisms. A number of manufacturers have already implemented VVL into their fleets (Toyota, Honda, and BMW), but overall this technology is still available for most of the fleet. There are two major classifications of variable valve lift, described below:

3.4.1.5.1 Discrete Variable Valve Lift (DVVL)

Discrete variable valve lift (DVVL) systems allow the selection between two or three discrete cam profiles by means of a hydraulically-actuated mechanical system. By optimizing the cam profile for specific engine operating regions, the pumping losses can be reduced by reducing the amount of throttling required to produce the desired engine power output. This increases the efficiency of the engine. These cam profiles consist of a low and a high-lift lobe, and may include an inert or blank lobe to incorporate cylinder deactivation (in the case of a 3-step DVVL system). DVVL is normally applied together with VVT control. DVVL is also known as Cam Profile Switching (CPS). DVVL is a mature technology with low technical risk.

NHTSA's and EPA's MY 2012-16 final rule, previously-received confidential manufacturer data, and report from NESCCAF, all estimated the effectiveness of DVVL to be between 1 to 4 percent above that realized by VVT systems. Based on the 2011 Ricardo study, NHTSA and EPA have revised the effectiveness range of DVVL systems to 2.8 to 3.9 percent above that realized by VVT systems.

In the 2012-2016 rule and the 2010 TAR, the agencies estimated the DMC of DVVL at $116 (2007$), $169 (2007$) and $241 (2007$) for an I4, V6 and V8 engine, respectively. These DMCs become $120 (2009$), $174 (2009$) and $248 (2009$) for this analysis all of which are considered applicable in the 2015MY. This technology is considered to be on the flat-portion of the learning curve and is applicable only to engines with overhead cam configurations. The agencies have applied a medium complexity ICM of 1.39 to this technology through 2018 and 1.29 thereafter. The resultant costs are shown in Table 3-26.

Table 3-26 Costs for Discrete Variable Valve Lift (2009$)

Cost type	Engine type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	OHC-I4	$114	$112	$109	$107	$105	$103	$101	$99	$97
DMC	OHC-V6	$165	$162	$159	$156	$152	$149	$146	$143	$141
DMC	OHC-V8	$236	$231	$227	$222	$218	$213	$209	$205	$201
IC	OHC-I4	$46	$46	$34	$34	$34	$34	$34	$34	$34
IC	OHC-V6	$67	$67	$50	$50	$50	$50	$50	$49	$49
IC	OHC-V8	$96	$95	$71	$71	$71	$71	$71	$71	$70
TC	OHC-I4	$160	$158	$144	$142	$139	$137	$135	$133	$131
TC	OHC-V6	$232	$229	$209	$205	$202	$199	$196	$193	$190
TC	OHC-V8	$332	$327	$298	$293	$289	$284	$280	$276	$271

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; OHC=overhead cam; OHV=overhead valve; all costs are incremental to the baseline.

3.4.1.5.2 Continuously Variable Valve Lift (CVVL)

In CVVL systems, valve lift is varied by means of a mechanical linkage, driven by an actuator controlled by the engine control unit. The valve opening and phasing vary as the lift is changed and the relation depends on the geometry of the mechanical system. BMW has considerable production experience with CVVL systems and has sold port-injected "Valvetronic" engines since 2001. Fiat is now offering "MultiAir" engines enabling precise control over intake valve lift. CVVL allows the airflow into the engine to be regulated by means of intake valve opening reduction, which improves engine efficiency by reducing pumping losses from throttling the intake system further upstream as with a conventionally throttled engine.

Variable valve lift gives a further reduction in pumping losses compared to that which can be obtained with cam phase control only, with CVVL providing greater effectiveness than DVVL, since it can be fully optimized for all engine speeds and loads, and is not limited to a two or three step compromise. There may also be a small reduction in valvetrain friction when operating at low valve lift, resulting in improved low load fuel consumption for cam phase control with variable valve lift as compared to cam phase control only. Most of the fuel economy effectiveness is achieved with variable valve lift on the intake valves only. CVVL is only applicable to double overhead cam (DOHC) engines.

The 2012-2016 final rule estimated the effectiveness for CVVL at 1.5 to 3.5 percent over an engine with DCP, but also recognize that it could go up as high as 5 percent above and beyond DCP to account for the implementation of more complex CVVL systems such as BMW's "Valvetronic" and Fiat "MultiAir" engines. Thus, the effectiveness range for CVVL in this joint TSD ranges from 1.5 to 7 percent depending on the complexity level of the application. NHTSA and EPA believe this estimate continues to be applicable for this proposal.

For this rulemaking, NHTSA has increased the incremental effectiveness values for this technology to a range of 3.6 to 4.9 percent from 1.5 to 3.5 percent in the MYs 20120-2016 final rule.

In the 2012-2016 rule and the 2010 TAR, the agencies estimated the DMC of CVVL at $174 (2007$), $320 (2007$), $349 (2007$), $866 (2007$) and $947 (2007$) for an OHC-I4, OHC-V6, OHC-V8, OHV-V6 and OHV-V8 engine, respectively. These DMCs become $180 (2009$), $330 (2009$), $360 (2009$), $893 (2009$) and $977 (2009$) for this analysis all of which are considered applicable in the 2015MY. This technology is considered to be on the flat-portion of the learning curve. The agencies have applied a medium complexity ICM of 1.39 to this technology through 2018 and 1.29 thereafter. The resultant costs are shown in Table 3-27.

Table 3-27 Costs for Continuous Variable Valve Lift (2009$)

Cost type	Engine type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	OHC-I4	$171	$168	$164	$161	$158	$155	$151	$148	$145
DMC	OHC-V6	$313	$307	$301	$295	$289	$283	$278	$272	$267
DMC	OHC-V8	$342	$335	$328	$322	$315	$309	$303	$297	$291
DMC	OHV-V6	$849	$832	$815	$799	$783	$767	$752	$737	$722
DMC	OHV-V8	$928	$910	$892	$874	$856	$839	$822	$806	$790
IC	OHC-I4	$69	$69	$52	$52	$51	$51	$51	$51	$51
IC	OHC-V6	$127	$127	$95	$94	$94	$94	$94	$94	$94
IC	OHC-V8	$139	$138	$103	$103	$103	$103	$102	$102	$102
IC	OHV-V6	$344	$343	$256	$256	$255	$255	$254	$254	$253
IC	OHV-V8	$376	$375	$280	$280	$279	$279	$278	$278	$277
TC	OHC-I4	$240	$237	$216	$212	$209	$206	$203	$200	$197
TC	OHC-V6	$440	$434	$396	$389	$383	$377	$372	$366	$360
TC	OHC-V8	$480	$473	$432	$425	$418	$412	$405	$399	$393
TC	OHV-V6	$1,193	$1,175	$1,072	$1,055	$1,038	$1,022	$1,006	$991	$976

TC	OHV-V8	$1,304	$1,285	$1,172	$1,154	$1,136	$1,118	$1,101	$1,084	$1,067

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; OHC=overhead cam; OHV=overhead valve; all costs are incremental to the baseline.

3.4.1.6 Variable Valve Actuation (VVA)

For this proposal, NHTSA has combined two valve control technologies for OHV engines. Coupled cam phasing (CCPO) and discrete valve lift (DVVLO) into one technology defined as variable valve actuation (VVA). The agency estimates the incremental effectiveness for VVA applied to and OHV engine as 2.71 to 3.59 percent. This effectiveness value is slightly lower than coupled cam phasing for overhead cam applications (CCPS) based on the assumption that VVA would be applied to an OHV engine after cylinder deactivation (DEAC). For more information on combining these technologies please refer to the NHTSA specific Preliminary Regulatory Impact Analysis (PRIA).

3.4.1.7 Stoichiometric Gasoline Direct Injection (SGDI)

Stoichiometric gasoline direct injection (SGDI), or Spark Ignition Direct injection (SIDI), engines inject fuel at high pressure directly into the combustion chamber (rather than the intake port in port fuel injection). SGDI requires changes to the injector design, an additional high pressure fuel pump, new fuel rails to handle the higher fuel pressures and changes to the cylinder head and piston crown design. Direct injection of the fuel into the cylinder improves cooling of the air/fuel charge within the cylinder, which allows for higher compression ratios and increased thermodynamic efficiency without the onset of combustion knock. Recent injector design advances, improved electronic engine management systems and the introduction of multiple injection events per cylinder firing cycle promote better mixing of the air and fuel, enhance combustion rates, increase residual exhaust gas tolerance and improve cold start emissions. SGDI engines achieve higher power density and match well with other technologies, such as boosting and variable valvetrain designs.

Several manufacturers are manufacturing vehicles with SGDI engines, including VW/Audi, BMW, Toyota (Lexus IS 350), Ford (Ecoboost), and General Motors (Chevrolet Impala and Cadillac CTS 3.6L). BMW, GM, Ford and VW/Audi have announced their plans to increase dramatically the number of SGDI engines in their portfolios.

NHTSA and EPA reviewed estimates from the 2012-2016 final rule and TAR, which stated an effectiveness range of SGDI to be between 2 and 3 percent. NHTSA and EPA reviewed estimates from the Alliance of Automobile Manufactures, which projects 3 percent gains in fuel efficiency and a 7 percent improvement in torque. The torque increase provides the opportunity to downsize the engine allowing an increase in efficiency of up to a 5.8 percent. NHTSA and EPA also reviewed other published literature, reporting 3 percent effectiveness for SGDI.[36] Confidential manufacturer data reported an efficiency effectiveness range of 1 to 2 percent. Based on data from the recent Ricardo study and reconfiguration of the new lumped parameter model, EPA and NHTSA have revised this value to 1.5 percent[w]. Combined with other technologies (*i.e.*, boosting, downsizing, and in some cases, cooled EGR), SGDI can achieve greater reductions in fuel consumption and CO_2 emissions compared to engines of similar power output.

The NHTSA and EPA cost estimates for SGDI take into account the changes required to the engine hardware, engine electronic controls, ancillary and Noise Vibration and Harshness (NVH) mitigation systems. Through contacts with industry NVH suppliers, and manufacturer press releases, the agencies believe that the NVH treatments will be limited to the mitigation of fuel system noise, specifically from the injectors and the fuel lines and have included corresponding cost estimates for these NVH controls. In the 2012-2016 FRM, the agencies estimated the DMC for SGDI at $213 (2007$), $321 (2007$) and $386 (2007$) for I3/I4, V6 and V8 engines, respectively. These DMCs become $220 (2009$), $331 (2009$) and $398 (2009$) for this analysis all of which are considered applicable in the 2012MY. This technology is considered to be on the flat-portion of the learning curve. The agencies have applied a medium complexity ICM of 1.39 to this technology through 2018 and 1.29 thereafter. The resultant costs are shown in Table 3-28.

Table 3-28 Costs for Stoichiometric Gasoline Direct Injection (2009$)

Cost type	Engine type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	I3/I4	$191	$187	$183	$179	$176	$172	$169	$165	$162
DMC	V6	$287	$281	$276	$270	$265	$260	$254	$249	$244
DMC	V8	$345	$339	$332	$325	$319	$312	$306	$300	$294
IC	I3/I4	$84	$84	$62	$62	$62	$62	$62	$62	$62
IC	V6	$126	$126	$94	$94	$94	$94	$94	$93	$93
IC	V8	$152	$152	$113	$113	$113	$113	$112	$112	$112
TC	I3/I4	$274	$270	$246	$242	$238	$234	$231	$227	$224
TC	V6	$413	$407	$370	$364	$359	$353	$348	$343	$338
TC	V8	$497	$490	$445	$438	$431	$425	$418	$412	$406

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; all costs are incremental to the baseline.

3.4.1.8 Turbocharging and Downsizing (TRBDS)

The specific power of a naturally aspirated engine is primarily limited by the rate at which the engine is able to draw air into the combustion chambers. Turbocharging and supercharging (grouped together here as boosting) are two methods to increase the intake manifold pressure and cylinder charge-air mass above naturally aspirated levels. Boosting increases the airflow into the engine, thus increasing the specific power level, and with it the ability to reduce engine displacement while maintaining performance. This effectively reduces the pumping losses at lighter loads in comparison to a larger, naturally aspirated engine.

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[w] However, because GDI is a key enabler for modern, highly downsized turbocharged engines, this difference will be overshadowed by the higher effectiveness for turbocharging and downsizing when they are combined into packages.

Almost every major manufacturer currently markets a vehicle with some form of boosting. While boosting has been a common practice for increasing performance for several decades, turbocharging has considerable potential to improve fuel economy and reduce CO_2 emissions when the engine displacement is also reduced. Specific power levels for a boosted engine often exceed 100 hp/L, compared to average naturally aspirated engine power densities of roughly 70 hp/L. As a result, engines can be downsized roughly 30 percent or higher while maintaining similar peak output levels. In the last decade, improvements to turbocharger turbine and compressor design have improved their reliability and performance across the entire engine operating range. New variable geometry turbines and ball-bearing center cartridges allow faster turbocharger spool-up (virtually eliminating the once-common “turbo lag”) while maintaining high flow rates for increased boost at high engine speeds. Low speed torque output has been dramatically improved for modern turbocharged engines. However, even with turbocharger improvements, maximum engine torque at very low engine speed conditions, for example launch from standstill, is increased less than at mid and high engine speed conditions. The potential to downsize engines may be less on vehicles with low displacement to vehicle mass ratios for example a very small displacement engine in a vehicle with significant curb weight, in order to provide adequate acceleration from standstill, particularly up grades or at high altitudes.

Use of GDI systems with turbocharged engines and air-to-air charge air cooling also reduces the fuel octane requirements for knock limited combustion and allows the use of higher compression ratios. Ford’s “Ecoboost” downsized, turbocharged GDI engines introduced on MY 2010 vehicles allow the replacement of V8 engines with V6 engines with improved in 0-60 mph acceleration and with fuel economy improvements of up to 12 percent.[37]

Recently published data with advanced spray-guided injection systems and more aggressive engine downsizing targeted towards reduced fuel consumption and CO_2 emissions reductions indicate that the potential for reducing CO_2 emissions for turbocharged, downsized GDI engines may be as much as 15 to 30 percent relative to port-fuel-injected engines.[14,15,16,17,18] Confidential manufacturer data suggests an incremental range of fuel consumption and CO_2 emission reduction of 4.8 to 7.5 percent for turbocharging and downsizing. Other publicly-available sources suggest a fuel consumption and CO_2 emission reduction of 8 to 13 percent compared to current-production naturally-aspirated engines without friction reduction or other fuel economy technologies: a joint technical paper by Bosch and Ricardo suggesting fuel economy gain of 8 to 10 percent for downsizing from a 5.7 liter port injection V8 to a 3.6 liter V6 with direct injection using a wall-guided direct injection system;[38] a Renault report suggesting a 11.9 percent NEDC fuel consumption gain for downsizing from a 1.4 liter port injection in-line 4-cylinder engine to a 1.0 liter in-line 4-cylinder engine, also with wall-guided direct injection;[39] and a Robert Bosch paper suggesting a 13 percent NEDC gain for downsizing to a turbocharged DI engine, again with wall-guided injection.[40] These reported fuel economy benefits show a wide range depending on the SGDI technology employed.

NHTSA and EPA reviewed estimates from the 2012-2016 final rule, the TAR, and existing public literature. The previous estimate from the MYs 2012-2016 suggested a 12 to 14 percent effectiveness improvement, which included low friction lubricant (level one), engine friction reduction (level one), DCP, DVVL and SGDI, over baseline fixed-valve engines, similar to the estimate for Ford’s Ecoboost engine, which is already in production. Additionally, the agencies analyzed Ricardo vehicle simulation data for various turbocharged engine packages. Based on this data, and considering the widespread nature of the public estimates, the effectiveness of turbocharging and downsizing is highly dependent upon implementation and degree of downsizing.

In alignment with these variances, for this proposal the agencies evaluated 4 different levels of downsized and turbocharged high Brake Mean Effective Pressure (BMEP)[x]. engines; 18-bar, 24-bar, 24-bar with cooled exhaust gas recirculation (EGR) and 27-bar with cooled EGR All engines are assumed to include gasoline direct injection (SGDI) and effectiveness values include the benefits of this technology. In addition, the agencies believe to implement in production a 27 bar boost level, it is necessary to incorporate cooled exhaust gas recirculation (EGR) and also require a 2-stage turbocharger as well as engine changes to increase robustness. The cooled EGR technology is discussed later in this section.

NHTSA and EPA have revised the effectiveness to reflect this new information and assume that turbocharging and downsizing, alone, will provide a 12 to 24.6 percent effectiveness improvement (dependent upon degree of downsizing and boost levels) over naturally aspirated, fixed-valve engines. More specifically, 12.1 to 14.9 percent for 18-bar engines, which is equal to the boost levels evaluated in the MYs 2012-2016 final rule, assuming 33 percent downsizing, 16.4 to 20.1 percent for 24-bar engines, assuming 50 percent downsizing, 19.3 to 23.0 percent for 24-bar engines with cooled EGR, assuming 50 percent downsizing and 20.6 to 24.6 percent for 27-bar engines with cooled EGR, assuming 56 percent downsizing. For comparison purposes an 18-bar engine with low friction lubricant (level one), engine friction reduction (level one), DCP, DVVL and SGDI, which is equivalent to MYs 2012-2016 assumed turbocharging and downsizing technology, now results in a 16.8 to 20.9 percent effectiveness improvement. Coupling turbocharging and downsizing with low friction lubricant (level one and two), engine friction reductions (level one and two), DCP, DVVL and SGDI, for the MYs 2017-2025 timeframe, yields 18.0 to 22.4 percent for 18-bar engines 20.4 to 25.2 percent for 24-bar engines, 23.2 to 27.9 percent for 24-bar engine with cooled EGR and 24.0 to 28.8 percent for 27-bar with cooled EGR over naturally aspirated, fixed-valve engines.

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[x] Brake Mean Effective Pressure is the average amount of pressure in pounds per square inch (psi) that must be exerted on the piston to create the measured horsepower. This indicates how effective an engine is at filling the combustion chamber with an air/fuel mixture, compressing it and achieving the most power from it. A higher BMEP value contributes to higher overall efficiency.

As noted above, the agencies relied on engine teardown analyses conducted by EPA, FEV and Munro to develop costs for turbocharged GDI engines.[41] In the 2012-2016 FRM, the agencies estimated the DMC for turbocharging to 18 bar BMEP at $404 (2007$) and $681 (2007$) for I4 and V6/V8 engines, respectively, where the higher cost for the V-configuration engines represents twin turbochargers versus the single turbocharger in the I-configuration engine. These DMCs become $417 (2009$) and $702 (2009$), respectively, for this analysis. In the 2010 TAR, the agencies presented costs for 24 bar BMEP turbocharging at 1.5x the cost of the 18 bar BMEP technology. This additional cost covered the incremental cost increase of a variable geometry turbocharger (see 2010 TAR at page B-12). Thus, the DMC for 24 bar BMEP would be $625 (2009$) and $1,053 (2009$) for I-configuration and V-configuration engines, respectively. Note also for this proposal, the agencies are estimating the DMC of the 27 bar BMEP technology at 2.5x the 18 bar BMEP technology, or $1,042 (2009$) and $1,756 (2009$) for I-configuration and V-configuration engines, respectively. All of these turbocharger-related DMCs are considered applicable in the 2012MY. The agencies consider each turbocharger technology to be on the flat portion of the learning curve and have applied a medium complexity ICM of 1.39 through 2018 for 18 bar and through 2024 for 24 and 27 bar, then 1.29 to each thereafter. The resultant costs are shown in Table 3-29.

Table 3-29 Costs for Turbocharging (2009$)

Cost type	Technology (BMEP)	Engine type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	18 bar	I-engine	$361	$354	$347	$340	$333	$327	$320	$314	$308
DMC	18 bar	V-engine	$609	$597	$585	$573	$562	$551	$540	$529	$518
DMC	24 bar	I-engine	$542	$531	$521	$510	$500	$490	$480	$471	$461
DMC	24 bar	V-engine	$914	$896	$878	$860	$843	$826	$810	$793	$778
DMC	27 bar	I-engine	$904	$886	$868	$850	$833	$817	$800	$784	$769
DMC	27 bar	V-engine	$1,523	$1,493	$1,463	$1,434	$1,405	$1,377	$1,349	$1,322	$1,296
IC	18 bar	I-engine	$159	$159	$119	$118	$118	$118	$118	$117	$117
IC	18 bar	V-engine	$268	$267	$200	$199	$199	$199	$198	$198	$198
IC	24 bar	I-engine	$238	$238	$237	$237	$236	$236	$236	$235	$176
IC	24 bar	V-engine	$402	$401	$400	$399	$399	$398	$397	$396	$297
IC	27 bar	I-engine	$397	$396	$396	$395	$394	$393	$393	$392	$293
IC	27 bar	V-engine	$669	$668	$667	$665	$664	$663	$662	$661	$494
TC	18 bar	I-engine	$520	$513	$466	$459	$451	$445	$438	$431	$425
TC	18 bar	V-engine	$877	$864	$785	$773	$761	$749	$738	$727	$716
TC	24 bar	I-engine	$780	$769	$758	$747	$736	$726	$716	$706	$637
TC	24 bar	V-engine	$1,316	$1,296	$1,278	$1,259	$1,241	$1,224	$1,207	$1,190	$1,074
TC	27 bar	I-engine	$1,301	$1,282	$1,263	$1,245	$1,227	$1,210	$1,193	$1,176	$1,062
TC	27 bar	V-engine	$2,193	$2,161	$2,130	$2,099	$2,069	$2,040	$2,011	$1,983	$1,790

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; all costs are incremental to the baseline.

The costs for the downsizing portion of the turbo/downsize technology is more complex. The agencies have described those cost and how they were developed—based primarily on FEV teardowns but some were scaled based on teardowns to generate costs for downsizing situations that were not covered by teardowns—in both the 2012-2016 FRM and the 2010 TAR. The DMCs used for this analysis are identical to those used in the 2010 TAR except that they have been updated to 2009 dollars. Notable is the fact that many of the downsizing costs are negative because they result in fewer parts and less material than the engine from which they are “derived.” For example a V8 engine could be replaced by a turbocharged V6 engine having two fewer cylinders and as many as eight fewer valves (in the case of a V8 DOHC downsized to a V6 DOHC). Importantly, the agencies have used an approach to calculating indirect costs that results in positive indirect costs regardless of whether the DMC is positive or negative. This is done by calculating indirect costs based on the absolute value of the DMC, then adding the indirect cost to the DMC to arrive at the total cost. This way, the agencies are never making a negative DMC "more negative" when accounting for the indirect costs. This approach has been used in the 2012-2016 final rule and the 2010 TAR. Given the history of the downsizing costs used by the agencies, many are considered applicable in the 2012MY and many in the 2017MY.[y] All are considered to be on the flat portion of the learning curve. The agencies have applied a medium complexity ICM of 1.39 through 2018 and 1.29 thereafter. The resultant costs are shown in Table 3-30.

Table 3-30 Costs for Engine Downsizing (2009$)

Cost type	Technology	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	I4 DOHC to I3	-$171	-$168	-$164	-$161	-$158	-$155	-$152	-$149	-$146
DMC	I4 DOHC to I4	-$75	-$74	-$72	-$71	-$69	-$68	-$67	-$65	-$64
DMC	V6 DOHC to I4	-$485	-$475	-$466	-$457	-$447	-$438	-$430	-$421	-$413
DMC	V6 SOHC 2V to I4	-$339	-$332	-$325	-$319	-$313	-$306	-$300	-$294	-$288
DMC	V6 OHV to I4	$276	$268	$260	$252	$244	$237	$232	$227	$223
DMC	V8 DOHC to I4	-$839	-$814	-$789	-$766	-$743	-$720	-$706	-$692	-$678
DMC	V8 DOHC to V6	-$243	-$238	-$233	-$228	-$224	-$219	-$215	-$211	-$207
DMC	V8 SOHC 2V to I4	-$645	-$625	-$607	-$588	-$571	-$554	-$543	-$532	-$521
DMC	V8 SOHC 3V to I4	-$718	-$696	-$675	-$655	-$635	-$616	-$604	-$592	-$580
DMC	V8 SOHC 2V to V6	-$74	-$73	-$71	-$70	-$68	-$67	-$66	-$64	-$63
DMC	V8 SOHC 3V to V6	-$138	-$135	-$132	-$130	-$127	-$124	-$122	-$119	-$117
DMC	V8 OHV to I4	-$237	-$230	-$223	-$217	-$210	-$204	-$200	-$196	-$192
DMC	V8 OHV to V6	$322	$312	$303	$294	$285	$276	$271	$265	$260
IC	I4 DOHC to I3	$75	$75	$56	$56	$56	$56	$56	$56	$56
IC	I4 DOHC to I4	$33	$33	$25	$25	$25	$25	$25	$24	$24
IC	V6 DOHC to I4	$213	$213	$159	$159	$158	$158	$158	$158	$157
IC	V6 SOHC 2V to I4	$149	$149	$111	$111	$111	$111	$110	$110	$110
IC	V6 OHV to I4	$107	$106	$79	$79	$79	$79	$79	$78	$78
IC	V8 DOHC to I4	$325	$324	$241	$241	$240	$239	$239	$238	$238
IC	V8 DOHC to V6	$107	$106	$80	$79	$79	$79	$79	$79	$79
IC	V8 SOHC 2V to I4	$250	$249	$186	$185	$184	$184	$184	$183	$183
IC	V8 SOHC 3V to I4	$278	$277	$207	$206	$205	$205	$204	$204	$204
IC	V8 SOHC 2V to V6	$33	$33	$24	$24	$24	$24	$24	$24	$24
IC	V8 SOHC 3V to V6	$60	$60	$45	$45	$45	$45	$45	$45	$45
IC	V8 OHV to I4	$92	$92	$68	$68	$68	$68	$68	$67	$67
IC	V8 OHV to V6	$125	$124	$93	$92	$92	$92	$92	$91	$91
TC	I4 DOHC to I3	-$96	-$93	-$108	-$105	-$102	-$99	-$96	-$93	-$90

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[y] The engine downsize costs based on actual FEV teardowns were considered applicable to the 2012MY, as was explained for some downsize costs in the 2012-2016 final rule and others in the 2010 TAR. For other downsize costs—the two changes from OHV engines to DOHC engines—the agencies did not use FEV teardowns or extrapolations from FEV teardowns, and instead used the methodology employed in the 2008 EPA Staff Report, a methodology determined by both agencies to result in cost estimates more appropriate for the 2017MY. The new downsize costs—those for V8 engines downsized to I4 engines—use a combination of V8 to V6 then V6 to I4 downsize costs and are considered applicable to the 2017MY within the context of this analysis.

TC	I4 DOHC to I4	-$42	-$41	-$48	-$46	-$45	-$43	-$42	-$41	-$40
TC	V6 DOHC to I4	-$272	-$263	-$307	-$298	-$289	-$280	-$272	-$263	-$255
TC	V6 SOHC 2V to I4	-$190	-$183	-$214	-$208	-$202	-$196	-$190	-$184	-$178
TC	V6 OHV to I4	$383	$374	$339	$331	$323	$316	$311	$306	$301
TC	V8 DOHC to I4	-$514	-$490	-$548	-$525	-$503	-$481	-$467	-$453	-$440
TC	V8 DOHC to V6	-$136	-$131	-$154	-$149	-$145	-$140	-$136	-$132	-$128
TC	V8 SOHC 2V to I4	-$395	-$377	-$421	-$403	-$386	-$370	-$359	-$348	-$338
TC	V8 SOHC 3V to I4	-$440	-$419	-$469	-$449	-$430	-$412	-$400	-$388	-$376
TC	V8 SOHC 2V to V6	-$42	-$40	-$47	-$46	-$44	-$43	-$42	-$40	-$39
TC	V8 SOHC 3V to V6	-$77	-$75	-$87	-$84	-$82	-$80	-$77	-$75	-$72
TC	V8 OHV to I4	-$145	-$139	-$155	-$148	-$142	-$136	-$132	-$128	-$124
TC	V8 OHV to V6	$446	$436	$395	$386	$377	$368	$362	$357	$351

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; all costs are incremental to the baseline; all resultant engines are DOHC.

Note that the V8 to I4 engine downsize is new for this proposal. This level of engine downsizing is considered for this analysis only if it also includes 27 bar BMEP turbo boost which, in addition, requires the addition of cooled EGR (discussed below). As a result, any 27 bar BMEP engine in this analysis will be I4 configuration and will include cooled EGR.

With the information shown in Table 3-29 and Table 3-30, the costs for any turbo/downsize change can be determined. These costs are shown in Table 3-31.

Table 3-31 Total Costs for Turbo/Downsizing (2009$)

Downsize Technology	Turbo Technology (BMEP)	2017	2018	2019	2020	2021	2022	2023	2024	2025
I4 DOHC to I3	18 bar	$424	$420	$357	$353	$350	$346	$342	$338	$335
I4 DOHC to I3	24 bar	$685	$677	$650	$642	$635	$627	$620	$613	$547
I4 DOHC to I3	27 bar	$1,205	$1,189	$1,155	$1,140	$1,126	$1,111	$1,097	$1,083	$972
I4 DOHC to I4	18 bar	$478	$472	$418	$412	$407	$401	$396	$390	$385
I4 DOHC to I4	24 bar	$738	$728	$710	$701	$692	$683	$674	$665	$598
I4 DOHC to I4	27 bar	$1,259	$1,241	$1,216	$1,199	$1,183	$1,167	$1,151	$1,135	$1,022
V6 DOHC to I4	18 bar	$248	$250	$159	$161	$163	$164	$166	$168	$170
V6 DOHC to I4	24 bar	$509	$507	$451	$449	$448	$446	$444	$442	$382
V6 DOHC to I4	27 bar	$1,029	$1,019	$957	$948	$939	$930	$921	$913	$807
V6 SOHC 2V to I4	18 bar	$330	$329	$251	$250	$250	$249	$248	$247	$246
V6 SOHC 2V to I4	24 bar	$591	$586	$544	$539	$535	$530	$526	$522	$459
V6 SOHC 2V to I4	27 bar	$1,111	$1,098	$1,049	$1,037	$1,026	$1,014	$1,003	$992	$884
V6 OHV to I4	18 bar	$903	$887	$805	$789	$775	$760	$749	$737	$726
V6 OHV to I4	24 bar	$1,163	$1,143	$1,097	$1,078	$1,060	$1,042	$1,026	$1,012	$938
V6 OHV to I4	27 bar	$1,683	$1,656	$1,602	$1,576	$1,551	$1,526	$1,504	$1,482	$1,363
V8 DOHC to I4	18 bar	$6	$23	-$82	-$66	-$51	-$36	-$29	-$22	-$15
V8 DOHC to I4	24 bar	$266	$279	$210	$222	$234	$245	$249	$252	$197
V8 DOHC to I4	27 bar	$787	$792	$716	$720	$725	$729	$726	$723	$622
V8 DOHC to V6	18 bar	$741	$733	$631	$624	$616	$609	$602	$595	$588
V8 DOHC to V6	24 bar	$1,180	$1,165	$1,124	$1,110	$1,097	$1,084	$1,071	$1,058	$946
V8 DOHC to V6	27 bar	$2,057	$2,029	$1,976	$1,950	$1,925	$1,900	$1,875	$1,851	$1,662
V8 SOHC 2V to I4	18 bar	$125	$136	$45	$55	$65	$75	$79	$83	$87
V8 SOHC 2V to	24 bar	$385	$393	$337	$344	$350	$356	$357	$357	$299

I4										
V8 SOHC 2V to I4	27 bar	$906	$905	$842	$842	$841	$840	$834	$828	$724
V8 SOHC 3V to I4	18 bar	$81	$94	-$3	$9	$21	$33	$38	$43	$48
V8 SOHC 3V to I4	24 bar	$341	$350	$289	$298	$306	$314	$316	$318	$261
V8 SOHC 3V to I4	27 bar	$861	$863	$795	$796	$797	$799	$793	$788	$686
V8 SOHC 2V to V6	18 bar	$835	$824	$738	$727	$717	$707	$697	$687	$677
V8 SOHC 2V to V6	24 bar	$1,274	$1,256	$1,231	$1,214	$1,197	$1,181	$1,165	$1,149	$1,035
V8 SOHC 2V to V6	27 bar	$2,151	$2,121	$2,083	$2,053	$2,025	$1,997	$1,969	$1,943	$1,751
V8 SOHC 3V to V6	18 bar	$800	$790	$698	$688	$679	$670	$661	$652	$644
V8 SOHC 3V to V6	24 bar	$1,238	$1,222	$1,191	$1,175	$1,160	$1,144	$1,130	$1,115	$1,002
V8 SOHC 3V to V6	27 bar	$2,116	$2,086	$2,043	$2,015	$1,987	$1,960	$1,934	$1,908	$1,718
V8 OHV to I4	18 bar	$375	$374	$311	$310	$309	$309	$306	$303	$300
V8 OHV to I4	24 bar	$635	$631	$603	$599	$594	$590	$584	$578	$513
V8 OHV to I4	27 bar	$1,155	$1,143	$1,108	$1,097	$1,085	$1,074	$1,061	$1,048	$938
V8 OHV to V6	18 bar	$1,323	$1,301	$1,180	$1,159	$1,138	$1,118	$1,101	$1,084	$1,067
V8 OHV to V6	24 bar	$1,762	$1,733	$1,673	$1,646	$1,618	$1,592	$1,569	$1,547	$1,426
V8 OHV to V6	27 bar	$2,639	$2,597	$2,525	$2,485	$2,446	$2,408	$2,373	$2,340	$2,142

All costs are total costs (Direct manufacturing costs + Indirect costs); all costs are incremental to the baseline; all resultant engines are DOHC; note that costs are shown for 27 bar BMEP engines with V6 engines. In fact, the agencies do not believe that manufacturers will employ 27 bar BMEP technology on V6 engines to comply with the proposed standards, instead using the additional boost to allow for downsizing V6 engines to smaller I4 engines than would be used for 18 bar BMEP or 24 bar BMEP I4 engines and/or downsizing V8 engines to I4 engines. As a result, whenever a 27 bar BMEP engine is chosen by either agency's model, the engine configuration will be an I4 and will include cooled EGR, as discussed in section 3.4.1.8.

3.4.1.9 Cooled Exhaust-Gas Recirculation (EGR)

While not considered in the technology packages used for assessing potential compliance pathways in the 2012-2016 light-duty rule, the agencies have considered an emerging technology referred to as cooled exhaust gas recirculation (cooled-EGR) as applied to downsized, turbocharged GDI engines. In the 2010 TAR, the agencies considered this technology as an advanced gasoline technology since it was considered an emerging and not yet available technology in the light-duty gasoline market. While a cooled or "boosted" EGR technology was discussed in the 2012-2016 light-duty rule record, the technology considered here is comparatively more advanced as described in the 2010 TAR. As such, the agencies have considered new costs and new effectiveness values for it. The effectiveness values used for vehicle packages with cooled EGR within this analysis reflect a conservative estimate of system performance at approximately 24-bar BMEP. Vehicle simulation modeling of technology packages using the more highly boosted and downsized cooled EGR engines (up to 27-bar BMEP, and utilizing EGR rates of 20-25%) with dual-stage turbocharging has been completed as part of EPA's contract with Ricardo Engineering as described in 3.3.1.2. For this NPRM, the agencies have updated the effectiveness of vehicle packages with cooled EGR using the new Ricardo vehicle simulation modeling runs.

Cooled exhaust gas recirculation or Boosted EGR is a combustion concept that involves utilizing EGR as a charge diluent for controlling combustion temperatures and cooling the EGR prior to its introduction to the combustion system. Higher exhaust gas residual levels at part load conditions reduce pumping losses for increased fuel economy. The additional charge dilution enabled by cooled EGR reduces the incidence of knocking combustion and obviates the need for fuel enrichment at high engine power. This allows for higher boost pressure and/or compression ratio and further reduction in engine displacement and both pumping and friction losses while maintaining performance. Engines of this type use GDI and both dual cam phasing and discrete variable valve lift. The EGR systems considered in this proposal would use a dual-loop system with both high and low pressure EGR loops and dual EGR coolers. The engines would also use single-stage, variable geometry turbocharging with higher intake boost pressure available across a broader range of engine operation than conventional turbocharged SI engines. Such a system is estimated to be capable of an additional 3 to 5 percent effectiveness relative to a turbocharged, downsized GDI engine without cooled-EGR.[42,43] The agencies have also considered a more advanced version of such a cooled EGR system that employs very high combustion pressures by using dual stage turbocharging. This modeling work has been completed by Ricardo Engineering. The simulation modeling is similar to work that Ricardo conducted for EPA for its 2008 staff report on GHG effectiveness of light-duty vehicle technologies.[44] The agencies have considered this more advanced cooled EGR approach for this proposal.

For the MYs 2012-2016 final rule and TAR, NHTSA and EPA assumed a 5 percent fuel consumption effectiveness for cooled EGR compared to a conventional downsized DI turbocharged engine.[45] [46] Based on the data from the Ricardo and Lotus reports, NHTSA and EPA estimate the incremental reduction in fuel consumption for EGR Boost to be 5 percent over a turbocharged and downsized DI engine. Thus, if cooled EGR is applied to 24-bar engine, adding the 19.3 percent from the turbocharging and downsizing to the 5 percent gain from cooled EGR results in total fuel consumption reduction of 22.1 percent. This is in agreement with the range suggested in the Lotus and Ricardo reports.

In the 2010 TAR, the agencies estimated the DMC of the cooled EGR system at $240 (2007$, see 2010 TAR at page B-12)). This DMC becomes $242 (2009$) for this analysis. This DMC is considered applicable in the 2012MY. The agencies consider cooled EGR technology to be on the flat portion of the learning curve and have applied a medium complexity ICM of 1.39 through 2024 then 1.29 thereafter. The resultant costs are shown in Table 3-32.

Table 3-32 Costs for Cooled EGR (2009$)

Cost	Engine type	2017	2018	2019	2020	2021	2022	2023	2024	2025

type										
DMC	All	$210	$206	$202	$198	$194	$190	$186	$182	$179
IC	All	$92	$92	$92	$92	$92	$91	$91	$91	$68
TC	All	$303	$298	$294	$290	$285	$281	$277	$274	$247

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; all costs are incremental to the baseline.

Note that, in the 2010 TAR, the agencies presented the cooled EGR system costs inclusive of turbo charging costs (see 2010 TAR, Table B2.2-1 at page B-12). For this analysis, the agencies are presenting the cooled EGR costs as a stand-alone technology that can be added to any turbo/downsized engine provided sufficient boost is provided and sufficient engine robustness is accounted for. As such, the cooled EGR system is considered applicable only the 24 bar BMEP and 27 bar BMEP engines. Further, the agencies believe that 24 bar BMEP engines are capable of maintaining NOx control without cooled EGR, so each agency’s respective models may choose 24 bar BMEP engines with and/or without cooled EGR. However, as noted above, 27 bar BMEP engines are considered to require cooled EGR to maintain NOx emission control. As such, neither agency’s model is allowed to choose 27 bar BMEP technology without also adding cooled EGR.

3.4.1.10 Diesel Engine Technology (DSL)

Diesel engines have several characteristics that give them superior fuel efficiency compared to conventional gasoline, spark-ignited engines. Pumping losses are much lower due to lack of (or greatly reduced) throttling in a diesel engine. The diesel combustion cycle operates at a higher compression ratio than does a gasoline engine. As a result, turbocharged light-duty diesels typically achieve much higher torque levels at lower engine speeds than equivalent-displacement naturally-aspirated gasoline engines. Future high BMEP turbocharged and downsized engines, mentioned above, are projected to improve torque levels at lower engine speeds thus reducing the diesel advantage in this area. Diesels also operate with a very lean air/fuel mixture. These attributes – reduced pumping losses, higher compression ratio and lean/air fuel mixture -- allow the engine to extract more energy from a given mass of fuel than a gasoline engine, and thus make it more efficient. Additionally, diesel fuel has higher energy content per gallon than does gasoline. While diesel fuel has a higher energy content than gasoline, it also contains more carbon per gallon than does gasoline: diesel produces 22.2 pounds of CO_2 per gallon when burned, while gasoline produces 19.4 pounds of CO_2 per gallon. This higher carbon content slightly offsets the GHG emissions benefit of diesel fuel relative to gasoline, however, the disbenefit is more than compensated by the greater efficiency of the diesel engine. Since diesel engines are more fuel efficient than current naturally aspirated PFI gasoline engines, the agencies anticipate that manufacturers will evaluate and potentially invest in diesel engine production as a way to comply with more stringent CAFE standards. However, there are two primary reasons why manufacturers might not choose to invest significantly in diesel engine technologies as a way to comply with the CAFE and GHG standards for MYs 2017-2025.

As discussed above, even though diesel has higher energy content than gasoline it also has a higher carbon density that results in higher amounts of CO_2 emitted per gallon, approximately 15 percent more than a gallon of gasoline. This is commonly referred to as the "carbon penalty" associated with using diesel fuel – a diesel vehicle yields greater fuel economy improvements compared to its CO_2 emissions reduction improvements, so a manufacturer that invests in diesel technology to meet CAFE standards may have more trouble meeting the GHG standards than if it used a different and more cost effective (from a GHG perspective) technology.

And second, diesel engines also have emissions characteristics that present challenges to meeting federal Tier 2 NOx emissions standards. By way of comparison for readers familiar with the European on-road fleet, which contains many more diesel vehicles than the U.S. on-road fleet, U.S. Tier 2 emissions fleet average requirement of bin 5 require roughly 45 to 65 percent more NO_x reduction compared to the Euro VI standards.

Despite considerable advances by manufacturers in developing Tier 2-compliant diesel engines, it remains somewhat of a systems-engineering challenge to maintain the full fuel consumption advantage of the diesel engine while meeting Tier 2 emissions regulations because some of the emissions reduction strategies can *increase* fuel consumption (relative to a Tier 1 compliant diesel engine), depending on the combination of strategies employed. A combination of combustion improvements (that reduce NO_X emissions leaving the engine) and aftertreatment (capturing and reducing NO_X emissions via a NOx adsorption catalyst, or via selective catalytic reduction (SCR) using a reductant such as urea) that have left the engine before they leave the vehicle tailpipe) are being introduced on Tier 2 compliant light-duty diesel vehicles today. However, recently there have been a small number of announcements that diesel engines will be added to some passenger cars, in some cases a segment first for a manufacturer[47], or that new passenger car diesel engines are being designed to meet all global emissions regulations.[48] This suggests to the agencies that some manufacturers may be planning to use diesel engines in their plans to meet the tighter CAFE standards in the mid-term, which may be enabled by advances in diesel engine and emission control technology. Manufacturers that focus on diesel engines have also stated to the agencies their expectation that diesel engines will continue to be a viable technology for improving fuel economy and GHG emissions in the future.

We spend time here discussing available emissions reduction technologies for diesel engines as part of this rulemaking because of the potential they have to impact fuel economy and GHG emissions for the vehicles that have them. With respect to combustion improvements, we note that several key advances in diesel engine combustion technology have made it possible to reduce emissions coming from the engine prior to aftertreatment, which reduces the need for aftertreatment. These technologies include improved fuel systems (higher injection pressure and multiple-injection capability), advanced controls and sensors to optimize combustion and emissions performance, higher EGR levels and EGR cooling to reduce NO_x, and advanced turbocharging systems. These systems are available today and they do not adversely impact fuel efficiency. However, additional improvements in these technologies will be needed to reduce engine emissions further, should future emissions standards become more stringent. Further development may also be needed to reduce the fuel efficiency penalty associated with EGR.

With respect to catalytic exhaust emission control systems, typical 3-way exhaust catalysts without NOx storage capability are not able to reduce NOx emissions from engines operated lean of stoichiometry (diesel or lean-burn gasoline)=. To reduce NOx, hydrocarbons, and particulate emissions, all diesels will require a catalyzed diesel particulate filter (CDPF) and sometimes a separate diesel oxidation catalyst (DOC), and either a lean NOx trap (LNT) [z] or the use of a selective catalytic reduction system, typically base-metal zeolite urea-SCR[aa].

The increased cost of diesel emissions control technologies relative to powertrains with stoichiometric gasoline engines that are approaching comparable efficiency may also make diesels less attractive to manufacturers as a technology solution for more stringent CAFE and GHG standards. However, recognizing that some manufacturers may still employ diesel technology to meet the future standards, the agencies have included diesels in our analysis as follows:

The agencies sought to ensure that diesel engines would have equivalent performance to comparable gasoline engine vehicles. For the Subcompact, Compact, and Midsize Passenger Car, Performance Subcompact Car, and Small Light Truck vehicle subclasses, the agencies assumed that an I4 gasoline base engine would be replaced by an in-line 4-cylinder diesel engine with displacement varying around 2.0 liters. For the Performance Compact, Performance Midsize, Large Passenger Car, Minivan, and Midsize Truck vehicle subclasses for the CAFE model, the agencies assumed that a V6 gasoline base engine would be replaced by an in-line 4-cylinder diesel engine with displacement varying around 2.8 liters. For the Large Truck and Performance Large Car vehicle subclasses for the CAFE model, the agencies assumed that a V8 gasoline base engine would be replaced with a V6 diesel engine with

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[z] A lean NO_x trap operates= by oxidizing NO to NO_2 in the exhaust and storing NO_2 on alkali sorbent material, most often BaO. When the control system determines (via mathematical model and typicalla NO_x sensor) that the trap is saturated with NO_x, it switches the engine into a operating mode just rich of stoichiometry that allow NOx to be released from the alkali storage and temporarily allow three-way function of the catalyst similar to three-way catalysts used in stoichiometric gasoline applications. LNTs preferentially store sulfate compounds from the fuel, whichreduces NOx storage capacity over time, thus the system must undergo periodic desulfurization by operating at a net-fuel-rich condition at high temperatures in order to retain NO_x trapping efficiency.

[aa] An SCR aftertreatment system uses a reductant (typically, ammonia derived from urea) that is injected into the exhaust stream ahead of the SCR catalyst. Ammonia is a strong reductant even under net lean conditions. It combines with NO_x in the SCR catalyst to form N_2 and water. The hardware configuration for an SCR system is sometimes more complicated than that of an LNT, due to the onboard urea storage and delivery system (which requires a urea pump and injector to inject urea into the exhaust stream), which generally makes an SCR system cost more than an LNT system. While a rich engine-operating mode is not required for NO_x reduction, the urea is typically injected at a rate of approximately 3 percent of the fuel consumed. The agencies understand that manufacturers designing SCR systems intend to align urea tank refills with standard maintenance practices such as oil changes as more diesel vehicles are introduced into the market. For diesel vehicles currently on the market, this is generally already the practice, and represents an ongoing maintenance cost for vehicles with this technology.

displacement varying around 4.0 liters to meet vehicle performance requirements. It was also assumed that diesel engines for all of these classes would utilize SCR aftertreatment systems given recent improvements in zeolite-based SCR systems and system efficiency. These assumptions impacted our estimates of the costs of implementing diesel engines as compared to the base gasoline engines.

Diesel engines are more costly than port-injected spark-ignition gasoline engines. These higher costs result from more costly components, more complex systems for emissions control, and other factors. The vehicle systems that are impacted include:

- Fuel systems (higher pressures and more responsive injectors);
- Controls and sensors to optimize combustion and emissions performance;
- Engine design (higher cylinder pressures require a more robust engine, but higher torque output means diesel engines can have reduced displacement);
- Turbocharger(s);
- Aftertreatment systems, which tend to be more costly for diesels;

In the MYs 2012-2016 final rule, the agencies estimated the DMC for converting a gasoline PFI engine with 3-way catalyst aftertreatment to a diesel engine with diesel aftertreatment at $1,697 (2007$), $2,399 (2007$), $1,956 (2007$) and $2,676 (2007$) for a small car, large car, medium/large MPV & small truck, and large truck, respectively (see final Joint TSD, Table 3-12 at page 3-44). All of these costs were for SCR-based diesel systems, with the exception of the small car, which was a LNT-based system. For this proposal, we are using the same methodology as used in the MYs 2012-2016 final rule, but have made four primary changes to the cost estimates. First, the agencies have not estimated costs for a LNT-based system, and instead have estimated costs for all vehicle types assuming they will employ SCR-based systems. Second, the agencies assumed that manufacturers would meet a Tier 2 bin 2 average rather than a Tier 2 bin 5 average, assuming that more stringent levels of compliance will be required in the future. In order to estimate costs for Tier 2 bin 2 compliant vehicles, catalyst volume costs were estimated based on an assumed increase in volume of 20 percent. This was the estimated necessary increase needed to meet Tier 2, bin 2 emission level of 0.02 grams of NOx per mile. Increased catalyst volume resulted in a higher cost estimate for diesel aftertreatment than was estimated for the MYs 2012-2016 final rule. The third is to update all platinum group metal costs from the March 2009 values used in the 2012-2016 final rule to February 2011 values.[bb] The February 2011 values were used for

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[bb] As reported by Johnson-Matthey, the March 2009 monthly average costs were $1,085 per Troy ounce and $1,169 per Troy ounce for platinum (Pt) and rhodium (Rh), respectively. As also reported by Johnson-Matthey, the February 2011 monthly average costs were $1,829 per Troy ounce and $2,476 per Troy ounce for Pt and Rh, respectively. See www.platinum.matthey.com.

purposes of this NPRM analysis because they represented the most recent monthly average prices available at the time the agencies "locked-down" all cost estimates for the purposes of moving into the modeling phase of analysis.[cc] The forth is to include an additional $50 DMC for all costs to cover costs associated with improvements to fuel and urea controls. All of the diesel costs are considered applicable to MY 2012. The agencies consider diesel technology to be on the flat portion of the learning curve and have applied a medium complexity ICM of 1.39 through 2018, and then an ICM of 1.29 thereafter. The resultant costs are shown in Table 3-33.

Table 3-33 Costs for Conversion to Advanced Diesel (2009$)

Cost type	Vehicle class	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact/Small car	$2,039	$1,999	$1,959	$1,919	$1,881	$1,843	$1,807	$1,770	$1,735
DMC	Large car	$2,498	$2,448	$2,399	$2,351	$2,304	$2,258	$2,213	$2,168	$2,125
DMC	Minivan	$2,044	$2,003	$1,963	$1,924	$1,885	$1,848	$1,811	$1,774	$1,739
DMC	Small truck	$2,061	$2,020	$1,980	$1,940	$1,901	$1,863	$1,826	$1,790	$1,754
DMC	Large truck	$2,858	$2,800	$2,744	$2,690	$2,636	$2,583	$2,531	$2,481	$2,431
IC	Subcompact/Small car	$896	$895	$669	$668	$666	$665	$664	$663	$662
IC	Large car	$1,098	$1,096	$819	$818	$816	$815	$813	$812	$811
IC	Minivan	$898	$897	$670	$669	$668	$667	$666	$664	$663
IC	Small truck	$906	$904	$676	$675	$674	$672	$671	$670	$669
IC	Large truck	$1,256	$1,253	$937	$935	$934	$932	$931	$929	$927
TC	Subcompact/Small car	$2,936	$2,893	$2,627	$2,587	$2,547	$2,509	$2,471	$2,433	$2,397
TC	Large car	$3,596	$3,544	$3,218	$3,169	$3,120	$3,073	$3,026	$2,980	$2,936
TC	Minivan	$2,942	$2,900	$2,633	$2,593	$2,553	$2,515	$2,477	$2,438	$2,402
TC	Small truck	$2,967	$2,924	$2,656	$2,615	$2,575	$2,535	$2,497	$2,460	$2,423
TC	Large truck	$4,114	$4,053	$3,681	$3,625	$3,570	$3,515	$3,462	$3,410	$3,358

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; all costs are incremental to the baseline.

For the MYs 2012-016 final rule and TAR, NHTSA and EPA estimated the fuel consumption reduction of a SCR-based diesel engine to be between 20 to 25 percent over a baseline gasoline engine. NHTSA and EPA have revisited these values and have now estimated, based on the Ricardo 2011 study, the effectiveness of a SCR-based diesel engine to be 28.4 to 30.5 percent. For purposes of CO_2 reduction, EPA estimates a 7 to 20 percent for light-duty diesels equipped with SCR.

[cc] Note that there is no good way of determining what PGM prices to use when conducting cost analyses. Spot prices are inherently dangerous to use because spot prices, like stock prices on the stock market, can vary considerably from day to day. One could argue that an average price is best, but average prices can vary considerably depending on the length of time included in the average. And if too much time is included in the average, then average prices from a time prior to PGM use in diesel engines may be included which would lead some to conclude that we had cherry picked our values. Given no good option, it seems most transparent and least self serving to simply choose a price and report its basis. In the end, the PGM costs represent 16-23 percent of the diesel DMC in this analysis. Further, diesels play very little to no role in enabling compliance with the proposed standards.

3.4.2 Transmission Technologies

NHTSA and EPA have also reviewed the transmission technology estimates used in the 2012-2016 final rule and the 2010 TAR. In doing so, NHTSA and EPA considered or reconsidered all available sources and updated the estimates as appropriate. The section below describes each of the transmission technologies considered for this rulemaking.

3.4.2.1 Improved Automatic Transmission Control (Aggressive Shift Logic and Early Torque Converter Lockup)

Calibrating the transmission shift schedule to upshift earlier and quicker, and to lock-up or partially lock-up the torque converter under a broader range of operating conditions can reduce fuel consumption and CO_2 emissions. However, this operation can result in a perceptible degradation in noise, vibration, and harshness (NVH). The degree to which NVH can be degraded before it becomes noticeable to the driver is strongly influenced by characteristics of the vehicle, and although it is somewhat subjective, it always places a limit on how much fuel consumption can be improved by transmission control changes. Aggressive Shift Logic and Early Torque Converter Lockup are best optimized simultaneously when added to an automatic transmission due to the fact that adding both of them requires only minor modifications to the transmission mechanical components or calibration software. As a result, these two technologies are combined in the modeling when added to an automatic transmission. Since a dual clutch transmission (DCT) has no torque converter, the early torque converter lockup technology is not included when adding ASL to the DCT.

3.4.2.2 Aggressive Shift Logic

During operation, a transmission’s controller manages the operation of the transmission by scheduling the upshift or downshift, and, in automatic transmissions, locking or allowing the torque converter to slip based on a preprogrammed shift schedule. The shift schedule contains a number of lookup table functions, which define the shift points and torque converter lockup based on vehicle speed and throttle position, and other parameters such as temperature. Aggressive shift logic (ASL) can be employed in such a way as to maximize fuel efficiency by modifying the shift schedule to upshift earlier and inhibit downshifts under some conditions, which reduces engine pumping losses and engine friction. The application of this technology does require a manufacturer to confirm that drivability, durability, and NVH are not significantly degraded.

For this proposal, the agencies are considering two levels of ASL. The first level is that discussed in the 2012-2016 final rule and the 2010 TAR. ASL-level 1 is an early upshift strategy whereby the transmission shifts to the next higher gear “earlier” (or at lower RPM during a gradual acceleration) than would occur in a traditional automatic transmission. This early upshift reduces fuel consumption by allowing the engine to operate at a lower RPM and higher load, which typically moves the engine into a more efficient operating region.

ASL-level 2 is a shift optimization strategy whereby the engine and/or transmission controller(s) continuously evaluate all possible gear options that would provide the necessary tractive power (while limiting the adverse effects on driveline NVH) and select the gear that lets the engine run in the most efficient operating zone. Ricardo acknowledged in its report that the ASL-level 2 ("shift optimization") strategy currently causes significant implications for drivability and hence affects consumer acceptability. However, Ricardo recommended the inclusion of this technology for the 2020-2025 time frame with the assumption that manufacturers will develop a means of yielding the fuel economy benefit without adversely affecting driver acceptability. The agencies believe these drivability challenges could include shift business – that is, a high level of shifting compared to current vehicles as perceived by the customers. The agencies note that in confidential discussions with two major transmission suppliers, the suppliers described transmission advances which reduce shifting time and provide smoother torque transitions than today's designs, making the shifting event less apparent to the driver, however these improvements will not influence the customer's perception of shift business related to the changes in engine speed.

In addition, the agencies note that several auto companies and transmission firms have announced future introduction of transmissions into the U.S. market with even a higher number of gears than were included in the Ricardo simulation and in the agencies' feasibility assessment for this proposal (which is 8 forward speeds). These announcements include both 9 and 10 speed transmissions which may present further challenges with shift business, given the availability of one or two additional gears. At the same time, the associated closer gear spacing will generally result in smaller engine speed changes during shifting that may be less noticeable to the driver.

The agencies are including shift optimization in the analysis under the premise that manufacturers and suppliers are developing means to mitigate these drivability issues by MY 2017, as assumed in the 2011 Ricardo study (more information on Ricardo's treatment of the optimized shift strategy is described in Section 6.4 of the 2011 Ricardo report). If manufacturers are not able to solve these drivability issues, the assumed effectiveness could be lower and the cost could be higher or both. The agencies are seeking comment on the feasibility of ASL-level 2 and the likelihood that manufacturers will be able to overcome the drivability issues.

In MYs 2012-2016 final rule, the agencies estimated an effectiveness improvement of 1 to 2 percent for aggressive shift logic which was supported by the 2002 NAS and NESCCAF reports as well as confidential manufacturer data. The agencies updated the effectiveness of ASL-level 1 ranging from 1.9 to 2.7 based on 2010 Ricardo study. In CAFE model an incremental effectiveness ranging for both ASL and early torque converter lockup ranging from 2.3 to 3.1 percent is applied (Early torque converter has effectiveness of 0.5 percent).

ASL-level 2 is new to this analysis which is based on the shift optimization algorithm in 2011 Ricardo study. The effectiveness for ASL-level 2 ranges from 5.1 to 7.0 percent improvement over transmission with unimproved shift logic or roughly 4 to 5 percent over a transmission that already incorporates aggressive shift logic. In the CAFE model, an incremental effectiveness ranging from 3.27 to 4.31 percent is applied.

In the 2012-2016 rule, the agencies estimated the DMC at $26 (2007$) which was considered applicable to the 2015MY. This DMC becomes $27 (2009$) for this analysis. The agencies consider ASL-level 1 technology to be on the flat portion of the learning curve and have applied a medium complexity ICM of 1.39 through 2018 then 1.29 thereafter. For ASL-level 2, the agencies are estimating the DMC at an equivalent $27 (2009$) except that this cost is considered applicable to the 2017MY. Essentially this yields a nearly negligible incremental cost for ASL-level 2 over ASL-level 1. The agencies consider ASL-level 2 technology to be on the flat portion of the learning curve and have applied a medium complexity ICM of 1.39 through 2024 then 1.29 thereafter. The timing of the ASL-level 2 ICMs is different than that for the level 1 technology because the level 2 technology is newer and not yet being implemented in the fleet. The resultant costs are shown in Table 3-34. Note that both levels of ASL technology are incremental to the baseline system, so ASL-level 2 is not incremental to ASL-level 1.

Table 3-34 Costs for Aggressive Shift Logic Levels 1 & 2 (2009$)

Cost type	Technology	Transmission type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	ASL-level 1	All	$26	$25	$25	$24	$24	$23	$23	$22	$22
DMC	ASL-level 2	All	$27	$26	$25	$25	$24	$23	$23	$22	$22
IC	ASL-level 1	All	$6	$6	$5	$5	$5	$5	$5	$5	$5
IC	ASL-level 2	All	$7	$7	$6	$6	$6	$6	$6	$6	$5
TC	ASL-level 1	All	$32	$32	$30	$29	$29	$28	$28	$27	$27
TC	ASL-level 2	All	$33	$33	$32	$31	$30	$30	$29	$29	$27

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; all costs are incremental to the baseline.

3.4.2.3 Early Torque Converter Lockup

A torque converter is a fluid coupling located between the engine and transmission in vehicles with automatic transmissions and continuously-variable transmissions (CVT). This fluid coupling allows for slip so the engine can run while the vehicle is idling in gear (as at a stop light), provides for smoothness of the powertrain, and also provides for torque multiplication during acceleration, and especially launch. During light acceleration and cruising, the inherent slip in a torque converter causes increased fuel consumption, so modern automatic transmissions utilize a clutch in the torque converter to lock it and prevent this slippage. Fuel consumption can be further reduced by locking up the torque converter at lower vehicle speeds, provided there is sufficient power to propel the vehicle, and noise and vibration are not excessive.[dd] If the torque converter cannot be fully locked up for maximum efficiency, a partial lockup strategy can be employed to reduce slippage. Early torque converter lockup is applicable to all vehicle types with automatic transmissions. Some torque converters will require upgraded clutch materials to withstand additional loading and the slipping conditions during partial lock-up. As with aggressive shift logic, confirmation of acceptable drivability, performance, durability and NVH characteristics is required to successfully implement this technology.

Regarding the effectiveness of Early Torque Converter Lockup, the 2012-2016 final rule, TAR, and the 2010 Ricardo study estimated an effectiveness improvement of 0.4 to 0.5 percent.

In the 2012-2016 rule, the agencies estimated the DMC at $24 (2007$) which was considered applicable to the 2015MY. This DMC remains $24 (2009$) for this analysis.[ee] The agencies consider early torque converter lockup technology to be on the flat portion of the learning curve and have applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter. The resultant costs are shown in Table 3-35.

Table 3-35 Costs for Early Torque Converter Lockup (2009$)

Cost type	Transmission type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Automatic	$23	$23	$22	$22	$21	$21	$21	$20	$20
IC	Automatic	$6	$6	$5	$5	$5	$5	$5	$5	$5
TC	Automatic	$29	$29	$27	$27	$26	$26	$25	$25	$24

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; all costs are incremental to the baseline.

3.4.2.4 High Efficiency Gearbox

For this rule, a high efficiency gearbox refers to some or all of a suite of incremental gearbox improvement technologies that should be available within the 2017 to 2025 timeframe. The majority of these improvements address mechanical friction within the gearbox. These improvements include but are not limited to: shifting clutch technology improvements (especially for smaller vehicle classes), improved kinematic design, dry sump lubrication systems, more efficient seals, bearings and clutches (reducing drag), component superfinishing and improved transmission lubricants. More detailed description can be found in the 2011 Ricardo report[49]. Note that the high efficiency gearbox technology is applicable to any type of transmission.

[dd] Although only modifications to the transmission calibration software are considered as part of this technology, very aggressive early torque converter lock up may require an adjustment to damper stiffness and hysteresis inside the torque converter.

[ee] As is true throughout this presentation of cost estimates, the agencies round costs to the nearest dollar. In the actual model input files, the cost in 2007$ would have been $23.68 and the cost in 2009$ is $24.42. So an impact of the dollar-year conversion is reflected in the analysis even when it does not appear so in this presentation.

EPA analyzed detailed transmission efficiency input data provided by Ricardo and implemented it directly into the lumped parameter model. Based on the LP effectiveness resulting from these inputs, EPA and NHTSA estimate that a high efficiency gearbox can provide a GHG or fuel consumption reduction in the range of 3.8 to 5.7 percent (3.8% for 4WD trucks with an unimproved rear axle) over a baseline automatic transmission in MY2017 and beyond.

The agencies estimate the DMC of the high efficiency gearbox at $200 (2009$). We have based this on the DMC for engine friction reduction in a V8 engine which, as presented in Table 3-22 is $193 (2009$). We have rounded this up to $200 for this analysis. This DMC is considered applicable for the 2017MY. The agencies consider high efficiency gearbox technology to be on the flat portion of the learning curve and have applied a low complexity ICM of 1.24 through 2024 then 1.19 thereafter. The resultant costs are shown in Table 3-36.

Table 3-36 Costs for High Efficiency Gearbox (2009$)

Cost type	Transmission type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Automatic/Dual clutch	$200	$194	$188	$183	$177	$172	$168	$165	$162
IC	Automatic/Dual clutch	$48	$48	$48	$48	$48	$48	$48	$48	$38
TC	Automatic/Dual clutch	$248	$242	$236	$231	$225	$220	$216	$213	$200

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; all costs are incremental to the baseline.

3.4.2.5 Automatic 6-, 7- and 8-Speed Transmissions (NAUTO and 8SPD)

Manufacturers can also choose to replace 4- and 5-speed transmission with 6-, 7-, or 8-speed automatic transmissions. Additional ratios allow for further optimization of engine operation over a wider range of conditions, but this is subject to diminishing returns as the number of speeds increases. As additional planetary gear sets are added (which may be necessary in some cases to achieve the higher number of ratios), additional weight and friction are introduced. Also, the additional shifting of such a transmission can be perceived as bothersome to some consumers, so manufacturers need to develop strategies for smooth shifts. Some manufacturers are replacing 4- and 5-speed automatics with 6-speed automatics, and 7- and 8-speed automatics have also entered production. While a six speed transmission application was most prevalent for the 2012-2016 final rule, eight speed transmissions are expected to be readily available and applied in the 2017 through 2025 timeframe.

As discussed in the MY 2011 CAFE final rule, confidential manufacturer data projected that 6-speed transmissions could incrementally reduce fuel consumption by 0 to 5 percent from a baseline 4-speed automatic transmission, while an 8-speed transmission could incrementally reduce fuel consumption by up to 6 percent from a baseline 4-speed automatic transmission. GM has publicly claimed a fuel economy improvement of up to 4 percent for its new 6-speed automatic transmissions.[50] The 2008 EPA Staff Technical Report found a 4.5 to 6.5 percent fuel consumption improvement for a 6-speed over a 4-speed automatic transmission.[51] Based on this information, NHTSA estimated in the MY 2011 rule, that the conversion to a 6-,7- and 8-speed transmission (NAUTO) from a 4 or 5-speed automatic transmission with IATC would have an incremental fuel consumption benefit of 1.4 percent to 3.4 percent, for all vehicle classes. From a baseline 4 or 5 speed transmission without IATC, the incremental fuel consumption benefit would be approximately 3 to 6 percent, which is consistent with the EPA Staff Report estimate. In MYs 2012-2016 final rule, NHTSA and EPA reviewed these effectiveness estimates and concluded that they remain accurate. While the CAFE model follows the incremental approach discussed above, the GHG model estimates the packaged effectiveness of 4.5 to 6.5 percent

In this NPRM analysis, the agencies divided the improvement for this technology into two steps, first from 4 or 5 speed transmission to 6 or 7 speed transmission (NAUTO), then from 6 or 7 speed transmission to 8 speed transmission (8SPD). The effectiveness estimates for NAUTO and 8SPD are based on 2011 Ricardo study. In this NPRM analysis, the effectiveness for a 6-speed transmission relative to a 4-speed base transmission ranges from 3.1 to 3.9 percent (2.1 percent for large truck with unimproved rear axle) including 7 percent of transmission gearbox efficiency improvement that the agencies assumed accompanying the new 6 speed transmission after MY 2010. NHTSA incorporated this effectiveness estimate into the CAFE model as incremental improvement over IATC ranging from 1.89 to 2.13 percent. In this NPRM analysis, the agencies assumed that 8-speed transmission will not start to phase in until MY2017. NHTSA applied 8-speed automatic transmission succeeding 6-speed automatic transmission to vehicles with towing requirement, such as Minivan, Midsize light truck and large light truck. All other vehicle subclasses use 8-speed DCT to succeed 6-speed DCT. The effectiveness for an 8-speed DCT relative to a 4-speed DCT transmission ranges from 11.1 to 13.1 percent for subcompact car, small car and small light truck. The effectiveness for an 8-speed automatic transmission relative to 4-speed automatic transmission ranges for large CUV and large truck ranges from 8.7 to 9.2 percent in Lump parameter model. This translates into effectiveness in the range of 3.85 to 4.57 percent for an 8-speed DCT relative to a 6-speed DCT and 4.9 to 5.34 percent for 8-speed automatic transmission relative to 6-speed automatic transmission in CAFE model.

In the 2010 TAR, the agencies estimated the DMC at -$13 (2008$) for a 6 speed automatic transmission relative to a 4 speed auto transmission, applicable in the 2017MY (see 2010 TAR, Table B2.1-1 at page B-10). For the 2012MY, that DMC was -$15 (2008$), although that value was not presented in the TAR. The latter DMC remains -$15 (2009$) for this analysis which is considered to be applicable in the 2012MY. The agencies consider 6 speed automatic transmission technology to be on the flat portion of the learning curve and have applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter. The resultant costs are shown in Table 3-37.

New for this analysis is the cost of an 8 speed automatic transmission. For the cost of this technology, the agencies have relied on a tear-down study completed by FEV since publication of the TAR.[52] In that study, the 8 speed auto transmission was found to be $62

(2007$) more costly than the 6 speed auto transmission. This DMC becomes $64 (2009$) for this analysis. Adding the $64 (2009$) to the -$15 (2009$) DMC for a 6 speed relative to a 4 speed, the 8 speed auto transmission relative to a 4 speed auto transmission would be $49 (2009$). The agencies consider this DMC to be applicable to the 2012MY. The agencies consider the 8 speed auto transmission technology to be on the flat portion of the learning curve and have applied a medium complexity ICM of 1.39 through the 2018MY then 1.29 thereafter.[ff] The resultant costs for both 6 speed and 8 speed auto transmissions are shown in Table 3-37.

Table 3-37 Costs for 6 and 8 Speed Automatic Transmissions (2009$)

Cost type	Transmission type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	6spAT from 4spAT	-$13	-$12	-$12	-$12	-$12	-$12	-$11	-$11	-$11
DMC	8spAT from 6spAT	$55	$54	$53	$52	$51	$50	$49	$48	$47
DMC	8spAT from 4spAT	$43	$42	$41	$40	$39	$38	$38	$37	$36
IC	6spAT from 4spAT	$4	$4	$3	$3	$3	$3	$3	$3	$3
IC	8spAT from 6spAT	$24	$24	$18	$18	$18	$18	$18	$18	$18
IC	8spAT from 4spAT	$19	$19	$14	$14	$14	$14	$14	$14	$14
TC	6spAT from 4spAT	-$9	-$9	-$9	-$9	-$9	-$9	-$8	-$8	-$8
TC	8spAT from 6spAT	$80	$78	$71	$70	$69	$68	$67	$66	$65
TC	8spAT from 4spAT	$61	$60	$55	$54	$53	$52	$52	$51	$50

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; sp=speed; AT=automatic transmission

Note that the cost for the 8 speed automatic transmission relative to the 6 speed automatic transmission is lower here than that used in the recent heavy-duty GHG rule. In that rule, we remained consistent with the proposal for that rule which carried an estimated DMC of $210 (2008$). That DMC was based on an estimate derived by NAS (see NAS 2010, Table 7-10). For this proposal, we have chosen to use the more recent DMC shown in Table 3-37 which is based on a tear-down analysis done by FEV.

3.4.2.6 Dual Clutch Transmissions / Automated Manual Transmissions (DCTAM)

An Automated Manual Transmission (AMT) is mechanically similar to a conventional manual transmission, but shifting and launch functions are automatically controlled by the electronics. There are two basic types of AMTs, single-clutch and dual-clutch (DCT). A single-clutch AMT is essentially a manual transmission with automated clutch and shifting. Because of shift quality issues with single-clutch designs, DCTs are far more common in the U.S. and are the basis of the estimates that follow. A DCT uses separate clutches (and separate gear shafts) for the even-numbered gears and odd-numbered gears. In this way, the next expected gear is pre-selected, which allows for faster and smoother shifting. For example, if the vehicle is accelerating in third gear, the shaft with gears one, three and five has gear three engaged and is transmitting power. The shaft with gears two, four, and six is

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[ff] This ICM would be applied to the 6 speed to 8 speed increment of $64 (2009$) applicable in 2012. The 4 speed to 6 speed increment would carry the low complexity ICM.

idle, but has gear four engaged. When a shift is required, the controller disengages the odd-gear clutch while simultaneously engaging the even-gear clutch, thus making a smooth shift. If, on the other hand, the driver slows down instead of continuing to accelerate, the transmission will have to change to second gear on the idling shaft to anticipate a downshift. This shift can be made quickly on the idling shaft since there is no torque being transferred on it.

In addition to single-clutch and dual-clutch AMTs, there are also wet clutch and dry clutch designs which are used for different types of vehicle applications. Wet clutch AMTs offer a higher torque capacity that comes from the use of a hydraulic system that cools the clutches. Wet clutch systems are less efficient than the dry clutch systems due to the losses associated with hydraulic pumping. Additionally, wet AMTs have a higher cost due to the additional hydraulic hardware required.

Overall, DCTs likely offer the greatest potential for effectiveness improvements among the various transmission options presented in this report because they offer the inherently lower losses of a manual transmission with the efficiency and shift quality advantages of electronic controls. The lower losses stem from the elimination of the conventional lock-up torque converter, and a greatly reduced need for high pressure hydraulic circuits to hold clutches or bands to maintain gear ratios (in automatic transmissions) or hold pulleys in position to maintain gear ratio (in Continuously Variable Transmissions). However, the lack of a torque converter will affect how the vehicle launches from rest, so a DCT will most likely be paired with an engine that offers sufficient torque at low engine speeds to allow for adequate launch performance or provide lower launch gears to approximate the torque multiplication of the torque converter to provide equivalent performance.

In MYs 2012-2016 final rule, EPA and NHTSA estimated a 5.5 to 9.5 percent improvement in fuel consumption over a baseline 4/5-speed automatic transmission for a wet clutch DCT, which was assumed for all but the smallest of vehicle subclasses, Subcompact and Compact cars and small LT. This results in an incremental effectiveness estimate of 2.7 to 4.1 percent over a 6-speed automatic transmission with IATC. For Subcompact and Compact Cars and small LT, which were assumed to use a dry clutch DCT, NHTSA estimated an 8 to 13 percent fuel consumption improvement over a baseline 4/5-speed automatic transmission, which equates to a 5.5 to 7.5 percent incremental improvement over the 6-speed transmission.

Based on the 2011 Ricardo study, EPA and NHTSA have concluded that 8 to 13 percent effectiveness is appropriate for 6-speed DCTs and 11 to 16 percent is appropriate for 8-speed DCTs for this proposal. These values include not only the DCT but also the increase in stepped gears and also a high efficiency gearbox (mentioned later). Independent of other technologies, this translates to an effectiveness for the DCT, alone, of 4 to 5% (for wet-clutch designs) and 5 to 6% (for dry-clutch designs) compared to a baseline automatic transmission of similar vintage and number of fixed gears.

In this NPRM analysis, NHTSA applied an incremental effectiveness of 4 percent for a 6-speed dry DCT and 3.4 to 3.8 percent for a wet DCT compared to a 6-speed automatic transmission based on the lumped parameter model which includes the accompanied transmission efficiency improvement for MY 2010 and after transmissions. This translates to an effectiveness range of 7.4 to 8.6 percent compared to a 4 speed automatic transmission for dry clutch design and 7.4 to 7.9 percent for a wet clutch design. NHTSA did not apply DCTs to vehicles with towing requirements, such as Minivan, Midsize light truck and large pickup truck. EPA did not apply DCTs to vehicle types classified as towing as described in Chapter 1 of EPA's Draft RIA.

In the 2010 TAR, the agencies estimated the DMC at -$234 (2008$) for a 6 speed dry-clutch DCT and -$165 for a 6 speed wet-clutch DCT with both DMCs applicable in the 2017MY (see 2010 TAR, Table B2.1-1 at page B-10) and both incremental to a 4 speed automatic transmission. In the 2010 TAR, we pointed to Chapter 3 of the 2012-2016 final joint TSD where we noted that the DCT costs of -$147 (2007$ and incremental to a 6-speed automatic transmission) were based on a FEV tear-down study that assumed 450,000 units of production. We went on to state that we did not consider there to be sufficient US capacity in the 2012-2016 timeframe to produce 450,000 units and for that reason we were adjusting the tear-down values accordingly. The TAR timeframe for consideration was 2017-2025, and in the TAR we argued that production capacity would exist and that the FEV tear-down results we valid without adjustment. We continue to believe that to be the case. In the final joint TSD supporting the 2012-2016 rule we also noted that the negative tear-down estimates found by FEV were not surprising when considering the relative simplicity of a dual-clutch transmission compared to an automatic transmission. Again, we continue to consider this to be true.

For this analysis, we consider the 2010 TAR DMCs to be applicable to the 2012MY, thus the DMCs become -$236 (2009$) and -$167 (2009$) for 6 speed dry- and wet-clutch DCTs, respectively, both applicable in the 2012MY and incremental to a 4 speed auto transmission. The agencies consider the 6 speed DCT technology to be on the flat portion of the learning curve and have applied a medium complexity ICM of 1.39 through 2018 then 1.29 thereafter. The resultant costs are shown in Table 3-38.

New for this analysis is costing for an 8 speed DCT. For the cost of this technology, the agencies have relied on a tear-down study completed by FEV since publication of the TAR.[53] In that study, the 8 speed DCT was found to be $198 (2007$) more costly than the 6 speed DCT. This DMC increment becomes $202 (2009$) for this analysis. Adding the $202 (2009$) to the -$236 (2009$) DMC and the -$167 (2009$) DMC for a 6 speed dry- and wet-clutch DCT, the 8 speed dry- and wet-clutch DCTs relative to a 4 speed auto transmission would be -$32 (2009$) and $38 (2009$), respectively. The agencies consider this DMC to be applicable to the 2012MY. The agencies consider the 8 speed DCT technology to be on the flat portion of the learning curve and have applied a medium complexity ICM of 1.39 through the 2024MY then 1.29 thereafter. The 8 speed DCT has a later switch to long term ICMs because it is a newer technology that is not currently implemented in the fleet. The resultant costs for both 6 speed and 8 speed DCTs are shown in Table 3-38.

Table 3-38 Costs for 6 & 8 Speed Dual Clutch Transmissions (2009$)

Cost type	Transmission type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	6spDCT-dry	-$205	-$201	-$197	-$193	-$189	-$185	-$182	-$178	-$174
DMC	6sp DCT-wet	-$145	-$142	-$139	-$136	-$133	-$131	-$128	-$125	-$123
DMC	8sp DCT-dry	-$28	-$27	-$27	-$26	-$26	-$25	-$25	-$24	-$24
DMC	8sp DCT-wet	$33	$32	$31	$31	$30	$30	$29	$28	$28
IC	6spDCT-dry	$90	$90	$67	$67	$67	$67	$67	$67	$67
IC	6sp DCT-wet	$64	$63	$47	$47	$47	$47	$47	$47	$47
IC	8sp DCT-dry	$12	$12	$12	$12	$12	$12	$12	$12	$9
IC	8sp DCT-wet	$14	$14	$14	$14	$14	$14	$14	$14	$11
TC	6spDCT-dry	-$115	-$111	-$130	-$126	-$122	-$118	-$115	-$111	-$108
TC	6sp DCT-wet	-$81	-$78	-$91	-$89	-$86	-$84	-$81	-$79	-$76
TC	8sp DCT-dry	-$16	-$15	-$14	-$14	-$13	-$13	-$12	-$12	-$15
TC	8sp DCT-wet	$47	$46	$46	$45	$44	$44	$43	$43	$38

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; sp=speed; dry=dry clutch; wet=wet-clutch
Note that all costs are relative to a 4 speed automatic transmission.

3.4.2.7 6-Speed Manual Transmissions (6MAN)

Manual transmissions are entirely dependent upon driver input to shift gears: the driver selects when to perform the shift and which gear to select. This is the most efficient transfer of energy of all transmission layouts, because it has the lowest internal gear losses, with a minimal hydraulic system, and the driver provides the energy to actuate the clutch. From a systems viewpoint, however, vehicles with manual transmissions have the drawback that the driver may not always select the optimum gear ratio for fuel economy. Nonetheless, increasing the number of available ratios in a manual transmission can improve fuel economy by allowing the driver to select a ratio that optimizes engine operation more often. Typically, this is achieved through adding overdrive ratios to reduce engine speed at cruising velocities (which saves fuel through reduced engine pumping losses) and pushing the torque required of the engine towards the optimum level. However, if the gear ratio steps are not properly designed, this may require the driver to change gears more often in city driving, resulting in customer dissatisfaction. Additionally, if gear ratios are selected to achieve improved launch performance instead of to improve fuel economy, then no fuel saving effectiveness is realized.

The 2012-2016 final rule estimated an effectiveness increase of 0.5 percent for replacing a 5-speed manual with a 6-speed manual transmission, which was derived from confidential manufacturer data. Based on the updated LPM, NHTSA has found that an effectiveness increase of 2.0 to 2.5 percent is possible when moving from a 5-speed to a 6-speed manual transmission with improved internals . NHTSA updated costs to reflect the ICM low complexity markup of 1.11 which resulted in an incremental compliance cost of $250 as compared to $338 for MY 2012. This represents a DMC of $225 (2007$) which becomes $232 (2009$) for this analysis, applicable in the 2012MY. NHTSA continues to consider a 6 speed manual transmission to be on the flat portion of the learning curve and has applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter. NHTSA’s resultant costs for a 6 speed manual transmission are shown in Table 3-39.

Table 3-39 Costs for 6 Speed Manual Transmission (2009$)

Cost type	Transmission type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	6sp manual	$202	$197	$194	$190	$186	$182	$179	$175	$171
IC	6sp manual	$56	$56	$45	$44	$44	$44	$44	$44	$44
TC	6sp manual	$257	$253	$238	$234	$230	$227	$223	$219	$216

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost; sp=speed; dry=dry clutch; wet=wet-clutch
Note that all costs are relative to a 5 speed manual transmission.

3.4.3 Vehicle electrification and hybrid electric vehicle technologies

For the costs presented in this electrification and hybrid vehicle section, we have estimated costs for vehicle classes since the technologies are closely linked to the size of the vehicle as opposed to the number of cylinders on the engine or its valvetrain configuration. The vehicle classes for which we have estimated costs are consistent with the seven vehicle classes developed for the lumped parameter model. Each agency has used the vehicle class specific costs and mapped those into their respective model-specific vehicle classes or types as shown in Table 3-40. This table simply presents the mapping of lumped parameter model vehicle classes (or cost vehicle classes) into model-specific vehicle classes (or vehicle types in the case of EPA's OMEGA model, please refer to Chapter 1 of EPA's draft RIA for more details) to help the reader understand how the vehicle classes used for costing relate to the vehicle classes used for modeling.

Table 3-40 Mapping of Vehicle Class into each Agency's Model-Specific Vehicle Classes or Types

EPA Vehicle Class for Cost Purpose	Lump Parameter Classification	Example	OMEGA Model Vehicle Type*	NHTSA/CAFE Model Classification
Subcompact Car	Small Car	Yaris	1	Subcompact Subcompact Perf PC
				Compact Compact Perf PC
Small Car	Std Car	Camry	2, 3	Mid-size PC Mid-size Perf PC
Large Car	Large Car	Chrysler 300	5, 6, 15	Large PC Large Perf Pc
Minivan	Large MPV	Dodge Grand Caravan	4, 7	
Small Truck	Small MPV	Saturn Vue	8	Small LT
Minivan with Towing	Large MPV	Dodge Grand Caravan	9, 10, 16, 17	Midsize LT
				MinVan LT
Large Truck	Truck	Ford F150	11, 12, 13, 14, 18, 19	Large LT

* OMEGA uses 19 vehicle types as shown here and described in detail in Chapter 1 of EPA's draft RIA.

3.4.3.1 Electrical Power Steering (EPS) / Electrohydraulic Power Steering (EHPS)

Electric power steering (EPS) and Electrohydraulic power steering (EHPS) provide a potential reduction in CO_2 emissions and fuel consumption over hydraulic power steering because of reduced overall accessory loads. This eliminates the parasitic losses associated with belt-driven power steering pumps which consistently draw load from the engine to pump hydraulic fluid through the steering actuation systems even when the wheels are not being turned. EPS is an enabler for all vehicle hybridization technologies since it provides power steering when the engine is off. EPS may be implemented on most vehicles with a standard 12V system. Some heavier vehicles may require a higher voltage system or EHPS which may add cost and complexity.

The 2012-2016 final rule, EPA and NHTSA estimated a 1 to 2 percent effectiveness for light duty vehicles based on the 2002 NAS report, Sierra Research Report and confidential OEM data. The 2010 Ricardo study also confirmed this estimate. NHTSA and EPA reviewed these effectiveness estimates and found them to be accurate, thus they have been retained for this proposal. For large pickup truck the agencies used EHPS due to the utility requirement of these vehicles. The effectiveness of EHPS is estimated to be 0.8 percent.

In the MY 2012-2016 final rule, the agencies estimated the DMC at $88 (2007$). Converting to 2009$, this DMC becomes $90 for this analysis, consistent with the recent heavy-duty GHG rule, which is considered applicable in the 2015MY. The agencies use the same DMC for EPS as for EHPS. Technically, EHPS is less costly than EPS. However, we believe that EHPS is likely to be used, if at all, on the largest trucks and utility vehicles. As such, it would probably need to be heavier-duty than typical EPS systems and the agencies consider the net effect to place EHPS on par with EPS in terms of costs. The agencies consider EPS/EHPS technology to be on the flat portion of the learning curve and have applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter. The resultant costs are shown in Table 3-41.

Table 3-41 Costs of Electrical/Electro-hydraulic Power Steering (2009$)

Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$86	$84	$82	$81	$79	$78	$76	$74	$73
IC	$22	$22	$17	$17	$17	$17	$17	$17	$17
TC	$108	$106	$100	$98	$96	$95	$93	$92	$90

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

3.4.3.2 Improved Accessories

The accessories on an engine, including the alternator, coolant and oil pumps are traditionally mechanically-driven. A reduction in CO_2 emissions and fuel consumption can be realized by driving them electrically, and only when needed ("on-demand").

Electric water pumps and electric fans can provide better control of engine cooling. For example, coolant flow from an electric water pump can be reduced and the radiator fan can be shut off during engine warm-up or cold ambient temperature conditions which will reduce warm-up time, reduce warm-up fuel enrichment, and reduce parasitic losses.

Indirect benefit may be obtained by reducing the flow from the water pump electrically during the engine warm-up period, allowing the engine to heat more rapidly and thereby reducing the fuel enrichment needed during cold starting of the engine. Further benefit may be obtained when electrification is combined with an improved, higher efficiency engine alternator. Intelligent cooling can more easily be applied to vehicles that do not typically carry heavy payloads, so larger vehicles with towing capacity present a challenge, as these vehicles have high cooling fan loads. Both agencies also included a higher efficiency alternator in this category to improve the cooling system. Both agencies also included a higher efficiency alternator in this category to improve the cooling system.

The agencies considered whether to include electric oil pump technology for the rulemaking. Because it is necessary to operate the oil pump any time the engine is running, electric oil pump technology has insignificant effect on efficiency. Therefore, the agencies decided to not include electric oil pump technology for this proposal.

In MYs 2012-2016 final rule, the agencies used the effectiveness value in the range of 1 to 2 percent based on technologies discussed above. NHTSA did not apply this technology to large pickup truck due to the utility requirement concern for this vehicle class.

For this proposal, the agencies are considering two levels of improved accessories. For level one of this technology (IACC1) NHTSA now incorporates a high efficiency alternator (70 percent efficiency). The second level of improved accessories (IACC2) adds the higher efficiency alternator and incorporates a mild regenerative alternator strategy, as well as intelligent cooling. NHTSA and EPA jointly reviewed the estimates of 1 to 2 percent effectiveness estimates used in the 2012-2016 final rule and TAR for level IACC1. More precisely, the agencies used effectiveness value in 1.2 to 1.8 percent range varying based on different vehicle subclasses. The incremental effectiveness for this technology in relative to EPS in the CAFE model is 0.91 to 1.61 percent. The combined effectiveness for IACC1 and IACC2 ranges from 3.1 to 3.9 percent and NHTSA applied incremental effectiveness of IACC2 in relative to IACC1 ranging from 1.74 to 2.55 percent.

In the 2012-2016 rule, the agencies estimated the DMC of IACC1 at $71 (2007$). Converting to 2009$, this DMC becomes $73 for this analysis, applicable in the 2015MY, and consistent with the heavy-duty GHG rule. The agencies consider IACC1 technology to be on the flat portion of the learning curve and have applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter.

Cost is higher for IACC2 due to the inclusion of a higher efficiency alternator and a mild level of regeneration. The agencies estimate the DMC of the higher efficiency alternator and the regeneration strategy at $45 (2009$) incremental to IACC1, applicable in the 2015MY. Including the costs for IACC1 results in a DMC for IACC2 of $118 (2009$) relative to the baseline case and applicable in the 2015MY. The agencies consider the IACC2 technology to be on the flat portion of the learning curve. The agencies have applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter. The resultant costs are shown in Table 3-42.

Table 3-42 Costs for Improved Accessory Technology – Levels 1 & 2 (2009$)

Cost type	IACC Technology	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	IACC1	$70	$68	$67	$66	$64	$63	$62	$61	$59
DMC	IACC2	$113	$110	$108	$106	$104	$102	$100	$98	$96
IC	IACC1	$18	$18	$14	$14	$14	$14	$14	$14	$14
IC	IACC2	$29	$29	$23	$23	$23	$23	$23	$23	$23
TC	IACC1	$87	$86	$81	$80	$78	$77	$76	$75	$73
TC	IACC2	$141	$139	$131	$129	$127	$124	$122	$120	$118

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost
Note that both levels of IACC technology are incremental to today's baseline case.

3.4.3.3 Air Conditioner Systems

We have a detailed description of the AC program in Chapter 5 of this draft joint TSD. The reader is directed to that chapter to learn the specifics of the program, the credits involved, and details behind the costs we have estimated. Table 3-43 is a copy of Table 5-17 showing the total costs for A/C controls used in this proposal.

Table 3-43 Total Costs for A/C Control Used in This Proposal (2009$)

Car/ Truck	Cost type	Rule	2017	2018	2019	2020	2021	2022	2023	2024	2025
Car	TC	Reference	$75	$74	$69	$68	$67	$66	$65	$64	$63
	TC	Control	$25	$40	$56	$65	$78	$76	$72	$70	$69
	TC	Both	$100	$114	$126	$133	$145	$142	$137	$134	$132
Truck	TC	Reference	$57	$56	$53	$52	$51	$50	$50	$49	$48
	TC	Control	$2	$46	$73	$81	$94	$92	$87	$85	$84
	TC	Both	$60	$102	$126	$133	$145	$142	$137	$134	$132
Fleet	TC	Both	$85	$110	$126	$133	$145	$142	$137	$134	$132

TC=Total cost

3.4.3.4 Stop-start (12V Micro Hybrid)

The stop-start technology we consider for this proposal—also known as idle-stop or 12-volt micro-hybrid—is the most basic hybrid system that facilitates idle-stop capability. When vehicle comes to a stop, the system will automatically shut down the internal combustion engine and restarts the engine when vehicle starts to move again. This is especially beneficial to reduce emission and fuel consumption when vehicle spends significant amount of time stopping in traffic jam. Along with other enablers, this system typically replaces the standard 12-volt starter with an improved unit capable of higher power and increased cycle life. These systems typically incorporate an improved battery to prevent voltage-droop on restart. Different from MY 2012-2016 rule, this technology is applied to all vehicle classes, including large pickup truck. In MYs 2012-2016 final rule, even though EPA did not use 12 volt stop-start technology, NHTSA and EPA jointly reviewed the assumption. The effectiveness NHTSA used in the CAFE model for MYs 2012-2016 final rule ranged from 2 to 4 percent, depending on whether the vehicle is equipped with a 4-, 6- or 8-cylinder engine, with the 4-cylinder engine having the lowest range and the 8-cylinder having the highest[gg]. In this NPRM analysis, when combining IACC1, IACC2 and 12V stop-start system, the estimated effectiveness based on 2010 Ricardo study ranges from 4.8 percent to 5.9 percent. The agencies applied this effectiveness in the NPRM analysis. For CAFE modeling, the incremental effectiveness for 12V stop-start relative to IACC2 is 1.68 to 2.2 percent.

In the 2012-2016 rule, the agencies estimated the DMC at $282 (2007$) to $350 (2007$) for small cars through large trucks, respectively. Converting to 2009$, these DMCs become $290 (2009$) through $361 (2009$) for this analysis which are considered applicable in the 2015MY. The agencies consider 12V stop-start technology to be on the steep portion of the learning curve in the 2012-2016 timeframe and flat thereafter and have applied a medium complexity ICM of 1.39 through 2018 then 1.29 thereafter. The resultant costs are shown in Table 3-44.

Table 3-44 EPA and NHTSA Costs for 12V Micro Hybrid or 12V Stop-Start (2009$)

Cost type	Vehicle Class	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact/ Small car	$282	$273	$265	$257	$249	$242	$235	$228	$221
DMC	Large car	$319	$310	$300	$291	$283	$274	$266	$258	$250
DMC	Minivan	$319	$310	$300	$291	$283	$274	$266	$258	$250
DMC	Small truck	$319	$310	$300	$291	$283	$274	$266	$258	$250
DMC	Large truck	$350	$340	$329	$320	$310	$301	$292	$283	$274
IC	Subcompact/ Small car	$112	$112	$83	$83	$83	$83	$82	$82	$82
IC	Large car	$127	$127	$94	$94	$94	$94	$93	$93	$93
IC	Minivan	$127	$127	$94	$94	$94	$94	$93	$93	$93
IC	Small truck	$127	$127	$94	$94	$94	$94	$93	$93	$93
IC	Large truck	$139	$139	$104	$103	$103	$103	$102	$102	$102

[gg] For a description of how Stop Start is considered for off-cycle credits refer to TSD Chapter 5.2.3.1.

TC	Subcompact/ Small car	$394	$385	$348	$340	$332	$324	$317	$310	$303
TC	Large car	$446	$436	$395	$385	$376	$368	$359	$351	$343
TC	Minivan	$446	$436	$395	$385	$376	$368	$359	$351	$343
TC	Small truck	$446	$436	$395	$385	$376	$368	$359	$351	$343
TC	Large truck	$490	$479	$433	$423	$413	$403	$394	$385	$376

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

3.4.3.5 Mild Hybrid

Mild hybrid systems, also called Higher Voltage Stop-Start and Belt Mounted Integrated Starter Generator (BISG) systems are similar to a micro-hybrid system, offering idle-stop functionality, except that they utilize larger electric machine and a higher capacity battery, typically 42 volts or above, thus enabling a limited level of regenerative braking unavailable for a MHEV. The larger electric machine and battery also enables a limited degree of power assist, which MHEV cannot provide. However, because of the limited torque capacity of the belt-driven design, these systems have a smaller electric machine, and thus less capability than crank-integrated or stronger hybrid systems. These systems replace the conventional alternator with a belt-driven starter/alternator and may add high voltage electrical accessories (which may include electric power steering and an auxiliary automatic transmission pump). The limited electrical requirements of these systems allow the use of lead-acid batteries or supercapacitors for energy storage.

The MY 2012-2016 final rule estimates the effectiveness for these technologies range from 3.0 to 7.5 percent depending on vehicle subclass. The CAFE model, which applies this effectiveness incrementally to the prior 12 Volt MHEV technology, uses estimates of 4 to 6 percent.

EPA estimates an incremental compliance cost range of $549 (small car) to $682 (large truck) for a MY 2012 vehicle and including a medium complexity ICM of 1.25 (2007$). With volume-based learning applied, these become $351 (small car) and $437 (large truck) for a MY 2016 vehicle (2007$). The cost estimate in the CAFE model is incremental to the 12 Volt micro hybrid systems as noted above, and therefore is adjusted upwards to $286 to reflect the additional battery capacity, wiring upgrades, and a larger optimized electric machine only. The $286 reflects volume-based learning factors and the ICM medium-complexity markup of 1.25. This technology is not applied in this NPRM analysis.

3.4.3.5.1 Integrated Motor Assist (IMA)/Crank Integrated Starter Generator (CISG)

IMA is a system developed and marketed by Honda[54] and is similar to CISG. They both utilize a thin axial electric motor bolted to the engine's crankshaft and connected to the transmission through a torque converter or clutch. The axial motor is motor/generator that typically operates above 100 volts (but lower than the stronger hybrid systems discussed below, which typically operate at around 300 volts) and can provide sufficient torque for launch as well as generate sufficient current to provide significant levels of brake energy recovery. The motor/generator also acts as the starter for the engine and can replace a typical accessory-driven alternator. Current IMA/CISG systems typically do not launch the vehicle on electric power alone, although some commercially available systems can cruise on electric power and dual-clutch IMA/CISG systems capable of all-electric drive are under development. IMA and CISG could be applied to all classes of vehicles. This technology is not used as an enabling technology in this NPRM analysis by either EPA or NHTSA.

EPA relied on a combination of certification data (comparing vehicles available with and without a hybrid system and backing out other components where appropriate) and manufacturer-supplied information to determine that the effectiveness of these systems in terms of CO_2 reduction is 30 percent for small cars, 25 percent for large cars, and 20 percent for minivans and small trucks similar to the range estimated by NHTSA for the respective vehicle classes. The effectiveness for small cars assumes engine downsizing to maintain approximately equivalent performance. The large car, minivan, and small truck effectiveness values assume less engine downsizing in order to improve vehicle performance and/or maintain towing and hauling performance.

In the 2012-2016 final rule, the agencies estimated the DMC at $1,973, $2,497, $2,508, $2,366 and $3,063 (all values in 2007$) for a small car, large car, minivan, small truck and large truck, respectively. These DMCs become $2,034, $2,575, $2,586, $2,440 and $3,159 (all values in 2009$) for this analysis. All of these DMCs are considered applicable in the 2015MY. The agencies consider the IMA technology to be on the steep portion of the learning curve and have applied a high1 complexity ICM of 1.56 through 2018 then 1.35 thereafter. The resultant costs are as shown in Table 3-45. As noted earlier, the IMA technology is not included as an enabling technology in this analysis, although it is included as a baseline technology because it exists in the 2008 baseline fleet. The agencies moved away from this technology and applied P2 hybrid instead because comparing to IMA, P2 is more cost effective.

Table 3-45 Costs for IMA Hybrids (2009$)

Cost type	Vehicle Class	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact/Small car	$1,973	$1,914	$1,857	$1,801	$1,747	$1,695	$1,644	$1,594	$1,547
DMC	Large car	$2,498	$2,423	$2,350	$2,280	$2,211	$2,145	$2,081	$2,018	$1,958
DMC	Minivan	$2,508	$2,433	$2,360	$2,289	$2,221	$2,154	$2,089	$2,027	$1,966
DMC	Small truck	$2,367	$2,296	$2,227	$2,160	$2,095	$2,032	$1,971	$1,912	$1,855
IC	Subcompact/Small car	$1,143	$1,139	$697	$695	$694	$692	$690	$689	$687
IC	Large car	$1,446	$1,441	$882	$880	$878	$876	$874	$872	$870
IC	Minivan	$1,452	$1,447	$886	$884	$882	$879	$877	$875	$873
IC	Small truck	$1,370	$1,366	$836	$834	$832	$830	$828	$826	$824
TC	Subcompact/Small car	$3,116	$3,053	$2,554	$2,496	$2,440	$2,386	$2,334	$2,283	$2,234
TC	Large car	$3,944	$3,864	$3,233	$3,160	$3,089	$3,021	$2,954	$2,890	$2,827
TC	Minivan	$3,961	$3,880	$3,246	$3,173	$3,102	$3,033	$2,967	$2,902	$2,839

TC	Small truck	$3,737	$3,662	$3,063	$2,994	$2,927	$2,862	$2,799	$2,738	$2,679

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

3.4.3.6 HEV, PHEV, EV and Fuel Cell Vehicle Technologies

A hybrid vehicle is a vehicle that combines two or more sources of propulsion energy, where one uses a consumable fuel (like gasoline), and one is rechargeable (during operation, or by another energy source). Hybrid technology is well established in the U.S. market and more manufacturers are adding hybrid models to their lineups. Hybrids reduce fuel consumption through three major mechanisms:

- The internal combustion engine can be optimized (through downsizing, modifying the operating cycle, or other control techniques) to operate at or near its most efficient point more of the time. Power loss from engine downsizing can be mitigated by employing power assist from the secondary power source.
- Some of the energy normally lost as heat while braking can be captured and stored in the energy storage system for later use.
- The engine is turned off when it is not needed, such as when the vehicle is coasting or when stopped.

Hybrid vehicles utilize some combination of the three above mechanisms to reduce fuel consumption and CO_2 emissions. A fourth mechanism to reduce petroleum fuel consumption, available only to plug-in hybrids, is by substituting the petroleum fuel energy with energy from another source, such as the electric grid. The effectiveness of fuel consumption and CO_2 reduction depends on the utilization of the above mechanisms and how aggressively they are pursued. One area where this variation is particularly prevalent is in the choice of engine size and its effect on balancing fuel economy and performance. Some manufacturers choose not to downsize the engine when applying hybrid technologies. In these cases, performance is vastly improved, while fuel efficiency improves significantly less than if the engine was downsized to maintain the same performance as the conventional version. While this approach has been used in cars such as the Lexus 600h luxury vehicle, it is more likely to be used in the future for vehicles like trucks where towing and/or hauling are an integral part of their performance requirements. In these cases, if the engine is downsized, the battery can be quickly drained during a long hill climb with a heavy load, leaving only a downsized engine to carry the entire load. Because towing capability is currently a heavily-marketed truck attribute, manufacturers are hesitant to offer a truck with downsized engine which can lead to a significantly diminished towing performance when the battery state of charge level is low, and therefore engines are traditionally not downsized for these vehicles.

Although hybrid vehicles using other energy storage concepts (flywheel, hydraulic) have been developed, the automotive systems in production for passenger cars and light trucks are all hybrid electric vehicles (HEV) that use battery storage and electric drive systems. This appears likely to be the case for the foreseeable future. HEVs are part of a continuum of vehicles using systems with differing levels of electric drive and electric energy storage. This range of vehicles includes relatively basic system without electric energy storage such as engine start/stop systems; HEV systems with varying degrees of electric storage and electric drive system capability including mild-hybrid electric vehicles (MHEV) with limited capability but lower cost; strong hybrid electric vehicles (SHEV) with full hybridization capability such as the P2 hybrid technology which the agencies evaluate as a compliance option in this NPRM; plug-in hybrid electric vehicles (PHEV) with differing degrees of all electric range and battery electric vehicles (EV) that rely entirely on electric drive and battery electric energy storage.

Different HEV, PHEV and EV concepts utilize these mechanisms differently, so they are treated separately for the purposes of this analysis. In many applications, particularly with PHEV and EV, the battery represents the most costly and system-limiting sub-component of the hybrid system. Currently, there are many battery chemistries being developed and refined for hybrid applications that are expected to enhance the performance of future hybrid vehicles. Section 3.4.3.6.4 contains a discussion of battery energy storage and the major hybrid concepts that were determined to be available during the MY 2017-2015 timeframe.

Fuel cell vehicles are a separate category of electric vehicle that rely entirely on electric propulsion with electricity produced on-board the vehicle using a proton-exchange-membrane fuel cell (PEMFC) fueled with hydrogen. Fuel cell vehicles under development are typically configured as a hybrid with battery storage used to provide brake energy recovery and improved response to fast transients in vehicle energy demand.

3.4.3.6.1 Power-split hybrid

Power-split hybrid (PSHEV) – a hybrid electric drive system that replaces the traditional transmission with a single planetary gear set and a motor/generator. This motor/generator uses the engine to either charge the battery or to supply additional power to the drive motor. A second, more powerful motor/generator is permanently connected to the vehicle’s final drive and always turns with the wheels. The planetary gear splits engine power between the first motor/generator and the drive motor to either charge the battery or supply power to the wheels. Power-split hybrids are not used as an enabling technology in this proposal.

In MYs 2012-2016 final rule, EPA and NHTSA used a combination of manufacturer-supplied information and a comparison of vehicles available with and without a hybrid system from EPA’s fuel economy test data to determine that the effectiveness is 19 to 36 percent for the classes to which it is applied. The estimate would depend on whether engine downsizing is also assumed. In the CAFE incremental model, the range of effectiveness used was 23 to 33 percent as engine downsizing is not assumed (and accounted for elsewhere).

For this analysis, in order to estimate baseline costs, the agencies are using power-split HEV costs generated by FEV as part of a tear-down study. In that study, FEV found the

DMC of the entire power-split system (battery-pack and non-battery components) to be $2,853 (2007$), $3,175 (2007$), $3,435 (2007$), $4,168 (2007$) for vehicle sized, for example, like a Ford Fiesta, Ford Focus, Ford Fusion and Ford Flex, respectively. For this analysis, these values become $2,942, $3,274, $3,542 and $4,298, respectively, all in 2009 dollars. In the 2012-2016 final rule, the agencies estimated the DMC of a large truck power-split system at $5,137 (2007$) which becomes $5,299 for this analysis (2009$) and we are using this value for the minivan-towing vehicle class. All of these DMCs are considered applicable in the 2015MY. The agencies consider the power-split technology to be on the flat portion of the learning curve and have applied a high1 complexity ICM of 1.56 through 2018 then 1.35 thereafter. The resultant costs are as shown in Table 3-46. As noted earlier, the IMA technology is not included as an enabling technology in this analysis, although it is included as a baseline technology because it exists in the 2008 baseline fleet.

Table 3-46 Costs for Power-Split Hybrids (2009$)

Cost type	Vehicle Class	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	$2,797	$2,741	$2,686	$2,632	$2,579	$2,528	$2,477	$2,428	$2,379
DMC	Small car	$3,112	$3,050	$2,989	$2,929	$2,871	$2,813	$2,757	$2,702	$2,648
DMC	Large car	$3,367	$3,300	$3,234	$3,169	$3,106	$3,044	$2,983	$2,923	$2,865
DMC	Minivan	$4,086	$4,004	$3,924	$3,845	$3,768	$3,693	$3,619	$3,547	$3,476
DMC	Small truck	$3,393	$3,325	$3,258	$3,193	$3,129	$3,067	$3,005	$2,945	$2,886
DMC	Minivan-towing	$5,037	$4,937	$4,838	$4,741	$4,646	$4,553	$4,462	$4,373	$4,286
IC	Subcompact	$1,649	$1,645	$1,008	$1,006	$1,005	$1,003	$1,001	$1,000	$998
IC	Small car	$1,835	$1,831	$1,122	$1,120	$1,118	$1,116	$1,114	$1,113	$1,111
IC	Large car	$1,985	$1,981	$1,214	$1,212	$1,210	$1,208	$1,206	$1,204	$1,202
IC	Minivan	$2,409	$2,403	$1,473	$1,470	$1,468	$1,465	$1,463	$1,461	$1,458
IC	Small truck	$2,000	$1,996	$1,223	$1,221	$1,219	$1,217	$1,215	$1,213	$1,211
IC	Minivan-towing	$2,970	$2,963	$1,816	$1,813	$1,810	$1,807	$1,804	$1,801	$1,798
TC	Subcompact	$4,445	$4,386	$3,694	$3,638	$3,584	$3,531	$3,479	$3,428	$3,377
TC	Small car	$4,947	$4,881	$4,111	$4,049	$3,989	$3,930	$3,872	$3,815	$3,759
TC	Large car	$5,352	$5,281	$4,448	$4,381	$4,315	$4,251	$4,188	$4,127	$4,067
TC	Minivan	$6,494	$6,407	$5,396	$5,315	$5,236	$5,158	$5,082	$5,007	$4,934
TC	Small truck	$5,392	$5,320	$4,481	$4,414	$4,348	$4,283	$4,220	$4,158	$4,097
TC	Minivan-towing	$8,007	$7,900	$6,654	$6,554	$6,456	$6,360	$6,266	$6,174	$6,084

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

3.4.3.6.2 2-mode hybrid

2-mode hybrid (2MHEV) – is a hybrid electric drive system that uses an adaptation of a conventional stepped-ratio automatic transmission by replacing some of the transmission clutches with two electric motors that control the ratio of engine speed to vehicle speed, while clutches allow the motors to be bypassed. This improves both the transmission torque capacity for heavy-duty applications and reduces fuel consumption and CO2 emissions at highway speeds relative to other types of hybrid electric drive systems. 2-mode hybrids have not been considered in this proposal. Depending on the comments that the agencies received for this NPRM, the agencies might re-consider this hybrid technology in vehicles with towing requirement, such as pickup trucks, in the final rule.

For MYs 2012-2016 final rule, the CAFE model considered a range of 23 to 33 percent with a midpoint of 28 percent, assuming no engine downsizing to preserve the utility nature of medium and large trucks (*e.g.*, maintaining full towing capability even in situations with low battery charge) and EPA estimates CO_2 emissions reduction effectiveness to be 25 percent for large trucks (LDT3 and LDT4 categories) based on vehicle certification data. EPA estimates an effectiveness of 40 percent for smaller vehicles.

The agencies have estimated the costs for 2-mode hybrids using costs used in the 2010 TAR. For this analysis, the 2-mode battery pack DMC is estimated at $1,078 (2009$) and the DMC of non-battery components is estimated at $2,938 (2009$). The battery pack DMC is considered to be applicable for the 2025MY while the non-battery pack DMC would be applicable for the 2012MY. The agencies consider the 2-mode battery packs to be on the steep portion of the learning curve during the 2017-2025 timeframe. The agencies have applied a high1 complexity ICM of 1.56 through 2018 then 1.35 thereafter. For 2-mode non-battery components, the agencies consider them to be on the flat portion of the learning curve in the 2017-2025 timeframe and have applied a high1 complexity ICM of 1.56 through 2018 then 1.35 thereafter. The resultant 2-mode hybrid costs are presented in Table 3-47.

Table 3-47 Costs for 2-Mode Hybrids (2009$)

Cost type	Vehicle Class	2017	2018	2019	2020	2021	2022	2023	2024	2025
Battery-pack										
DMC	Minivan/Minivan-towing/Large truck	$2,105	$1,684	$1,684	$1,348	$1,348	$1,348	$1,348	$1,348	$1,078
TC	Minivan/Minivan-towing/Large truck	$2,779	$2,331	$2,076	$1,728	$1,728	$1,728	$1,728	$1,728	$1,450
Non-battery pack components										
DMC	Minivan/Minivan-towing/Large truck	$2,549	$2,498	$2,448	$2,399	$2,351	$2,304	$2,258	$2,213	$2,169
IC	Minivan/Minivan-towing/Large truck	$1,631	$1,628	$999	$998	$996	$995	$993	$992	$990
TC	Minivan/Minivan-towing/Large truck	$4,180	$4,126	$3,448	$3,397	$3,348	$3,299	$3,252	$3,205	$3,159
Battery-pack and non-battery pack components										
TC	Minivan/Minivan-towing/Large truck	$6,960	$6,457	$5,524	$5,126	$5,076	$5,027	$4,980	$4,933	$4,610

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

3.4.3.6.3 P2 Hybrid

A P2 hybrid is a vehicle with an electric drive motor coupled to the engine crankshaft via a clutch. The engine and the drive motor are mechanically independent of each other, allowing the engine or motor to power the vehicle separately or combined. This is similar to the Honda HEV architecture with the exception of the added clutch, and larger batteries and motors. Examples of this include the Hyundai Sonata HEV and Infiniti M35h. The agencies believe that the P2 is an example of a "strong" hybrid technology that is typical of what we will see in the timeframe of this rule. The agencies could have equally chosen the power-split architecture as the representative HEV architecture. These two HEV's have similar average effectiveness values (combined city and highway fuel economy), though the P2 systems may have lower cost due to the lower number of parts and complexity.

The P2 Hybrid is a newly emerging hybrid technology that uses a transmission integrated electric motor placed between the engine and a gearbox or CVT, much like the IMA system described above except with a wet or dry separation clutch which is used to decouple the motor/transmission from the engine. In addition, a P2 Hybrid would typically be equipped with a larger electric machine. Disengaging the clutch allows all-electric operation and more efficient brake-energy recovery. Engaging the clutch allows efficient coupling of the engine and electric motor and, when combined with a DCT transmission, reduces gear-train losses relative to PSHEV or 2MHEV systems.

For purposes of this rulemaking analysis, the agencies are assuming that P2 hybrids will become the dominant technology in the MYs 2017-2025 timeframe, replacing costlier power-split or 2-mode architectures while providing substantially similar efficiency improvement. At the present time, P2 hybrids are relatively new to the market and the agencies have not attempted to quantify any measurable performance differential between these technologies. As mentioned, the 2011 Hyundai Sonata, 2011 Volkswagen Touareg Hybrid, the 2011 Porsche S Hybrid, and the 2012 Infiniti M35 Hybrid are examples of P2 hybrids currently in production and available to consumers. The agencies are aware of some articles in trade journals, newspapers and other reviews that some first generation P2 hybrid vehicles with planetary gear transmissions have trade-offs in NVH and drivability – though these reviews do not cover all of the P2 systems available today, and a number of reviews are very positive with respect to NVH and drivability. The agencies recognize that manufacturers will have several years to test, develop and improve P2 technology in the years before 2017. We expect that manufacturers will address any perceived integration issues in early production models. However, we believe it is important to continue to monitor development of P2 hybrids and market acceptance of this technology. We will continue to gather information on these issues and consider them as part of the mid-term evaluation.

The agencies request comment regarding the potential of P2 hybrids to overcome these issues or others, and we specifically seek comment from automakers developing and considering P2 technology on whether they believe these to be significant impediments to deployment and how they may be addressed.

The effectiveness used for vehicle packages with the P2-hybrid configuration within this analysis reflects a conservative estimate of system performance. Vehicle simulation modeling of technology packages using the P-2 hybrid has recently been completed under a contract with Ricardo Engineering. The agencies have updated the effectiveness of hybrid electric vehicle packages using the new Ricardo vehicle simulation modeling runs for this analysis.

Due to the lower cost and comparative effectiveness of P2 hybrid in relative to other strong hybrid technologies, such as power-split hybrid and 2-mode hybrid, the agencies assume P2 hybrid application for all vehicle sub-classes in this NPRM analysis and increased HEV effectiveness by approximately 2% comparing to 2012-2016 light duty GHG/CAFE final rule based on published data for new HEVs that have entered into production, such as 2011 Hyundai Sonata hybrid, 2010 Hyundai Elantra LPI HEV (Korean market only), 2011 Infiniti G35 Hybrid and 2011 Volkswagen Touareg Hybrid). In addition, for the Large Car, Minivan and Small Truck subclasses, the agencies further increased HEV effectiveness by assuming that towing capacity could be reduced from their current rating[hh] to approximately 1,500 pounds for some vehicles in these subclasses without significantly impacting consumers' need for utility in these vehicles.[ii] - The agencies believe that consumers for these vehicles who require higher towing capacity could acquire it by purchasing a vehicle with a more capable non-hybrid powertrain (as they do today).[jj] Moreover, it is likely that some fraction of consumers who purchase the larger engine option do so for purposes of hauling and acceleration performance, not just maximum towing.

A reduction in towing capacity allows greater engine downsizing, which increases estimated overall HEV system incremental effectiveness by 5 to 10 percent for Large Cars, Minivans, and Small Trucks, similar to the HEV effectiveness value assumed for Small Cars and Compact Cars.[kk]

Based on the recent Ricardo study, the effectiveness for P2 hybrid used in this NPRM is 46.2 percent for subcompact and compact passenger cars, 48.6 percent for midsize passenger car, 49.4 percent for large passenger car, 46.1 percent for small light truck, 45.7 percent for midsize SUV, truck and minivan and 45.1 percent for large pickup truck.

The agencies have applied a high complexity ICM to both the battery and non-battery component costs for P2 hybrid. But for battery for P2 hybrid, the ICM switches from short

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[hh] Current small SUVs and Minivans have an approximate average towing capacity of 2000 lbs (without a towing package), but range from no towing capacity to 3500 pounds.

[ii] We note that there are some gasoline vehicles in the large car/minivan/small truck segments sold today which do not have any towing rating.

[jj] The agencies recognize that assuming that certain consumers will choose to purchase non-hybrid vehicles in order to obtain their desired towing capacity could lead to some increase in fuel consumption and CO_2 emissions as compared to assuming that towing capacity is maintained for hybrid vehicles across the board. However, the agencies think it likely that the net improvement in fuel consumption and CO_2 emissions due to the increased numbers of hybrids available for consumers to choose will offset any potential increase in fuel consumption and CO_2 emissions resulting from consumers selecting the higher-performance non-hybrid powertrain vehicles.

[kk] The effectiveness of HEVs for heavier vehicles which require conventional towing capabilities is markedly less because the rated power of the IC engine must be similar to its non-hybrid brethren. As such, there is less opportunity for downsizing with these vehicles.

term value of 1.56 to long term value of 1.35 at 2024 while for the non-battery component the switch happens at 2018.

The costs for P2 hybrids without mass reduction as used in the Volpe model are listed in Table 3-48. NHTSA accounts the cost impact from the interaction between mass reduction and sizing of the electrification system (battery and non-battery system) as a cost synergy as described in section 3.4.3.9. Estimated costs for P2 HEVs with mass reduction as used in the OMEGA model are presented in Sections 3.4.3.9 and 3.4.3.10 below.

Table 3-48 NHTSA Costs for P2 Hybrid Applied in Volpe Model without Mass Reduction (2009$)

Tech.	Cost type	NHTSA Vehicle Class	2017	2018	2019	2020	2021	2022	2023	2024	2025
Battery	DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$716	$695	$674	$654	$634	$615	$597	$579	$561
Battery		Midsize PC/Perf PC	$758	$735	$713	$692	$671	$651	$631	$612	$594
Battery	DMC	Large PC/Perf PC	$864	$838	$813	$788	$765	$742	$719	$698	$677
Battery	DMC	Midsize LT Minivan	$929	$901	$874	$848	$822	$798	$774	$750	$728
Battery	DMC	Small LT	$822	$797	$773	$750	$728	$706	$685	$664	$644
Battery	DMC	Large LT	$964	$935	$907	$880	$854	$828	$803	$779	$756
Non-battery	DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$1,467	$1,438	$1,409	$1,381	$1,353	$1,326	$1,300	$1,274	$1,248
Non-battery	DMC	Midsize PC/Perf PC	$1,537	$1,506	$1,476	$1,446	$1,417	$1,389	$1,361	$1,334	$1,307
Non-battery	DMC	Large PC/Perf PC	$1,775	$1,739	$1,705	$1,671	$1,637	$1,604	$1,572	$1,541	$1,510
Non-battery	DMC	Midsize LT Minivan	$1,756	$1,721	$1,687	$1,653	$1,620	$1,588	$1,556	$1,525	$1,494
Non-battery	DMC	Small LT	$1,690	$1,656	$1,623	$1,591	$1,559	$1,528	$1,497	$1,467	$1,438
Non-battery	DMC	Large LT	$1,803	$1,767	$1,732	$1,697	$1,663	$1,630	$1,597	$1,566	$1,534
Battery	IC	Subcompact PC/Perf PC Compact PC/Perf PC	$404	$402	$401	$400	$398	$397	$396	$395	$242
Battery	IC	Midsize PC/Perf PC	$427	$426	$424	$423	$421	$420	$419	$418	$257
Battery	IC	Large PC/Perf PC	$487	$485	$483	$482	$480	$479	$477	$476	$292
Battery	IC	Midsize LT Minivan	$523	$522	$520	$518	$517	$515	$513	$512	$314
Battery	IC	Small LT	$463	$462	$460	$459	$457	$456	$454	$453	$278
Battery	IC	Large LT	$543	$542	$540	$538	$536	$535	$533	$531	$326
Non-battery	IC	Subcompact PC/Perf PC Compact PC/Perf PC	$939	$937	$575	$574	$573	$572	$572	$571	$570
Non-battery	IC	Midsize PC/Perf PC	$983	$981	$602	$601	$601	$600	$599	$598	$597
Non-battery	IC	Large PC/Perf PC	$1,136	$1,133	$696	$695	$694	$693	$692	$691	$690
Non-battery	IC	Midsize LT Minivan	$1,124	$1,121	$688	$687	$686	$685	$684	$683	$682
Non-battery	IC	Small LT	$1,081	$1,079	$663	$662	$661	$660	$659	$658	$657
Non-battery	IC	Large LT	$1,154	$1,151	$707	$706	$705	$704	$703	$702	$701
Battery	TC	Subcompact PC/Perf PC Compact PC/Perf PC	$1,120	$1,097	$1,075	$1,053	$1,032	$1,012	$992	$973	$804
Battery	TC	Midsize PC/Perf PC	$1,185	$1,161	$1,137	$1,114	$1,092	$1,071	$1,050	$1,030	$850
Battery	TC	Large PC/Perf PC	$1,350	$1,323	$1,296	$1,270	$1,245	$1,220	$1,197	$1,174	$969
Battery	TC	Midsize LT Minivan	$1,452	$1,423	$1,394	$1,366	$1,339	$1,313	$1,287	$1,262	$1,042
Battery	TC	Small LT	$1,285	$1,259	$1,233	$1,209	$1,185	$1,162	$1,139	$1,117	$922
Battery	TC	Large LT	$1,508	$1,477	$1,447	$1,418	$1,390	$1,363	$1,336	$1,311	$1,082
Non-battery	TC	Subcompact PC/Perf PC Compact PC/Perf PC	$2,406	$2,375	$1,984	$1,955	$1,927	$1,899	$1,871	$1,845	$1,818
Non-battery	TC	Midsize PC/Perf PC	$2,520	$2,487	$2,078	$2,048	$2,018	$1,989	$1,960	$1,932	$1,904
Non-battery	TC	Large PC/Perf PC	$2,911	$2,873	$2,401	$2,365	$2,331	$2,297	$2,264	$2,232	$2,200
Non-battery	TC	Midsize LT Minivan	$2,880	$2,843	$2,375	$2,340	$2,306	$2,273	$2,240	$2,208	$2,177
Non-battery	TC	Small LT	$2,772	$2,736	$2,286	$2,252	$2,220	$2,187	$2,156	$2,125	$2,095
Non-battery	TC	Large LT	$2,957	$2,919	$2,439	$2,403	$2,368	$2,334	$2,300	$2,267	$2,235

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

3.4.3.6.4 Plug-In Hybrid

Plug-In Hybrid Electric Vehicles (PHEVs) are very similar to Hybrid Electric Vehicles, but with three significant functional differences. The first is the addition of a means to charge the battery pack from an outside source of electricity (*e.g.*, the electric grid). Second, a PHEV would have a larger battery pack with more energy storage, and a greater capability to be discharged. Finally, a PHEV would have a control system that allows the battery pack to be significantly depleted during normal operation.

Table 3-49 below, illustrates how PHEVs compare functionally to both hybrid electric vehicles (HEV) and electric vehicles (EV). These characteristics can change significantly within each vehicle class/subclass, so this is simply meant as an illustration of the general characteristics. In reality, the design options are so varied that all these vehicles exist on a continuum with HEVs on one end and EVs on the other.

Table 3-49 Conventional, HEVs, PHEVs, and EVs Compared

	Increasing Electrification			
Attribute	Conventional	HEV	PHEV	EV
Drive Power	Engine	Blended Engine/Electric	Blended Engine/Electric	Electric
Engine Size	Full Size	Full Size or Smaller	Smaller or Much Smaller	No Engine
Electric Range	None	None to Very Short	Short to Medium	Medium to Long
Battery Charging	None	On-Board	Grid/On-Board	Grid Only

Deriving some of their propulsion energy from the electric grid provides several advantages for PHEVs. PHEVs offer a significant opportunity to replace petroleum used for transportation energy with domestically-produced electricity. The reduction in petroleum usage does, of course, depend on the amount of electric drive the vehicle is capable of under its duty cycle. PHEVs also provide electric utilities the possibility to increase electric generation during “off-peak” periods overnight when there is excess generation capacity and electricity prices are lower. Utilities like to increase this “base load” because it increases overall system efficiency and lowers average costs. PHEVs can lower localized emissions of criteria pollutants and air toxics especially in urban areas by operating on electric power. The emissions from the power generation occur outside the urban area at the power generation plant which provides health benefits for residents of the more densely populated urban areas by moving emissions of ozone precursors out of the urban air shed. Unlike most other alternative fuel technologies, PHEVs can initially use an existing infrastructure for refueling (charging and liquid refueling) so investments in infrastructure may be reduced.

In analyzing the impacts of grid-connected vehicles like PHEVs and EVs, the emissions from the electrical generation can be accounted for if a full upstream and downstream analysis is desired. While this issue is being studied on an on-going basis, upstream CO_2 emissions are not unique to grid-connected technologies and so are not included in this analysis. Sec II of the Preamble has more information on upstream emissions.

PHEVs will be considerably more costly than conventional vehicles and some other advanced technologies due to the fact that PHEVs require both conventional internal combustion engine and electrical driving system and the larger expensive battery pack. To take full advantage of their capability, consumers would have to be willing to charge the vehicles during electricity off-peak hours during the night, and would need access to electric power where they park their vehicles. For many urban dwellers who may park on the street, or in private or public lots or garages, charging may not be practical. Charging may be possible at an owner's place of work, but that would increase grid loading during peak hours which would eliminate some of the benefits to utilities of off-peak charging versus on-peak. Oil savings will still be the same in this case assuming the vehicle can be charged fully.

The effectiveness potential of PHEVs depends on many factors, the most important being the energy storage capacity designed into the battery pack. To estimate the fuel consumption and tailpipe CO_2 reduction potential of PHEVs, EPA has developed an in-house vehicle energy model (PEREGRIN) to estimate the fuel consumption/CO_2 emissions reductions of PHEVs. This model is based on the PERE (Physical Emission Rate Estimator) physics-based model used as a fuel consumption input for EPA's MOVES mobile source emissions model.

How EPA Estimates PHEV Effectiveness

The PHEV small car, large car, minivan and small trucks were modeled using parameters from a midsize car similar to today's hybrids and scaled to each vehicle's weight. The large truck PHEV was modeled separately assuming no engine downsizing. PHEVs can have a wide variation in the All Electric Range (AER) that they offer. Some PHEVs are of the "blended" type where the engine is on during most of the vehicle operation, but the proportion of electric energy that is used to propel the vehicle is significantly higher than that used in a PSHEV or 2MHEV. Each PHEV was modeled with enough battery capacity for a 20-mile-equivalent AER and a power requirement to provide similar performance to a hybrid vehicle. 20 miles was selected because it offers a good compromise for vehicle performance, weight, battery packaging and cost. Given expected near-term battery capability, a 20 mile range represents the likely capability that will be seen in PHEVs in the near-to-mid term.

To calculate the total energy use of a PHEV, the PHEV can be thought of as operating in two distinct modes, electric (EV) mode, and hybrid (HEV) mode. At the tailpipe, the CO_2 emissions during EV operation are zero. The EV mode fuel economy can then be combined with the HEV mode fuel economy using the Utility Factor calculation in SAE J1711 to determine a total MPG value for the vehicle. (See Table 3-50)

Table 3-50 Sample Calculation of PHEV Gasoline-Equivalent CO_2 Reduction

	Midsize Car	Large Truck
EV energy comb (0.55 city / 0.45 hwy)	0.252 kwh/mi	0.429 kwh/mi

EV range (from PEREGRIN)	20 miles	20 miles
SAE J1711 utility factor	0.30	0.30
HEV mode comb FE (0.55 city / 0.45 hwy)	49.1 mpg	25.6 mpg
Total UF-adjusted FE (UF*FCEV + (1-UF)*FCHEV)	70.1 mpg	36.6 mpg
Baseline FE	29.3 mpg	19.2 mpg
Percent FE gain	139%	90%
Percent CO_2 reduction	-58%	-47%

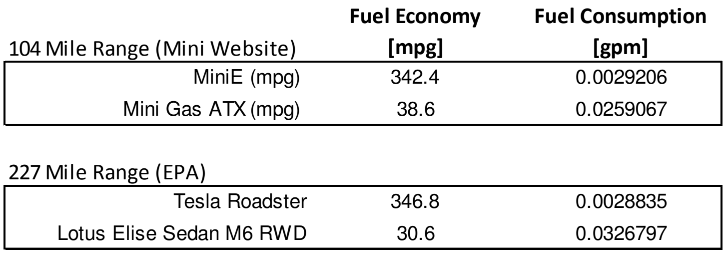
Calculating a total fuel consumption and tailpipe CO_2 reduction based on model outputs and the Utility Factor calculations results in a 58 percent reduction for small cars, large cars, minivans, and small trucks. For large trucks, the result is a 47 percent reduction. The lower improvement is due to less engine downsizing in the large truck class.

How NHTSA Estimates PHEV Effectiveness

For CAFE calculation, PHEV is treated as a dual fuel vehicle. NHTSA needs to consider using dual fuel vehicle calculation for PHEV and uses a petroleum equivalency factor as stated in 49 U.S.C. 32904 and 32905.

When deciding PHEV and EV effectiveness, NHTSA referenced the fuel economy of 3 pairs of vehicles for which NHTSA has fuel economy data in the CAFE database. These three vehicles pairs are MiniE electric vehicle versus gasoline powered Mini with automatic transmission, Tesla Roadster electric vehicle versus gasoline powered rear-wheel-drive Lotus Elise Sedan with a 6-speed manual transmission, and Nissan Leaf electric vehicle versus gasoline powered Nissan Sentra with automatic transmission. The fuel economy and fuel consumption for the first two pairs are shown in Table 3-51. Nissan Leaf information is used but not shown in the table because it is confidential information. Because technologies are applied in the CAFE model in an incremental manner, the effectiveness for each technology is incremental to the previous technology. In the electrification decision tree of the CAFE model, the order of technology selection starts from gasoline only powertrain, then moves to strong hybrid, to plug-in hybrid electric vehicle, and finally to electric vehicle. So the incremental effectiveness for each step has to be defined.

Table 3-51 EV Fuel Economy and Fuel Consumption



104 Mile Range (Mini Website)	Fuel Economy [mpg]	Fuel Consumption [gpm]
MiniE (mpg)	342.4	0.0029206
Mini Gas ATX (mpg)	38.6	0.0259067
227 Mile Range (EPA)		
Tesla Roadster	346.8	0.0028835
Lotus Elise Sedan M6 RWD	30.6	0.0326797

In order to calculate the effectiveness of PHEV for purposes of a CAFE standard, fuel economy for strong hybrid electric vehicle (SHEV) is calculated first using the incremental effectiveness of strong hybrid from LPM model which is around 46 percent. For an example, the derived fuel economy for SHEV based on Mini Gas ATX is 71.7 mpg. Then the fuel economy from gasoline source for PHEV is assumed to be the same as SHEV fuel economy, i.e. 71.7 mpg in the case of Mini E. The petroleum equivalent fuel economy from the electricity source is set to be the same as the EV fuel economy, i.e. 342.4 mpg in the case of Mini E. The combined fuel economy for PHEV is calculated using the 50-50 weighting factor as follows.

$$PHEV\ Combined\ Fuel\ Economy = \frac{1}{\frac{Gasoline\ FE\ Weighing\ Factor}{Gasoline\ Fuel\ Economy} + \frac{Electric\ FE\ Weighing\ Factor}{EV\ Fuel\ Economy}}$$

$$= \frac{1}{\frac{0.5}{71.7} + \frac{0.5}{342.4}} = 118.6\ mpg$$

NHTSA decided to use a 50-50 weighing factor in the calculation above by modeling a 30-mile range PHEV. According to SAE standard J1711, a vehicle with 27.4 to 28.2 mile charge depleting range has a 0.5 utility factor. This utility factor value of 0.5 is equivalent to 50-50 weighting for dual fuel vehicle calculation. In the NPRM analysis, EPA models a 20-mile range and a 40-mile range PHEV.

The incremental fuel consumption reduction for PHEV is then calculated in relative to strong HEV. Using the example of Mini E, the incremental fuel consumption reduction for PHEV relative to SHEV is 39.5 percent as shown below.

$$Incremental\ Fuel\ Consumption\ Reduction\ for\ PHEV = \frac{\left(\frac{1}{PHEV\ Fuel\ Economy} - \frac{1}{SHEV\ Fuel\ Economy}\right)}{\frac{1}{SHEV\ Fuel\ Economy}} x100\%$$

$$= \frac{\left(\frac{1}{118.6} - \frac{1}{71.7}\right)}{\frac{1}{71.7}} x100\% = -39.5\%$$

Table 3-52 lists the incremental effectiveness calculation for two pairs of vehicles, MiniE and Tesla Roaster. Incremental fuel consumption calculation for PHEV based on Nissan Leaf is not shown in Table 3-52 due to confidentiality of the fuel economy rating. The derived incremental effectiveness for Nissan Leaf is 40.6%. The average incremental effectiveness of these three pairs of vehicles is 40.65 percent which is used in CAFE modeling.

Table 3-52 Incremental Effectiveness Calculation for purposes of CAFE modeling

Mini E

	Gasoline	SHEV2	PHEV1	EV1
Combined Fuel Economy [mpg]	***38.6***	71.7	118.6	***342.4***
Gasoline Fuel Economy [mpg]		71.7	71.7	
Electric Petroleum Equivalent Fuel Economy [mpg]			342.4	
Combined Fuel Consumption[gpm]		0.0139414	0.0084310	0.0029206
Gasoline Fuel Consumption [gpm]		0.0139414	0.0139414	
Incremental Combined Fuel Consumption [%]			**39.5%**	**65.4%**
Gasoline Weighing Factor[%]			50%	0%
Electricity Weighing Factor [%]			50%	100%

Tesla

	Gasoline	SHEV2	PHEV1	EV1
Combined Fuel Economy [mpg]	***30.6***	56.7	97.4	***346.8***
Gasoline Fuel Economy [mpg]		56.7	56.7	
Electric Petroleum Equivalent Fuel Economy [mpg]			346.8	
Combined Fuel Consumption[gpm]		0.017647	0.0102653	0.0028835
Gasoline Fuel Consumption [gpm]		0.017647	0.0176471	
Incremental Combined Fuel Consumption [%]			**41.8%**	**71.9%**
Gasoline Weighing Factor[%]			50%	0%
Electricity Weighing Factor [%]			50%	100%

Once the fuel economy of the PHEV is calculated, the effectiveness of PHEV incremental to EV can be calculated similarly using the formula below.

$$Incremental\ Fuel\ Consumption\ Improvement\ for\ EV$$
$$= \frac{\left(\frac{1}{EV\ Fuel\ Economy} - \frac{1}{PHEV\ Fuel\ Economy}\right)}{\frac{1}{PHEV\ Fuel\ Economy}} x100\%$$

The average effectiveness for the three pairs of vehicles of 68.54% is used in CAFE modeling.

The cost of PHEV consists of three parts, the cost for battery, the cost for non-battery systems and the cost for charger and the labor to install it. Costs for PHEVs without mass reduction as used in the Volpe model are listed in Table 3-53 to Table 3-55. NHTSA accounts the cost impact from the interaction between mass reduction and sizing of the electrification system (battery and non-battery system) as a cost synergy as described in section 3.4.3.9. Sections 3.4.3.9 and 3.4.3.10 contain the cost for PHEVs with mass reduction as used in EPA's OMEGA model. PHEV20 and PHEV40 are sized by EPA with the methodologies discussed in section 3.4.3.8.

The battery pack DMCs for PHEV20 and PHEV40 are calculated using ANL's BatPac model. NHTSA modeled a PHEV 30 for this proposal, for which NHTSA averaged the costs of PHEV20s and PHEV40s.

The agencies have applied a high complexity ICM to non-battery component cost for PHEV and PHEV charger, which switch from short term value of 1.56 to long term value of 1.35 at 2018. The agencies applied a higher ICM factor to the battery of PHEV due to the fact that it a more complex technology. The ICM for PHEV battery switches from short term value of 1.77 to long term value of 1.50 at 2024.

Table 3-53 NHTSA Costs for PHEV20 Applied in the Volpe Model with No Mass Reduction (2009$)

Tech.	Cost type	NHTSA Vehicle Class	2017	2018	2019	2020	2021	2022	2023	2024	2025
Battery	DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$5,082	$4,066	$4,066	$3,253	$3,253	$3,253	$3,253	$3,253	$2,602
Battery		Midsize PC/Perf PC	$5,363	$4,291	$4,291	$3,433	$3,433	$3,433	$3,433	$3,433	$2,746
Battery	DMC	Large PC/Perf PC	$6,505	$5,204	$5,204	$4,163	$4,163	$4,163	$4,163	$4,163	$3,331
Non-battery	DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$2,556	$2,505	$2,455	$2,406	$2,358	$2,311	$2,264	$2,219	$2,175
Non-battery	DMC	Midsize PC/Perf PC	$2,820	$2,764	$2,709	$2,654	$2,601	$2,549	$2,498	$2,448	$2,399
Non-battery	DMC	Large PC/Perf PC	$3,903	$3,825	$3,749	$3,674	$3,600	$3,528	$3,458	$3,389	$3,321
Charger	DMC	All	$59	$47	$47	$38	$38	$38	$38	$38	$30
Charger Labor	DMC	All	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000
Battery	IC	Subcompact PC/Perf PC Compact PC/Perf PC	$2,186	$2,112	$2,112	$2,052	$2,052	$2,052	$2,052	$2,052	$1,292
Battery	IC	Midsize PC/Perf PC	$2,307	$2,228	$2,228	$2,165	$2,165	$2,165	$2,165	$2,165	$1,364
Battery	IC	Large PC/Perf PC	$2,798	$2,703	$2,703	$2,626	$2,626	$2,626	$2,626	$2,626	$1,654
Non-battery	IC	Subcompact PC/Perf PC Compact PC/Perf PC	$1,635	$1,632	$1,002	$1,000	$999	$997	$996	$995	$993
Non-battery	IC	Midsize PC/Perf PC	$1,804	$1,801	$1,106	$1,104	$1,102	$1,101	$1,099	$1,097	$1,096
Non-battery	IC	Large PC/Perf PC	$2,497	$2,492	$1,530	$1,528	$1,525	$1,523	$1,521	$1,519	$1,517
Charger	IC	All	$19	$18	$18	$17	$17	$17	$17	$17	$10
Charger Labor	IC	All	$0	$0	$0	$0	$0	$0	$0	$0	$0
Battery	TC	Subcompact PC/Perf PC Compact	$7,269	$6,177	$6,177	$5,304	$5,304	$5,304	$5,304	$5,304	$3,894

		PC/Perf PC									
Battery	TC	Midsize PC/Perf PC	$7,671	$6,519	$6,519	$5,598	$5,598	$5,598	$5,598	$5,598	$4,110
Battery	TC	Large PC/Perf PC	$9,303	$7,907	$7,907	$6,789	$6,789	$6,789	$6,789	$6,789	$4,985
Non-battery	TC	Subcompact PC/Perf PC Compact PC/Perf PC	$4,191	$4,137	$3,457	$3,406	$3,357	$3,308	$3,260	$3,214	$3,168
Non-battery	TC	Midsize PC/Perf PC	$4,625	$4,565	$3,814	$3,758	$3,704	$3,650	$3,597	$3,546	$3,495
Non-battery	TC	Large PC/Perf PC	$6,401	$6,318	$5,279	$5,202	$5,126	$5,052	$4,979	$4,907	$4,837
Charger	TC	All	$77	$65	$65	$55	$55	$55	$55	$55	$40
Charger Labor	TC	All	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-54 NHTSA Costs for PHEV40 Applied in the Volpe Model with No Mass Reduction (2009$)

Tech.	Cost type	NHTSA Vehicle Class	2017	2018	2019	2020	2021	2022	2023	2024	2025
Battery	DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$7,126	$5,701	$5,701	$4,561	$4,561	$4,561	$4,561	$4,561	$3,649
Battery		Midsize PC/Perf PC	$7,884	$6,307	$6,307	$5,046	$5,046	$5,046	$5,046	$5,046	$4,037
Battery	DMC	Large PC/Perf PC	$10,140	$8,112	$8,112	$6,490	$6,490	$6,490	$6,490	$6,490	$5,192
Non-battery	DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$2,557	$2,506	$2,455	$2,406	$2,358	$2,311	$2,265	$2,220	$2,175
Non-battery	DMC	Midsize PC/Perf PC	$2,820	$2,763	$2,708	$2,654	$2,601	$2,549	$2,498	$2,448	$2,399
Non-battery	DMC	Large PC/Perf PC	$3,902	$3,824	$3,748	$3,673	$3,599	$3,527	$3,457	$3,388	$3,320
Charger	DMC	All	$357	$286	$286	$229	$229	$229	$229	$229	$183
Charger Labor	DMC	All	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000
Battery	IC	Subcompact PC/Perf PC Compact PC/Perf PC	$3,066	$2,112	$2,112	$2,052	$2,052	$2,052	$2,052	$2,052	$1,292
Battery	IC	Midsize PC/Perf PC	$3,392	$2,228	$2,228	$2,165	$2,165	$2,165	$2,165	$2,165	$1,364
Battery	IC	Large PC/Perf PC	$4,362	$2,703	$2,703	$2,626	$2,626	$2,626	$2,626	$2,626	$1,654
Non-battery	IC	Subcompact PC/Perf PC Compact	$1,636	$1,632	$1,002	$1,001	$999	$998	$996	$995	$993

		PC/Perf PC									
Non-battery	IC	Midsize PC/Perf PC	$1,804	$1,800	$1,105	$1,104	$1,102	$1,100	$1,099	$1,097	$1,096
Non-battery	IC	Large PC/Perf PC	$2,496	$2,491	$1,530	$1,527	$1,525	$1,523	$1,520	$1,518	$1,516
Charger	IC	All	$114	$110	$110	$106	$106	$106	$106	$106	$63
Charger Labor	IC	All	$0	$0	$0	$0	$0	$0	$0	$0	$0
Battery	TC	Subcompact PC/Perf PC Compact PC/Perf PC	$10,191	$7,812	$7,812	$6,612	$6,612	$6,612	$6,612	$6,612	$4,941
Battery	TC	Midsize PC/Perf PC	$11,276	$8,536	$8,536	$7,211	$7,211	$7,211	$7,211	$7,211	$5,400
Battery	TC	Large PC/Perf PC	$14,502	$10,815	$10,815	$9,116	$9,116	$9,116	$9,116	$9,116	$6,846
Non-battery	TC	Subcompact PC/Perf PC Compact PC/Perf PC	$4,192	$4,138	$3,458	$3,407	$3,357	$3,309	$3,261	$3,214	$3,168
Non-battery	TC	Midsize PC/Perf PC	$4,624	$4,564	$3,813	$3,758	$3,703	$3,649	$3,596	$3,545	$3,494
Non-battery	TC	Large PC/Perf PC	$6,399	$6,316	$5,277	$5,200	$5,124	$5,050	$4,977	$4,906	$4,836
Charger	TC	All	$472	$396	$396	$335	$335	$335	$335	$335	$246
Charger Labor	TC	All	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-55 NHTSA Costs Applied in Volpe Model for PHEV30 with No Mass Reduction (2009$)

Tech.	Cost type	NHTSA Vehicle Class	2017	2018	2019	2020	2021	2022	2023	2024	2025
Battery	DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$6,104	$4,883	$4,883	$3,907	$3,907	$3,907	$3,907	$3,907	$3,125
Battery		Midsize PC/Perf PC	$6,624	$5,299	$5,299	$4,239	$4,239	$4,239	$4,239	$4,239	$3,391
Battery	DMC	Large PC/Perf PC	$8,323	$6,658	$6,658	$5,327	$5,327	$5,327	$5,327	$5,327	$4,261
Non-battery	DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$2,556	$2,505	$2,455	$2,406	$2,358	$2,311	$2,265	$2,219	$2,175
Non-battery	DMC	Midsize PC/Perf PC	$2,820	$2,764	$2,708	$2,654	$2,601	$2,549	$2,498	$2,448	$2,399
Non-battery	DMC	Large PC/Perf PC	$3,903	$3,825	$3,748	$3,673	$3,600	$3,528	$3,457	$3,388	$3,320
Charger	DMC	All	$208	$166	$166	$133	$133	$133	$133	$133	$107

Charger Labor	DMC	All	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000
Battery	IC	Subcompact PC/Perf PC Compact PC/Perf PC	$2,626	$2,112	$2,112	$2,052	$2,052	$2,052	$2,052	$2,052	$1,292
Battery	IC	Midsize PC/Perf PC	$2,849	$2,228	$2,228	$2,165	$2,165	$2,165	$2,165	$2,165	$1,364
Battery	IC	Large PC/Perf PC	$3,580	$2,703	$2,703	$2,626	$2,626	$2,626	$2,626	$2,626	$1,654
Non-battery	IC	Subcompact PC/Perf PC Compact PC/Perf PC	$1,635	$1,632	$1,002	$1,001	$999	$998	$996	$995	$993
Non-battery	IC	Midsize PC/Perf PC	$1,804	$1,800	$1,105	$1,104	$1,102	$1,100	$1,099	$1,097	$1,096
Non-battery	IC	Large PC/Perf PC	$2,497	$2,492	$1,530	$1,528	$1,525	$1,523	$1,521	$1,518	$1,516
Charger	IC	All	$67	$64	$64	$62	$62	$62	$62	$62	$37
Charger Labor	IC	All	$0	$0	$0	$0	$0	$0	$0	$0	$0
Battery	TC	Subcompact PC/Perf PC Compact PC/Perf PC	$8,730	$6,995	$6,995	$5,958	$5,958	$5,958	$5,958	$5,958	$4,418
Battery	TC	Midsize PC/Perf PC	$9,473	$7,527	$7,527	$6,404	$6,404	$6,404	$6,404	$6,404	$4,755
Battery	TC	Large PC/Perf PC	$11,903	$9,361	$9,361	$7,952	$7,952	$7,952	$7,952	$7,952	$5,915
Non-battery	TC	Subcompact PC/Perf PC Compact PC/Perf PC	$4,192	$4,137	$3,457	$3,407	$3,357	$3,308	$3,261	$3,214	$3,168
Non-battery	TC	Midsize PC/Perf PC	$4,624	$4,564	$3,814	$3,758	$3,703	$3,649	$3,597	$3,545	$3,495
Non-battery	TC	Large PC/Perf PC	$6,400	$6,317	$5,278	$5,201	$5,125	$5,051	$4,978	$4,907	$4,837
Charger	TC	All	$275	$230	$230	$195	$195	$195	$195	$195	$143
Charger Labor	TC	All	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

3.4.3.6.5 Electric vehicles

Electric vehicles (EV) – are vehicles with all-electric drive and with vehicle systems powered by energy-optimized batteries charged primarily from grid electricity. While the 2016 FRM did not anticipate a significant penetration of EVs, in this analysis, EVs with several ranges have been included. The GHG effectiveness is unchanged from estimates used for 2016 model year vehicles in the 2012-2016 final rule which is 100 percent GHG reduction. NHTSA uses petroleum equivalency factor in calculating the effectiveness for EVs as stated in the section above for PHEV.

Once the fuel economy of the PHEV is calculated as shown in the previous section, the effectiveness of PHEV incremental to EV can be calculated similarly using the formula below.

$$Incremental\ Fuel\ Consumption\ Improvement\ for\ EV = \frac{\left(\frac{1}{EV\ Fuel\ Economy} - \frac{1}{PHEV\ Fuel\ Economy}\right)}{\frac{1}{PHEV\ Fuel\ Economy}} x100\%$$

The average effectiveness for the three pairs of vehicles of 68.54% is used in CAFE modeling.

Battery costs assume that battery packs for EV applications will be designed to last for the full useful life of the vehicle at a useable state of charge equivalent to 80% of the nominal battery pack capacity. NHTSA applied a 75-mile range EV and a 150-mile range EV in this NPRM analysis. As this technology is entering the market, the OEM will try to keep the cost low at the beginning so that there will be more penetration. Due to the high cost of the battery packs at this early stage of EVs, OEM will try to limit the battery pack size to reduce cost. Also the early adopters for this technology are normally urban drivers and range anxiety is not a big concern to them. Therefore NHTSA applied a 75-mile range EV for early adoption of this technology in the market. As the technology develops and as the market penetration increases, OEMs need to help the consumers overcome the range anxiety and longer driving range will be expected. NHTSA applied 150-mile EV for this broad market adoption of this technology.

The cost of an EV consists of three parts, cost of battery pack, cost of non-battery systems, and cost of charger and charger installation labor. The agencies have applied a high complexity ICM to non-battery component cost for EVs and EV chargers, which switch from short term value of 1.56 to long term value of 1.35 at 2018. The agencies applied a higher ICM factor to the battery of EVs due to the fact that it a more complex technology. The ICM for EV battery switches from short term value of 1.77 to long term value of 1.50 at 2024. The agencies present costs of EVs in Sections 3.4.3.9 and 3.4.3.10. The costs of EVs without mass reduction as applied in Volpe model are listed in Table 3-56 to Table 3-58. NHTSA accounts the cost impact from the interaction between mass reduction and sizing of electrification system (battery and non-battery system) as cost synergy as described in section 3.4.3.9.

Table 3-56 NHTSA Costs Applied in Volpe Model for EV75 with No Mass Reduction (2009$)

Tech.	Cost type	NHTSA Vehicle Class	2017	2018	2019	2020	2021	2022	2023	2024	2025
Battery	DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$10,594	$8,475	$8,475	$6,780	$6,780	$6,780	$6,780	$6,780	$5,424

Battery		Midsize PC/Perf PC	$11,500	$9,200	$9,200	$7,360	$7,360	$7,360	$7,360	$7,360	$5,888
Battery	DMC	Large PC/Perf PC	$14,009	$11,207	$11,207	$8,966	$8,966	$8,966	$8,966	$8,966	$7,173
Non-battery	DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$411	$399	$387	$375	$364	$353	$346	$339	$332
Non-battery	DMC	Midsize PC/Perf PC	$749	$727	$705	$684	$663	$643	$630	$618	$605
Non-battery	DMC	Large PC/Perf PC	$1,255	$1,217	$1,181	$1,145	$1,111	$1,077	$1,056	$1,035	$1,014
Charger	DMC	All	$391	$313	$313	$250	$250	$250	$250	$250	$200
Charger Labor	DMC	All	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000
Battery	IC	Subcompact PC/Perf PC Compact PC/Perf PC	$4,557	$4,401	$4,401	$4,277	$4,277	$4,277	$4,277	$4,277	$2,694
Battery	IC	Midsize PC/Perf PC	$4,947	$4,778	$4,778	$4,642	$4,642	$4,642	$4,642	$4,642	$2,924
Battery	IC	Large PC/Perf PC	$6,027	$5,820	$5,820	$5,655	$5,655	$5,655	$5,655	$5,655	$3,562
Non-battery	IC	Subcompact PC/Perf PC Compact PC/Perf PC	$317	$316	$315	$314	$313	$312	$312	$311	$200
Non-battery	IC	Midsize PC/Perf PC	$577	$575	$574	$572	$570	$569	$568	$567	$365
Non-battery	IC	Large PC/Perf PC	$966	$963	$961	$958	$956	$953	$952	$950	$611
Charger	IC	All	$114	$110	$110	$106	$106	$106	$106	$106	$63
Charger Labor	IC	All	$0	$0	$0	$0	$0	$0	$0	$0	$0
Battery	TC	Subcompact PC/Perf PC Compact PC/Perf PC	$15,152	$12,877	$12,877	$11,057	$11,057	$11,057	$11,057	$11,057	$8,118
Battery	TC	Midsize PC/Perf PC	$16,447	$13,978	$13,978	$12,002	$12,002	$12,002	$12,002	$12,002	$8,812
Battery	TC	Large PC/Perf PC	$20,036	$17,028	$17,028	$14,621	$14,621	$14,621	$14,621	$14,621	$10,735
Non-battery	TC	Subcompact PC/Perf PC Compact PC/Perf PC	$728	$714	$702	$689	$677	$665	$658	$650	$533
Non-battery	TC	Midsize PC/Perf PC	$1,326	$1,302	$1,278	$1,256	$1,234	$1,212	$1,198	$1,185	$970
Non-battery	TC	Large PC/Perf PC	$2,221	$2,180	$2,141	$2,103	$2,066	$2,031	$2,007	$1,985	$1,625
Charger	TC	All	$505	$422	$422	$356	$356	$356	$356	$356	$263
Charger Labor	TC	All	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-57 NHTSA Costs for EV100 Applied in Volpe Model with No Mass Reduction (2009$)

Tech.	Cost type	NHTSA Vehicle Class	2017	2018	2019	2020	2021	2022	2023	2024	2025
Battery	DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$12,422	$9,938	$9,938	$7,950	$7,950	$7,950	$7,950	$7,950	$6,360
Battery		Midsize PC/Perf PC	$13,679	$10,943	$10,943	$8,755	$8,755	$8,755	$8,755	$8,755	$7,004
Battery	DMC	Large PC/Perf PC	$15,823	$12,658	$12,658	$10,127	$10,127	$10,127	$10,127	$10,127	$8,101
Non-battery	DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$413	$400	$388	$377	$365	$354	$347	$340	$334
Non-battery	DMC	Midsize PC/Perf PC	$748	$726	$704	$683	$662	$642	$630	$617	$605
Non-battery	DMC	Large PC/Perf PC	$1,253	$1,216	$1,179	$1,144	$1,109	$1,076	$1,055	$1,033	$1,013
Charger	DMC	All	$391	$313	$313	$250	$250	$250	$250	$250	$200
Charger Labor	DMC	All	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000
Battery	IC	Subcompact PC/Perf PC Compact PC/Perf PC	$5,344	$5,161	$5,161	$5,015	$5,015	$5,015	$5,015	$5,015	$3,159
Battery	IC	Midsize PC/Perf PC	$5,884	$5,683	$5,683	$5,522	$5,522	$5,522	$5,522	$5,522	$3,478
Battery	IC	Large PC/Perf PC	$6,807	$6,574	$6,574	$6,387	$6,387	$6,387	$6,387	$6,387	$4,023
Non-battery	IC	Subcompact PC/Perf PC Compact PC/Perf PC	$318	$317	$316	$315	$314	$313	$313	$312	$201
Non-battery	IC	Midsize PC/Perf PC	$576	$574	$573	$571	$570	$568	$567	$566	$365
Non-battery	IC	Large PC/Perf PC	$965	$962	$959	$957	$954	$952	$950	$949	$611
Charger	IC	All	$125	$120	$120	$116	$116	$116	$116	$116	$69
Charger Labor	IC	All	$0	$0	$0	$0	$0	$0	$0	$0	$0
Battery	TC	Subcompact PC/Perf PC Compact PC/Perf PC	$17,766	$15,099	$15,099	$12,965	$12,965	$12,965	$12,965	$12,965	$9,519
Battery	TC	Midsize PC/Perf PC	$19,563	$16,626	$16,626	$14,276	$14,276	$14,276	$14,276	$14,276	$10,482
Battery	TC	Large PC/Perf PC	$22,630	$19,232	$19,232	$16,514	$16,514	$16,514	$16,514	$16,514	$12,125
Non-battery	TC	Subcompact PC/Perf PC Compact	$730	$717	$704	$692	$680	$668	$660	$653	$535

		PC/Perf PC									
Non-battery	TC	Midsize PC/Perf PC	$1,324	$1,300	$1,277	$1,254	$1,232	$1,211	$1,197	$1,183	$969
Non-battery	TC	Large PC/Perf PC	$2,218	$2,178	$2,139	$2,101	$2,064	$2,028	$2,005	$1,982	$1,623
Charger	TC	All	$516	$432	$432	$366	$366	$366	$366	$366	$269
Charger Labor	TC	All	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-58 NHTSA Costs for EV150 Applied in Volpe Model with No Mass Reduction (2009$)

Cost type	NHTSA Vehicle Class	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$16,195	$12,956	$12,956	$10,365	$10,365	$10,365	$10,365	$10,365	$8,292
	Midsize PC/Perf PC	$17,944	$14,355	$14,355	$11,484	$11,484	$11,484	$11,484	$11,484	$9,187
DMC	Large PC/Perf PC	$21,463	$17,170	$17,170	$13,736	$13,736	$13,736	$13,736	$13,736	$10,989
DMC	Subcompact PC/Perf PC Compact PC/Perf PC	$415	$403	$391	$379	$368	$357	$350	$343	$336
DMC	Midsize PC/Perf PC	$746	$723	$702	$681	$660	$640	$628	$615	$603
DMC	Large PC/Perf PC	$1,254	$1,216	$1,180	$1,144	$1,110	$1,077	$1,055	$1,034	$1,014
DMC	All	$391	$313	$313	$250	$250	$250	$250	$250	$200
DMC	All	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000
IC	Subcompact PC/Perf PC Compact PC/Perf PC	$6,967	$6,728	$6,728	$6,538	$6,538	$6,538	$6,538	$6,538	$4,118
IC	Midsize PC/Perf PC	$7,719	$7,455	$7,455	$7,243	$7,243	$7,243	$7,243	$7,243	$4,562
IC	Large PC/Perf PC	$9,233	$8,917	$8,917	$8,664	$8,664	$8,664	$8,664	$8,664	$5,457
IC	Subcompact PC/Perf PC Compact PC/Perf PC	$320	$319	$318	$317	$316	$315	$315	$314	$202
IC	Midsize PC/Perf PC	$574	$573	$571	$570	$568	$567	$566	$565	$363
IC	Large PC/Perf PC	$966	$963	$960	$958	$955	$953	$951	$949	$611
IC	All	$125	$120	$120	$116	$116	$116	$116	$116	$69

IC	All	$0	$0	$0	$0	$0	$0	$0	$0	$0
TC	Subcompact PC/Perf PC Compact PC/Perf PC	$23,162	$19,684	$19,684	$16,902	$16,902	$16,902	$16,902	$16,902	$12,410
TC	Midsize PC/Perf PC	$25,663	$21,810	$21,810	$18,727	$18,727	$18,727	$18,727	$18,727	$13,750
TC	Large PC/Perf PC	$30,696	$26,087	$26,087	$22,400	$22,400	$22,400	$22,400	$22,400	$16,446
TC	Subcompact PC/Perf PC Compact PC/Perf PC	$735	$722	$709	$696	$684	$672	$664	$657	$538
TC	Midsize PC/Perf PC	$1,320	$1,296	$1,273	$1,250	$1,228	$1,207	$1,193	$1,180	$966
TC	Large PC/Perf PC	$2,220	$2,179	$2,140	$2,102	$2,065	$2,029	$2,006	$1,984	$1,625
TC	All	$516	$432	$432	$366	$366	$366	$366	$366	$269
TC	All	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000

3.4.3.6.6 Fuel cell electric vehicles

Fuel cell electric vehicles (FCEVs) – utilize a full electric drive platform but consume electricity generated by an on-board fuel cell and hydrogen fuel. Fuel cells are electro-chemical devices that directly convert reactants (hydrogen and oxygen via air) into electricity, with the potential of achieving more than twice the efficiency of conventional internal combustion engines. High pressure gaseous hydrogen storage tanks are used by most automakers for FCEVs that are currently under development. The high pressure tanks are similar to those used for compressed gas storage in more than 10 million CNG vehicles worldwide, except that they are designed to operate at a higher pressure (350 bar or 700 bar vs. 250 bar for CNG). Due to the uncertainty of the future availability for this technology, FCEVs were not included in any OMEGA or Volpe model runs.

3.4.3.7 Batteries for MHEV, HEV, PHEV and EV Applications

The design of battery secondary cells can vary considerably between MHEV, HEV, PHEV and EV applications.

MHEV batteries: Due to their lower voltage (12-42 VDC) and reduced power and energy requirements, MHEV systems may continue to use lead-acid batteries even long term (2017 model year and later). MHEV battery designs differ from those of current starved-electrolyte (typical maintenance free batteries) or flooded-electrolyte (the older style lead-acid batteries requiring water “top-off”) batteries used for starting, lighting and ignition (SLI) in automotive applications. Standard SLI batteries are primarily designed to provide high-current for engine start-up and then recharge immediately after startup via the vehicle's charging system. Deeply discharging a standard SLI battery will greatly shorten its life. MHEV applications are expected to use:

- Extended-cycle-life flooded (ELF) lead-acid batteries
- Absorptive glass matt, valve-regulated lead-acid (AGM/VRLA) batteries –or –
- Asymmetric lead-acid battery/capacitor hybrids (*e.g.*, flooded ultrabatteries)

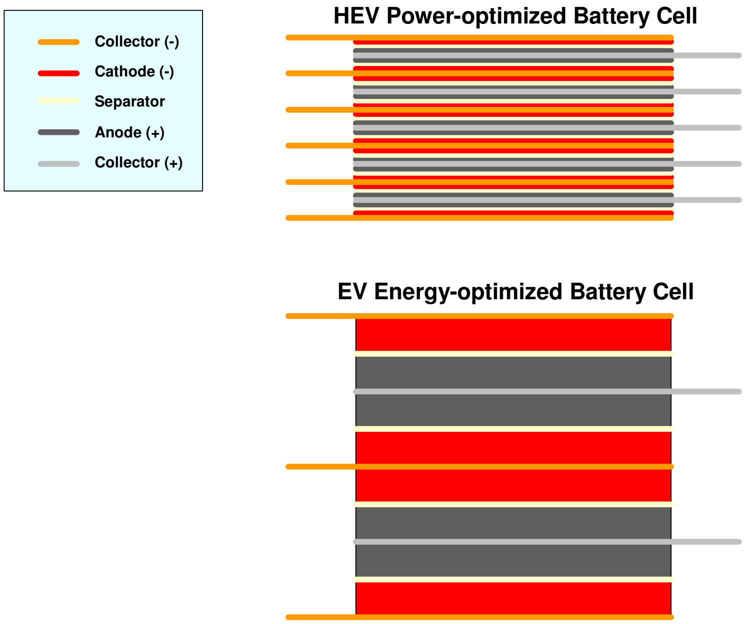
MHEV systems using electrolytic double-layer capacitors are also under development and may provide improved performance and reduced cost in the post-2017 timeframe.

HEV batteries: HEV applications operate in a narrow, short-cycling, charge-sustaining state of charge (SOC). Energy capacity in HEV applications is somewhat limited by the ability of the battery and power electronics to accept charge and by space and weight constraints within the vehicle design. HEV battery designs tend to be optimized for high power density rather than high energy density, with thinner cathode and anode layers and more numerous current collectors and separators (Figure 3-20).

EV batteries: EV batteries tend to be optimized for high energy density and are considerably larger and heavier than HEV batteries in order to provide sufficient energy capacity. EV battery cells tend to have thicker cathode and anode layers and fewer collectors and separators than HEV cells. This reduced the specific cost on a per-kW-hr basis for EV battery cells relative to HEV battery cells.

PHEV batteries: PHEV battery designs are intermediate between power-optimized HEV and energy-optimized EV battery cell designs. PHEV batteries must provide both charge depleting operation similar to an EV and charge sustaining operation similar to an HEV. Unlike HEV applications, charge-sustaining operation with PHEVs occurs at a relatively low battery state of charge (SOC) which can pose a significant challenge with respect to attaining acceptable battery cycle life. In the case of the GM Volt, this limits charge depleting operation to a minimum SOC of approximately 30 percent.[55] An alternative approach for PHEV applications that has potential to allow extension of charge depletion to a lower battery SOC is using energy-optimized lithium-ion batteries for charge depleting operation in combination with the use of supercapacitors for charge sustaining operation.[56]

Figure 3-20: Schematic representation of power and energy optimized prismatic-layered battery cells



Power-split hybrid vehicles from Toyota, Ford and Nissan (which uses the Toyota system under license), integrated motor assist hybrid vehicles from Honda and the GM 2-mode hybrid vehicles currently use nickel-metal hydride (NiMH) batteries. Lithium-ion (Li-ion) batteries offer the potential to approximately double both the energy and power density relative to current NiMH batteries, enabling much more electrical-energy-intensive automotive applications such as PHEVs and EVs.

Li-ion batteries for high-volume automotive applications differ substantially from those used in consumer electronics applications with respect to cathode chemistry, construction and cell size. Li-ion battery designs currently in production by CPI (LG-Chem) for the GM Volt PHEV and by AESC and GS-Yuasa (respectively) for the Nissan Leaf and Mitsubishi i-Miev use large-format, layered-prismatic cells assembled into battery modules. The modules are then combined into battery packs.

Two families of cathode chemistries are used in large-format, automotive Li-ion batteries currently in production – LiMn2O4-spinel (CPI, GS-Yuasa, AESC) and LiFePO4 (A123 Systems). Current production batteries typically use graphite anodes. Automotive Li-ion batteries using lithium nickel manganese cobalt (NMC) oxide cathodes with graphite anodes are in advanced stages of development for PHEV and EV applications. The agencies expect large-format Li-ion batteries to completely replace NiMH batteries for post-2017 HEV applications. We also expect that large-format stacked and/or folded prismatic Li-ion cell designs will continue to be used for PHEV and EV applications and that NMC/graphite Li-ion batteries will be a mature technology for 2017-2025 light-duty vehicle applications.

3.4.3.8 HEV, PHEV and EV System Sizing Methodology

Battery packs are (and will continue to be) one of the most expensive components for EVs, PHEVs and HEVs. To obtain reasonable cost estimates for electrified vehicles, it was therefore important to establish a reliable approach for determining battery attributes for each vehicle and class. Both battery energy content ("size") and power rating are key inputs used to establish costs per ANL's battery costing model. For EVs and PHEVs in particular, battery size and weight are closely related, and so battery weight must be known as well. The following section details the steps taken to size a battery for

a) EVs and PHEVs (at various all-electric ranges),

b) a more simplified separate approach for MHEVs and HEVs.

3.4.3.8.1 Battery Pack Sizing for EVs and PHEVs

Calculation of required battery pack energy requirements for EVs and PHEVs is not straightforward. Because vehicle energy consumption is strongly dependent on weight, and battery packs are very heavy, the weight of the battery pack itself can change the energy required to move the vehicle. As vehicle energy consumption increases, the battery size must increase for a given range (in the case of EVs and PHEVs) – as a result, vehicle weight increases, and per-mile energy consumption increases as well, increasing the battery size, and so on.

EPA built spreadsheets to estimate the required battery size for each vehicle and class (reference here?) Listed below are the steps EPA has taken in these spreadsheets to estimate not only battery size, but associated weight for EVs and PHEVs of varying ranges and designs.

1. Establish baseline FE/energy consumption
2. Assume nominal weight of electrified vehicle (based on weight reduction target)
3. Calculate vehicle energy demand at this target weight
4. Calculate required battery energy
5. Calculate actual battery and vehicle weight
6. Do vehicle weight and battery size match estimated values?

Iterate steps 2-6 until assumed weight reduction target (and nominal vehicle weight) reconciles with required battery size and calculated weight of vehicle.

Baseline vehicle energy consumption is estimated based on a fitted trendline for FE vs. inertia weight, or ETW (from FE Trends data for 2008 MY vehicles, table M-80) and converting to Wh/mi. It is shown in Figure 3-21.

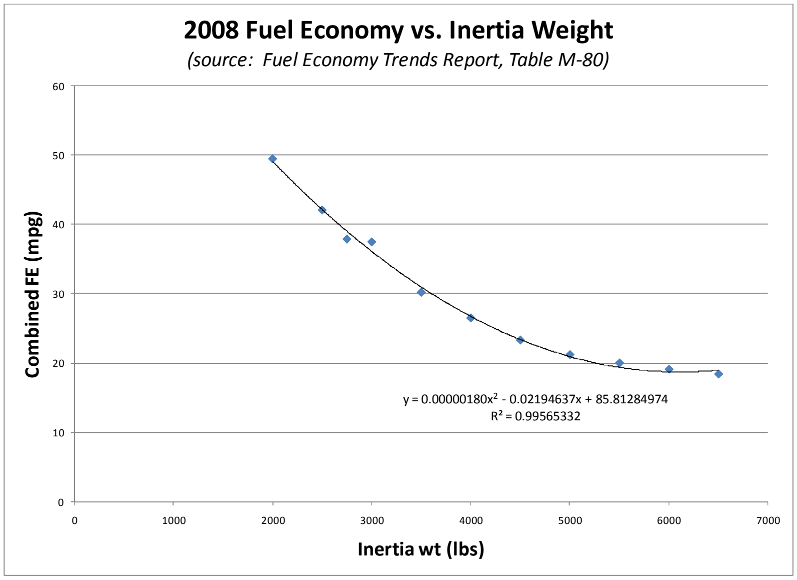


Figure 3-21: Average fuel economy based on inertia weight (ETW) from FE Trends data

Then, fuel economy was converted into energy consumption (assuming 33700 Wh energy in 1 gallon of gasoline) and used to populate a range of test weights between 2000 and 6000 lbs. A linear trendline was used to fit this curve and then applied for estimating generic energy consumption for baseline vehicles of a given ETW, and is shown below in Figure 3-22.

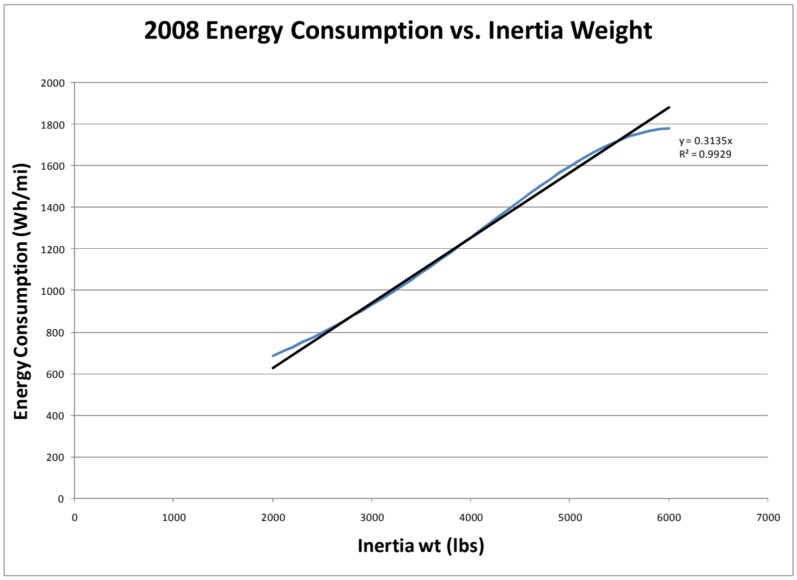


Figure 3-22: Equivalent energy consumption (in Wh/mi) for baseline vehicles

To calculate battery pack size, the electrified vehicle weight must first be known; to calculate vehicle weight, the battery pack size must first be known. This circular reference required an iterative solution. EPA assumed a target vehicle glider (a rolling chassis with no powertrain) weight reduction and applied that to the baseline curb weight. The resulting nominal vehicle weight was then used to calculate the vehicle energy demand. To calculate the energy demand (efficiency) of an electric vehicle in Wh/mi, the following information was needed:

- Baseline energy consumption / mpg
- Efficiency (η) improvement of electric vehicle
- Change in road loads

In Table 3-59 below, the following definitions apply:

- Brake eff (brake efficiency) – the % amount of chemical fuel energy converted to energy at the engine crankshaft (or, for batteries, the amount of stored electrical energy converted to shaft energy entering the transmission)
- D/L eff (driveline efficiency) – the % of the brake energy entering the transmission delivered through the driveline to the wheels
- Wheel eff (wheel efficiency) – the product of brake and driveline efficiency

- Cycle eff (cycle efficiency) – the % of energy delivered to the wheels used to overcome road loads and power the vehicle (it does not include energy lost as braking heat)

- Vehicle efficiency – the product of wheel and cycle efficiency

- Road loads – the amount of resistant energy the vehicle must overcome during a city/highway test. Composed of vehicle weight (inertia), aerodynamic drag and rolling resistance

Table 3-59: EV efficiency and energy demand calculations

Overall EV efficiency calculations, by vehicle class

Class	Brake eff	D/L eff	Wheel eff	Cycle eff	Vehicle efficiency	Road Loads	Energy Reduction	**Energy** Efficiency Increase	IW-based base ICE nominal mpgge	Base fuel energy reqd W-hr/mi	FTP fuel energy reqd W-hr/mi	Onroad fuel energy reqd W-hr/mi
Baseline gas ICE	24%	81%	20%	77%	15%	100%						
Subcompact	85%	93%	79%	97%	77%	91%	**82%**	464%	37	911	**161**	**230**
Small car	85%	93%	79%	97%	77%	91%	**82%**	464%	32	1060	**188**	**268**
Large car	85%	93%	79%	97%	77%	91%	**82%**	464%	26	1279	**227**	**324**
Small Truck	85%	93%	79%	97%	77%	91%	**82%**	464%	26	1314	**233**	**333**
Minivan	85%	93%	79%	97%	77%	91%	**82%**	464%	24	1401	**248**	**355**
Truck	85%	93%	79%	97%	77%	91%	**82%**	464%	21	1597	**283**	**404**

The energy efficiency of a baseline vehicle (around 15%), as indicated in the table above, was estimated using efficiency terms derived from EPA's lumped parameter model (engine/battery brake efficiency, driveline efficiency, cycle efficiency and road load ratio to baseline). To calculate the energy consumption of an EV (or PHEV in charge-depleting mode), the following assumptions were made:

- "Brake" efficiency (for an EV, the efficiency of converting battery energy to tractive energy at the transmission input shaft) was estimated at 85% - assuming, roughly a 95% efficiency for the battery, motor, and power electronics, respectively.

- The driveline efficiency (including the transmission) was comparable to the value calculated by the lumped parameter model for an advanced 6-speed dual-clutch transmission at 93%.

- The cycle efficiency assumes regenerative braking where 95% recoverable braking energy is recaptured. As a result, most of the energy delivered to the wheels is used to overcome road loads.

- The road loads were based on the weight reduction of the vehicle. In the case of a 100 mile EV with a 10% weight reduction, road loads (as calculated by the LP model) are reduced to 91% of the baseline vehicle[ll].

  The energy consumption of the EV includes ratio of the roadloads of the EV to the baseline vehicle, and the ratio of the efficiency of the EV compared to the baseline vehicle. It is expressed mathematically as shown below in Equation 3-1: EV energy consumption

Equation 3-1: EV energy consumption

$$E_{EV\_FTP}(Wh/mi) = E_{baseline\_FTP} * \left(\frac{\%Roadload_{new}}{\%Roadload_{old}} * \frac{\eta_{vehicle\_old}}{\eta_{vehicle\_new}} \right)$$

In the table 3-x, the baseline energy required (in Wh/mi) is in the column labeled "Base fuel energy reqd". The energy required for each vehicle class EV over the FTP is in the column "FTP fuel energy reqd W-hr/mi" and incorporates the equation above. This energy rate refers to the laboratory or unadjusted test cycle value, as opposed to a real-world "onroad" value. EPA assumes a 30% fuel economy shortfall, based loosely on the 5-cycle Fuel Economy Labeling Rule (year) which is directionally correct for electrified vehicles. This corresponds to an increase in fuel consumption of 43%. Applying this 43% increase gives the onroad energy consumption values for EVs as shown in the far right column of the previous table. From this value, one can determine an appropriate battery pack size for the vehicle.

The required battery energy for EVs equals the onroad energy consumption, multiplied by the desired range, divided by the useful state-of-charge window of the battery. It is calculated as follows in Equation 3-2

Equation 3-2: Required battery pack energy (size) for EVs

$$BP(kWh) = \frac{E_{onroad}(\frac{Wh}{mi}) \times range(mi)}{SOC\%}$$

Assumed usable SOC (battery state-of-charge) windows were 80% for EVs (10-90%) and 70% for PHEVs (15%-85%). The battery pack sizes are listed in orange in Table 3-60 for the 100-mile EV case and show both the onroad energy consumption ("EV adj Wh/mi" column) and the nominal battery energy content or "battery pack size".

[ll] Included in this example road load calculation is a 10% reduction in rolling resistance and aerodynamic drag.

Table 3-60: Battery pack sizes for 100-mile EV based on inertia weight

Category	BASELINE curb wt lbs	Inertia wt lbs	EV unadj Wh/mi	EV adj Wh/mi	100 mi batt pack size kWh
Subcompact	2628	2928	161	230	28.8
Small car	3118	3418	188	268	33.5
Large car	3751	4051	227	324	40.5
Small Truck	3849	4149	233	333	41.6
Minivan	4087	4387	248	355	44.3
Truck	4646	4946	283	404	50.5

EPA used the following formula to determine weight of an EV (Equation 3-3):

Equation 3-3: EV weight calculation

$$W_{EV} = W_{base} - WR_{glider} - W_{ICE\_powertrain} + W_{electric\_drive}$$

Any weight reduction technology was applied only to the glider (baseline vehicle absent powertrain) as defined in Equation 3-4.

Equation 3-4: Weight reduction of the glider

$$WR_{glider} = \%WR * (W_{base} - W_{ICE\_powertrain})$$

In the case of a PHEV's, it was assumed that the base ICE powertrain remains so it is not deducted; the proper equation for PHEVs is shown in Equation 3-5.

Equation 3-5: Weight calculation for PHEV

$$W_{PHEV} = W_{base} - WR_{glider} + W_{electric\_drive}$$

Listed in Table 3-61 are the assumed baseline ICE-powertrain weights, by vehicle class:

Table 3-61: Baseline ICE-powertrain weight assumptions, by class

ICE powertrain weight estimates

Class	Engine	Trans (diff not included)	Fuel system (50% fill)	Engine mounts/NVH treatments	Exhaust	12V battery	Total ICE powertrain weight
Subcompact	250	125	50	25	20	25	**495**
Small car	300	150	60	25	25	30	**590**
Large car	375	175	70	25	30	35	**710**
Small Truck	300	150	60	25	25	30	**590**
Minivan	400	200	80	25	30	40	**775**
Truck	550	200	100	25	40	50	**965**

EPA then estimated the weight of the electric drive subsystem using the energy content of the battery pack as an input. EPA scaled the weight by applying a specific energy for the electric drive subsystem - including the battery pack, drive motor, wiring, power electronics, etc. – of 120 Wh/kg (or 18.33 lb/kWh). This specific energy value is based on adding components to an assumed battery pack specific energy of 150 Wh/kg[mm]. Then, the gearbox (the only subsystem excluded from the electric drive scaling) was added to the weight of the electric drive subsystem; this total was included into the electric vehicle weight calculation as $W_{electric\_drive}$[nn]. A summary table of electric drive weights for 100-mile EVs is shown as Table 3-62.

Table 3-62: Total electric drive weights for 100-mile EVs

EV powertrain weight estimates - 100 mile range

Class	Battery pack size (kWh)	2020 electric content (lbs)	Gearbox (power-split or other)	2020 EV powertrain total
Subcompact	28.8	528	50	**578**
Small car	33.5	615	60	**675**
Large car	40.5	742	70	**812**
Small Truck	41.6	762	60	**822**
Minivan	44.3	813	80	**893**
Truck	50.5	926	100	**1026**

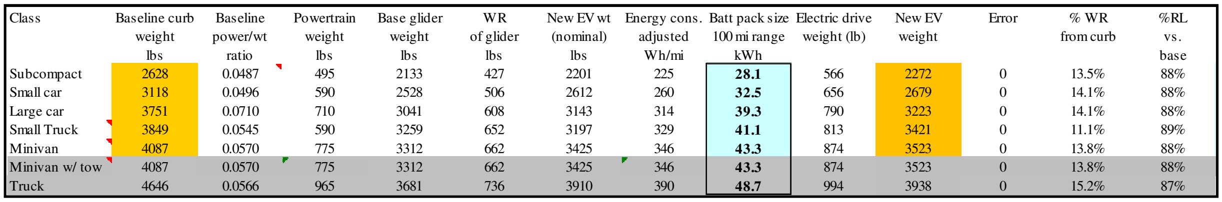
The difference between the actual weight and the predicted or nominal weight should be zero. However, if not then a revised weight reduction was used for another iteration of steps 2-6 until the two vehicle weights match. Spreadsheet tools such as “solver” in MS Excel were used for automating this iterative process.

[mm] 150 Wh/kg is a conservative estimate for year 2017 and beyond: outputs from ANL’s battery cost model show specific energy values of 160- 180 Wh/kg for a similar timeframe.

[nn] Applies only to the EV. Because the baseline ICE powertrain weight (which includes gearbox weight) was not deducted from the PHEV, it is not added back in for the PHEV.

Table 3-63 shows example results for 100-mile range EVs; in this case a 10% applied glider weight reduction for a variety of vehicle classes.

Table 3-63: Sample calculation sheet for 100-mile EVs



Class	Baseline curb weight lbs	Baseline power/wt ratio	Powertrain weight lbs	Base glider weight lbs	WR of glider lbs	New EV wt (nominal) lbs	Energy cons. adjusted Wh/mi	Batt pack size 100 mi range kWh	Electric drive weight (lb)	New EV weight	Error	% WR from curb	%RL vs. base
Subcompact	2628	0.0487	495	2133	427	2201	225	**28.1**	566	2272	0	13.5%	88%
Small car	3118	0.0496	590	2528	506	2612	260	**32.5**	656	2679	0	14.1%	88%
Large car	3751	0.0710	710	3041	608	3143	314	**39.3**	790	3223	0	14.1%	88%
Small Truck	3849	0.0545	590	3259	652	3197	329	**41.1**	813	3421	0	11.1%	89%
Minivan	4087	0.0570	775	3312	662	3425	346	**43.3**	874	3523	0	13.8%	88%
Minivan w/ tow	4087	0.0570	775	3312	662	3425	346	**43.3**	874	3523	0	13.8%	88%
Truck	4646	0.0566	965	3681	736	3910	390	**48.7**	994	3938	0	15.2%	87%

Table 3-64 shows the effect on net electric vehicle weight reduction after 20% glider weight reduction was applied to EVs and PHEVs. As battery pack size increases for larger-range EVs and PHEVs, the overall realized vehicle weight reduction decreases (because it requires more energy to carry the extra battery weight). In this example, EVs with a 150 mile range require almost 20% weight reduction to the glider to make up for the additional weight of the electric drive and battery pack compared to a conventional ICE-based powertrain.

Table 3-64: Actual weight reduction percentages for EVs and PHEVs with 20% weight reduction applied to glider

	75 Mile EV actual % WR vs. base vehicle	100 Mile EV actual % WR vs. base vehicle	150 Mile EV actual % WR vs. base vehicle	20 Mile PHEV actual % WR vs. base vehicle	40 Mile PHEV actual % WR vs. base vehicle
Subcompact	19%	14%	2%	12%	7%
Small car	19%	14%	2%	12%	7%
Large car	19%	14%	2%	12%	7%
Small Truck	16%	11%	-1%	12%	8%
Minivan	19%	14%	2%	12%	7%
Truck (w/ towing)	19%	14%	2%	10%	6%

Because there is no "all-electric range" requirement for HEVs, battery pack sizes were relatively consistent for a given weight class. Furthermore, because battery pack sizes are at least an order of magnitude smaller for HEVs than for all-electric vehicles, the sensitivity of HEV vehicle weight (and hence energy consumption) to battery pack size is rather insignificant. For these reasons, a more direct approach (rather than an iterative process) works for battery sizing of HEVs.

- HEV batteries were scaled similar to the 2010 Fusion Hybrid based on nominal battery energy per lb ETW (equivalent test weight), at 0.37 Wh/lb.

- A higher usable SOC window of 40% (compared to 30% for Fusion Hybrid) reduced the required Li-Ion battery size to 75% of the Fusion Hybrid's NiMH battery. This resulted in a 0.28 Wh/lb ETW ratio.

- In comparing anecdotal data for HEVs, the agencies assumed a slight weight increase of 4-5% for HEVs compared to baseline non-hybridized vehicles. The added weight of the Li-Ion pack, motor and other electric hardware were offset partially by the reduced size of the base engine.

3.4.3.9 HEV, PHEV and EV battery pack design and cost analysis using the ANL BatPac model

The U.S. Department of Energy (DOE) has established long term industry goals and targets for advanced battery systems as it does for many energy efficient technologies. Argonne National Laboratory (ANL) was funded by DOE to provide an independent assessment of Li-ion battery costs because of their expertise in the field as one of the primary DOE National Laboratories responsible for basic and applied battery energy storage technologies for future HEV, PHEV and EV applications. A basic description of the ANL Li-ion battery cost model and initial modeling results for PHEV applications were published in a peer-reviewed technical paper presented at EVS-24[57]. ANL has extended modeling inputs and pack design criteria within the battery cost model to include analysis of manufacturing costs for EVs and HEVs as well has PHEVs.[58] In early 2011, ANL issued a draft report detailing the methodology, inputs and outputs of their Battery Performance and Cost (BatPac) model.[59] A complete independent peer-review of the BatPac model and its inputs and results for HEV, PHEV and EV applications has been completed[60]. ANL recently provided the agencies with an updated report documenting the BatPac model that fully addresses the issues raised within the peer review.[61] Based on the feedback from peer-reviewers, ANL has updated the model in the following areas.

1. Battery pack price is adjusted upward. This adjustment is based on the feedback from several peer-reviewers, and changes are related to limiting electrode thickness to 100 microns, changing allocation of overhead cost to more closely represent a Tier 1 auto supplier, increasing cost of tabs, changing capital cost of material preparation, etc;
2. Battery management system cost is increased to represent the complete monitoring and control needs for proper battery operation and safety as shown in Table 5.3 in the report;
3. Battery automatic and manual disconnect unit cost is added based on safety considerations as shown in Table 5.3 in the report;
4. Liquid thermal management system is added. ANL states in the report that the closure design it uses in the model does not have sufficient surface area to be cooled by air effectively as shown in Table 5.3 in the report.

This model and the peer review report are available in the public dockets for this rulemaking [60,62].

NHTSA and EPA have decided to use the updated ANL BatPac model, dated July 17, 2011, for estimating large-format lithium-ion batteries for this proposal for the following reasons. First, the ANL model has been described and presented in the public domain and does not rely upon confidential business information (which would therefore not be reviewable by the public). The model was developed by scientists at ANL who have significant experience in this area. The model uses a bill of materials methodology which the agencies believe is the preferred method for developing cost estimates. The ANL model appropriately considers the vehicle applications power and energy requirements, which are two of the fundamental parameters when designing a lithium-ion battery for an HEV, PHEV, or EV. The ANL model can estimate high volume production costs, which the agencies believe is appropriate for the 2025 time frame. Finally, the ANL model's cost estimates, while generally lower than the estimates we received from the OEMs, is consistent with some of the supplier cost estimates the agencies received from large-format lithium-ion battery pack manufacturers. A portion of those data was received from on-site visits to vehicle manufacturers and battery suppliers done by the EPA in 2008.

The ANL battery cost model is based on a bill of materials approach in addition to specific design criteria for the intended application of a battery pack. The costs include materials, manufacturing processes, the cost of capital equipment, plant area, and labor for each manufacturing step as well as the design criteria include a vehicle application's power and energy storage capacity requirements, the battery's cathode and anode chemistry, and the number of cells per module and modules per battery pack. The model assumes use of a laminated multi-layer prismatic cell and battery modules consisting of double-seamed rigid containers. The model also assumes that the battery modules are liquid-cooled. The model takes into consideration the cost of capital equipment, plant area and labor for each step in the manufacturing process for battery packs and places relevant limits on electrode coating thicknesses and other processes limited by existing and near-term manufacturing processes. The ANL model also takes into consideration annual pack production volume and economies of scale for high-volume production.

Basic user inputs to BatPaC include performance goals (power and energy capacity), choice of battery chemistry (of five predefined chemistries), the vehicle type for which the battery is intended (HEV, PHEV, or EV), the desired number of cells and modules, and the volume of production. BatPaC then designs the cells, modules, and battery pack, and provides an itemized cost breakdown at the specified production volume.

BatPaC provides default values for engineering properties and material costs that allow the model to operate without requiring the user to supply detailed technical or experimental data. In general, the default properties and costs represent what the model authors consider to be reasonable values representing the state of the art expected to be available to large battery manufacturers in the year 2020. Users are encouraged to change these defaults as necessary to represent their own expectations or their own proprietary data.

In using BatPaC, it is extremely important that the user monitor certain properties of the cells, modules, and packs that it generates, to ensure that they stay within practical design guidelines, adjusting related inputs if necessary. In particular, pack voltage and individual cell capacity should be limited to appropriate ranges for the application. These design guidelines are not rigidly defined but approximate ranges are beginning to emerge in the industry.

Also inherent in BatPaC are certain modeling assumptions that are still open to some uncertainty or debate in the industry. For some, such as the available portion of total battery energy (aka "SOC window") for a PHEV/EV/HEV, the user can easily modify a single parameter to represent a value other than the default. For others, such as the type of thermal management employed (BatPaC is limited to liquid cooling and does not support passive or active air cooling), or the packaging of cells and modules in a pack (parallel modules are not supported), changes can often be made by modifying the relevant cost outputs or performing workarounds in the use of the model.

The cost outputs used by the agencies to determine 2025 HEV, PHEV and EV battery costs were based on the following inputs and assumptions.

EPA selected basic user inputs as follows. For performance goals, EPA used the power and energy requirements derived from the scaling analysis described in the previous section. Specifically, these covered each of the seven classes of vehicles (Subcompact, Small Car, Large Car, Small Truck, Minivan, Minivan with Towing, Large Truck) under each of the five weight reduction scenarios (0%, 2%, 7.5%, 10%, and 20%). The chosen battery chemistries were NMC441-G (for EVs and PHEV40) and LMO-G (for P2 HEVs and PHEV20). Vehicle types were EV75, EV100, EV150 (using the BatPaC "EV" setting); PHEV20 and PHEV40 (using the "PHEV" setting), and P2 HEV (using the "HEV-HP" setting). All modules were composed of 32 cells each, with each pack having a varying number of modules. Cost outputs were generated for annual production volumes of 50K, 125K, 250K, and 450K packs. The cost outputs for the 450K production volume are used in the NPRM analysis.

For engineering properties and material costs, and for other parameters not identified below, EPA used the defaults provided in the model.

For design guidelines regarding pack voltage and cell capacity, EPA chose guidelines based on knowledge of current practices and developing trends of battery manufacturers and OEMs, supplemented by discussions with the BatPaC authors. Specifically: (1) allowable pack voltage was targeted to approximately 120V for HEVs and approximately 350-400V for EVs and PHEVs (with some EV150 packs for larger vehicles allowed to about 460-600V); (2) allowable cell capacity was limited to less than 80 A-hr.

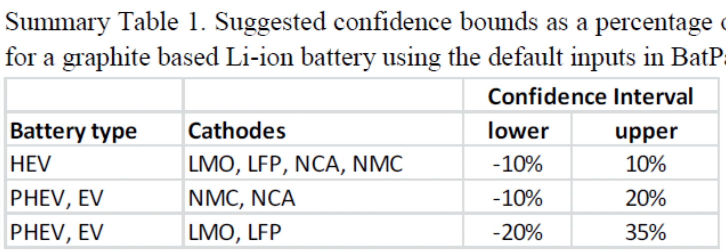
EPA made several modeling assumptions that differed from the default model: (1) The SOC window for PHEV20 was limited to 50% rather than the default 70%. (2) The SOC window for HEVs was increased to 40% rather than the default 25%. (3) EV packs were modeled as two half-packs to avoid exceeding pack voltage guidelines. Although the model provided for a potential solution by placing parallel cells within modules, EPA felt that likely industry practices would be better represented by placing parallel modules within a pack, or by dividing the pack into two parallel packs for packaging flexibility. Because the model did not support parallel modules, each EV pack was modeled as two half-packs, each at half the target power and energy, to be installed in parallel. Per ANL recommendation, half-packs were modeled at twice the full-pack production volume, the projected half-pack cost was then doubled, and costs for the battery management system (BMS), disconnects, and thermal management were added only once, and module controls added twice. (4) HEV packs were assumed to be air cooled instead of liquid cooled (except for large work trucks and minivans with towing, which are still modeled as liquid-cooled). Because the model did not support air cooling, EPA replaced the model's projected cost for liquid cooling with a cost for air cooling (blower motor, ducting, and temperature feedback) derived from FEV's teardown studies. EPA is working with ANL and investigating the potential for modifying the BatPac model to include air cooling as an option

Additionally, EPA did not include warranty costs computed by BatPaC in the total battery cost because these are accounted for elsewhere by means of indirect cost multipliers (ICMs).

Table 3-65 Summary of Inputs and Assumptions Used with BatPaC

Category of input/Assumptions	BatPaC Default or Suggested Values	Agency Inputs for NPRM Analysis
Annual production volume	n/a	450,000
Battery chemistry	n/a	for HEV, PHEV20: LMO-G for PHEV40, EV: NMC441-G
Allowable pack voltage	for HEV: 160-260 V for PHEV, EV: 290-360 V	for HEV: ~ 120 V for PHEV, EV: ~ 360-600 V
Allowable cell capacity	< 60 A-hr	< 80 A-hr
Cells per module	16-32	32
SOC window for HEVs	25%	40%
SOC window for PHEV20	70%	50%
Thermal management	Liquid	Air, for small/medium HEVs Liquid for all others
EV pack configuration	• Single pack, cells in series • Single pack, some parallel cells	Two packs, cells in series, packs in parallel

The cost projections produced by BatPaC are sensitive to the inputs and assumptions the user provides. Significant uncertainty remains regarding which will best represent manufacturer practice in the year 2020. The battery pack cost projection from BatPac model ranges from \$167/kWh for EV150 large truck to \$267/kWh for PHEV40 large car with NMC as chemistry and to \$375/kWh for PHEV20 sub-compact car as shown in Table 3-66to Table 3-71. The agencies note that costs used in the analysis are lower than the costs generally reported in stakeholder meetings, which ranged from \$300/kW-hour to \$400/kW-hour range for 2020 and \$250 to \$300/kW-hour range for 2025. A comparison of BatPac modeling results to the costs used in the 2012-2016 final rule and to cost estimates compiled by EPA from battery suppliers and auto OEMs is shown in Figure 3-24. The agencies also reviewed publically available PHEV and EV battery cost literature including reports from Anderman[63], Frost & Sullivan[64], TIAX[65], Boston Consulting Group[66], NRC[67] etc. EPA and NHTSA anticipate that public comment or further research may lead to the use of different inputs and assumptions that may change the cost projections used for the final rule. Due to the the uncertainties inherent in estimating battery costs through the 2025 model year, a sensitivity analysis will be provided in each agency's RIA using a a range of costs estimated by DOE technical experts to represent a reasonable outer bounds to the results from the BatPaC model. In a recent report to NHTSA and EPA, DOE and ANL suggested the following range for the sensitivity study with 95% confidence interval after analyzing the confidence bound using the BatPac model. The agencies plan to use this suggested range for the sensitivity study.



Summary Table 1. Suggested confidence bounds as a percentage of the calculated point estimate for a graphite based Li-ion battery using the default inputs in BatPaC.

		Confidence Interval	
Battery type	Cathodes	lower	upper
HEV	LMO, LFP, NCA, NMC	-10%	10%
PHEV, EV	NMC, NCA	-10%	20%
PHEV, EV	LMO, LFP	-20%	35%

Figure 3-23 Table from ANL Recommendation[68]

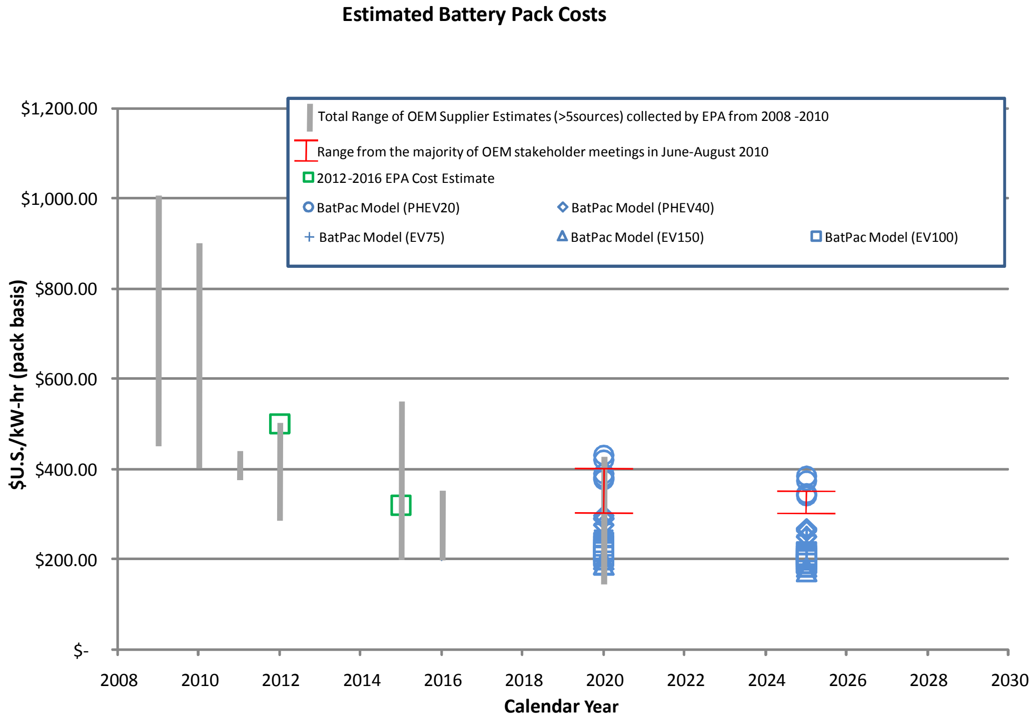


Figure 3-24 Comparison of direct manufacturing costs per unit of energy storage ($/kW-hr) between the estimates used by EPA in the 2012-2016 GHG final rule, the BatPaC model results for PHEV20, PHEV40, EV75, EV100 and EV150 packages compared to estimates from OEM battery suppliers (2009 dollars, markups not included). Multiple points shown for the BatPaC model results for PHEV 20, PHEV40, EV75, EV100 and EV150 reflect the range of energy-specific costs for EPA's subcompact through large-car package categories (see Table x for details). A range of OEM estimated battery costs from stakeholder meetings is also shown for comparison (red bars) which may or may not reflect additional cost markups.

While it is expected that other Li-ion battery chemistries with higher energy density, higher power density and lower cost will likely be available in the 2017-2025 timeframe, the specific chemistries used for the cost analysis were chosen due to their known characteristics and to be consistent with both public available information on current and near term HEV, PHEV and EV product offerings from Hyundai, GM and Nissan as well as confidential business information on future products currently under development.[69,70,71,72] The cost outputs from the BatPaC model used by the agencies in this analysis are shown in Table 3-66 through Table 3-71 for different levels of applied weight reduction technology. We differentiate between "applied" weight reduction and "net" weight reduction in this analysis due to the fact that in order to achieve the same amount of mass reduction, more mass reduction technologies might need to be applied to vehicles with electrifications than with traditional powertrain because of the added weight of the electrification systems such as battery, and in an effort to make clear that we have estimated vehicle level battery pack costs—and motor and other electrified vehicle specific costs—based on the net weight reduction of the vehicle. For example, a typical EV150 battery back and associated motors and other EV-specific equipment increases vehicle weight roughly 18 percent. As a result, an EV150 that applied 20 percent mass reduction technology (see section 3.4.5.5 for a full discussion of mass reduction technologies and costs) would have a net weight reduction of only 2 percent. In such a case, the agencies would estimate mass reduction costs associated with a 20 percent applied mass reduction, and EV150 costs associated with only a 2 percent net mass reduction (lower net mass reduction results in higher battery pack and motor costs). Similarly, HEV battery packs increase vehicle weight by roughly 5 or 6 percent. Therefore, for an HEV with 20 percent applied mass reduction technology—and costs associated with 20 percent applied mass reduction—would have HEV costs associated with a 15 percent net mass reduction. Furthermore, such an HEV would have an effectiveness level improvement associated with a 15 percent net mass reduction rather than a 20 percent net reduction.

Table 3-66 Direct Manufacturing Costs for P2 HEV battery packs at different levels of applied vehicle weight reduction (2009 dollars, markups not included)

P2 HEV (LMO) @ 450K/yr volume	0% weight reduction		2% weight reduction		7.5% weight reduction		10% weight reduction		20% weight reduction	
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Subcompact	$716	$886	$713	$898	$704	$934	$700	$951	$691	$997
Small Car	$757	$802	$754	$813	$743	$845	$739	$861	$725	$900
Large Car	$864	$772	$858	$781	$843	$809	$836	$823	$819	$859
Minivan	$847	$699	$842	$708	$828	$734	$821	$747	$803	$779
Minivan+towing	$928	$766	$923	$776	$909	$806	$902	$821	$887	$851
Small Truck	$822	$717	$817	$727	$802	$752	$796	$765	$781	$801
Large Truck	$964	$706	$958	$715	$942	$742	$934	$755	$920	$783

Table 3-67 Direct Manufacturing Costs for PHEV20 battery packs at different levels of applied vehicle weight reduction (2009 dollars, markups not included)

PHEV20 (LMO) @ 450K/yr volume	0% weight reduction		2% weight reduction		7.5% weight reduction		10% weight reduction		20% weight reduction	
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Subcompact	$2,602	$375	$2,585	$377	$2,539	$381	$2,516	$382	$2,501	$384
Small Car	$2,746	$340	$2,726	$342	$2,671	$345	$2,647	$345	$2,628	$347

Large Car	$3,331	$342	$3,299	$343	$3,213	$343	$3,176	$343	$3,145	$344
Minivan	$3,296	$309	$3,267	$310	$3,188	$311	$3,153	$311	$3,126	$312
Minivan+towing	$3,296	$309	$3,267	$310	$3,188	$311	$3,153	$311	$3,139	$313
Small Truck	$3,143	$314	$3,116	$315	$3,042	$316	$3,010	$317	$2,974	$319
Large Truck	$3,522	$290	$3,470	$289	$3,381	$289	$3,342	$289	$3,334	$290

Table 3-68 Direct Manufacturing Costs for PHEV40 battery pack at different levels of applied vehicle weight reduction (2009 dollars, markups not included)

PHEV40 (NMC) @ 450K/yr volume	0% weight reduction		2% weight reduction		7.5% weight reduction		10% weight reduction		20% weight reduction	
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Subcompact	$3,655	$264	$3,622	$264	$3,590	$268	$3,590	$268	$3,590	$268
Small Car	$4,043	$251	$3,986	$250	$3,883	$250	$3,888	$251	$3,888	$251
Large Car	$5,193	$267	$5,128	$266	$4,969	$266	$4,969	$266	$4,969	$266
Minivan	$5,041	$236	$4,985	$236	$4,883	$238	$4,893	$237	$4,893	$237
Minivan+towing	$5,041	$236	$4,985	$236	$4,905	$239	$4,916	$238	$4,916	$238
Small Truck	$4,788	$239	$4,737	$239	$4,602	$239	$4,598	$239	$4,598	$239
Large Truck	$5,512	$227	$5,449	$227	$5,345	$226	$5,345	$226	$5,345	$226

Table 3-69 Direct Manufacturing Costs for EV75 battery packs at different levels of applied vehicle weight reduction (2009 dollars, markups not included)

EV75 (NMC) @ 450K/yr volume	0% weight reduction		2% weight reduction		7.5% weight reduction		10% weight reduction		20% weight reduction	
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Subcompact	$5,418	$238	$5,384	$239	$5,340	$244	$5,306	$246	$5,155	$252
Small Car	$5,892	$223	$5,842	$223	$5,731	$225	$5,692	$226	$5,494	$232
Large Car	$7,180	$225	$7,102	$225	$6,907	$225	$6,822	$225	$6,509	$228
Minivan	$7,198	$206	$7,128	$206	$6,942	$206	$6,864	$206	$6,528	$209
Minivan+towing	$7,198	$206	$7,128	$206	$6,942	$206	$6,864	$206	$6,528	$209
Small Truck	$6,827	$208	$6,763	$208	$6,592	$209	$6,520	$209	$6,306	$211
Large Truck	$7,613	$191	$7,764	$197	$7,557	$197	$7,468	$197	$7,116	$200

Table 3-70 Direct Manufacturing Costs for EV100 battery packs at different levels of applied vehicle weight reduction (2009 dollars, markups not included)

EV100 (NMC) @ 450K/yr volume	0% weight reduction		2% weight reduction		7.5% weight reduction		10% weight reduction		20% weight reduction	
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Subcompact	$6,360	$210	$6,316	$211	$6,206	$213	$6,162	$214	$6,074	$216
Small Car	$7,001	$198	$6,951	$199	$6,782	$200	$6,727	$201	$6,600	$203
Large Car	$8,101	$190	$8,016	$190	$7,802	$191	$7,711	$191	$7,526	$192
Minivan	$8,414	$180	$8,348	$181	$8,183	$182	$8,116	$183	$7,980	$184
Minivan+towing	$8,414	$180	$8,348	$181	$8,183	$182	$8,116	$183	$7,980	$184
Small Truck	$8,047	$184	$7,981	$184	$7,825	$186	$7,763	$187	$7,700	$187
Large Truck	$9,232	$174	$9,158	$174	$8,970	$175	$8,895	$176	$8,671	$178

Table 3-71 Direct Manufacturing Costs for EV150 battery packs at different levels of applied vehicle weight reduction (2009 dollars, markups not included)

EV150 (NMC) @ 450K/yr volume	0% weight reduction		2% weight reduction		7.5% weight reduction		10% weight reduction		20% weight reduction	
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Subcompact	$8,292	$182	$8,260	$183	$8,260	$183	$8,260	$183	$8,260	$183
Small Car	$9,189	$174	$9,115	$174	$9,115	$174	$9,115	$174	$9,115	$174
Large Car	$10,991	$172	$10,902	$173	$10,902	$173	$10,902	$173	$10,902	$173
Minivan	$11,747	$168	$11,650	$168	$11,650	$168	$11,650	$168	$11,650	$168
Minivan+towing	$11,747	$168	$11,650	$168	$11,650	$168	$11,650	$168	$11,650	$168
Small Truck	$11,253	$170	$11,253	$170	$11,253	$170	$11,253	$170	$11,253	$170
Large Truck	$13,337	$167	$13,227	$168	$13,172	$168	$13,172	$168	$13,172	$168

Specifically for modeling purposes, both agencies wanted HEV/PHEV/EV battery pack costs based on net weight reduction rather than applied weight reduction as shown in Table 3-66 through Table 3-71 above. The agencies did this by first determining the average weight differences (applied weight reduction vs net weight reduction) for each of the 7 major vehicle classes (subcompact, small car, large car, minivan, small truck, minivan+towing & large truck) and each of the electrification types (P2 HEV, PHEV & EV). Due to the weight increases of adding electrification system and battery pack and the weight decreases by applying smaller or no conventional internal combustion engine, the net mass reduction for HEV, PHEV and EV varies for different electrification package and vehicle classes. For an example, for a 20-mile subcompact PHEV, 5% mass reduction of the glider is offset by the additional weight of electrification system, i.e. 5% mass reduction needs to be applied to glider to achieve a net 0% overall vehicle mass reduction for a PHEV20 subcompact passenger car. Those weight reduction differences are shown in Table 3-72.

Table 3-72 EPA and NHTSA Weight Reduction Offset Associated with Electrification Technologies

Vehicle Class	P2 HEV	PHEV20	PHEV40	EV75	EV100	EV150
Subcompact	5%	7%	13%	0%	6%	18%
Small car	5%	7%	12%	-1%	5%	17%
Large car	5%	7%	13%	-1%	5%	18%
Minivan	5%	7%	13%	-1%	6%	18%
Small truck	5%	7%	12%	3%	8%	20%
Minivan+towing	6%	8%	14%	-1%	6%	18%
Large truck	6%	9%	14%	-2%	4%	16%

Notes:
For example, PHEV40-specific technologies add 12-14% to vehicle weight so that a 20% applied weight reduction would result in a 6-8% net weight reduction.
While an EV75 can actually reduce vehicle weight by 1-2% (i.e., battery packs and motors weigh less than the removed internal combustion engine and transmission), the agencies used a value of 0% where negative entries are shown.

The agencies then generated linear regressions of battery pack costs against percentage net weight reduction using the costs shown in Table 3-66 through Table 3-71 and the weight reduction offsets shown in Table 3-72. These results are shown in Table 3-73.

Table 3-73 EPA and NHTSA Linear Regressions of Battery Pack Direct Manufacturing Costs vs Net Weight Reduction (2009$)

Vehicle Class	P2 HEV	PHEV20	PHEV40	EV75	EV100	EV150
Subcompact	-$177x+$716	-$862x+$2,602	-$867x+$3,649	-$1,350x+$5,424	-$2,064x+$6,360	-$2,019x+$8,292
Small car	-$218x+$758	-$998x+$2,746	-$2,093x+$4,037	-$2,033x+$5,888	-$2,849x+$7,004	-$3,100x+$9,187
Large car	-$300x+$864	-$1,568x+$3,331	-$3,152x+$5,192	-$3,460x+$7,173	-$4,019x+$8,101	-$3,770x+$10,989
Minivan	-$294x+$848	-$1,439x+$3,296	-$2,090x+$5,035	-$3,480x+$7,201	-$3,090x+$8,414	-$4,566x+$11,746
Small truck	-$277x+$822	-$1,338x+$3,143	-$2,444x+$4,787	-$3,148x+$6,828	-$2,971x+$8,045	$11,253
Minivan+towing	-$294x+$929					
Large truck	-$317x+$964					

Notes:
"x" in the equations represents the net weight reduction as a percentage, so a subcompact P2 HEV battery pack with a 20% applied weight reduction and, therefore, a 15% net weight reduction would cost (-$177)x(15%)+$716=$689.
The small truck EV150 regression has no slope since the net weight reduction is always 0 due to the 20% weight reduction hit.
The agencies did not regress PHEV or EV costs for the minivan+towing and large truck vehicle classes since we do not believe these vehicle classes would use the technologies.

For P2 HEV battery packs, the direct manufacturing costs shown in Table 3-73 are considered applicable to the 2017MY. The agencies consider the P2 battery packs technology to be on the flat portion of the learning curve during the 2017-2025 timeframe. The agencies have applied a high1 complexity ICM of 1.56 through 2024 then 1.35 thereafter. For PHEV and EV battery packs, the direct manufacturing costs shown in Table 3-73 are considered applicable to the 2025MY. For the PHEV and EV battery packs, the agencies have applied the learning curve discussed in Section 3.2.3. The agencies have applied a high2 complexity ICM of 1.77 through 2024 then 1.50 thereafter. The resultant costs for P2 HEV, PHEV20, PHEV40, EV75, EV100 and EV150 battery packs are shown in Table 3-74 through Table 3-79, respectively.

Table 3-74 Costs for P2 HEV Battery Packs (2009$)

Cost type	Vehicle class	Applied WR	Net WR	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	10%	5%	$707	$686	$666	$646	$626	$607	$589	$572	$554
DMC	Subcompact	15%	10%	$699	$678	$657	$638	$618	$600	$582	$564	$547
DMC	Subcompact	20%	15%	$690	$669	$649	$629	$611	$592	$574	$557	$541
DMC	Small car	10%	5%	$747	$725	$703	$682	$661	$641	$622	$603	$585
DMC	Small car	15%	10%	$736	$714	$693	$672	$652	$632	$613	$595	$577
DMC	Small car	20%	15%	$725	$703	$682	$662	$642	$623	$604	$586	$568
DMC	Large car	10%	5%	$849	$823	$798	$775	$751	$729	$707	$686	$665
DMC	Large car	15%	10%	$834	$809	$784	$761	$738	$716	$694	$674	$653
DMC	Large car	20%	15%	$819	$794	$770	$747	$725	$703	$682	$661	$642
DMC	Minivan	10%	5%	$833	$808	$784	$760	$737	$715	$694	$673	$653
DMC	Minivan	15%	10%	$818	$794	$770	$747	$724	$703	$682	$661	$641
DMC	Minivan	20%	15%	$804	$779	$756	$733	$711	$690	$669	$649	$630
DMC	Small truck	10%	5%	$808	$784	$760	$738	$715	$694	$673	$653	$633
DMC	Small truck	15%	10%	$794	$770	$747	$725	$703	$682	$662	$642	$622
DMC	Small truck	20%	15%	$780	$757	$734	$712	$691	$670	$650	$631	$612
DMC	Minivan-towing	10%	4%	$917	$889	$863	$837	$812	$787	$764	$741	$719
DMC	Minivan-towing	15%	9%	$902	$875	$849	$823	$799	$775	$752	$729	$707
DMC	Minivan-towing	20%	14%	$888	$861	$835	$810	$786	$762	$739	$717	$696
DMC	Large truck	10%	4%	$952	$923	$895	$868	$842	$817	$793	$769	$746
DMC	Large truck	15%	9%	$936	$908	$880	$854	$828	$804	$779	$756	$733
DMC	Large truck	20%	14%	$920	$892	$866	$840	$814	$790	$766	$743	$721
IC	Subcompact	10%	5%	$399	$397	$396	$395	$393	$392	$391	$390	$239
IC	Subcompact	15%	10%	$394	$392	$391	$390	$389	$387	$386	$385	$236
IC	Subcompact	20%	15%	$389	$387	$386	$385	$384	$382	$381	$380	$233
IC	Small car	10%	5%	$421	$420	$418	$417	$415	$414	$413	$412	$253
IC	Small car	15%	10%	$415	$413	$412	$411	$409	$408	$407	$406	$249
IC	Small car	20%	15%	$409	$407	$406	$405	$403	$402	$401	$400	$245
IC	Large car	10%	5%	$478	$477	$475	$474	$472	$471	$469	$468	$287
IC	Large car	15%	10%	$470	$468	$467	$465	$464	$462	$461	$459	$282
IC	Large car	20%	15%	$461	$460	$458	$457	$455	$454	$453	$451	$277
IC	Minivan	10%	5%	$470	$468	$466	$465	$463	$462	$461	$459	$282
IC	Minivan	15%	10%	$461	$460	$458	$457	$455	$454	$452	$451	$277
IC	Minivan	20%	15%	$453	$451	$450	$448	$447	$446	$444	$443	$272
IC	Small truck	10%	5%	$455	$454	$452	$451	$449	$448	$447	$445	$274
IC	Small truck	15%	10%	$448	$446	$445	$443	$442	$440	$439	$438	$269
IC	Small truck	20%	15%	$440	$438	$437	$435	$434	$433	$431	$430	$264
IC	Minivan-towing	10%	4%	$517	$515	$513	$512	$510	$508	$507	$505	$310
IC	Minivan-towing	15%	9%	$509	$507	$505	$503	$502	$500	$499	$497	$305
IC	Minivan-towing	20%	14%	$500	$499	$497	$495	$494	$492	$491	$489	$300
IC	Large truck	10%	4%	$536	$534	$533	$531	$529	$528	$526	$524	$322

IC	Large truck	15%	9%	$527	$526	$524	$522	$520	$519	$517	$516	$317
IC	Large truck	20%	14%	$518	$517	$515	$513	$512	$510	$509	$507	$311
TC	Subcompact	10%	5%	$1,106	$1,083	$1,062	$1,040	$1,020	$1,000	$980	$961	$794
TC	Subcompact	15%	10%	$1,092	$1,070	$1,048	$1,027	$1,007	$987	$968	$949	$784
TC	Subcompact	20%	15%	$1,078	$1,056	$1,035	$1,014	$994	$975	$956	$937	$774
TC	Small car	10%	5%	$1,168	$1,144	$1,121	$1,098	$1,077	$1,056	$1,035	$1,015	$838
TC	Small car	15%	10%	$1,151	$1,127	$1,105	$1,082	$1,061	$1,040	$1,020	$1,000	$826
TC	Small car	20%	15%	$1,134	$1,111	$1,088	$1,066	$1,045	$1,025	$1,005	$986	$814
TC	Large car	10%	5%	$1,327	$1,300	$1,274	$1,248	$1,223	$1,199	$1,176	$1,153	$952
TC	Large car	15%	10%	$1,304	$1,277	$1,251	$1,226	$1,202	$1,178	$1,155	$1,133	$936
TC	Large car	20%	15%	$1,280	$1,254	$1,229	$1,204	$1,180	$1,157	$1,135	$1,113	$919
TC	Minivan	10%	5%	$1,303	$1,276	$1,250	$1,225	$1,201	$1,177	$1,154	$1,132	$935
TC	Minivan	15%	10%	$1,280	$1,253	$1,228	$1,203	$1,180	$1,156	$1,134	$1,112	$918
TC	Minivan	20%	15%	$1,257	$1,231	$1,206	$1,182	$1,158	$1,136	$1,114	$1,092	$902
TC	Small truck	10%	5%	$1,264	$1,238	$1,213	$1,188	$1,165	$1,142	$1,120	$1,098	$907
TC	Small truck	15%	10%	$1,242	$1,217	$1,192	$1,168	$1,145	$1,122	$1,101	$1,080	$891
TC	Small truck	20%	15%	$1,220	$1,195	$1,171	$1,148	$1,125	$1,103	$1,081	$1,061	$876
TC	Minivan-towing	10%	4%	$1,434	$1,405	$1,376	$1,349	$1,322	$1,296	$1,271	$1,246	$1,029
TC	Minivan-towing	15%	9%	$1,411	$1,382	$1,354	$1,327	$1,301	$1,275	$1,250	$1,226	$1,013
TC	Minivan-towing	20%	14%	$1,388	$1,359	$1,332	$1,305	$1,279	$1,254	$1,230	$1,206	$996
TC	Large truck	10%	4%	$1,488	$1,457	$1,428	$1,399	$1,372	$1,345	$1,319	$1,293	$1,068
TC	Large truck	15%	9%	$1,463	$1,433	$1,404	$1,376	$1,349	$1,322	$1,297	$1,272	$1,050
TC	Large truck	20%	14%	$1,438	$1,409	$1,380	$1,353	$1,326	$1,300	$1,275	$1,250	$1,032

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-75 Costs for PHEV20 Battery Packs (2009$)

Cost type	Vehicle class	Applied WR	Net WR	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	10%	3%	$5,032	$4,026	$4,026	$3,220	$3,220	$3,220	$3,220	$3,220	$2,576
DMC	Subcompact	15%	8%	$4,948	$3,958	$3,958	$3,167	$3,167	$3,167	$3,167	$3,167	$2,533
DMC	Subcompact	20%	13%	$4,864	$3,891	$3,891	$3,113	$3,113	$3,113	$3,113	$3,113	$2,490
DMC	Small car	10%	3%	$5,305	$4,244	$4,244	$3,395	$3,395	$3,395	$3,395	$3,395	$2,716
DMC	Small car	15%	8%	$5,208	$4,166	$4,166	$3,333	$3,333	$3,333	$3,333	$3,333	$2,666
DMC	Small car	20%	13%	$5,110	$4,088	$4,088	$3,270	$3,270	$3,270	$3,270	$3,270	$2,616
DMC	Large car	10%	3%	$6,413	$5,131	$5,131	$4,104	$4,104	$4,104	$4,104	$4,104	$3,284
DMC	Large car	15%	8%	$6,260	$5,008	$5,008	$4,006	$4,006	$4,006	$4,006	$4,006	$3,205
DMC	Large car	20%	13%	$6,107	$4,886	$4,886	$3,908	$3,908	$3,908	$3,908	$3,908	$3,127
DMC	Minivan	10%	3%	$6,353	$5,082	$5,082	$4,066	$4,066	$4,066	$4,066	$4,066	$3,253
DMC	Minivan	15%	8%	$6,212	$4,970	$4,970	$3,976	$3,976	$3,976	$3,976	$3,976	$3,181
DMC	Minivan	20%	13%	$6,072	$4,857	$4,857	$3,886	$3,886	$3,886	$3,886	$3,886	$3,109
DMC	Small truck	10%	3%	$6,059	$4,847	$4,847	$3,878	$3,878	$3,878	$3,878	$3,878	$3,102
DMC	Small truck	15%	8%	$5,929	$4,743	$4,743	$3,794	$3,794	$3,794	$3,794	$3,794	$3,035
DMC	Small truck	20%	13%	$5,798	$4,638	$4,638	$3,711	$3,711	$3,711	$3,711	$3,711	$2,969
IC	Subcompact	10%	3%	$2,165	$2,091	$2,091	$2,031	$2,031	$2,031	$2,031	$2,031	$1,279
IC	Subcompact	15%	8%	$2,128	$2,056	$2,056	$1,997	$1,997	$1,997	$1,997	$1,997	$1,258
IC	Subcompact	20%	13%	$2,092	$2,021	$2,021	$1,963	$1,963	$1,963	$1,963	$1,963	$1,237
IC	Small car	10%	3%	$2,282	$2,204	$2,204	$2,142	$2,142	$2,142	$2,142	$2,142	$1,349
IC	Small car	15%	8%	$2,240	$2,164	$2,164	$2,102	$2,102	$2,102	$2,102	$2,102	$1,324
IC	Small car	20%	13%	$2,198	$2,123	$2,123	$2,063	$2,063	$2,063	$2,063	$2,063	$1,299
IC	Large car	10%	3%	$2,759	$2,664	$2,664	$2,589	$2,589	$2,589	$2,589	$2,589	$1,631
IC	Large car	15%	8%	$2,693	$2,601	$2,601	$2,527	$2,527	$2,527	$2,527	$2,527	$1,592

IC	Large car	20%	13%	$2,627	$2,537	$2,537	$2,465	$2,465	$2,465	$2,465	$2,465	$1,553
IC	Minivan	10%	3%	$2,733	$2,639	$2,639	$2,565	$2,565	$2,565	$2,565	$2,565	$1,615
IC	Minivan	15%	8%	$2,672	$2,581	$2,581	$2,508	$2,508	$2,508	$2,508	$2,508	$1,580
IC	Minivan	20%	13%	$2,612	$2,523	$2,523	$2,451	$2,451	$2,451	$2,451	$2,451	$1,544
IC	Small truck	10%	3%	$2,607	$2,517	$2,517	$2,446	$2,446	$2,446	$2,446	$2,446	$1,541
IC	Small truck	15%	8%	$2,550	$2,463	$2,463	$2,393	$2,393	$2,393	$2,393	$2,393	$1,507
IC	Small truck	20%	13%	$2,494	$2,409	$2,409	$2,340	$2,340	$2,340	$2,340	$2,340	$1,474
TC	Subcompact	10%	3%	$7,197	$6,116	$6,116	$5,252	$5,252	$5,252	$5,252	$5,252	$3,856
TC	Subcompact	15%	8%	$7,076	$6,014	$6,014	$5,164	$5,164	$5,164	$5,164	$5,164	$3,791
TC	Subcompact	20%	13%	$6,956	$5,911	$5,911	$5,076	$5,076	$5,076	$5,076	$5,076	$3,727
TC	Small car	10%	3%	$7,587	$6,448	$6,448	$5,537	$5,537	$5,537	$5,537	$5,537	$4,065
TC	Small car	15%	8%	$7,448	$6,330	$6,330	$5,435	$5,435	$5,435	$5,435	$5,435	$3,990
TC	Small car	20%	13%	$7,308	$6,211	$6,211	$5,333	$5,333	$5,333	$5,333	$5,333	$3,916
TC	Large car	10%	3%	$9,172	$7,795	$7,795	$6,693	$6,693	$6,693	$6,693	$6,693	$4,914
TC	Large car	15%	8%	$8,953	$7,609	$7,609	$6,533	$6,533	$6,533	$6,533	$6,533	$4,797
TC	Large car	20%	13%	$8,734	$7,423	$7,423	$6,374	$6,374	$6,374	$6,374	$6,374	$4,679
TC	Minivan	10%	3%	$9,086	$7,722	$7,722	$6,630	$6,630	$6,630	$6,630	$6,630	$4,868
TC	Minivan	15%	8%	$8,885	$7,551	$7,551	$6,484	$6,484	$6,484	$6,484	$6,484	$4,760
TC	Minivan	20%	13%	$8,684	$7,380	$7,380	$6,337	$6,337	$6,337	$6,337	$6,337	$4,653
TC	Small truck	10%	3%	$8,666	$7,365	$7,365	$6,324	$6,324	$6,324	$6,324	$6,324	$4,643
TC	Small truck	15%	8%	$8,479	$7,206	$7,206	$6,188	$6,188	$6,188	$6,188	$6,188	$4,543
TC	Small truck	20%	13%	$8,292	$7,047	$7,047	$6,051	$6,051	$6,051	$6,051	$6,051	$4,443

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-76 Costs for PHEV40 Battery Packs (2009$)

Cost type	Vehicle class	Applied WR	Net WR	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	15%	2%	$7,092	$5,674	$5,674	$4,539	$4,539	$4,539	$4,539	$4,539	$3,631
DMC	Subcompact	20%	7%	$7,007	$5,606	$5,606	$4,485	$4,485	$4,485	$4,485	$4,485	$3,588
DMC	Small car	15%	3%	$7,761	$6,209	$6,209	$4,967	$4,967	$4,967	$4,967	$4,967	$3,974
DMC	Small car	20%	8%	$7,557	$6,046	$6,046	$4,836	$4,836	$4,836	$4,836	$4,836	$3,869
DMC	Large car	15%	2%	$10,017	$8,014	$8,014	$6,411	$6,411	$6,411	$6,411	$6,411	$5,129
DMC	Large car	20%	7%	$9,709	$7,767	$7,767	$6,214	$6,214	$6,214	$6,214	$6,214	$4,971
DMC	Minivan	15%	2%	$9,752	$7,802	$7,802	$6,241	$6,241	$6,241	$6,241	$6,241	$4,993
DMC	Minivan	20%	7%	$9,548	$7,638	$7,638	$6,111	$6,111	$6,111	$6,111	$6,111	$4,889
DMC	Small truck	15%	3%	$9,206	$7,365	$7,365	$5,892	$5,892	$5,892	$5,892	$5,892	$4,713
DMC	Small truck	20%	8%	$8,967	$7,174	$7,174	$5,739	$5,739	$5,739	$5,739	$5,739	$4,591
IC	Subcompact	15%	2%	$3,051	$2,946	$2,946	$2,863	$2,863	$2,863	$2,863	$2,863	$1,803
IC	Subcompact	20%	7%	$3,014	$2,911	$2,911	$2,829	$2,829	$2,829	$2,829	$2,829	$1,782
IC	Small car	15%	3%	$3,339	$3,225	$3,225	$3,133	$3,133	$3,133	$3,133	$3,133	$1,973
IC	Small car	20%	8%	$3,251	$3,140	$3,140	$3,051	$3,051	$3,051	$3,051	$3,051	$1,921
IC	Large car	15%	2%	$4,309	$4,162	$4,162	$4,044	$4,044	$4,044	$4,044	$4,044	$2,547
IC	Large car	20%	7%	$4,177	$4,034	$4,034	$3,919	$3,919	$3,919	$3,919	$3,919	$2,469
IC	Minivan	15%	2%	$4,195	$4,052	$4,052	$3,937	$3,937	$3,937	$3,937	$3,937	$2,480
IC	Minivan	20%	7%	$4,107	$3,967	$3,967	$3,854	$3,854	$3,854	$3,854	$3,854	$2,428
IC	Small truck	15%	3%	$3,960	$3,825	$3,825	$3,716	$3,716	$3,716	$3,716	$3,716	$2,341
IC	Small truck	20%	8%	$3,858	$3,726	$3,726	$3,620	$3,620	$3,620	$3,620	$3,620	$2,280
TC	Subcompact	15%	2%	$10,143	$8,620	$8,620	$7,402	$7,402	$7,402	$7,402	$7,402	$5,434
TC	Subcompact	20%	7%	$10,022	$8,517	$8,517	$7,313	$7,313	$7,313	$7,313	$7,313	$5,370
TC	Small car	15%	3%	$11,100	$9,434	$9,434	$8,100	$8,100	$8,100	$8,100	$8,100	$5,947
TC	Small car	20%	8%	$10,808	$9,185	$9,185	$7,887	$7,887	$7,887	$7,887	$7,887	$5,791
TC	Large car	15%	2%	$14,326	$12,175	$12,175	$10,455	$10,455	$10,455	$10,455	$10,455	$7,676
TC	Large car	20%	7%	$13,886	$11,801	$11,801	$10,133	$10,133	$10,133	$10,133	$10,133	$7,440

TC	Minivan	15%	2%	$13,947	$11,853	$11,853	$10,178	$10,178	$10,178	$10,178	$10,178	$7,473
TC	Minivan	20%	7%	$13,655	$11,605	$11,605	$9,965	$9,965	$9,965	$9,965	$9,965	$7,316
TC	Small truck	15%	3%	$13,166	$11,190	$11,190	$9,608	$9,608	$9,608	$9,608	$9,608	$7,054
TC	Small truck	20%	8%	$12,825	$10,899	$10,899	$9,359	$9,359	$9,359	$9,359	$9,359	$6,871

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-77 Costs for EV75 Battery Packs (2009$)

Cost type	Vehicle class	Applied WR	Net WR	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	10%	10%	$10,331	$8,264	$8,264	$6,612	$6,612	$6,612	$6,612	$6,612	$5,289
DMC	Subcompact	15%	15%	$10,199	$8,159	$8,159	$6,527	$6,527	$6,527	$6,527	$6,527	$5,222
DMC	Subcompact	20%	20%	$10,067	$8,054	$8,054	$6,443	$6,443	$6,443	$6,443	$6,443	$5,154
DMC	Small car	10%	10%	$11,103	$8,882	$8,882	$7,106	$7,106	$7,106	$7,106	$7,106	$5,685
DMC	Small car	15%	15%	$10,904	$8,723	$8,723	$6,979	$6,979	$6,979	$6,979	$6,979	$5,583
DMC	Small car	20%	20%	$10,706	$8,565	$8,565	$6,852	$6,852	$6,852	$6,852	$6,852	$5,481
DMC	Large car	10%	10%	$13,333	$10,667	$10,667	$8,533	$8,533	$8,533	$8,533	$8,533	$6,827
DMC	Large car	15%	15%	$12,996	$10,396	$10,396	$8,317	$8,317	$8,317	$8,317	$8,317	$6,654
DMC	Large car	20%	20%	$12,658	$10,126	$10,126	$8,101	$8,101	$8,101	$8,101	$8,101	$6,481
DMC	Minivan	10%	10%	$13,385	$10,708	$10,708	$8,566	$8,566	$8,566	$8,566	$8,566	$6,853
DMC	Minivan	15%	15%	$13,045	$10,436	$10,436	$8,349	$8,349	$8,349	$8,349	$8,349	$6,679
DMC	Minivan	20%	20%	$12,705	$10,164	$10,164	$8,131	$8,131	$8,131	$8,131	$8,131	$6,505
DMC	Small truck	10%	10%	$12,722	$10,177	$10,177	$8,142	$8,142	$8,142	$8,142	$8,142	$6,513
DMC	Small truck	15%	15%	$12,414	$9,931	$9,931	$7,945	$7,945	$7,945	$7,945	$7,945	$6,356
DMC	Small truck	20%	20%	$12,107	$9,685	$9,685	$7,748	$7,748	$7,748	$7,748	$7,748	$6,199
IC	Subcompact	10%	10%	$4,444	$4,292	$4,292	$4,170	$4,170	$4,170	$4,170	$4,170	$2,627
IC	Subcompact	15%	15%	$4,387	$4,237	$4,237	$4,117	$4,117	$4,117	$4,117	$4,117	$2,593
IC	Subcompact	20%	20%	$4,331	$4,182	$4,182	$4,064	$4,064	$4,064	$4,064	$4,064	$2,560
IC	Small car	10%	10%	$4,776	$4,613	$4,613	$4,482	$4,482	$4,482	$4,482	$4,482	$2,823
IC	Small car	15%	15%	$4,691	$4,530	$4,530	$4,402	$4,402	$4,402	$4,402	$4,402	$2,773
IC	Small car	20%	20%	$4,605	$4,448	$4,448	$4,322	$4,322	$4,322	$4,322	$4,322	$2,722
IC	Large car	10%	10%	$5,736	$5,540	$5,540	$5,382	$5,382	$5,382	$5,382	$5,382	$3,390
IC	Large car	15%	15%	$5,591	$5,399	$5,399	$5,246	$5,246	$5,246	$5,246	$5,246	$3,304
IC	Large car	20%	20%	$5,445	$5,259	$5,259	$5,110	$5,110	$5,110	$5,110	$5,110	$3,218
IC	Minivan	10%	10%	$5,758	$5,561	$5,561	$5,403	$5,403	$5,403	$5,403	$5,403	$3,403
IC	Minivan	15%	15%	$5,612	$5,420	$5,420	$5,266	$5,266	$5,266	$5,266	$5,266	$3,317
IC	Minivan	20%	20%	$5,466	$5,278	$5,278	$5,129	$5,129	$5,129	$5,129	$5,129	$3,230
IC	Small truck	10%	10%	$5,473	$5,285	$5,285	$5,135	$5,135	$5,135	$5,135	$5,135	$3,235
IC	Small truck	15%	15%	$5,340	$5,158	$5,158	$5,011	$5,011	$5,011	$5,011	$5,011	$3,156
IC	Small truck	20%	20%	$5,208	$5,030	$5,030	$4,887	$4,887	$4,887	$4,887	$4,887	$3,078
TC	Subcompact	10%	10%	$14,775	$12,556	$12,556	$10,782	$10,782	$10,782	$10,782	$10,782	$7,916
TC	Subcompact	15%	15%	$14,586	$12,396	$12,396	$10,644	$10,644	$10,644	$10,644	$10,644	$7,815
TC	Subcompact	20%	20%	$14,398	$12,236	$12,236	$10,507	$10,507	$10,507	$10,507	$10,507	$7,714
TC	Small car	10%	10%	$15,879	$13,495	$13,495	$11,588	$11,588	$11,588	$11,588	$11,588	$8,508
TC	Small car	15%	15%	$15,595	$13,254	$13,254	$11,381	$11,381	$11,381	$11,381	$11,381	$8,356
TC	Small car	20%	20%	$15,311	$13,012	$13,012	$11,173	$11,173	$11,173	$11,173	$11,173	$8,203
TC	Large car	10%	10%	$19,069	$16,206	$16,206	$13,916	$13,916	$13,916	$13,916	$13,916	$10,217
TC	Large car	15%	15%	$18,586	$15,796	$15,796	$13,563	$13,563	$13,563	$13,563	$13,563	$9,958
TC	Large car	20%	20%	$18,103	$15,385	$15,385	$13,211	$13,211	$13,211	$13,211	$13,211	$9,699
TC	Minivan	10%	10%	$19,143	$16,269	$16,269	$13,969	$13,969	$13,969	$13,969	$13,969	$10,256
TC	Minivan	15%	15%	$18,657	$15,855	$15,855	$13,615	$13,615	$13,615	$13,615	$13,615	$9,996
TC	Minivan	20%	20%	$18,170	$15,442	$15,442	$13,260	$13,260	$13,260	$13,260	$13,260	$9,735
TC	Small truck	10%	10%	$18,194	$15,463	$15,463	$13,277	$13,277	$13,277	$13,277	$13,277	$9,748
TC	Small truck	15%	15%	$17,755	$15,089	$15,089	$12,956	$12,956	$12,956	$12,956	$12,956	$9,513

TC	Small truck	20%	20%	$17,315	$14,715	$14,715	$12,636	$12,636	$12,636	$12,636	$12,636	$9,277

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-78 Costs for EV100 Battery Packs (2009$)

Cost type	Vehicle class	Applied WR	Net WR	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	10%	4%	$12,261	$9,809	$9,809	$7,847	$7,847	$7,847	$7,847	$7,847	$6,278
DMC	Subcompact	15%	9%	$12,059	$9,648	$9,648	$7,718	$7,718	$7,718	$7,718	$7,718	$6,174
DMC	Subcompact	20%	14%	$11,858	$9,486	$9,486	$7,589	$7,589	$7,589	$7,589	$7,589	$6,071
DMC	Small car	10%	5%	$13,401	$10,721	$10,721	$8,576	$8,576	$8,576	$8,576	$8,576	$6,861
DMC	Small car	15%	10%	$13,122	$10,498	$10,498	$8,398	$8,398	$8,398	$8,398	$8,398	$6,719
DMC	Small car	20%	15%	$12,844	$10,275	$10,275	$8,220	$8,220	$8,220	$8,220	$8,220	$6,576
DMC	Large car	10%	5%	$15,430	$12,344	$12,344	$9,875	$9,875	$9,875	$9,875	$9,875	$7,900
DMC	Large car	15%	10%	$15,038	$12,030	$12,030	$9,624	$9,624	$9,624	$9,624	$9,624	$7,699
DMC	Large car	20%	15%	$14,645	$11,716	$11,716	$9,373	$9,373	$9,373	$9,373	$9,373	$7,498
DMC	Minivan	10%	4%	$16,192	$12,954	$12,954	$10,363	$10,363	$10,363	$10,363	$10,363	$8,290
DMC	Minivan	15%	9%	$15,890	$12,712	$12,712	$10,170	$10,170	$10,170	$10,170	$10,170	$8,136
DMC	Minivan	20%	14%	$15,588	$12,471	$12,471	$9,977	$9,977	$9,977	$9,977	$9,977	$7,981
DMC	Small truck	10%	2%	$15,597	$12,478	$12,478	$9,982	$9,982	$9,982	$9,982	$9,982	$7,986
DMC	Small truck	15%	7%	$15,307	$12,246	$12,246	$9,796	$9,796	$9,796	$9,796	$9,796	$7,837
DMC	Small truck	20%	12%	$15,017	$12,013	$12,013	$9,611	$9,611	$9,611	$9,611	$9,611	$7,689
IC	Subcompact	10%	4%	$5,275	$5,094	$5,094	$4,950	$4,950	$4,950	$4,950	$4,950	$3,118
IC	Subcompact	15%	9%	$5,188	$5,010	$5,010	$4,868	$4,868	$4,868	$4,868	$4,868	$3,066
IC	Subcompact	20%	14%	$5,101	$4,926	$4,926	$4,787	$4,787	$4,787	$4,787	$4,787	$3,015
IC	Small car	10%	5%	$5,765	$5,567	$5,567	$5,410	$5,410	$5,410	$5,410	$5,410	$3,407
IC	Small car	15%	10%	$5,645	$5,452	$5,452	$5,297	$5,297	$5,297	$5,297	$5,297	$3,337
IC	Small car	20%	15%	$5,525	$5,336	$5,336	$5,185	$5,185	$5,185	$5,185	$5,185	$3,266
IC	Large car	10%	5%	$6,638	$6,411	$6,411	$6,229	$6,229	$6,229	$6,229	$6,229	$3,923
IC	Large car	15%	10%	$6,469	$6,248	$6,248	$6,071	$6,071	$6,071	$6,071	$6,071	$3,824
IC	Large car	20%	15%	$6,300	$6,085	$6,085	$5,912	$5,912	$5,912	$5,912	$5,912	$3,724
IC	Minivan	10%	4%	$6,966	$6,727	$6,727	$6,536	$6,536	$6,536	$6,536	$6,536	$4,117
IC	Minivan	15%	9%	$6,836	$6,602	$6,602	$6,415	$6,415	$6,415	$6,415	$6,415	$4,040
IC	Minivan	20%	14%	$6,706	$6,476	$6,476	$6,293	$6,293	$6,293	$6,293	$6,293	$3,964
IC	Small truck	10%	2%	$6,710	$6,480	$6,480	$6,296	$6,296	$6,296	$6,296	$6,296	$3,966
IC	Small truck	15%	7%	$6,585	$6,359	$6,359	$6,179	$6,179	$6,179	$6,179	$6,179	$3,892
IC	Small truck	20%	12%	$6,460	$6,239	$6,239	$6,062	$6,062	$6,062	$6,062	$6,062	$3,818
TC	Subcompact	10%	4%	$17,536	$14,903	$14,903	$12,797	$12,797	$12,797	$12,797	$12,797	$9,395
TC	Subcompact	15%	9%	$17,247	$14,658	$14,658	$12,586	$12,586	$12,586	$12,586	$12,586	$9,241
TC	Subcompact	20%	14%	$16,959	$14,413	$14,413	$12,376	$12,376	$12,376	$12,376	$12,376	$9,086
TC	Small car	10%	5%	$19,165	$16,288	$16,288	$13,986	$13,986	$13,986	$13,986	$13,986	$10,268
TC	Small car	15%	10%	$18,767	$15,950	$15,950	$13,696	$13,696	$13,696	$13,696	$13,696	$10,055
TC	Small car	20%	15%	$18,370	$15,612	$15,612	$13,405	$13,405	$13,405	$13,405	$13,405	$9,842
TC	Large car	10%	5%	$22,068	$18,755	$18,755	$16,104	$16,104	$16,104	$16,104	$16,104	$11,824
TC	Large car	15%	10%	$21,507	$18,278	$18,278	$15,695	$15,695	$15,695	$15,695	$15,695	$11,523
TC	Large car	20%	15%	$20,946	$17,801	$17,801	$15,285	$15,285	$15,285	$15,285	$15,285	$11,222
TC	Minivan	10%	4%	$23,158	$19,681	$19,681	$16,899	$16,899	$16,899	$16,899	$16,899	$12,407
TC	Minivan	15%	9%	$22,726	$19,314	$19,314	$16,584	$16,584	$16,584	$16,584	$16,584	$12,176
TC	Minivan	20%	14%	$22,294	$18,947	$18,947	$16,269	$16,269	$16,269	$16,269	$16,269	$11,945
TC	Small truck	10%	2%	$22,307	$18,958	$18,958	$16,278	$16,278	$16,278	$16,278	$16,278	$11,951
TC	Small truck	15%	7%	$21,892	$18,605	$18,605	$15,976	$15,976	$15,976	$15,976	$15,976	$11,729
TC	Small truck	20%	12%	$21,477	$18,252	$18,252	$15,673	$15,673	$15,673	$15,673	$15,673	$11,507

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-79 Costs for EV150 Battery Packs (2009$)

Cost type	Vehicle class	Applied WR	Net WR	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	20%	2%	$16,116	$12,893	$12,893	$10,314	$10,314	$10,314	$10,314	$10,314	$8,251
DMC	Small car	20%	3%	$17,762	$14,210	$14,210	$11,368	$11,368	$11,368	$11,368	$11,368	$9,094
DMC	Large car	20%	2%	$21,316	$17,052	$17,052	$13,642	$13,642	$13,642	$13,642	$13,642	$10,914
DMC	Minivan	20%	2%	$22,763	$18,210	$18,210	$14,568	$14,568	$14,568	$14,568	$14,568	$11,655
DMC	Small truck	20%	0%	$21,979	$17,583	$17,583	$14,066	$14,066	$14,066	$14,066	$14,066	$11,253
IC	Subcompact	20%	2%	$6,933	$6,696	$6,696	$6,506	$6,506	$6,506	$6,506	$6,506	$4,098
IC	Small car	20%	3%	$7,641	$7,379	$7,379	$7,170	$7,170	$7,170	$7,170	$7,170	$4,516
IC	Large car	20%	2%	$9,170	$8,856	$8,856	$8,605	$8,605	$8,605	$8,605	$8,605	$5,420
IC	Minivan	20%	2%	$9,792	$9,457	$9,457	$9,189	$9,189	$9,189	$9,189	$9,189	$5,788
IC	Small truck	20%	0%	$9,455	$9,131	$9,131	$8,872	$8,872	$8,872	$8,872	$8,872	$5,588
TC	Subcompact	20%	2%	$23,049	$19,588	$19,588	$16,820	$16,820	$16,820	$16,820	$16,820	$12,349
TC	Small car	20%	3%	$25,403	$21,589	$21,589	$18,538	$18,538	$18,538	$18,538	$18,538	$13,610
TC	Large car	20%	2%	$30,485	$25,908	$25,908	$22,247	$22,247	$22,247	$22,247	$22,247	$16,333
TC	Minivan	20%	2%	$32,555	$27,668	$27,668	$23,757	$23,757	$23,757	$23,757	$23,757	$17,443
TC	Small truck	20%	0%	$31,434	$26,714	$26,714	$22,939	$22,939	$22,939	$22,939	$22,939	$16,842

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

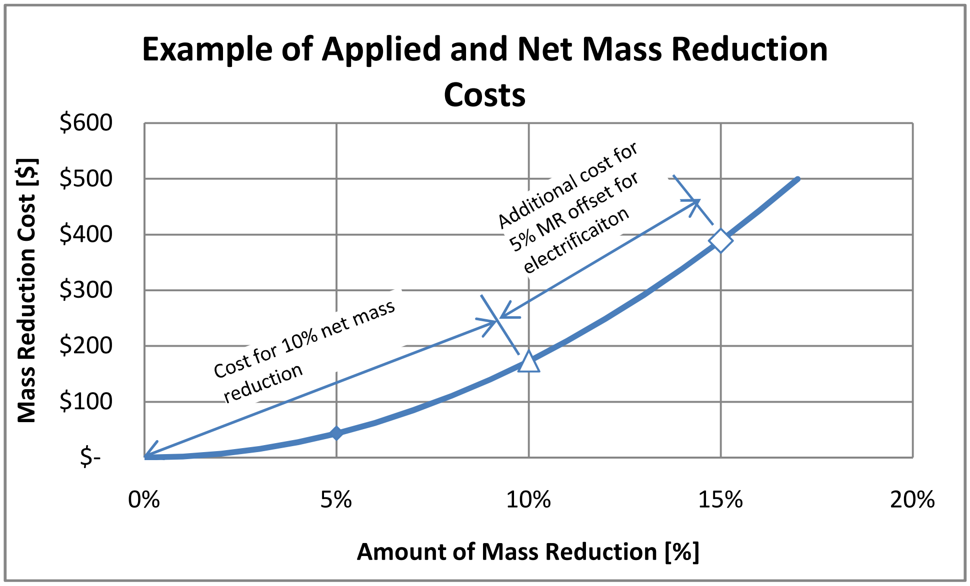
Because CAFE Volpe model does not use pre-built package and it applies technologies as necessary to meet the fuel consumption reduction requirement, cost interaction between any particular technology and other technologies has to be flexible so that when a technology is picked, the model will automatically look through the cost synergy defined in a table and apply cost adjustment accordingly. The total cost for mass reduction and electrification is composed of the following four parts.

(1) Cost of net mass reduction;
(2) Cost of electrification with zero mass reduction;
(3) Mass reduction cost synergy for increased or decreased amount of mass reduction due to switching from conventional powertrain to electrification systems as define in Figure 3-25. For an example, if a midsize passenger car needs both10 percent net mass reduction and P2 hybrid to meet the CAFE target, the model will need to find the cost of additional 5 percent of mass reduction to consider the vehicle weight increase due to switching from conventional powertrain system to P2 electrification packages. This additional 5 percent of mass reduction is calculated starting from 10 percent mass reduction, not zero as shown in Figure 3-25 because mass reduction cost versus mass reduction percent is not a linear function. The cost increases faster as the amount of mass reduction becomes higher.
(4) Electrification system cost synergy (battery and non-battery components) due to mass reduction as defined in Table 3-73 and Table 3-86: Continuing the example in the steps above, if a midsize passenger car needs both10 percent net mass reduction and P2 hybrid to meet the CAFE target, after calculating the costs above, the model will need to find the cost of electrification systems,

including battery system and non-battery system, with the required net amount of mass reduction using the equations in Table 3-73 and Table 3-86. Then the delta cost between this cost and the cost calculated in step 2, i.e. electrification system cost with zero applied mass reduction is calculated and treated as a cost synergy. These cost deltas are normally a negative, i.e. cost reduction, due to the downsizing of electrification system resulting from mass reduction.

The sum of item (3) and (4) in the above list are calculate as cost synergy and store in the cost synergy table as defined in NHTSA's RIA.

Figure 3-25 Mass Reduction Cost Example for Applied and Net Mass Reduction



The agencies have also carefully reconsidered the power and energy requirements for each electrified vehicle type, which has a significant impact on the cost estimates for HEVs, PHEVs, and EVs as compared to the estimates used in the 2012-2016 rulemaking.

The agencies note that, for this analysis, the agencies have assumed batteries will be capable of lasting the lifetime of the vehicle, which is consistent with the expected customer demands from this technology (as manufacturers have confirmed). Lastly, the agencies have focused attention on an emerging HEV technology known as a P2-hybrid, a technology not considered in the 2012-2016 light-duty rule.

The agencies have also considered, for this analysis, the costs associated with in-home chargers expected to be necessary for PHEVs and EVs. Further details on in-home chargers and their estimated costs are presented in Section 3.4.4.

3.4.3.10 Non-battery costs for MHEVs, HEVs, PHEVs, EVs and FCEVs

This section addresses the costs of non-battery components which are required for electric drive vehicles. Some of these components are not found in every electric-drive vehicle (e.g. an HEV does not have an on-board battery charger as found in a PHEV or EV). Others are found in all electric drive vehicles and/or must be scaled to the vehicle type or class to properly represent the cost. The agencies derived the costs of these components from the FEV teardown study and the 2010 TAR. Where appropriate, costs were scaled to vehicle class and in the case of the motor and inverter, the sizing methodology used for battery sizing was applied.

The electric drive motor and inverter provide the motive power for any electric-drive vehicle converting electrical energy from the battery into kinetic energy for propulsion. In an electric-drive vehicle, energy stored in the battery is routed to the inverter which converts it to a voltage and wave form that can be used by the motor.

In many cases, such as HEVs, the combined cost of the motor and inverter exceed the battery cost. As batteries become larger in PHEVs and EVs, the battery cost grows faster than motor and inverter cost. For this analysis, the agencies used the vehicle power requirement calculation discussed in 3.4.3.8 to calculate the required motor and inverter size for each vehicle class at each weight reduction point. Then, for the HEVs and PHEVs, a regression was created from the FEV teardown data for motors and inverters and this regression was used to calculate the motor and inverter cost for each combination of vehicle class and weight reduction. This regression was $14.48x(motor size in kW)+$763.54. The results are shown as the “Motor assembly” line item in Table 3-80, Table 3-81 and Table 3-82 which show our scaled DMC for P2 HEV, PHEV20 and PHEV40, respectively.

For EVs, the agencies used the motor and inverter cost regression from the 2010 TAR (see TAR at page B-21). Since the FEV teardown was conducted on an HEV Ford Fusion, the agencies believe the technology for an EV is different enough to warrant using the TAR regression. The regression presented in the TAR showed the DMC being equal to $8.28x(motor size in kW)+$181.43. The results are presented as separate line items for “Motor inverter” and “Motor assembly” in Table 3-83, Table 3-84 and Table 3-85 which show our scaled DMC for EV75, EV100 and EV150, respectively.

In addition to electric drive motors and inverters, there are several other components in electric drive vehicles that are required. These components include the following:

- *Body Modifications* which are required on HEVs and PHEVs include changes to sheet metal to accommodate electric drive components and the addition of fasteners to secure components such as electric cables. These costs come from the FEV teardown and are scaled by vehicle class. For EVs, these costs are assumed to be included in the base vehicle because they are less likely to be adapted from conventional vehicles.

- *Brake System* changes include the addition of a braking system that can control the vehicle's regenerative braking system—a key enabler of electric drive vehicle efficiency. The brake system costs are from the FEV teardown and are scaled to vehicle class.

- *Climate Control System* includes components such as an electric air conditioning compressor that enables operation while the engine is off for HEVs and PHEVs as well as for an EV which has no engine. Climate control system costs come from the FEV teardown and are scaled to vehicle class.

- *Conventional vehicle battery and alternator* are deleted in these vehicles, for a cost savings, replaced by the DC-DC converter which converts the high-voltage traction battery to a nominal 12V DC to operate the vehicle's accessories. This credit comes from the FEV teardown study and is scaled to vehicle class.

- *DC-DC converter* converts the high-voltage battery voltage to a nominal 12V battery voltage to run vehicle accessories such as the radio, lights and wipers. This cost comes from the FEV teardown study and is scaled to vehicle class.

- *Power distribution and Control* consists of those components which route electricity to the motor, inverter and contains the controllers to operate and monitor the electric drive system. This cost applies to HEVs and PHEVs and comes from the FEV teardown study. It is scaled to vehicle class.

- *On-Vehicle Charger* consists of the components necessary to charge a PHEV or EV from an outlet. It includes the charging port, wiring and electronics necessary to convert a 120V or 240V AC input to the high-voltage DC power necessary to charge the battery. Because the FEV teardown study subject vehicle did not have an on-vehicle charger, the costs from the TAR were used for this item. It is not scaled to vehicle class, however the EV charger is assumed to cost twice the amount of the PHEV charger to account for a higher current capacity. This cost does not include off-vehicle charger components which are discussed in Section 3.4.4, below.

- *Supplemental heating* is required for passenger comfort on PHEVs and EVs which may operate for long periods with no engine heat available. This cost comes from the FEV teardown study and is scaled to vehicle class. The supplemental heater on the EV is assumed to be three times more costly than the PHEV because the entire cabin comfort is dependent on the supplemental heater. In a PHEV, it is assumed that in extreme conditions, the internal combustion engine will start to provide additional cabin heat and defrost functions.

- *High Voltage Wiring* is an item used on EVs only. It includes the high voltage cabling from the battery to the inverter and motor as well as control components.

It is equivalent to the power distribution and control used on HEVs and PHEVs and comes from the FEV teardown study. It is scaled to vehicle class.

- *Delete Internal Combustion Engine and Transmission* For EVs, the engine and transmission are deleted and a credit is applied. These credits come from work done in support of the 2010 TAR and are scaled to vehicle class.

The results of the scaling exercise applied to non-battery components are presented in Table 3-80 through Table 3-85 for P2 HEVs, PHEV20, PHEV40, EV75, EV100 and EV150, respectively.

Table 3-80 Scaled Non-battery DMC by Applied Vehicle Weight Reduction for P2 HEV (2009$)

System	Subcompact	Small car	Large car	Minivan	Minivan+towing	Small truck	Large truck
0% WR							
Body system	$6	$6	$6	$7	$7	$6	$7
Brake system	$233	$238	$242	$242	$242	$240	$248
Climate controls	$154	$164	$176	$220	$220	$202	$194
Delete electrical	-$62	-$67	-$85	-$89	-$89	-$89	-$97
DC-DC converter	$115	$126	$157	$167	$167	$167	$183
Power Distr & control	$203	$207	$210	$210	$210	$207	$219
Motor assembly	$1,038	$1,096	$1,342	$1,270	$1,270	$1,212	$1,327
Total	$1,688	$1,771	$2,048	$2,027	$2,027	$1,946	$2,082
2% WR							
Body system	$6	$6	$6	$7	$7	$6	$7
Brake system	$233	$238	$242	$242	$242	$240	$248
Climate controls	$154	$164	$176	$220	$220	$202	$194
Delete electrical	-$62	-$67	-$85	-$89	-$89	-$89	-$97
DC-DC converter	$115	$126	$157	$167	$167	$167	$183
Power Distr & control	$203	$207	$210	$210	$210	$207	$219
Motor assembly	$1,038	$1,096	$1,327	$1,255	$1,255	$1,212	$1,313
Total	$1,688	$1,771	$2,034	$2,013	$2,013	$1,946	$2,067
7.5% WR							
Body system	$6	$6	$6	$7	$7	$6	$7
Brake system	$233	$238	$242	$242	$242	$240	$248
Climate controls	$154	$164	$176	$220	$220	$202	$194
Delete electrical	-$62	-$67	-$85	-$89	-$89	-$89	-$97
DC-DC converter	$115	$126	$157	$167	$167	$167	$183
Power Distr & control	$203	$207	$210	$210	$210	$207	$219
Motor assembly	$1,024	$1,067	$1,298	$1,226	$1,226	$1,183	$1,284
Total	$1,673	$1,742	$2,005	$1,984	$1,984	$1,917	$2,038
10% WR							
Body system	$6	$6	$6	$7	$7	$6	$7
Brake system	$233	$238	$242	$242	$242	$240	$248
Climate controls	$154	$164	$176	$220	$220	$202	$194
Delete electrical	-$62	-$67	-$85	-$89	-$89	-$89	-$97
DC-DC converter	$115	$126	$157	$167	$167	$167	$183
Power Distr & control	$203	$207	$210	$210	$210	$207	$219
Motor assembly	$1,009	$1,067	$1,284	$1,226	$1,226	$1,168	$1,284
Total	$1,659	$1,742	$1,990	$1,984	$1,984	$1,903	$2,038
20% WR							
Body system	$6	$6	$6	$7	$7	$6	$7
Brake system	$233	$238	$242	$242	$242	$240	$248
Climate controls	$154	$164	$176	$220	$220	$202	$194
Delete electrical	-$62	-$67	-$85	-$89	-$89	-$89	-$97

DC-DC converter	$115	$126	$157	$167	$167	$167	$183
Power Distr & control	$203	$207	$210	$210	$210	$207	$219
Motor assembly	$995	$1,053	$1,255	$1,197	$1,197	$1,154	$1,255
Total	$1,644	$1,727	$1,961	$1,955	$1,955	$1,888	$2,009

Table 3-81 Scaled Non-battery DMC by Applied Vehicle Weight Reduction for PHEV20 (2009$)[a]

System	Subcompact	Small car	Large car	Minivan	Small truck
0% WR					
Body system	$6	$6	$6	$7	$6
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
Power Distr & control	$203	$207	$210	$210	$207
On vehicle charger	$103	$103	$103	$103	$103
Supplemental heater	$42	$45	$48	$60	$55
Motor assembly	$2,151	$2,426	$3,640	$3,279	$3,019
Total	$2,947	$3,249	$4,498	$4,200	$3,911
2% WR					
Body system	$6	$6	$6	$7	$6
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
Power Distr & control	$203	$207	$210	$210	$207
On vehicle charger	$103	$103	$103	$103	$103
Supplemental heater	$42	$45	$48	$60	$55
Motor assembly	$2,122	$2,397	$3,583	$3,221	$2,975
Total	$2,918	$3,220	$4,440	$4,142	$3,868
7.5% WR					
Body system	$6	$6	$6	$7	$6
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
Power Distr & control	$203	$207	$210	$210	$207
On vehicle charger	$103	$103	$103	$103	$103
Supplemental heater	$42	$45	$48	$60	$55
Motor assembly	$2,036	$2,310	$3,424	$3,091	$2,860
Total	$2,831	$3,133	$4,281	$4,012	$3,752
10% WR					
Body system	$6	$6	$6	$7	$6
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
Power Distr & control	$203	$207	$210	$210	$207
On vehicle charger	$103	$103	$103	$103	$103
Supplemental heater	$42	$45	$48	$60	$55
Motor assembly	$2,007	$2,267	$3,351	$3,033	$2,802
Total	$2,802	$3,090	$4,209	$3,954	$3,694
20% WR					
Body system	$6	$6	$6	$7	$6

Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
Power Distr & control	$203	$207	$210	$210	$207
On vehicle charger	$103	$103	$103	$103	$103
Supplemental heater	$42	$45	$48	$60	$55
Motor assembly	$1,978	$2,238	$3,294	$2,990	$2,744
Total	$2,773	$3,061	$4,151	$3,911	$3,637

a The agencies have not estimated PHEV or EV costs for the minivan+towing and large truck vehicle classes since we do not believe these vehicle classes would use the technologies.

Table 3-82 Scaled Non-battery DMC by Applied Vehicle Weight Reduction for PHEV40 (2009$)

System	Subcompact	Small car	Large car	Minivan	Small truck
0% WR					
Body system	$6	$6	$6	$7	$6
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
Power Distr & control	$203	$207	$210	$210	$207
On vehicle charger	$103	$103	$103	$103	$103
Supplemental heater	$42	$45	$48	$60	$55
Motor assembly	$2,151	$2,426	$3,640	$3,279	$3,019
Total	$2,947	$3,249	$4,498	$4,200	$3,911
2% WR					
Body system	$6	$6	$6	$7	$6
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
Power Distr & control	$203	$207	$210	$210	$207
On vehicle charger	$103	$103	$103	$103	$103
Supplemental heater	$42	$45	$48	$60	$55
Motor assembly	$2,122	$2,397	$3,583	$3,221	$2,975
Total	$2,918	$3,220	$4,440	$4,142	$3,868
7.5% WR					
Body system	$6	$6	$6	$7	$6
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
Power Distr & control	$203	$207	$210	$210	$207
On vehicle charger	$103	$103	$103	$103	$103
Supplemental heater	$42	$45	$48	$60	$55
Motor assembly	$2,050	$2,310	$3,438	$3,106	$2,860
Total	$2,845	$3,133	$4,296	$4,026	$3,752
10% WR					
Body system	$6	$6	$6	$7	$6
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
Power Distr & control	$203	$207	$210	$210	$207
On vehicle charger	$103	$103	$103	$103	$103
Supplemental heater	$42	$45	$48	$60	$55
Motor assembly	$2,050	$2,310	$3,438	$3,106	$2,845
Total	$2,845	$3,133	$4,296	$4,026	$3,738
20% WR					
Body system	$6	$6	$6	$7	$6
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
Power Distr & control	$203	$207	$210	$210	$207
On vehicle charger	$103	$103	$103	$103	$103

Supplemental heater	$42	$45	$48	$60	$55
Motor assembly	$2,050	$2,310	$3,438	$3,106	$2,845
Total	$2,845	$3,133	$4,296	$4,026	$3,738

a The agencies have not estimated PHEV or EV costs for the minivan+towing and large truck vehicle classes since we do not believe these vehicle classes would use the technologies.

Table 3-83 Scaled Non-battery DMC by Applied Vehicle Weight Reduction for EV75 (2009$)

System	Subcompact	Small car	Large car	Minivan	Small truck
0% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$693	$830	$1,437	$1,256	$1,126
Controls	$119	$119	$119	$119	$119
Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$1,007	$1,169	$1,887	$1,673	$1,520
Total	$415	$745	$1,254	$1,005	$1,186
2% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$679	$816	$1,408	$1,227	$1,105
Controls	$119	$119	$119	$119	$119
Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$990	$1,152	$1,853	$1,639	$1,494
Total	$384	$713	$1,191	$942	$1,139
7.5% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$635	$773	$1,328	$1,162	$1,047
Controls	$119	$119	$119	$119	$119
Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$939	$1,101	$1,759	$1,562	$1,426
Total	$289	$619	$1,017	$800	$1,013
10% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$621	$751	$1,292	$1,134	$1,018
Controls	$119	$119	$119	$119	$119

Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$922	$1,075	$1,716	$1,528	$1,392
Total	$258	$571	$938	$737	$950
20% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$563	$671	$1,155	$1,018	$946
Controls	$119	$119	$119	$119	$119
Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$853	$982	$1,554	$1,392	$1,306
Total	$132	$398	$639	$485	$792

a The agencies have not estimated PHEV or EV costs for the minivan+towing and large truck vehicle classes since we do not believe these vehicle classes would use the technologies.

Table 3-84 Scaled Non-battery DMC by Applied Vehicle Weight Reduction for EV100 (2009$)

System	Subcompact	Small car	Large car	Minivan	Small truck
0% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$693	$830	$1,437	$1,256	$1,126
Controls	$119	$119	$119	$119	$119
Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$1,007	$1,169	$1,887	$1,673	$1,520
Total	$415	$745	$1,254	$1,005	$1,186
2% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$679	$816	$1,408	$1,227	$1,105
Controls	$119	$119	$119	$119	$119
Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$990	$1,152	$1,853	$1,639	$1,494
Total	$384	$713	$1,191	$942	$1,139
7.5% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$635	$773	$1,328	$1,162	$1,047
Controls	$119	$119	$119	$119	$119
Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$939	$1,101	$1,759	$1,562	$1,426
Total	$289	$619	$1,017	$800	$1,013
10% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$621	$751	$1,292	$1,134	$1,018
Controls	$119	$119	$119	$119	$119

Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$922	$1,075	$1,716	$1,528	$1,392
Total	$258	$571	$938	$737	$950
20% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$599	$715	$1,235	$1,083	$1,004
Controls	$119	$119	$119	$119	$119
Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$896	$1,033	$1,648	$1,468	$1,374
Total	$210	$493	$812	$627	$918

a The agencies have not estimated PHEV or EV costs for the minivan+towing and large truck vehicle classes since we do not believe these vehicle classes would use the technologies.

Table 3-85 Scaled Non-battery DMC by Applied Vehicle Weight Reduction for EV150 (2009$)

System	Subcompact	Small car	Large car	Minivan	Small truck
0% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$693	$830	$1,437	$1,256	$1,141
Controls	$119	$119	$119	$119	$119
Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$1,007	$1,169	$1,887	$1,673	$1,537
Total	$415	$745	$1,254	$1,005	$1,218
2% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$679	$816	$1,408	$1,227	$1,141
Controls	$119	$119	$119	$119	$119
Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$990	$1,152	$1,853	$1,639	$1,537
Total	$384	$713	$1,191	$942	$1,218
7.5% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$679	$809	$1,401	$1,227	$1,141
Controls	$119	$119	$119	$119	$119
Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$990	$1,144	$1,844	$1,639	$1,537
Total	$384	$697	$1,175	$942	$1,218
10% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$679	$809	$1,401	$1,227	$1,141
Controls	$119	$119	$119	$119	$119

Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$990	$1,144	$1,844	$1,639	$1,537
Total	$384	$697	$1,175	$942	$1,218
20% WR					
Brake system	$233	$238	$242	$242	$240
Climate controls	$154	$164	$176	$220	$202
Delete electrical	-$62	-$67	-$85	-$89	-$89
DC-DC converter	$115	$126	$157	$167	$167
High voltage wiring	$203	$207	$210	$210	$207
Supplemental heater	$85	$90	$97	$120	$110
On vehicle charger	$309	$309	$309	$309	$309
Motor inverter	$679	$809	$1,401	$1,227	$1,141
Controls	$119	$119	$119	$119	$119
Delete IC engine	-$1,565	-$1,565	-$2,418	-$2,347	-$1,849
Delete transmission	-$877	-$877	-$877	-$877	-$877
Motor assembly	$990	$1,144	$1,844	$1,639	$1,537
Total	$384	$697	$1,175	$942	$1,218

a The agencies have not estimated PHEV or EV costs for the minivan+towing and large truck vehicle classes since we do not believe these vehicle classes would use the technologies.

Similar to the approach taken for battery pack costs, the agencies generated linear regressions of non-battery system costs against percent of net mass reduction and the results are shown in Table 3-86. This was done using the same weight reduction offsets as used for battery packs as presented in Table 3-72. The agencies separated battery pack costs from the remainder of the systems for each type of electrified vehicle. The advantage of separating the battery pack costs from other system costs is that it allows each to carry unique indirect cost multipliers and learning effects which are important given that battery technology is an emerging technology, while electric motors and inverters are more stable technologies.

Table 3-86 Linear Regressions of Non-Battery System Direct Manufacturing Costs vs Net Mass reduction (2009$)

Vehicle Class	P2 HEV	PHEV20	PHEV40	EV75	EV100	EV150
Subcompact	-$323x+$1,691	-$1,478x+$2,946	-$1,473x+$2,947	-$1,505x+$411	-$1,535x+$413	-$1,976x+$415
Small car	-$321x+$1,771	-$1,602x+$3,251	-$1,613x+$3,250	-$1,803x+$749	-$1,787x+$748	-$1,924x+$746
Large car	-$581x+$2,046	-$2,930x+$4,499	-$2,860x+$4,498	-$3,180x+$1,255	-$3,137x+$1,253	-$3,278x+$1,254
Minivan	-$466x+$2,024	-$2,433x+$4,196	-$2,441x+$4,196	-$2,687x+$1,002	-$2,696x+$1,002	-$2,969x+$1,005
Small truck	-$428x+$1,948	-$2,186x+$3,912	-$2,201x+$3,912	-$2,390x+$1,188	-$2,383x+$1,187	$1,218
Minivan+towing	-$492x+$2,024					
Large truck	-$488x+$2,079					

Notes:

"x" in the equations represents the net weight reduction as a percentage, so the non-battery components for a subcompact P2 HEV with a 20% applied weight reduction and, therefore, a 15% net weight reduction would cost (-$323)x(15%)+$1,691=$1,643.

The small truck EV150 regression has no slope since the net weight reduction is always 0 due to the 20% weight reduction hit.

The agencies did not regress PHEV or EV costs for the minivan+towing and large truck vehicle classes since we do not believe these vehicle classes would use the technologies.

For P2 HEV non-battery components, the direct manufacturing costs shown in Table 3-86 are considered applicable to the 2017MY. The agencies consider the P2 non-battery component technologies to be on the flat portion of the learning curve during the 2017-2025 timeframe. The agencies have applied a high1 complexity ICM of 1.56 through 2018 then 1.35 thereafter. For PHEV and EV non-battery components, the direct manufacturing costs shown in Table 3-86 are considered applicable to the 2025MY. The agencies consider the PHEV and EV non-battery component technologies to be on the flat portion of the learning curve during the 2017-2025 timeframe. The agencies have applied a high2 complexity ICM of 1.77 through 2024 then 1.50 thereafter. The resultant costs for P2 HEV, PHEV20, PHEV40, EV75, EV100 and EV150 non-battery components are shown in Table 3-87 through Table 3-92, respectively.

Table 3-87 Costs for P2 HEV Non-Battery Components (2009$)

Cost type	Vehicle class	Applied WR	Net WR	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	10%	5%	$1,453	$1,424	$1,396	$1,368	$1,340	$1,314	$1,287	$1,262	$1,236
DMC	Subcompact	15%	10%	$1,439	$1,410	$1,382	$1,355	$1,327	$1,301	$1,275	$1,249	$1,224
DMC	Subcompact	20%	15%	$1,425	$1,397	$1,369	$1,341	$1,315	$1,288	$1,262	$1,237	$1,212
DMC	Small car	10%	5%	$1,523	$1,492	$1,463	$1,433	$1,405	$1,377	$1,349	$1,322	$1,296
DMC	Small car	15%	10%	$1,509	$1,479	$1,449	$1,420	$1,392	$1,364	$1,337	$1,310	$1,284
DMC	Small car	20%	15%	$1,495	$1,465	$1,436	$1,407	$1,379	$1,351	$1,324	$1,298	$1,272
DMC	Large car	10%	5%	$1,750	$1,715	$1,681	$1,647	$1,614	$1,582	$1,550	$1,519	$1,489
DMC	Large car	15%	10%	$1,725	$1,690	$1,656	$1,623	$1,591	$1,559	$1,528	$1,497	$1,467
DMC	Large car	20%	15%	$1,699	$1,665	$1,632	$1,599	$1,567	$1,536	$1,505	$1,475	$1,446
DMC	Minivan	10%	5%	$1,735	$1,701	$1,667	$1,633	$1,601	$1,569	$1,537	$1,506	$1,476
DMC	Minivan	15%	10%	$1,715	$1,681	$1,647	$1,614	$1,582	$1,550	$1,519	$1,489	$1,459
DMC	Minivan	20%	15%	$1,695	$1,661	$1,628	$1,595	$1,563	$1,532	$1,501	$1,471	$1,442
DMC	Small truck	10%	5%	$1,672	$1,638	$1,605	$1,573	$1,542	$1,511	$1,481	$1,451	$1,422
DMC	Small truck	15%	10%	$1,653	$1,620	$1,588	$1,556	$1,525	$1,494	$1,464	$1,435	$1,406
DMC	Small truck	20%	15%	$1,635	$1,602	$1,570	$1,538	$1,508	$1,477	$1,448	$1,419	$1,391
DMC	Minivan-towing	10%	4%	$1,739	$1,704	$1,670	$1,637	$1,604	$1,572	$1,541	$1,510	$1,480
DMC	Minivan-towing	15%	9%	$1,718	$1,684	$1,650	$1,617	$1,585	$1,553	$1,522	$1,491	$1,462
DMC	Minivan-towing	20%	14%	$1,697	$1,663	$1,629	$1,597	$1,565	$1,534	$1,503	$1,473	$1,443
DMC	Large truck	10%	4%	$1,786	$1,751	$1,716	$1,681	$1,648	$1,615	$1,582	$1,551	$1,520
DMC	Large truck	15%	9%	$1,765	$1,730	$1,695	$1,661	$1,628	$1,596	$1,564	$1,532	$1,502
DMC	Large truck	20%	14%	$1,744	$1,709	$1,675	$1,641	$1,609	$1,576	$1,545	$1,514	$1,484
IC	Subcompact	10%	5%	$930	$928	$570	$569	$568	$567	$566	$565	$565
IC	Subcompact	15%	10%	$921	$919	$564	$563	$562	$562	$561	$560	$559
IC	Subcompact	20%	15%	$912	$910	$559	$558	$557	$556	$555	$554	$554
IC	Small car	10%	5%	$974	$972	$597	$596	$595	$594	$593	$592	$592
IC	Small car	15%	10%	$965	$963	$591	$591	$590	$589	$588	$587	$586
IC	Small car	20%	15%	$956	$954	$586	$585	$584	$583	$582	$582	$581
IC	Large car	10%	5%	$1,119	$1,117	$686	$685	$684	$683	$682	$681	$680
IC	Large car	15%	10%	$1,103	$1,101	$676	$675	$674	$673	$672	$671	$670
IC	Large car	20%	15%	$1,087	$1,085	$666	$665	$664	$663	$662	$661	$660
IC	Minivan	10%	5%	$1,110	$1,108	$680	$679	$678	$677	$676	$675	$674
IC	Minivan	15%	10%	$1,097	$1,095	$672	$671	$670	$669	$668	$667	$666
IC	Minivan	20%	15%	$1,084	$1,082	$664	$663	$662	$661	$660	$659	$658

IC	Small truck	10%	5%	$1,069	$1,067	$655	$654	$653	$652	$651	$650	$649
IC	Small truck	15%	10%	$1,058	$1,055	$648	$647	$646	$645	$644	$643	$642
IC	Small truck	20%	15%	$1,046	$1,044	$641	$640	$639	$638	$637	$636	$635
IC	Minivan-towing	10%	4%	$1,113	$1,110	$682	$681	$680	$679	$678	$677	$676
IC	Minivan-towing	15%	9%	$1,099	$1,097	$673	$672	$671	$670	$669	$668	$667
IC	Minivan-towing	20%	14%	$1,085	$1,083	$665	$664	$663	$662	$661	$660	$659
IC	Large truck	10%	4%	$1,143	$1,141	$700	$699	$698	$697	$696	$695	$694
IC	Large truck	15%	9%	$1,129	$1,127	$692	$691	$690	$689	$688	$687	$686
IC	Large truck	20%	14%	$1,116	$1,113	$684	$683	$682	$681	$680	$679	$678
TC	Subcompact	10%	5%	$2,383	$2,352	$1,965	$1,936	$1,908	$1,881	$1,853	$1,827	$1,801
TC	Subcompact	15%	10%	$2,360	$2,329	$1,946	$1,918	$1,890	$1,862	$1,836	$1,809	$1,784
TC	Subcompact	20%	15%	$2,337	$2,307	$1,927	$1,899	$1,871	$1,844	$1,818	$1,792	$1,766
TC	Small car	10%	5%	$2,497	$2,465	$2,059	$2,029	$2,000	$1,971	$1,942	$1,914	$1,887
TC	Small car	15%	10%	$2,474	$2,442	$2,041	$2,011	$1,981	$1,953	$1,925	$1,897	$1,870
TC	Small car	20%	15%	$2,451	$2,419	$2,022	$1,992	$1,963	$1,935	$1,907	$1,879	$1,853
TC	Large car	10%	5%	$2,869	$2,832	$2,366	$2,332	$2,298	$2,264	$2,232	$2,200	$2,168
TC	Large car	15%	10%	$2,828	$2,791	$2,332	$2,298	$2,265	$2,232	$2,200	$2,168	$2,137
TC	Large car	20%	15%	$2,787	$2,750	$2,298	$2,265	$2,232	$2,199	$2,168	$2,136	$2,106
TC	Minivan	10%	5%	$2,846	$2,809	$2,347	$2,312	$2,279	$2,246	$2,213	$2,182	$2,151
TC	Minivan	15%	10%	$2,812	$2,776	$2,320	$2,286	$2,252	$2,220	$2,188	$2,156	$2,126
TC	Minivan	20%	15%	$2,779	$2,743	$2,292	$2,259	$2,226	$2,193	$2,162	$2,131	$2,100
TC	Small truck	10%	5%	$2,741	$2,706	$2,261	$2,228	$2,195	$2,163	$2,132	$2,102	$2,072
TC	Small truck	15%	10%	$2,711	$2,675	$2,236	$2,203	$2,171	$2,139	$2,108	$2,078	$2,049
TC	Small truck	20%	15%	$2,680	$2,645	$2,211	$2,178	$2,146	$2,115	$2,085	$2,055	$2,026
TC	Minivan-towing	10%	4%	$2,852	$2,815	$2,352	$2,318	$2,284	$2,251	$2,218	$2,187	$2,155
TC	Minivan-towing	15%	9%	$2,817	$2,780	$2,323	$2,289	$2,256	$2,223	$2,191	$2,160	$2,129
TC	Minivan-towing	20%	14%	$2,782	$2,746	$2,294	$2,261	$2,228	$2,196	$2,164	$2,133	$2,102
TC	Large truck	10%	4%	$2,929	$2,891	$2,416	$2,381	$2,346	$2,312	$2,279	$2,246	$2,214
TC	Large truck	15%	9%	$2,895	$2,857	$2,387	$2,352	$2,318	$2,284	$2,252	$2,219	$2,188
TC	Large truck	20%	14%	$2,860	$2,823	$2,359	$2,324	$2,290	$2,257	$2,224	$2,193	$2,161

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-88 Costs for PHEV20 Non-Battery Components (2009$)

Cost type	Vehicle class	Applied WR	Net WR	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	10%	3%	$2,518	$2,467	$2,418	$2,370	$2,322	$2,276	$2,230	$2,186	$2,142
DMC	Subcompact	15%	8%	$2,454	$2,404	$2,356	$2,309	$2,263	$2,218	$2,173	$2,130	$2,087
DMC	Subcompact	20%	13%	$2,389	$2,342	$2,295	$2,249	$2,204	$2,160	$2,117	$2,074	$2,033
DMC	Small car	10%	3%	$2,779	$2,723	$2,669	$2,615	$2,563	$2,512	$2,461	$2,412	$2,364
DMC	Small car	15%	8%	$2,709	$2,655	$2,602	$2,550	$2,499	$2,449	$2,400	$2,352	$2,305
DMC	Small car	20%	13%	$2,640	$2,587	$2,535	$2,484	$2,435	$2,386	$2,338	$2,292	$2,246
DMC	Large car	10%	3%	$3,827	$3,751	$3,676	$3,602	$3,530	$3,459	$3,390	$3,322	$3,256
DMC	Large car	15%	8%	$3,700	$3,626	$3,554	$3,482	$3,413	$3,345	$3,278	$3,212	$3,148
DMC	Large car	20%	13%	$3,573	$3,502	$3,431	$3,363	$3,296	$3,230	$3,165	$3,102	$3,040
DMC	Minivan	10%	3%	$3,577	$3,505	$3,435	$3,366	$3,299	$3,233	$3,168	$3,105	$3,043
DMC	Minivan	15%	8%	$3,471	$3,402	$3,334	$3,267	$3,202	$3,138	$3,075	$3,014	$2,953
DMC	Minivan	20%	13%	$3,366	$3,298	$3,232	$3,168	$3,104	$3,042	$2,982	$2,922	$2,863
DMC	Small truck	10%	3%	$3,337	$3,271	$3,205	$3,141	$3,078	$3,017	$2,956	$2,897	$2,839

DMC	Small truck	15%	8%	$3,243	$3,178	$3,114	$3,052	$2,991	$2,931	$2,872	$2,815	$2,759
DMC	Small truck	20%	13%	$3,148	$3,085	$3,023	$2,963	$2,903	$2,845	$2,788	$2,733	$2,678
IC	Subcompact	10%	3%	$1,611	$1,607	$987	$985	$984	$982	$981	$980	$978
IC	Subcompact	15%	8%	$1,570	$1,566	$962	$960	$959	$957	$956	$955	$953
IC	Subcompact	20%	13%	$1,529	$1,526	$937	$935	$934	$932	$931	$930	$928
IC	Small car	10%	3%	$1,778	$1,774	$1,089	$1,088	$1,086	$1,084	$1,083	$1,081	$1,080
IC	Small car	15%	8%	$1,733	$1,730	$1,062	$1,060	$1,059	$1,057	$1,056	$1,054	$1,053
IC	Small car	20%	13%	$1,689	$1,685	$1,035	$1,033	$1,032	$1,030	$1,028	$1,027	$1,026
IC	Large car	10%	3%	$2,448	$2,443	$1,500	$1,498	$1,496	$1,493	$1,491	$1,489	$1,487
IC	Large car	15%	8%	$2,367	$2,362	$1,450	$1,448	$1,446	$1,444	$1,442	$1,440	$1,438
IC	Large car	20%	13%	$2,286	$2,281	$1,401	$1,398	$1,396	$1,394	$1,392	$1,390	$1,388
IC	Minivan	10%	3%	$2,288	$2,284	$1,402	$1,400	$1,398	$1,396	$1,394	$1,392	$1,390
IC	Minivan	15%	8%	$2,221	$2,216	$1,361	$1,359	$1,357	$1,355	$1,353	$1,351	$1,349
IC	Minivan	20%	13%	$2,153	$2,149	$1,319	$1,317	$1,315	$1,313	$1,311	$1,309	$1,308
IC	Small truck	10%	3%	$2,135	$2,131	$1,308	$1,306	$1,304	$1,302	$1,300	$1,298	$1,297
IC	Small truck	15%	8%	$2,074	$2,070	$1,271	$1,269	$1,267	$1,265	$1,263	$1,262	$1,260
IC	Small truck	20%	13%	$2,014	$2,010	$1,234	$1,232	$1,230	$1,228	$1,226	$1,225	$1,223
TC	Subcompact	10%	3%	$4,128	$4,075	$3,405	$3,355	$3,306	$3,258	$3,211	$3,165	$3,120
TC	Subcompact	15%	8%	$4,023	$3,971	$3,318	$3,270	$3,222	$3,175	$3,129	$3,085	$3,041
TC	Subcompact	20%	13%	$3,918	$3,867	$3,231	$3,184	$3,138	$3,092	$3,048	$3,004	$2,961
TC	Small car	10%	3%	$4,556	$4,497	$3,758	$3,703	$3,649	$3,596	$3,544	$3,493	$3,443
TC	Small car	15%	8%	$4,442	$4,385	$3,664	$3,610	$3,558	$3,506	$3,455	$3,406	$3,357
TC	Small car	20%	13%	$4,328	$4,272	$3,570	$3,517	$3,466	$3,416	$3,367	$3,318	$3,271
TC	Large car	10%	3%	$6,276	$6,194	$5,176	$5,100	$5,026	$4,953	$4,881	$4,811	$4,743
TC	Large car	15%	8%	$6,067	$5,988	$5,004	$4,931	$4,859	$4,788	$4,719	$4,652	$4,585
TC	Large car	20%	13%	$5,859	$5,783	$4,832	$4,761	$4,692	$4,624	$4,557	$4,492	$4,428
TC	Minivan	10%	3%	$5,865	$5,789	$4,837	$4,766	$4,697	$4,629	$4,562	$4,497	$4,433
TC	Minivan	15%	8%	$5,692	$5,618	$4,695	$4,626	$4,558	$4,492	$4,428	$4,364	$4,302
TC	Minivan	20%	13%	$5,519	$5,447	$4,552	$4,485	$4,420	$4,356	$4,293	$4,231	$4,171
TC	Small truck	10%	3%	$5,472	$5,401	$4,513	$4,447	$4,382	$4,319	$4,257	$4,196	$4,136
TC	Small truck	15%	8%	$5,317	$5,248	$4,385	$4,321	$4,258	$4,196	$4,136	$4,076	$4,018
TC	Small truck	20%	13%	$5,161	$5,094	$4,257	$4,195	$4,133	$4,073	$4,015	$3,957	$3,901

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-89 Costs for PHEV40 Non-Battery Components (2009$)

Cost type	Vehicle class	Applied WR	Net WR	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	15%	2%	$2,531	$2,481	$2,431	$2,382	$2,335	$2,288	$2,242	$2,197	$2,153
DMC	Subcompact	20%	7%	$2,467	$2,418	$2,370	$2,322	$2,276	$2,230	$2,186	$2,142	$2,099
DMC	Small car	15%	3%	$2,778	$2,722	$2,668	$2,614	$2,562	$2,511	$2,461	$2,411	$2,363
DMC	Small car	20%	8%	$2,708	$2,654	$2,601	$2,549	$2,498	$2,448	$2,399	$2,351	$2,304
DMC	Large car	15%	2%	$3,853	$3,776	$3,700	$3,626	$3,554	$3,483	$3,413	$3,345	$3,278
DMC	Large car	20%	7%	$3,729	$3,654	$3,581	$3,509	$3,439	$3,370	$3,303	$3,237	$3,172
DMC	Minivan	15%	2%	$3,598	$3,526	$3,456	$3,387	$3,319	$3,252	$3,187	$3,124	$3,061
DMC	Minivan	20%	7%	$3,492	$3,422	$3,354	$3,287	$3,221	$3,157	$3,094	$3,032	$2,971
DMC	Small truck	15%	3%	$3,336	$3,270	$3,204	$3,140	$3,077	$3,016	$2,955	$2,896	$2,838
DMC	Small truck	20%	8%	$3,241	$3,176	$3,113	$3,050	$2,989	$2,930	$2,871	$2,813	$2,757
IC	Subcompact	15%	2%	$1,619	$1,616	$992	$991	$989	$988	$986	$985	$983
IC	Subcompact	20%	7%	$1,578	$1,575	$967	$966	$964	$963	$961	$960	$959
IC	Small car	15%	3%	$1,777	$1,773	$1,089	$1,087	$1,086	$1,084	$1,082	$1,081	$1,079
IC	Small car	20%	8%	$1,732	$1,729	$1,061	$1,060	$1,058	$1,057	$1,055	$1,054	$1,052
IC	Large car	15%	2%	$2,465	$2,460	$1,510	$1,508	$1,506	$1,503	$1,501	$1,499	$1,497
IC	Large car	20%	7%	$2,385	$2,381	$1,462	$1,459	$1,457	$1,455	$1,453	$1,451	$1,449

IC	Minivan	15%	2%	$2,302	$2,297	$1,410	$1,408	$1,406	$1,404	$1,402	$1,400	$1,398
IC	Minivan	20%	7%	$2,234	$2,230	$1,369	$1,367	$1,365	$1,363	$1,361	$1,359	$1,357
IC	Small truck	15%	3%	$2,134	$2,130	$1,308	$1,306	$1,304	$1,302	$1,300	$1,298	$1,296
IC	Small truck	20%	8%	$2,073	$2,069	$1,270	$1,268	$1,266	$1,265	$1,263	$1,261	$1,259
TC	Subcompact	15%	2%	$4,150	$4,096	$3,423	$3,373	$3,324	$3,276	$3,228	$3,182	$3,137
TC	Subcompact	20%	7%	$4,046	$3,993	$3,337	$3,288	$3,240	$3,193	$3,147	$3,102	$3,058
TC	Small car	15%	3%	$4,555	$4,496	$3,757	$3,702	$3,648	$3,595	$3,543	$3,492	$3,442
TC	Small car	20%	8%	$4,440	$4,382	$3,662	$3,608	$3,556	$3,504	$3,454	$3,404	$3,356
TC	Large car	15%	2%	$6,317	$6,235	$5,210	$5,134	$5,059	$4,986	$4,914	$4,844	$4,775
TC	Large car	20%	7%	$6,114	$6,035	$5,043	$4,969	$4,896	$4,825	$4,756	$4,688	$4,621
TC	Minivan	15%	2%	$5,900	$5,824	$4,866	$4,795	$4,725	$4,657	$4,589	$4,524	$4,459
TC	Minivan	20%	7%	$5,726	$5,652	$4,723	$4,654	$4,586	$4,519	$4,454	$4,390	$4,328
TC	Small truck	15%	3%	$5,471	$5,400	$4,512	$4,446	$4,381	$4,318	$4,255	$4,194	$4,135
TC	Small truck	20%	8%	$5,314	$5,245	$4,383	$4,319	$4,256	$4,194	$4,134	$4,074	$4,016

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-90 Costs for EV75 Non-Battery Components (2009$)

Cost type	Vehicle class	Applied WR	Net WR	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	10%	10%	$261	$253	$245	$238	$231	$224	$219	$215	$211
DMC	Subcompact	15%	15%	$185	$180	$174	$169	$164	$159	$156	$153	$150
DMC	Subcompact	20%	20%	$110	$107	$104	$100	$97	$95	$93	$91	$89
DMC	Small car	10%	10%	$569	$552	$535	$519	$504	$488	$479	$469	$460
DMC	Small car	15%	15%	$479	$464	$450	$437	$424	$411	$403	$395	$387
DMC	Small car	20%	20%	$389	$377	$366	$355	$344	$334	$327	$320	$314
DMC	Large car	10%	10%	$937	$909	$881	$855	$829	$804	$788	$772	$757
DMC	Large car	15%	15%	$778	$754	$732	$710	$688	$668	$654	$641	$629
DMC	Large car	20%	20%	$619	$600	$582	$565	$548	$531	$521	$510	$500
DMC	Minivan	10%	10%	$733	$711	$690	$669	$649	$630	$617	$605	$593
DMC	Minivan	15%	15%	$599	$581	$563	$547	$530	$514	$504	$494	$484
DMC	Minivan	20%	20%	$464	$451	$437	$424	$411	$399	$391	$383	$375
DMC	Small truck	10%	10%	$949	$920	$893	$866	$840	$815	$799	$783	$767
DMC	Small truck	15%	15%	$829	$805	$780	$757	$734	$712	$698	$684	$670
DMC	Small truck	20%	20%	$710	$689	$668	$648	$629	$610	$598	$586	$574
IC	Subcompact	10%	10%	$201	$200	$200	$199	$198	$198	$198	$197	$127
IC	Subcompact	15%	15%	$143	$142	$142	$142	$141	$141	$141	$140	$90
IC	Subcompact	20%	20%	$85	$85	$84	$84	$84	$84	$83	$83	$54
IC	Small car	10%	10%	$438	$437	$436	$434	$433	$432	$431	$431	$277
IC	Small car	15%	15%	$369	$368	$367	$366	$365	$364	$363	$362	$233
IC	Small car	20%	20%	$299	$298	$298	$297	$296	$295	$295	$294	$189
IC	Large car	10%	10%	$721	$719	$717	$715	$713	$712	$710	$709	$456
IC	Large car	15%	15%	$599	$597	$595	$594	$592	$591	$590	$589	$379
IC	Large car	20%	20%	$476	$475	$474	$472	$471	$470	$469	$468	$301
IC	Minivan	10%	10%	$565	$563	$561	$560	$558	$557	$556	$555	$357
IC	Minivan	15%	15%	$461	$460	$459	$457	$456	$455	$454	$453	$292
IC	Minivan	20%	20%	$358	$357	$356	$355	$354	$353	$352	$352	$226
IC	Small truck	10%	10%	$731	$729	$727	$725	$723	$721	$720	$718	$462
IC	Small truck	15%	15%	$639	$637	$635	$633	$632	$630	$629	$628	$404
IC	Small truck	20%	20%	$547	$545	$544	$542	$541	$539	$538	$538	$346
TC	Subcompact	10%	10%	$461	$453	$445	$437	$429	$422	$417	$412	$338
TC	Subcompact	15%	15%	$328	$322	$316	$311	$305	$300	$297	$293	$240
TC	Subcompact	20%	20%	$195	$191	$188	$185	$181	$178	$176	$174	$143
TC	Small car	10%	10%	$1,007	$989	$971	$954	$937	$921	$910	$900	$737

TC	Small car	15%	15%	$847	$832	$817	$802	$788	$775	$766	$757	$620
TC	Small car	20%	20%	$688	$675	$663	$651	$640	$629	$622	$615	$503
TC	Large car	10%	10%	$1,658	$1,628	$1,598	$1,570	$1,543	$1,516	$1,499	$1,482	$1,213
TC	Large car	15%	15%	$1,376	$1,351	$1,327	$1,304	$1,281	$1,258	$1,244	$1,230	$1,007
TC	Large car	20%	20%	$1,095	$1,075	$1,056	$1,037	$1,019	$1,001	$990	$979	$801
TC	Minivan	10%	10%	$1,298	$1,274	$1,251	$1,229	$1,207	$1,187	$1,173	$1,160	$950
TC	Minivan	15%	15%	$1,060	$1,041	$1,022	$1,004	$986	$969	$958	$947	$776
TC	Minivan	20%	20%	$822	$807	$793	$779	$765	$752	$743	$735	$602
TC	Small truck	10%	10%	$1,680	$1,649	$1,619	$1,591	$1,563	$1,536	$1,518	$1,501	$1,229
TC	Small truck	15%	15%	$1,468	$1,441	$1,416	$1,390	$1,366	$1,342	$1,327	$1,312	$1,075
TC	Small truck	20%	20%	$1,257	$1,234	$1,212	$1,190	$1,169	$1,149	$1,136	$1,123	$920

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-91 Costs for EV100 Non-Battery Components (2009$)

Cost type	Vehicle class	Applied WR	Net WR	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	10%	4%	$351	$341	$331	$321	$311	$302	$296	$290	$284
DMC	Subcompact	15%	9%	$275	$266	$258	$251	$243	$236	$231	$226	$222
DMC	Subcompact	20%	14%	$198	$192	$186	$181	$175	$170	$166	$163	$160
DMC	Small car	10%	5%	$659	$639	$620	$601	$583	$566	$554	$543	$532
DMC	Small car	15%	10%	$569	$552	$536	$520	$504	$489	$479	$470	$460
DMC	Small car	20%	15%	$480	$466	$452	$438	$425	$412	$404	$396	$388
DMC	Large car	10%	5%	$1,096	$1,063	$1,031	$1,001	$970	$941	$923	$904	$886
DMC	Large car	15%	10%	$939	$911	$884	$857	$832	$807	$791	$775	$759
DMC	Large car	20%	15%	$783	$759	$736	$714	$693	$672	$659	$645	$632
DMC	Minivan	10%	4%	$894	$867	$841	$816	$792	$768	$752	$737	$723
DMC	Minivan	15%	9%	$759	$737	$714	$693	$672	$652	$639	$626	$614
DMC	Minivan	20%	14%	$625	$606	$588	$570	$553	$536	$526	$515	$505
DMC	Small truck	10%	2%	$1,140	$1,105	$1,072	$1,040	$1,009	$979	$959	$940	$921
DMC	Small truck	15%	7%	$1,020	$990	$960	$931	$903	$876	$859	$842	$825
DMC	Small truck	20%	12%	$901	$874	$848	$822	$798	$774	$758	$743	$728
IC	Subcompact	10%	4%	$271	$270	$269	$268	$268	$267	$266	$266	$171
IC	Subcompact	15%	9%	$211	$211	$210	$210	$209	$209	$208	$208	$134
IC	Subcompact	20%	14%	$152	$152	$151	$151	$151	$150	$150	$150	$96
IC	Small car	10%	5%	$507	$506	$504	$503	$502	$500	$500	$499	$321
IC	Small car	15%	10%	$438	$437	$436	$435	$434	$433	$432	$431	$277
IC	Small car	20%	15%	$370	$369	$368	$367	$366	$365	$364	$363	$234
IC	Large car	10%	5%	$844	$842	$839	$837	$835	$833	$831	$830	$534
IC	Large car	15%	10%	$723	$721	$719	$717	$715	$714	$712	$711	$458
IC	Large car	20%	15%	$603	$601	$599	$598	$596	$594	$593	$592	$381
IC	Minivan	10%	4%	$689	$687	$685	$683	$681	$679	$678	$677	$436
IC	Minivan	15%	9%	$585	$583	$581	$580	$578	$577	$576	$575	$370
IC	Minivan	20%	14%	$481	$480	$478	$477	$476	$474	$474	$473	$304
IC	Small truck	10%	2%	$877	$875	$873	$870	$868	$866	$864	$863	$555
IC	Small truck	15%	7%	$786	$783	$781	$779	$777	$775	$774	$773	$497
IC	Small truck	20%	12%	$694	$692	$690	$688	$686	$685	$683	$682	$439
TC	Subcompact	10%	4%	$622	$611	$600	$589	$579	$569	$562	$556	$455
TC	Subcompact	15%	9%	$486	$477	$469	$460	$452	$444	$439	$434	$356
TC	Subcompact	20%	14%	$350	$344	$338	$332	$326	$320	$317	$313	$256
TC	Small car	10%	5%	$1,166	$1,145	$1,124	$1,104	$1,085	$1,066	$1,054	$1,042	$853
TC	Small car	15%	10%	$1,008	$990	$972	$955	$938	$922	$911	$901	$738
TC	Small car	20%	15%	$850	$834	$819	$805	$791	$777	$768	$759	$622
TC	Large car	10%	5%	$1,940	$1,905	$1,871	$1,838	$1,805	$1,774	$1,754	$1,734	$1,420

TC	Large car	15%	10%	$1,663	$1,632	$1,603	$1,575	$1,547	$1,520	$1,503	$1,486	$1,217
TC	Large car	20%	15%	$1,385	$1,360	$1,335	$1,312	$1,289	$1,266	$1,252	$1,238	$1,014
TC	Minivan	10%	4%	$1,583	$1,554	$1,526	$1,499	$1,473	$1,447	$1,431	$1,414	$1,158
TC	Minivan	15%	9%	$1,344	$1,320	$1,296	$1,273	$1,251	$1,229	$1,215	$1,201	$984
TC	Minivan	20%	14%	$1,105	$1,085	$1,066	$1,047	$1,029	$1,011	$999	$988	$809
TC	Small truck	10%	2%	$2,017	$1,980	$1,945	$1,910	$1,877	$1,844	$1,823	$1,803	$1,476
TC	Small truck	15%	7%	$1,806	$1,773	$1,741	$1,710	$1,680	$1,651	$1,633	$1,614	$1,322
TC	Small truck	20%	12%	$1,595	$1,566	$1,538	$1,511	$1,484	$1,458	$1,442	$1,426	$1,167

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 3-92 Costs for EV150 Non-Battery Components (2009$)

Cost type	Vehicle class	Applied WR	Net WR	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Subcompact	20%	2%	$376	$365	$354	$343	$333	$323	$316	$310	$304
DMC	Small car	20%	3%	$688	$667	$647	$628	$609	$591	$579	$567	$556
DMC	Large car	20%	2%	$1,188	$1,153	$1,118	$1,085	$1,052	$1,021	$1,000	$980	$961
DMC	Minivan	20%	2%	$946	$917	$890	$863	$837	$812	$796	$780	$764
DMC	Small truck	20%	0%	$1,218	$1,181	$1,146	$1,111	$1,078	$1,046	$1,025	$1,004	$984
IC	Subcompact	20%	2%	$289	$289	$288	$287	$286	$285	$285	$285	$183
IC	Small car	20%	3%	$530	$528	$527	$525	$524	$523	$522	$521	$335
IC	Large car	20%	2%	$915	$913	$910	$907	$905	$903	$901	$900	$579
IC	Minivan	20%	2%	$728	$726	$724	$722	$720	$718	$717	$716	$461
IC	Small truck	20%	0%	$938	$935	$932	$930	$927	$925	$924	$922	$593
TC	Subcompact	20%	2%	$665	$653	$641	$630	$619	$608	$601	$594	$487
TC	Small car	20%	3%	$1,218	$1,196	$1,174	$1,153	$1,133	$1,114	$1,101	$1,088	$891
TC	Large car	20%	2%	$2,104	$2,065	$2,028	$1,992	$1,957	$1,923	$1,901	$1,880	$1,540
TC	Minivan	20%	2%	$1,674	$1,643	$1,614	$1,585	$1,557	$1,530	$1,513	$1,496	$1,225
TC	Small truck	20%	0%	$2,155	$2,116	$2,078	$2,041	$2,005	$1,971	$1,948	$1,926	$1,578

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

3.4.4 Hardware costs for charging grid-connected vehicles

Grid-connected vehicles such as EVs and PHEVs require a means to charge their on-board batteries to enable their electric range capabilities. These vehicles require certain hardware to charge, both on-vehicle and off-vehicle. The agencies’ September 2010 Technical Assessment Report contains an in-depth analysis of the topic of charging and infrastructure. The TAR analysis and assumptions did not receive any significant comment, and a review of the current state of the industry indicates the assumptions in the TAR are still valid. Therefore, the assumptions for the cost of Electric Vehicle Support Equipment (EVSE) are unchanged. Additionally, while some of the characteristics of the modeled grid-connected vehicles such as battery size and energy demand have changed somewhat due to further analysis, the application of Level 1 and Level 2 charging by vehicle type based on charge time has not changed.

Three charging levels are currently under consideration. Level 1 charging uses a standard 120 volt (V), 15-20 amps (A) rated (12-16 A usable) circuit and is available in standard residential and commercial buildings. Level 2 charging uses a single phase, 240 V, 20-80 A circuit and allows much shorter charge times. Level 3 charging—sometimes colloquially called "quick" or "fast" charging—uses a 480 V, three-phase circuit, available in mainly industrial areas, typically providing 60-150 kW of off-board charging power. It is expected that 97 to 99% of charging will take place at home, so a cost for a home charger, appropriate to the duty cycle of the vehicle, is added to the vehicle cost. Level 3 charging is available to commercial users and vehicles that charge at Level 3 stations will be assumed to pay at the charge station for the convenience of fast charging. Therefore Level 3 charger costs are not included in overall vehicle cost.

The specific equipment required for charging a grid-connected vehicle consists of the following:

Charger: A charger that converts electricity from alternating current (AC) from the electricity source to direct current (DC) required for the battery, and also converts the incoming 120 or 240 volt current to 300 or higher volts. Grid-connected vehicles carry an on-board charger capable of accepting AC current from a wall plug (Level 1 circuit) or, from a Level 2 charging station. On-board charger power capability ranges from 1.4 to 10 kW and is usually proportional to the vehicle's battery capacity. The lowest charging power, 1.4 kW, is expected only when grid-connected vehicles are connected to 120 volt (Level 1) outlets, and all currently known PHEV and EV on-board chargers are expected to provide at least 3.3 kW charging when connected to a Level 2 (220 volt, 20+ A) charging station. The latest SAE connection recommended practice, J1772, allows for delivery of up to ~19 kW to an on-board vehicle charger. For higher capacity charging under Level 3, a charging station that delivers DC current directly to the vehicle's battery is incorporated off-board in the wall or pedestal mounted.

Charging Station: The charging station needed to safely deliver energy from the electric circuit to the vehicle, called electric vehicle support equipment (EVSE). The EVSE may at a minimum, be a specialized cordset that connects a household Level 1/120V socket to the vehicle; otherwise, the EVSE will include a cordset and a charging station (a wall or pedestal mounted box incorporating a charger and other equipment). Charging stations may include optional advanced features such as timers to delay charging until off-peak hours, communications equipment to allow the utility to regulate charging, or even electricity metering capabilities. Stakeholders are working on which features are best located on the EVSE or on the vehicle itself, and it is possible that redundant capabilities and features may be present in both the vehicle and EVSEs in the near future until these issues are worked out. EVSE and vehicle manufacturers are also working to ensure that current SAE-compliant "basic" EVSEs are charge-compatible with future grid-connected vehicles.

Dedicated Circuit: A Level 1 circuit is standard household current, 120V AC, rated at 15 or 20 A (12 or 16 A usable). A Level 2 circuit is rated at 208 to 240V and up to 80 A and is similar to the type of circuit that powers electric stoves (up to 50 A) and dryers (usually 30 A). Generally, Level 1 and 2 circuits used for electric vehicle recharging must be dedicated circuits, i.e., there cannot be other appliances on that circuit. For a Level 2 circuit, the homeowner or other user must install a charging station and will need a permit. A homeowner may choose to install the charger on a separately-metered circuit to take advantage of special electrical rates for off-peak charging, where available.

In addition to the costs of purchasing and installing charging equipment, charging station installation may include the costs of upgrading existing electrical panels and installing the electrical connection from the panel to the desired station location. These costs may be dramatically lowered if new construction incorporates the panel box and wiring required for charging stations, or even includes charging stations or outlets for charging stations as standard equipment.

The current costs of charging stations are highly variable depending on the level of service (and alternative power capabilities within these categories), location (individual residence, grouped residences, retail or business, parking lot or garage), level of sophistication of the station, and installation requirements, including electrical upgrading requirements. Estimated costs for charging stations are included in Table 3-93 below.

Table 3-93: Estimated Costs for Charging Stations Used in the 2010 TAR (2008$)

Level	Location	Equipment	Installation
1	Single Residence	$30- $200 (charge cord only, included at no cost to consumer with EV/PHEV) when an accessible household plug (e.g., in a garage or adjacent to a driveway) with a ground fault interrupter is already available	$400-$1000+ may be necessary depending on difficulty of installing a new circuit at the desired location, but in most cases, owners with sufficient panel capacity would opt for a more capable 220 VAC Level 2 installation instead of a Level 1 dedicated circuit because the additional installation cost is only marginally higher
2	Residential, Apartment Complex, or Fleet Depot[b]	3.3 kW EVSE (each): $300-$4,000 6.6 kW EVSE (each): $400-$4,000	3.3- 6.6 kW installation cost: $400-$2,300 without wiring/service panel upgrade, or $2,000-$5,000 with panel upgrade

refs: 73,74,75,76,a

[a] Detailed information on charger cost for each charging level and location and specific sources for cost estimates are available in the TAR, Appendix G.

[b] Level 2 EVSE installation costs vary considerably for single-family residences, multi-family residences, and fleet depots, depending upon the need for wiring and service panel upgrades. The range depicted here reflects the anticipated variability of these costs. However, EPRI estimates that the typical residential Level 2 installation costs to be approximately $1,500. See the TAR, Appendix G for additional information.

3.4.4.1 Application of charging level by vehicle type

The home charging availability for a specific consumer will need to be differentiated among EV/PHEVs with different battery capacity. The electric outlets in existing homes are most likely ready for Level 1 charging, which is about sufficient for fully recharging a PHEV20 SUV during normal nighttime, provided the outlet is not being heavily utilized by other loads. Shorter available charging time or owning a PHEV or an EV with a larger battery make the capability to fully charge overnight with a Level 1 system less likely, but upgrading to a Level 2 system in such cases will allow full recharge to happen more quickly.

Table 3-94 shows the application of charge level by vehicle type and range. Charging types were chosen based on nominal time to charge a fully-depleted battery in a vehicle with 0% net weight reduction. Charge times exceeding 9 hours for Level 1 were deemed unacceptable and Level 2 charging was specified. For charge times between 6 hours and 9 hours on Level 1, a mix of Level 1 and Level 2 was specified. This was done to recognize the varying consumer value of faster, but more expensive, Level 2 charging over Level 1 charging.

Table 3-94: Charger Type by Vehicle Technology and Class

	PHEV20	PHEV40	EV75	EV100	EV150
Subcompact	100% L1	25% L1 75% L2	100% L2	100% L2	100% L2
Small Car	100% L1	10% L1 90% L2	100% L2	100% L2	100% L2
Large Car	100% L1	100% L2	100% L2	100% L2	100% L2
Minivan	100% L1	100% L2	100% L2	100% L2	100% L2
Small Truck	100% L1	100% L2	100% L2	100% L2	100% L2
Large Truck	50% L1 50% L2	100% L2	100% L2	100% L2	100% L2

For this proposal, the resultant costs associated with in-home chargers and installation of in-home chargers are included in the total cost for an EV and or PHEV. However, here we summarize specially the costs for chargers and installation labor. The agencies have estimated the DMC of a level 1 charge cord at $30 (2009$) based on typical costs of similar electrical equipment sold to consumers today and that for a level 2 charger at $202 (2009$). Labor associated with installing either of these chargers is estimated at $1,009 (2009$). Further, we have estimated that all PHEV20 vehicles (PHEVs with a 20 mile range) would be charged via a level 1 charger and that all EVs, regardless of range, would be charged via a level 2 charger. For the PHEV40 vehicles (PHEVs with a 40 mile range), we have estimated that: 25% of subcompacts would be charged with a level 1 charger with the remainder charged via a level 2 charger; 10% of small cars would be charged with a level 1 charger with the remainder charged via a level 2 charger; and all remaining PHEV 40 vehicles would be charged via a level 2 charger. All costs presented here are considered applicable in the 2025 model year. The agencies have applied the learning curve presented in Section 3.2.3 to all charger costs. The agencies have also applied a High1 ICM of 1.56 through 2024 then 1.34 thereafter. Installation costs, being labor costs, have no learning impacts or ICMs applied. The resultant costs are shown in Table 3-95.

Table 3-95 Costs for EV/PHEV In-home Chargers (2009$)

Cost type	Technology	Vehicle Class	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	PHEV20 Charger	All	$59	$47	$47	$38	$38	$38	$38	$38	$30
DMC	PHEV40 Charger	Subcompact	$311	$248	$248	$199	$199	$199	$199	$199	$159
		Small car	$361	$289	$289	$231	$231	$231	$231	$231	$185
		Larger car Minivan Small truck	$394	$315	$315	$252	$252	$252	$252	$252	$202
DMC	EV Charger	All	$394	$315	$315	$252	$252	$252	$252	$252	$202
IC	PHEV20 Charger	All	$19	$18	$18	$18	$18	$18	$18	$18	$10
IC	PHEV40 Charger	Subcompact	$99	$95	$95	$92	$92	$92	$92	$92	$55
		Small car	$115	$111	$111	$107	$107	$107	$107	$107	$64
		Larger car Minivan Small truck	$126	$121	$121	$117	$117	$117	$117	$117	$70
IC	EV Charger	All	$126	$121	$121	$117	$117	$117	$117	$117	$70
TC	PHEV20 Charger	All	$78	$65	$65	$55	$55	$55	$55	$55	$41
TC	PHEV40 Charger	Subcompact	$410	$344	$344	$291	$291	$291	$291	$291	$214
		Small car	$476	$399	$399	$338	$338	$338	$338	$338	$249
		Larger car Minivan Small truck	$521	$437	$437	$369	$369	$369	$369	$369	$272
TC	EV Charger	All	$521	$437	$437	$369	$369	$369	$369	$369	$272
TC	Charger labor	All	$1,009	$1,009	$1,009	$1,009	$1,009	$1,009	$1,009	$1,009	$1,009

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

3.4.5 Other Technologies Assessed that Reduce CO2 and Improve Fuel Economy

In addition to the technologies already mentioned, the technologies generally considered in the agencies' analysis are described below. They fall into five broad categories:

engine technologies, transmission technologies, vehicle technologies, electrification/accessory technologies, hybrid technologies and mass reduction

3.4.5.1 Lower Rolling Resistance Tires

Tire rolling resistance is the frictional loss associated mainly with the energy dissipated in the deformation of the tires under load and thus influences fuel economy and CO_2 emissions. Other tire design characteristics (*e.g.*, materials, construction, and tread design) influence durability, traction (both wet and dry grip), vehicle handling, and ride comfort in addition to rolling resistance. A typical low rolling resistance tire's attributes could include: increased specified tire inflation pressure, material changes, and tire construction with less hysteresis, geometry changes (*e.g.*, reduced aspect ratios), and reduction in sidewall and tread deflection. These changes would generally be accompanied with additional changes to vehicle suspension tuning and/or suspension design.

The agencies expect that greater reductions in tire rolling resistance will be possible during the rulemaking timeframe than are currently available, as tire manufacturers continue to improve their products in order to meet increasing demand by auto OEMs for tires that contribute more to their vehicles' fuel efficiency. Thus, for this proposal, the agencies are considering two "levels" of lower rolling resistance tires. The first level ("LRR1") is defined as a 10 percent reduction in rolling resistance from a base tire, which was estimated to be a 1 to 2 percent effectiveness improvement MYs 2012-2016 final rule. Based on the 2011 Ricardo study the agencies are now using 1.9% for all classes. LRR1 tires are widely available today, and appear to comprise a larger and larger portion of tire manufacturers' product lines as the technology continues to improve and mature. The second level ("LRR2") is defined as a 20 percent reduction in rolling resistance from a base tire, yielding an estimated 3.9 percent effectiveness. In the CAFE model this results in a 2.0% incremental effectiveness increase form LRR1. LRR2 represents an additional level of rolling resistance improvement beyond what the agencies considered in the MYs 2012-2016 rulemaking analysis.

In the 2012-2016 light duty vehicle rule, the agencies estimated the incremental DMC at an increase of $5 (2007$) per vehicle. This included costs associated with five tires per vehicle, four primary and one spare with no learning applied due to the commodity based nature of this technology. Looking forward from 2016, the agencies continue to apply this same estimated DMC adjusted for 2009 dollars.[oo] The agencies consider LRRT1 to be fully learned out or "off" the learning curve (*i.e.*, the DMC does not change year-over-year) and have applied a low complexity ICM of 1.24 through 2018, and then 1.19 thereafter, due to the fact that this technology is already well established in the marketplace.

[oo] As noted elsewhere in this chapter, we show dollar values to the nearest dollar. However, dollars and cents are carried through each agency's respective analysis. Thus, while the cost for lower rolling resistance tires in the 2012-2016 final rule was shown as $5, the specific value used in that rule was $5.15 (2007$) and is now $5.31 (2009$). We show $5 for presentation simplicity.

To analyze the feasibility and cost for a second level of rolling resistance improvement, EPA, NHTSA, and CARB met with a number of the largest tire suppliers in the United States. The suppliers were generally optimistic about the ability of tire rolling resistance to improve in the future without the need to sacrifice traction (safety) or tread life (durability). Suppliers all generally stated that rolling resistance levels could be reduced by 20 percent relative to today’s tires by MY 2017. As such, the agencies agreed, based on these discussions, to consider LRR2 as initially available for purposes of this analysis in MY 2017, but not widespread in the marketplace until MYs 2022-2023. In alignment with introduction of new technology, the agencies limited the phase-in schedule to 15 percent of a manufacturer’s fleet starting in 2017, and did not allow complete application (100 percent of a manufacturer’s fleet) until 2023. The agencies believe that this schedule aligns with the necessary efforts for production implementation such as system and electronic systems calibration and verification.

LRR2 technology does not yet exist in the marketplace, making cost estimation challenging without disclosing potentially confidential business information. To develop a transparent cost estimate, the agencies relied on LRR1 history, costs, market implementation, and information provided by the 2010 NAS report. The agencies assumed low rolling resistance technology (“LRR1”) first entered the marketplace in the 1993 time frame with more widespread adoption being achieved in recent years, yielding approximately 15 years to maturity and widespread adoption.

Then, using MY 2017 as the starting point for market entry for LRR2 and taking into account the advances in industry knowledge and an assumed increase in demand for improvements in this technology, the agencies interpolated DMC for LRR2 at $10 (2009$) per tire, or $40 ($2009) per vehicle. This estimate is generally fairly consistent with CBI suggestions by tire suppliers. The agencies have not included a cost for the spare tire because we believe manufacturers are not likely to include a LRR2 as a spare given the $10 DMC. In some cases and when possible pending any state-level requirements, manufacturers have removed spare tires replacing them with tire repair kits to reduce both cost and weight associated with a spare tire.[77] The agencies consider this estimated cost for LRR2 to be applicable in MY 2021. Further, the agencies consider LRR2 technology to be on the steep portion of the learning curve where costs would reduce quickly in a relative short amount of time. The agencies have applied a low complexity ICM of 1.24 through 2024, and then 1.19 thereafter. The ICM timing for LRR2 is different from that for LRR1 because LRR2 is brand-new for this rulemaking and is not yet being implemented in the fleet. The resultant costs are shown in Table 3-96. Note that both LRR1 and LRR2 are incremental to the baseline system, so LRR2 is not incremental to LRR1.

Table 3-96 Costs for Lower Rolling Resistance Tires Levels 1 & 2 (2009$)

Cost type	Lower Rolling Resistance	2017	2018	2019	2020	2021	2022	2023	2024	2025

	Tire Technology									
DMC	Level 1	$5	$5	$5	$5	$5	$5	$5	$5	$5
DMC	Level 2	$63	$63	$50	$50	$40	$39	$38	$37	$35
IC	Level 1	$1	$1	$1	$1	$1	$1	$1	$1	$1
IC	Level 2	$10	$10	$10	$10	$10	$10	$10	$10	$8
TC	Level 1	$6	$6	$6	$6	$6	$6	$6	$6	$6
TC	Level 2	$72	$72	$60	$60	$50	$48	$47	$46	$43

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost
Note that both levels of lower rolling resistance tires are incremental to today's baseline tires.

Given that the proposed standards cover such a long timeframe, the agencies also considered introducing a third level of rolling resistance reduction ("LRR3"), defined as a 30 percent reduction in rolling resistance. The agencies evaluated the potential of LRR3 entering the marketplace during this proposed rulemaking timeframe.

Tire technologies that enable improvements of 10 and 20 percent have been in existence for many years. Achieving improvements up to 20 percent involves optimizing and integrating multiple technologies, with a primary contributor being the adoption of a silica tread technology.[78] This approach was based on the use of a new silica along with a specific polymer and coupling agent combination. The use of the polymer, coupling agent and silica was known to reduce tire rolling resistance at the expense of tread wear, but new approach novel silica reduced the tread wear tradeoff.

Tire suppliers have indicated there are one or more innovations/inventions that they expect to occur in order to move the industry to the next quantum reduction of rolling resistance. However, based on the historical development and integration of tire technologies, there appears to be little evidence supporting improvements beyond LRRT2 by 2025. Therefore, the agencies decided not to incorporate LRRT3 at this time.

The agencies seek comment, however, on whether we should consider application of a 30 percent reduction from today's rolling resistance levels being available for mass production implementation by MY 2025 or sooner. The agencies seek comment on the viability of this technology, maturity by MY 2025, as well as market introduction timing and the technological ways that this level of rolling resistance improvement will be achieved without any tradeoffs in terms of vehicle handling capability and tire life from what consumers expect today. Finally, the agencies appreciate any cost information regarding the potential incorporation of LRRT3 relative to today's costs as well as during the timeframe covered by this proposal.

3.4.5.2 Low Drag Brakes

Low drag brakes reduce the sliding friction of disc brake pads on rotors when the brakes are not engaged because the brake pads are pulled away from the rotating disc either by mechanical or electric methods

The 2012-2016 final rule and TAR estimated the effectiveness of low drag brakes to be as much as 1 percent. NHTSA and EPA have slightly revised the effectiveness down to 0.8% based on the 2011 Ricardo study and updated lumped-parameter model.

In the 2012-2016 rule, the agencies estimated the DMC at $57 (2007$). This DMC becomes $58 (2009$) for this analysis. The agencies consider low drag brake technology to be off the learning curve (i.e., the DMC does not change year-over-year) and have applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter. The resultant costs are shown in Table 3-97.

Table 3-97 Costs for Low Drag Brakes (2009$)

Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$58	$58	$58	$58	$58	$58	$58	$58	$58
IC	$14	$14	$11	$11	$11	$11	$11	$11	$11
TC	$73	$73	$70	$70	$70	$70	$70	$70	$70

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

3.4.5.3 Front or Secondary Axle Disconnect for Four-Wheel Drive Systems

Energy is required to continually drive the front, or secondary, axle in a four-wheel drive system even when the system is not required during most operating conditions. This energy loss directly results in increased fuel consumption and CO_2 emissions. Many part-time four-wheel drive systems use some type of front axle disconnect to provide shift-on-the-fly capabilities. The front axle disconnect is normally part of the front differential assembly. As part of a shift-on-the-fly four-wheel drive system, the front axle disconnect serves two basic purposes. First, in two-wheel drive mode, it disengages the front axle from the front driveline so the front wheels do not turn the front driveline at road speed, saving wear and tear. Second, when shifting from two- to four-wheel drive “on the fly” (while moving), the front axle disconnect couples the front axle to the front differential side gear only when the transfer case’s synchronizing mechanism has spun the front driveshaft up to the same speed as the rear driveshaft. Four-wheel drive systems that have a front axle disconnect typically do not have either manual- or automatic-locking hubs. To isolate the front wheels from the rest of the front driveline, front axle disconnects use a sliding sleeve to connect or disconnect an axle shaft from the front differential side gear. NHTSA and EPA are not aware of any manufacturer offering this technology in the U.S. today on unibody frame vehicles; however, it is possible this technology could be introduced by manufacturers within the MYs 2017-2025 time period.

The 2012-2016 final rule estimated an effectiveness improvement of 1.0 to 1.5 percent for axle disconnect. Based on the 2011 Ricardo report, NHTSA and EPA refined this range to 1.2 to 1.4 percent.

In the 2012-2016 rule, the agencies estimated the DMC at $78 (2007$) which was considered applicable to the 2015MY. This DMC becomes $81 (2009$) for this analysis.

The agencies consider secondary axle disconnect technology to be on the flat portion of the learning curve and have applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter. The resultant costs are shown in Table 3-98.

Table 3-98 Costs for Secondary Axle Disconnect (2009$)

Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$77	$75	$74	$72	$71	$69	$68	$66	$65
IC	$19	$19	$15	$15	$15	$15	$15	$15	$15
TC	$96	$94	$89	$88	$86	$85	$83	$82	$81

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

3.4.5.4 Aerodynamic Drag Reduction

Many factors affect a vehicle's aerodynamic drag and the resulting power required to move it through the air. While these factors change with air density and the square and cube of vehicle speed, respectively, the overall drag effect is determined by the product of its frontal area and drag coefficient. Reductions in these quantities can therefore reduce fuel consumption and CO_2 emissions. Although frontal areas tend to be relatively similar within a vehicle class (mostly due to market-competitive size requirements), significant variations in drag coefficient can be observed. Significant changes to a vehicle's aerodynamic performance may need to be implemented during a redesign (*e.g.*, changes in vehicle shape). However, shorter-term aerodynamic reductions, with a somewhat lower effectiveness, may be achieved through the use of revised exterior components (typically at a model refresh in mid-cycle) and add-on devices that are currently being applied. The latter list would include revised front and rear fascias, modified front air dams and rear valances, addition of rear deck lips and underbody panels, and lower aerodynamic drag exterior mirrors.

The 2012-2016 final rule estimated that a fleet average of 10 to 20 percent total aerodynamic drag reduction is attainable which equates to incremental reductions in fuel consumption and CO_2 emissions of 2 to 3 percent for both cars and trucks. These numbers are generally supported by the Ricardo study and public technical literature and therefore NHTSA and EPA are retaining these estimates, as confirmed by joint review, for the purposes of this proposal.

For this proposal, the agencies are considering two levels of aero improvements. The first level is that discussed in the 2012-2016 final rule and the 2010 TAR and includes such body features as air dams, tire spats, and perhaps one underbody panel. In the 2012-2016 rule, the agencies estimated the DMC of aero-level 1 at $39 (2007$). This DMC becomes $40 (2009$) for this analysis, applicable in the 2015MY. The agencies consider aero-level 1 technology to be on the flat portion of the learning curve and have applied a low complexity ICM of 1.24 through 2018 then 1.19 thereafter.

The second level of aero—level 2 which includes such body features as active grille shutters[pp], rear visors, larger under body panels or low-profile roof racks —was discussed in the 2010 TAR where the agencies estimated the DMC at $120 (2008$) incremental to the baseline vehicle. The agencies inadvertently used that cost as inclusive of aero-level 1 technologies when it should have been incremental to aero-1 technologies. As a result, the agencies now consider the TAR cost to more appropriately be incremental to aero-level 1 with a DMC for this analysis of $121 (2009$). The agencies consider this cost to be applicable in the 2015MY. Further, the agencies consider aero-level 2 technology to be on the flat portion of the learning curve. The agencies have applied a medium complexity ICM of 1.39 through 2024 then 1.29 thereafter. The timing of the aero-level 2 ICMs is different than that for the level 1 technology because the level 2 technology is newer and not yet being implemented in the fleet. The resultant costs are shown in Table 3-99.

Table 3-99 Costs for Aerodynamic Drag Improvements – Levels 1 & 2 (2009$)

Cost type	Aero Technology	Incremental to	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	Level 1	Baseline	$38	$38	$37	$36	$35	$35	$34	$33	$33
DMC	Level 2	Aero-level 1	$115	$113	$110	$108	$106	$104	$102	$100	$98
IC	Level 1	Baseline	$10	$10	$8	$8	$8	$8	$8	$8	$8
IC	Level 2	Aero-level 1	$47	$46	$46	$46	$46	$46	$46	$46	$34
TC	Level 1	Baseline	$48	$47	$45	$44	$43	$42	$42	$41	$40
TC	Level 2	Aero-level 1	$162	$159	$157	$155	$152	$150	$148	$146	$132
TC	Level 2	Baseline	$210	$207	$201	$198	$195	$192	$190	$187	$173

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

3.4.5.5 Mass Reduction

Over the past 20 years, there has been a generally increasing trend in the weight of the light duty vehicle fleet as shown in Figure 3-26 from EPA's Fuel Economy Trends Report.[79] There have been a number of factors contributing to this weight increase including manufacturers choosing to build and consumers choosing to purchase larger vehicles including heavier trucks, SUVs, and CUVs. Also contributing to this weight increase has been an increase in vehicle content including; safety features (air bags, antilock brakes, energy absorbent and intrusion resistant vehicle structures, etc.), noise reduction (additional damping material), added comfort (air conditioning), luxury features (infotainment systems, power locks and windows), etc.

This increased weight in the fleet has been partially enabled by the increased efficiency of vehicles, especially in engines and transmissions. The impressive improvements in efficiency during this period have allowed for greater weight carrying and volume capacity

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[pp] For details on how active aerodynamics are considered for off-cycle credits, see TSD Chapter 5.2.2.

(and towing), safety, consumer features and vehicle refinement, as well as greater acceleration performance.

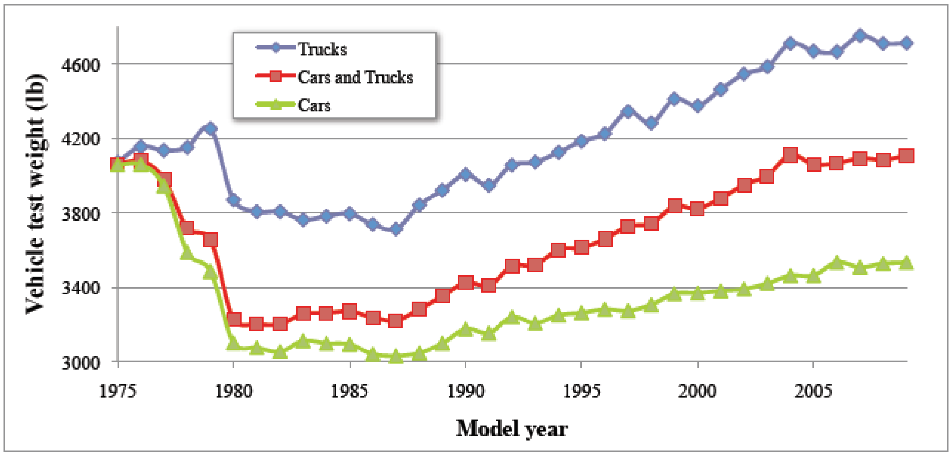


Figure 3-26 Light Duty Fleet Weight characteristics 1975-2010

Since 1987, on average, the overall fleet has become heavier and faster while fuel economy has not shown marked or consistent increases. A calculation by University of California Davis[80] shows the combined impact of the fleet getting heavier while having approximately stable fuel economy from 1987 to 2009 in ton-mpg terms. The improvement in the fleet's technical efficiency is illustrated below in Figure 3-27. During the same period, there are many improvements in vehicle performance, such as faster vehicle acceleration shown in Figure 3-27 and reduced fatality in the fleet as shown in Figure 3-28.

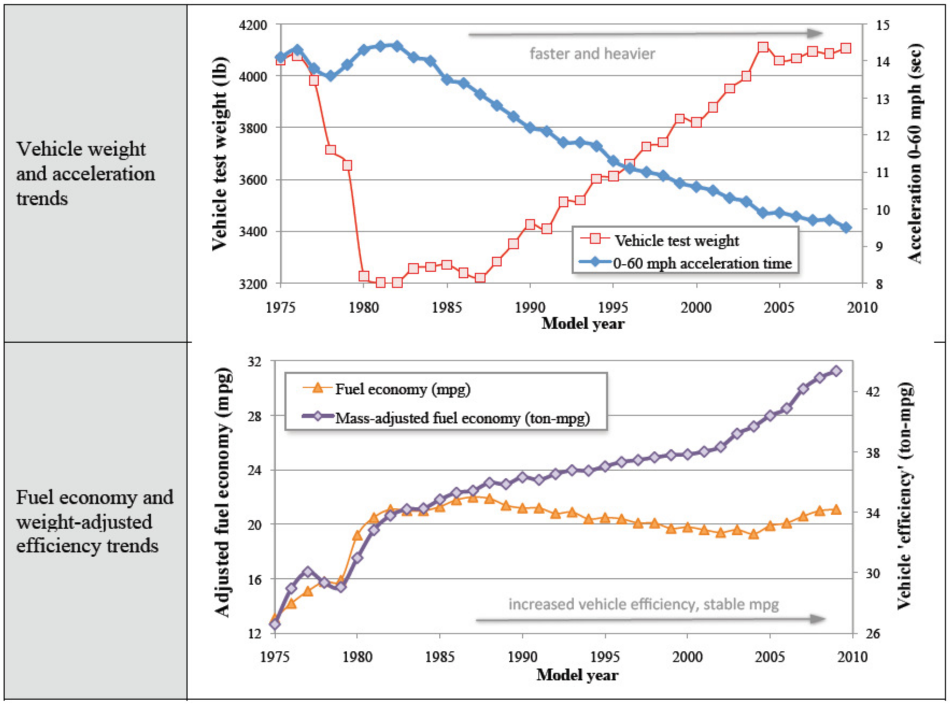


Figure 3-27 U.S. Light duty Fleet trends for weight, acceleration, fuel economy and weight-adjusted fuel economy for model years 1975-2009

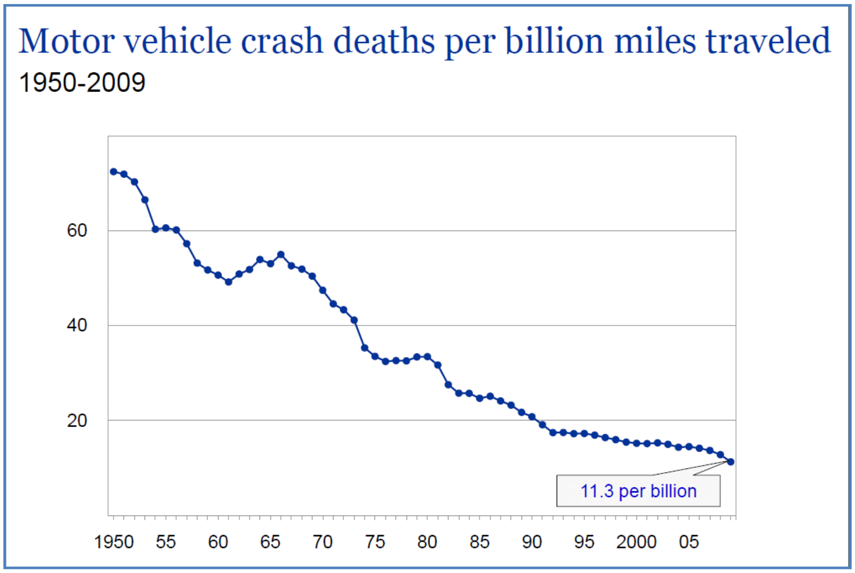
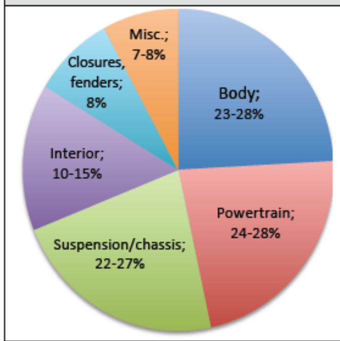


Figure 3-28 U.S. Vehicle Fatality for the past 60 years[81]

Reducing a vehicle's mass, or "down-weighting" the vehicle, decreases fuel consumption by reducing the energy demand needed to overcome forces resisting motion. Mass reduction can be also achieved by vehicle "downsizing" where a vehicle is physically reduced in size by reducing exterior dimensions, such as shifting from a midsize vehicle to a compact vehicle. Both vehicle down-weighting and vehicle downsizing can yield lower GHG emission and reduce fuel consumption. But vehicle downsizing is dependent on the consumer choices which are influenced by many factors, such as the consumer's utility needs, fuel prices, economic conditions, etc. [qq] In this NPRM analysis, the agencies are not analyzing downsizing since we are assuming that the attribute based standards will not exert any regulatory pressure for manufacturers to change the size of vehicles in order to come into compliance with the proposed standards (as described in Section II.F of the Preamble and Chapter 2 of the joint TSD). Instead we are assuming that manufacturers will favor down-weighting of a vehicle through material substitution, design optimization and adopting other advance manufacturing technologies while not compromising a vehicle's attributes and functionalities, such as occupant or cargo space, vehicle safety, comfort, acceleration performance, etc. While keeping everything else constant, the lighter a vehicle is, the less fuel is needed to drive the vehicle over a driving cycle. Researchers and industry have used a rule of thumb, based on testing and simulation, that 10 percent reduction in vehicle mass can be expected to generate a 6 to 7 percent increase in fuel economy if the vehicle powertrain and other components are also downsized accordingly.[82] A recent 2010 Ricardo study, funded by EPA, updated this range to 5 to 8 percent increase in fuel economy.

Mass reduction has an important relationship with vehicle powertrain selection and sizing. Vehicle powertrain selection depends on an OEM's product strategy, and may include a variety of options such as: naturally aspirated, boosted and downsized gasoline, diesel, or vehicle electrification (P/H/EV). Regardless of the strategy selected, vehicle mass reduction for non-powertrain systems is an important enabler to further reduce vehicle fuel consumption and reduce the size of the powertrain system. Often times the term "glider" is used to include all of the vehicle parts except for the powertrain of the vehicle. Figure 3-29 illustrates a typical vehicle system mass breakdown[83]. Normally the non-powertrain systems account for 75 percent of vehicle weight and this is what the agencies are focusing on for this discussion.

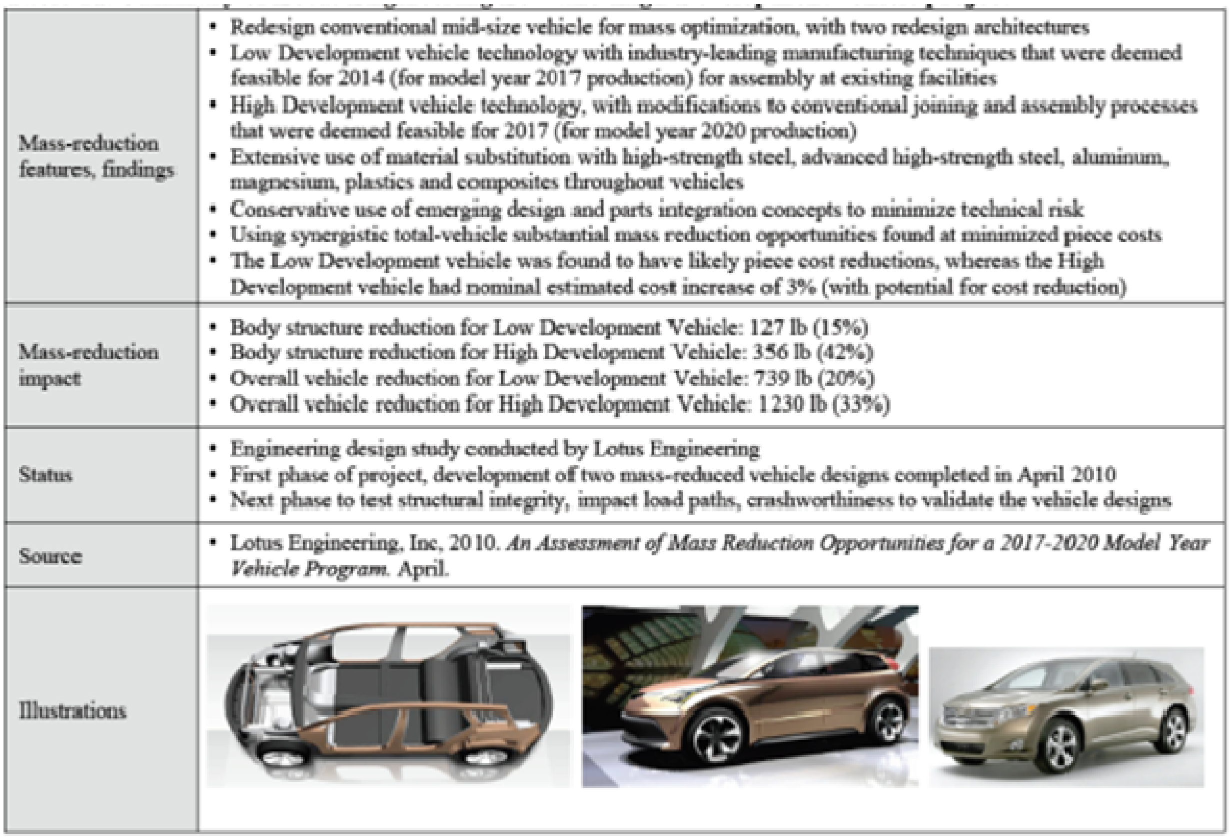
[qq] Vehicle mass reduction is very different that vehicle "down-sizing". Vehicle downsizing can confuse or confound the analysis of mass-reduction technology trends; however these are distinctly different factors.

Approximate vehicle mass breakdown[a]	System	Major components in system
 	Body-in-white	Passenger compartment frame, cross and side beams, roof structure, front-end structure, underbody floor structure, panels
	Powertrain	Engine, transmission, exhaust system, fuel tank
	Chassis	Chassis, suspension, tires, wheels, steering, brakes
	Interior	Seats, instrument panel, insulation, trim, airbags
	Closures	Front and rear doors, hood, lift gate
	Miscellaneous	Electrical, lighting, thermal, windows, glazing

[a] *Based on Stodolsky et al, 1995a; Bjelkengren, 2008; Lotus Engineering, 2010; the actual system definitions and system component inclusion can vary, and percentage weight breakdown can vary substantially by vehicle*

Figure 3-29 Vehicle system mass approximation

Mass reduction can potentially be applied to any of a vehicle's subsystems, including the engine, exhaust system, transmission, chassis, suspension, brakes, body, closure panels, glazing, seats and other interior components, engine cooling systems, and HVAC systems. Manufacturers generally tend to undertake larger amounts of mass reduction systematically and more broadly across all vehicle systems when redesigning a vehicle. For example, if a manufacturer applies a smaller, lighter engine with lower torque-output to a vehicle, this can allow the use of a smaller, lighter-weight transmission and drive line components, because those components need not be as heavy and robust to support equivalent performance in the redesigned vehicle with a smaller engine. Likewise, the combined mass reductions of the engine, drivetrain, and body in turn reduce stresses on the suspension components, steering components, wheels, tires, and brakes, which can allow further reductions in the mass of these subsystems. Reducing the unsprung masses such as the brakes, control arms, wheels, and tires further reduce stresses in the suspension mounting points which will allow for further optimization and potential mass reduction. When redesigning vehicles, OEMs normally set weight targets by benchmarking other vehicles in the same segment and projecting weight trends into the future, and then identifying targets for all components and subsystems that support achieving the target. The agencies believe this holistic approach, taking into consideration of all secondary mass savings, is the most effective way for OEMs to achieve large amount of mass reduction. During a vehicle redesign where mass reduction is a strategic vehicle program goal, OEMs can consider modular systems design, secondary mass effects, multi-material concepts, and new manufacturing processes to help optimize vehicles for much greater potential mass reduction. Figure 3-30 illustrates an example of this approach and how significant mass reduction opportunities can be achieved when a complete vehicle redesign is undertaken.



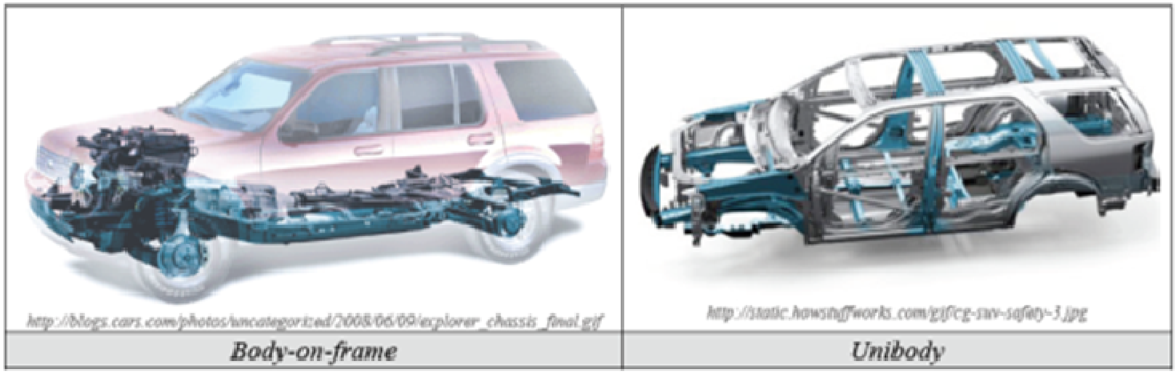
Mass-reduction features, findings	• Redesign conventional mid-size vehicle for mass optimization, with two redesign architectures • Low Development vehicle technology with industry-leading manufacturing techniques that were deemed feasible for 2014 (for model year 2017 production) for assembly at existing facilities • High Development vehicle technology, with modifications to conventional joining and assembly processes that were deemed feasible for 2017 (for model year 2020 production) • Extensive use of material substitution with high-strength steel, advanced high-strength steel, aluminum, magnesium, plastics and composites throughout vehicles • Conservative use of emerging design and parts integration concepts to minimize technical risk • Using synergistic total-vehicle substantial mass reduction opportunities found at minimized piece costs • The Low Development vehicle was found to have likely piece cost reductions, whereas the High Development vehicle had nominal estimated cost increase of 3% (with potential for cost reduction)
Mass-reduction impact	• Body structure reduction for Low Development Vehicle: 127 lb (15%) • Body structure reduction for High Development Vehicle: 356 lb (42%) • Overall vehicle reduction for Low Development Vehicle: 739 lb (20%) • Overall vehicle reduction for High Development Vehicle: 1230 lb (33%)
Status	• Engineering design study conducted by Lotus Engineering • First phase of project, development of two mass-reduced vehicle designs completed in April 2010 • Next phase to test structural integrity, impact load paths, crashworthiness to validate the vehicle designs
Source	• Lotus Engineering, Inc, 2010. *An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program*. April.
Illustrations	

Figure 3-30 Summary of Lotus Engineering Low and High Development vehicle projects

It is appropriate for both manufacturers and the agencies to consider mass reduction in terms of "percent by which the redesigned vehicle is lighter than the previous version," recognizing that that percent likely represents both "primary" mass reduction (that which the manufacturer set out to make lighter) and "secondary" mass reduction (from ancillary systems and components that can now be lighter due to having made the primary mass reductions).

As in the MYs 2012-2016 rulemaking analysis, the agencies are assuming that up to 1.25 kg of secondary mass reduction can occur for each kg of primary mass reduction, when all subsystems are redesigned to take the initial primary mass reduction into account.[84] We note that this estimate may not be applicable in all real-world instances of mass reduction, and that the literature indicates that the amount of secondary mass reduction potentially available varies significantly from an additional 50% to 125% depending on what is assumed, such as which components or systems primary mass reduction is applied to, and whether the powertrain is available for downsizing. [85] [86] [87] The ability to reduce mass is affected by the consideration of component sharing among different vehicles to achieve production economies of scale that affect cost and that also affect the number of unique parts that must be managed in production and for service. In addition, the engineering resources and capital for tooling and equipment that would be needed to optimize every vehicle component at each redesign affects the ability to fully optimize a new vehicle to achieve all of the theoretically possible secondary mass reduction. While there is agreement in the literature that primary mass reduction can enable secondary mass reduction, the agencies recognize that care must be taken when reviewing reports on mass reduction methods and practices to ascertain if compounding effects have been considered and how.

Mass reduction can occur through a variety of techniques available to manufacturers. As summarized by NAS in its 2011 report, there are two key strategies for reducing vehicle mass, changing the design to use less material or substituting light-weighting materials for heavier materials while maintaining performance (safety and stiffness).[88] The first approach is to use less material comparing to the baseline component by optimizing the design and structure of the component, system or vehicle structure. For an example, a "body on frame" vehicle can be redesigned with a lighter "unibody" construction by eliminating the number of components and reducing the weight of the overall body structure, resulting in significant mass reduction and related cost reduction. The unibody design dominates the passenger car segment and has an increasing penetration into what used to be body-on-frame vehicles, such as SUVs. This technique was used in the 2011 Ford Explorer redesign in addition to extensive use of high strength steels[89]. Figure 3-31 depicts body-on-frame and unibody designs for two sport utility vehicles.. .



http://blogs.cars.com/photos/uncategorized/2008/06/09/explorer_chassis_final.gif

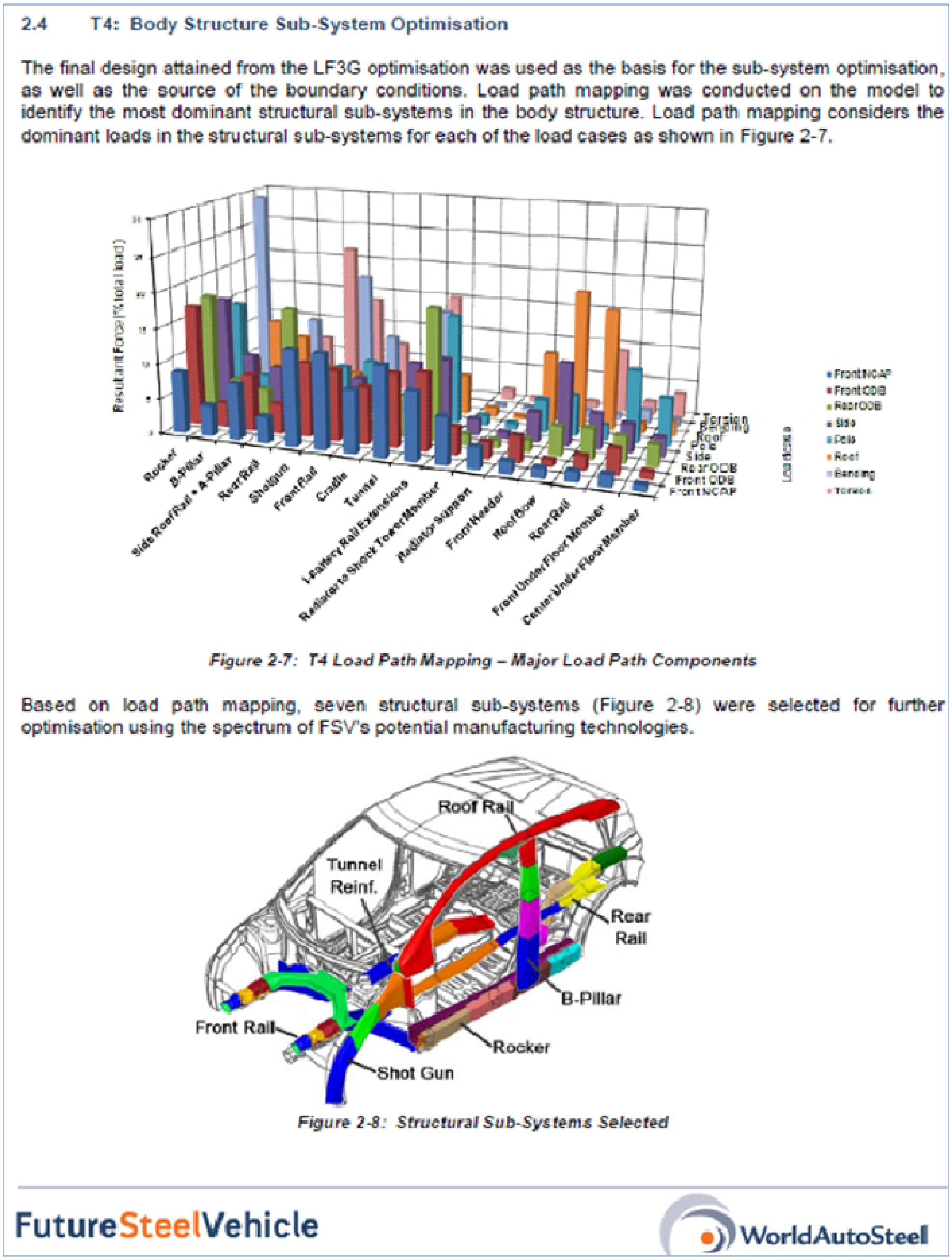
http://static.howstuffworks.com/gif/cg-suv-safety-3.jpg

Body-on-frame

Unibody

Figure 3-31 Illustration of Body-on-Frame (BoF) and Unibody vehicle construction

Manufactures can also continue to utilize Computer Aided Engineering (CAE) tools to further reduce inefficiencies in vehicle design. For example, the Future Steel Vehicle (FSV) project[90] sponsored by the WorldAutoSteel, used three levels of optimization, topology optimization, low fidelity 3G (Geometry Grade and Gauge) optimization and sub-system optimization, to achieve 30 percent mass reduction in vehicle body structure with a unibody design. Designs similar to some used in the FSV project have been applied in production vehicles, such as the B-pillar of new Ford Focus.[91] An example of this process in shown in the Future Steel Vehicle project shown in Figure 3-32.



2.4 T4: Body Structure Sub-System Optimisation

The final design attained from the LF3G optimisation was used as the basis for the sub-system optimisation, as well as the source of the boundary conditions. Load path mapping was conducted on the model to identify the most dominant structural sub-systems in the body structure. Load path mapping considers the dominant loads in the structural sub-systems for each of the load cases as shown in Figure 2-7.

Figure 2-7: T4 Load Path Mapping – Major Load Path Components

Based on load path mapping, seven structural sub-systems (Figure 2-8) were selected for further optimisation using the spectrum of FSV's potential manufacturing technologies.

Figure 2-8: Structural Sub-Systems Selected

Figure 3-32 Example of vehicle body load path mapping for mass optimization

Vehicle manufacturers have long used these continually-improving CAE tools to optimize vehicle designs. But because any design must maintain component and system functionality, there are practical limitations to the amount of additional design improvement and mass reduction that can be achieved through optimization. Additionally, ultimate optimization of vehicle design for mass reduction may be limited by OEMs' typical use of a common platform for multiple vehicle models. While optimization may concentrate of the vehicle that has the largest production volume for a platform, designs must also support the most demanding functional requirements of all of the vehicles that share that platform. In addition, the engineering resources and capital for tooling and equipment that would be needed to optimize every vehicle component at each redesign affects the ability to fully optimize a new vehicle to achieve all of the theoretically possible secondary mass reduction. Therefore, it is inherent that some level of mass inefficiency will exist on many or all of the vehicles that share a platform. The agencies seek comment and information on the degree to which shared vehicle components and architectures affect the feasible amount of mass reduction and the cost for mass reduction relative to what could be achieved if mass reduction was optimized for a single vehicle design.

Using less material can also be achieved through improving the manufacturing process, such as by using improved joining technologies and parts consolidation. This method is often used in combination with applying new materials. For example, more precise manufacturing techniques, such as laser welding, may reduce the flange size necessary for welding and thus marginally decrease the mass of an assembly. Also, when complex assemblies are constructed from fewer pieces, the mass of the assembly tends to be lower. Additionally, while synergies in mass reduction certainly exist, and while certain technologies (*e.g.*, parts consolidation and molding of advanced composites) can enable one another, others (*e.g.*, laser welding and magnesium casting) may be incompatible.

The second key strategy to reduce mass of an assembly or component involves the substitution of lower density and/or higher strength materials. Table 3-100 shows material usage typical to high-volume vehicles. Material substitution includes replacing materials, such as mild steel, with advanced and regular higher-strength steels, aluminum, magnesium and/or composite materials. The substitution of advanced high strength steel (AHSS) can reduce the mass of a steel part because AHSS has higher strength than mild steel and therefore less material is needed in strength-critical components despite the fact that its density is not significantly different from mild steel. Some manufacturers are considering even more advanced materials for many applications, but the advanced microstructure and limited industry experience with some materials may make these longer-term solutions. For example, advanced composite materials (such as carbon fiber-reinforced plastic), depending on the specific fiber, matrix, reinforcement architecture, and processing method, can be subject to dozens of competing damage and failure mechanisms that may complicate a manufacturer's ability to ensure equivalent levels of durability and crashworthiness. As the industry gains experience with these materials, these concerns will inevitably diminish, but may remain relevant during the timeframe of this rulemaking. Material substitution also tends to be quite manufacturer and situation specific in practice; some materials work better than others for some vehicle components and a manufacturer may invest more heavily in adjusting its manufacturing to a particular type of advanced material and complicate its ability to consider others. The agencies recognize that like any type of mass reduction, material substitution has to be conducted not only with consideration to maintaining equivalent component strength, but also to maintaining all the other attributes of that component, system or vehicle, such as crashworthiness, durability, and noise, vibration and harshness (NVH).

Automobiles also utilize a wide range of plastic types, including polypropylenes, polyesters, and vinyl esters. These materials are utilized in hatches, roofs, interior panels, instrument panels, and hundreds of other parts. Although primarily replacing nonstructural vehicle components, plastics have continued to make in-roads in bumper systems and in composite beam applications and a number of studies have found potential to supplant structural beams and frame component. Additionally included in this general category are the more costly composites, like glass fiber and carbon fiber reinforced polymers. These materials, to date, are used primarily in limited applications in low-production-volume vehicles.

Table 3-100 Distribution of Material in Typical Contemporary Vehicles (e.g. Toyota Camry and Chevrolet Malibu)

Material	Comments	Approximate Content in Cars Today, by Weight (percent)
Iron and mild steel	Under 480 Mpa	55
High-strength steel	≥ 480 Mpa (in body structure)	15
Aluminum	No aluminum closure panels; aluminum engine block and head and wheels	10
Plastic	Miscellaneous parts, mostly interior trim, light lenses, facia, instrument panel	10
Other (magnesium, titanium, rubber, etc.)	Miscellaneous parts	10

If vehicle mass is reduced sufficiently, a manufacturer may use a smaller, lighter, and potentially more efficient powertrain while maintaining vehicle acceleration performance. If a powertrain is downsized, approximately half of the mass reduction may be attributed to the reduced torque requirement which results from the lower vehicle mass. The lower torque requirement enables a reduction in engine displacement, changes to transmission torque converter and gear ratios, and changes to final drive gear ratio. The reduced powertrain torque enables the downsizing and/or mass reduction of powertrain components and accompanying reduced rotating mass (*e.g.*, for transmission, driveshafts/halfshafts, wheels, and tires) with similar powertrain durability.

All manufacturers are using some or all of these methods to some extent to reduce mass in the vehicles they are producing today, and the agencies expect that the industry will continue to learn and improve the application of these techniques for more vehicles during the rulemaking timeframe. We consider mass reduction in net percentage terms in our analysis not only because effectively determining specific appropriate mass reduction methods for each vehicle in the baseline fleet is a large task beyond the scope of this rulemaking, but also because we recognize that even as manufacturers reduce mass to make vehicles more efficient, they may also be adding mass in the form of increased vehicle content, some of which is feature and safety content in response to market forces and other governmental regulations. For these reasons, when the agencies discuss the amount of mass reduction that we are assuming is feasible for purposes of our analysis, we are implicitly balancing both the considerable opportunities that we believe exist for mass reduction in the future, and the reality that vehicle manufacturing is complex and that mass reduction methods must be applied thoughtfully and judiciously as safety and content demands on vehicles continue to increase over time. Despite our considerable discussion of the topic, the agencies' application of mass reduction in our analysis is fairly simplified. As applied in our models, the percentage reduction for a given vehicle that is assumed for a given year is an abstraction for the use of all the mass reduction methods described above (and in the literature search portion of the above cost discussion). This represents the significant complexity of mass reduction technologies for improving fuel economy and reducing CO_2 emissions.

How much mass reduction do the agencies believe is feasible in the rulemaking timeframe?

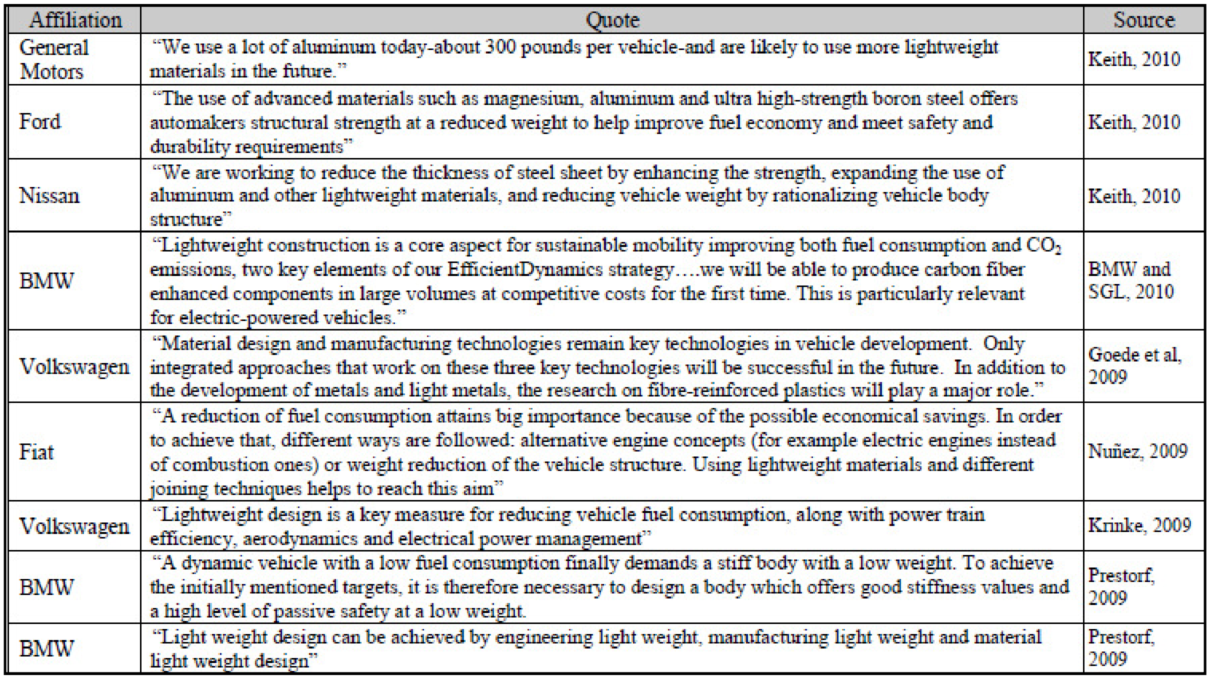
Feasibility, if narrowly defined as the ability to reduce mass without any other constraints, is nearly unbounded. However, the feasible amount of mass reduction is affected by other considerations. Cost effectiveness is one of those constraints and is discussed in the cost section, above. In the analysis for the MYs 2012-2016 rulemaking, NHTSA assumed different amounts of mass reduction (defined as net reduction of a percentage of total vehicle mass) were feasible for different vehicle subclasses in different model years. In addition, it was assumed that more mass was taken out at a redesign and/or later in the rulemaking timeframe than at a refresh and/or earlier in the rulemaking timeframe. More specifically, NHTSA assumed that mass could be reduced 1.5 percent at any refresh or redesign, and that mass could be reduced an additional incremental 3.5-8.5 percent (3.5 for smaller vehicles, 8.5 for the largest vehicles) at redesigns after MY 2014 to provide leadtime for these larger mass reduction amounts. The amount (percentage) of mass reduction that the NHTSA used in the analysis generally aligned with information that the agencies received, during the MY 2012-2016 rulemaking, from manufacturers related to their plans to reduce mass of larger vehicles more than smaller vehicles in the 2012-2016 timeframe. Based on the NHTSA's analysis, it was estimated that mass reduction in response to the MY 2012-2016 program would achieve a safety-neutral result.

In the analysis for the current rulemaking for MYs 2017-2025, the agencies reviewed a number of public reports and accompanying data, as well as confidential information from manufacturers and believe that mass reduction of up to 20 percent can be achieved in a cost effective manner using technologies currently in production. More detail on studies reviewed by the agencies and additional studies currently in progress by the agencies is located in Table 3-103 and Preamble section II.G.

From a general planning perspective, nearly all automakers have made some public statement regarding vehicle mass reduction being a core part of the overall technology strategy that they will utilize to achieve future fuel economy and CO2 emission standards.

Estimates from Ducker Worldwide indicate that the automobile industry will see an annual increase in AHSS of about 10% through 2020[92]. Ford has stated that it intends to reduce the weight of its vehicles by 250-750 lb per model from 2011 to 2020[93]. For context, the midpoint of that range of reductions would correspond to a 12% reduction from the current Ford new light duty vehicle sales fleet. Similarly, Nissan has a target of a 15% mass reduction per vehicle by 2015[94]. This reduction would represent over a 500-lb reduction from their 2008 light duty vehicle average. Mazda's has released a statement about achieving a 220-lb reduction per vehicle by 2016[95]. This is equivalent to about a 6% reduction for the company's current fleet. Toyota stated that it could end up reducing the mass of the Corolla and mid-size models by 30% and 10%, respectively, in the 2015 timeframe. The low end of those targets, 10%, is equivalent to 350 lb per Toyota vehicle in 2008. Land Rover remains committed to a goal of reducing curb weights of its S.U.V.'s by as much as 500 kilograms over the next 10 years[96]. Several reports are summarized in the University of California study as shown in Table 3-101[97].[98]

Table 3-101 Automaker industry statements regarding plans for vehicle mass-reduction technology



Affiliation	Quote	Source
General Motors	"We use a lot of aluminum today-about 300 pounds per vehicle-and are likely to use more lightweight materials in the future."	Keith, 2010
Ford	"The use of advanced materials such as magnesium, aluminum and ultra high-strength boron steel offers automakers structural strength at a reduced weight to help improve fuel economy and meet safety and durability requirements"	Keith, 2010
Nissan	"We are working to reduce the thickness of steel sheet by enhancing the strength, expanding the use of aluminum and other lightweight materials, and reducing vehicle weight by rationalizing vehicle body structure"	Keith, 2010
BMW	"Lightweight construction is a core aspect for sustainable mobility improving both fuel consumption and CO_2 emissions, two key elements of our EfficientDynamics strategy….we will be able to produce carbon fiber enhanced components in large volumes at competitive costs for the first time. This is particularly relevant for electric-powered vehicles."	BMW and SGL, 2010
Volkswagen	"Material design and manufacturing technologies remain key technologies in vehicle development. Only integrated approaches that work on these three key technologies will be successful in the future. In addition to the development of metals and light metals, the research on fibre-reinforced plastics will play a major role."	Goede et al, 2009
Fiat	"A reduction of fuel consumption attains big importance because of the possible economical savings. In order to achieve that, different ways are followed: alternative engine concepts (for example electric engines instead of combustion ones) or weight reduction of the vehicle structure. Using lightweight materials and different joining techniques helps to reach this aim"	Nuñez, 2009
Volkswagen	"Lightweight design is a key measure for reducing vehicle fuel consumption, along with power train efficiency, aerodynamics and electrical power management"	Krinke, 2009
BMW	"A dynamic vehicle with a low fuel consumption finally demands a stiff body with a low weight. To achieve the initially mentioned targets, it is therefore necessary to design a body which offers good stiffness values and a high level of passive safety at a low weight.	Prestorf, 2009
BMW	"Light weight design can be achieved by engineering light weight, manufacturing light weight and material light weight design"	Prestorf, 2009

The agencies also believe the practical limits of mass reduction will be different for each vehicle model as each model starts with a different mix of conventional and advanced materials, components, and features intended to meet the function and price of a particular market segment. A vehicle that already has a significant fraction of advanced high strength steel (AHSS) or any other advanced material in its structure, for example, will not have the opportunity to realize the same percentage of mass reduction as a vehicle of more traditional construction. Given the myriad methods of achieving mass reduction, and the difficulty in obtaining data, accounting for the current level of mass reduction technology for every model in production in a baseline model year would be an impractical task. However, the agencies believe that reducing vehicle weight to reduce fuel consumption has a continuum of solutions and the technologies employed will have levels of effectiveness and feasibility that will vary by manufacturers and by vehicle. In estimating the amount of mass reduction for this analysis, the agencies also consider fleet safety effects for mass reduction. See the Preamble II.G for a detailed discussion of the safety considerations in establishing CAFE and GHG standards. In the CAFE and OMEGA analyses, the agencies considered several levels of mass reduction to all of the models in each subclass as discussed below.

Based on the many aspects of mass reduction (i.e. feasibility, cost and safety) , for the proposal the agencies believe that mass reduction of up to 20 percent is feasible on light trucks, CUVs and minivans, but that less mass reduction should be implemented on other vehicle types to avoid increases in societal fatalities. While the agencies continue to examine mass reduction further, we remain alert to safety considerations and seek to ensure that any CAFE and CO_2 standards can be achieved in a safety-neutral manner.

In the CAFE model, NHTSA applied the amounts of mass reduction shown in Table 3-102, which enabled us to achieve overall fleet fatality estimates of close to zero.

Table 3-102 MASS REDUCTION AMOUNT APPLIED IN CAFE MODEL

Absolute %	Subcompact and Subcompact Perf. PC	Compact and Compact Perf. PC	Midsize PC and Midsize Perf. PC	Large PC and Large Perf. PC	Minivan LT	Small, Midsize and Large LT
MR1*	0.0%	2.0%	1.5%	1.5%	1.5%	1.5%
MR2	0.0%	0.0%	5.0%	7.5%	7.5%	7.5%
MR3	0.0%	0.0%	0.0%	10.0%	10.0%	10.0%
MR4	0.0%	0.0%	0.0%	0.0%	15.0%	15.0%
MR5	0.0%	0.0%	0.0%	0.0%	20.0%	20.0%

Notes:

*MR1-MR5: different levels of mass reduction used in CAFE model

The amounts of mass reduction shown in Table 3-102, however, are for conventional vehicles. The amount of mass reduction applied in the OMEGA model follows the safety neutral analysis approach described in Section II.G of the Preamble. The results are described on a variety of tables within EPA's draft RIA (Chapter 3.8.2). The agencies assume that vehicles with hybrid and electric powertrain are heavier than conventional vehicles because of the mass of battery systems. In comparing anecdotal data for HEVs, EPA and NHTSA assumes a slight weight increase of 4-5% for HEVs compared to baseline non-hybridized vehicles. The added weight of the Li-ion pack, motor and other electric hardware were offset partially by the reduced size of the base engine as stated in TSD section 3.4.3.8. This assumption, which we believe accurately, reflects real-world HEV, PHEV and EV construction, as an example, for a subcompact PHEV with 20 mile range operating on electricity, because of the additional weight of the electrification system, the agencies assume that to achieve no change in total vehicle mass, it would be necessary to reduce the mass of the glider (the vehicle without the powertrain), by 6 percent. The mass reduction for P/H/EVs can be found section 3.4.3.9 in TSD, section 3.4.3.8 and in EPA's RIA Chapter 1 and NHTSA's RIA Chapter V section E.3.h.4.

How much do the agencies estimate mass reduction will cost in the rulemaking timeframe?

Automakers are currently utilizing various mass reduction techniques across the light-duty vehicle fleet, and will continue to use and in some cases expand these approaches for the 2017 to 2025 time frame. These approaches may include optimized design, geometry, part consolidations, and materials substitution. Unlike the other technologies described in this chapter, mass reduction is potentially more complex in that we cannot define it as a single piece of equipment or hardware change to implement the technological improvement. Mass reduction, depending upon the level of reduction targeted, has the potential to impact nearly every system on the vehicle. Because of this complexity, there are unique challenges to estimating the cost for mass reduction and for demonstrating the feasibility of reducing vehicle mass by a given amount. This section describes the cost estimates used for the agencies' analysis.

In the analysis for the MYs 2012-2016 rulemaking, the agencies assumed a constant cost for mass reduction of $1.32 for each pound reduced up to a mass reduction level of 10 percent (or $1.48/lb using an ICM factor of 1.1 for a low-complexity technology). The $1.32/lb estimate was based on averaging three studies: the 2002 NAS Report, a 2008 study by Sierra Research, and a 2007 study by MIT researchers.[rr]

Since the MYs 2012-2016 final rule, the agencies have given further consideration to the cost of mass reduction, and now believe that a cost that varies with the level of mass reduction provides a better estimate. The agencies believe that as the vehicle fleet progresses from lower to higher levels of mass reduction and becomes increasingly optimized for mass and other attributes, the cost for mass reduction will progressively increase. The higher levels of mass reduction may, for example, require applying more advanced materials and technologies than lower levels of mass reduction, which means that the cost of achieving those higher levels may increase accordingly. The unit cost of mass reduction versus the

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[rr] Specifically, the 2002 NAS Report estimated that vehicle weight could be reduced by 5 percent (without engine downsizing) at a cost of $210-$350, which translates into $1.50/lb assuming a 3,800 lb base vehicle and using the midpoint cost; Sierra Research estimated that a 10 percent reduction (with compounding) could be accomplished for $1.01/lb, and MIT researchers estimated that a 14 percent reduction (with no compounding) could be accomplished for $1.36/lb. References for these studies are available in endnotes to Chapter 3 of the TSD for the MYs 2012-2016 final rule.

amount of mass reduction might be linear, parabolic, or some other higher order relationship. In the 2017-2025 Notice of Intent, 75 FR 62739 (Oct. 13, 2010), CARB, EPA and NHTSA derived a second order curve based on a study with two vehicle redesigns conducted by Lotus Engineering completed in 2010, such that zero mass reduction had zero cost, and the dollars per pound increased with greater levels of mass reduction. Since the publication of the TAR, the agencies have identified a number of additional studies in the literature relating to the costs of vehicle mass reduction, which are discussed below. The studies show that for low or high mass reduction, the costs can range from small cost savings to significant cost increases. The economic costs associated with mass reduction are difficult to determine conclusively due to the broad range of methods s employed to achieve mass reduction. The costs on a specific vehicle or component depend on many factors, such as the design, materials selected, raw material price, appropriate manufacturing processes, production volume, component functionality, required engineering and development, etc. Cost data thus varies widely in the literature. Of the various studies reviewed by the agencies, not all are equal in their original intent, rigor, transparency, or applicability to this regulatory purpose. The individual studies range from complete vehicle redesign to advanced optimization of individual components, and were conducted by researchers with a wide range of experience and background. Some of the studies were literature reviews, while others developed new designs for lighter components or complete lighter vehicles, while yet others built physical components or systems, and conducted testing on those components and systems. Some of the studies focused only on a certain sub-system (which is a building block for the overall vehicle design), while some of them took a systematical approach and re-designed the whole vehicle to achieve the maximum mass reduction and cost reduction. The latter studies typically identified a specific baseline vehicle, and then utilized different engineering approaches and investigated a variety of mass-reduction concepts that could be applied to that vehicle. Some of the differences between studies emanate from the characteristics of the baseline vehicle and its adaptability to the new technology or method, and the cost assumptions relating to the original components and the redesigned components. Assumptions regarding the degree and cost of any associated mass decompounding can also confound comparisons.[ss] Despite this variation in the literature, in actual practice, we believe manufacturers will choose a target mass reduction for a whole vehicle and for each sub-system, and work to find the lowest total cost method to achieve those targets. Such a process would consider numerous primary and

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[ss] The concept of secondary weight savings or mass compounding (also called mass decompounding) derives from the qualitative understanding that as vehicle weight decreases, other vehicle systems can also decrease in mass while maintaining the original vehicle level of performance and function. For instance, following a primary weight reduction in the vehicle (e.g. Body in White), the designs of some of the other dependant vehicle subsystems (tires, suspensions, brakes, powertrain, body structure) may be redesigned and reduced in mass to account for the overall lighter vehicle. The lighter vehicle is also associated with lighter loads, less friction and drag, and may require less power to be accelerated, and the powertrain may therefore be scaled down in size with a potential for reduced mass, even while maintaining equivalent acceleration performance and functionality. The compounded or secondary mass savings from these additional systems may then drive further mass reductions in the original primary weight reduction (e.g. Body in White). Mass compounding factors found in literature are rough estimates of the secondary mass reduction amount.

secondary cost factors (including engineering, facilities, equipment, tooling, and retraining costs) as well as technological and manufacturing risks.[tt]

Regardless of the confidence in specific estimates, the agencies must select a curve that will be applied to the whole fleet that will define the average cost per pound of mass reduction as a function of total percentage of mass reduction. There are many significant challenges that make it difficult for the agencies to establish an estimated cost curve based on the literature, such as the differences in the baselines used in the studies, whether the studies considered platform sharing and powertrain sharing, and other considerations. The agencies initially considered using the flat rate cost estimate that was used for the last rulemaking, $1.32/lb, but as discussed above, there are appropriate reasons to consider a variable cost curve. The agencies then considered the cost estimates from the TAR, but have noted that there is more data available at present that could potentially be useful in informing our estimates. Nonetheless, coalescing these disparate datasets into a single curve has limitations since the various studies are not directly comparable.

With these challenges in mind, and because the agencies have not finished the significant mass reduction studies targeted for the CAFE and GHG rulemaking (described below), the agencies examined all the studies in Table 3-103 including information supplied by manufacturers (during meetings held subsequent to the TAR) when deciding the mass reduction cost estimate used for this NPRM.[uu] The agencies considered three major factors in examining these studies. First, whether a study was rigorous in terms of how it evaluates and validates mass reduction from technological and design perspectives. This includes consideration of a study's comprehensiveness, the technical rigor of its methodology, the validation methods employed, and the relevance of the technologies evaluated in the study given our rulemaking time frame. Second, whether a study was rigorous in terms of its estimation of costs, including the completeness and rigor of the methodology, such as whether the study includes data for all categories of direct manufacturing costs, and whether the study presents detailed cost information for both the baseline and the light-weighted design. And third, the degree of peer review, including if the study is peer-reviewed, and whether it has effectively addressed any critical technical, methodological, and cost issues raised by the peer-review, if this information is available.

Some of the variation may be attributed to the complexity of mass reduction as it is not one single discrete technology and can have direct as well as indirect effects on other

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[tt] We also note that the cost of mass reduction in the Volpe model is quantified on a per pound basis that is a function of the percentage decrease in vehicle mass. We assume that OEMs would find the most cost-effective approach to achieve such a mass reduction. Realistically, this would depend heavily on the baseline vehicle as well as the size and adaptability of the initial design to the new technology. Thus, the Volpe model strives to be realistic in the aggregate while recognizing that the figures proposed for any specific model may be debatable.

[uu] The agencies considered confidential cost information provided by OEMs that covered a range of components, systems, designs and materials. Some of these cost estimates are higher than some of the literature studies, and manufacturers provided varying levels of detail on the basis for the costs such as whether mass compounding is included, or whether the costs include markup factors.

systems and components. The 2010 NAS study speaks to this point when it states on page 7-1 that “The term material substitution oversimplifies the complexity of introducing advanced materials, because seldom does one part change without changing others around it.” These variations underscore that there is not a unique mass reduction solution as there are many different methods with varying costs for taking mass out of vehicles, and every manufacturer, even every vehicle, could have a different approach depending on the specific vehicle, assembly plant and model year of implementation. The agencies recognize that there are challenges to characterizing the mass reduction plans for the entire future fleet due to the complexity and variety of methods available. So far the agencies have not found any study that addresses how to generalize the mass reduction that is achievable on a single vehicle to the whole fleet.

Table 3-103 contains a summary of the data contained in the studies, and the OEM CBI data, which the agencies reviewed. There is a degree of uncertainty associated with comparing the costs from the range of studies in the literature when trying to summarize them in a single table, and we encourage interested stakeholders to carefully review the information in the literature. For some of the cost estimates presented in the papers there are unknowns such as: what year the costs are estimated for, whether mass decompounding (and potential resultant cost savings) was taken into account, and whether mark-ups or indirect costs were included. The agencies tried to normalize the cost estimations from all these studies by converting them to 2009 year dollar, applying mass compounding factor of 1.35 for mass reduction amount more than 10 percent if it has not been applied in the study and factoring out the RPE specified in the study to derive direct manufacture costs for comparison. There are some papers that give cost for only component mass reduction, others that have more general subsystem costs and others yet that estimate total vehicle mass reduction costs (which often include and present data at the subsystem level). Other studies have multiple scenarios for different materials, different vehicle structures and mass reduction strategies. Thus, a single study which contains more than one vehicle can be broken down into a range of vehicle types, or at the subsystem level, or even at the component level. While Table 3-103 is inclusive of all of the information reviewed by the agencies, for the reasons described above the technical staff for the two agencies applied various different approaches in evaluating the information. The linear mass-cost relationship developed for this proposal and presented below is the consensus assessment from the two agencies of the appropriate mass cost for this proposal.

Table 3-103 Mass Reduction Studies Considered for Estimating Mass Reduction Cost for this NPRM

Studies	Cost Year	Cost Information from Studies									
		Mass Reduction [lb]	Compounding Factor	Mass Reduction with Compounding [lb]	Baseline Vehicle Weight [lb]	Mass Reductioning w/Compounding [%]	Cost [$]	RPE	Dollar Multiplier to 2009	2009 Direct Manufacturing Cost [$]	Unit Cost of Mass Reduction [$/lb]
Individual Cost Data Points											
AISI, 1998 (ULSAB)	1998	103	1	103	2977	3.5%	-$32	1.0	1.28	-$41	-$0.40
AISI, 2000 (ULSAC)	2000	6	1	6	2977	0.2%	$15	1.0	1.24	$18	$2.99
Austin et al, 2008 (Sierra Research) - ULS Unibody	2008	320	1	320	3200	10.0%	$209	1.61	1.01	$131	$0.41
Austin et al, 2008 (Sierra Research) - AL Unibody	2008	573	1	573	3200	17.9%	$1,805	1.61	1.01	$1,134	$1.98
Austin et al, 2008 (Sierra Research) - ULS BoF	2008	176	1	176	4500	3.9%	$171	1.61	1.01	$107	$0.61
Austin et al, 2008 (Sierra Research) - AL BoF	2008	298	1	298	4500	6.6%	$1,411	1.61	1.01	$887	$2.98
Bull et al, 2008 (Alum Assoc.) - AL BIW	2008	279	1	279	3378	8.3%	$455	1.0	1.01	$460	$1.65
Bull et al, 2008 (Alum Assoc.) - AL Closure	2008	70	1	70	3378	2.1%	$151	1.0	1.01	$153	$2.17
Bull et al, 2008 (Alum Assoc.) - Whole Vehicle	2008	573	1	573	3378	17.0%	$122	1.0	1.03	$126	$0.22
Cheah et al, 2007 (MIT) - 20%	2007	712	1	712	3560	20.0%	$646	1.0	1.03	$667	$0.94
Das, 2008 (ORNL) - AL Body & Panel	2008	637	1	637	3363	19.0%	$180	1.5	1.01	$121	$0.19
Das, 2008 (ORNL) - FRPMC	2008	536	1.0	536	3363	15.9%	-$280	1.5	1.01	-$189	-$0.35
Das, 2009 (ORNL) - CF Body & Panel, AL Chassis	2009	933	1	933	3363	27.7%	$1,490	1.5	1.00	$993	$1.06
Das, 2010 (ORNL) - CF Body & Panel, Mg Chassis	2010	1173	1	1173	3363	34.9%	$373	1.5	1.00	$248	$0.21
EEA, 2007 - Midsize Car - Adv Steel	2007	236	1	236	3350	7.0%	$179	1.0	1.03	$185	$0.78
EEA, 2007 - Midsize Car - Plast/Comp	2007	254	1	254	3350	7.6%	$239	1.0	1.03	$247	$0.97
EEA, 2007 - Car - Avg. Al/Mg	2007	657	1.35	887	4500	14.6%	$1,411	1.0	1.03	$1,458	$1.64
EEA, 2007 - Midsize Car - Al	2007	586	1.35	791	3350	23.6%	$1,388	1.0	1.03	$1,434	$1.81
EEA, 2007 - Midsize Car - Mg	2007	712	1.35	961	3350	28.7%	$1,508	1.0	1.03	$1,558	$1.62
EEA, 2007 - Light Truck - Adv Steel	2007	422	1	422	4750	8.9%	$291	1.0	1.03	$301	$0.71
EEA, 2007 - Light Truck - Plast/Comp	2007	456	1	456	4750	9.6%	$398	1.0	1.03	$411	$0.90
EEA, 2007 - Light Truck - Al	2007	873	1.35	1179	4750	24.8%	$1,830	1.0	1.03	$1,891	$1.60
EEA, 2007 - Light Truck - Mg	2007	1026	1.35	1385	4750	29.2%	$1,976	1.0	1.03	$2,042	$1.47
Geck et al, 2008 (Ford)	2008	1310	1	1310	5250	25.0%	$500	1.0	1.01	$506	$0.39
Lotus, 2010 - LD	2010	660	1	660	3740	17.6%	-$121	1.0	1.00	-$120	-$0.18
Lotus, 2010 - HD	2010	1217	1	1217	3740	32.5%	$362	1.0	1.00	$360	$0.30
Montalbo et al, 2008 (GM/MIT) - Closure - HSS	2008	25	1	25	4000	0.6%	$10	1.0	1.01	$10	$0.41
Montalbo et al, 2008 (GM/MIT) - Closure - AL	2008	120	1	120	4000	3.0%	$110	1.0	1.01	$111	$0.92
Montalbo et al, 2008 (GM/MIT) - Closure - Mg/AL	2008	139	1	139	4000	3.5%	$110	1.0	1.01	$111	$0.80
Plotkin et al, 2009 (Argonne)	2009	683	1	683	3250	21.0%	$1,300	1.0	1.00	$1,300	$1.90

Table 3-103 (… Continue) Mass Reduction Studies Considered for Estimating Mass Reduction Cost for this NPRM

Studies	Cost Year	Cost Information from Studies									
		Mass Reduction [lb]	Compounding Factor	Mass Reduction with Compounding [lb]	Baseline Vehicle Weight [lb]	Mass Reductioning w/Compounding [%]	Cost [$]	RPE	Dollar Multiplier to 2009	2009 Direct Manufacturing Cost [$]	Unit Cost of Mass Reduction [$/lb]
Cost Curves											
NAS, 2010 - Average	2010					10.0%					$1.50
NAS, 2010	2010					1.0%					$ 1.41
	2010					2.0%					$ 1.46
	2010					5.0%					$ 1.65
	2010					10.0%					$ 1.52
	2010					20.0%					$ 1.88
OEM1-Average	2010					9.5%					$11.60
OEM1	2010					8.0%					$ 6.00
	2010					9.0%					$ 7.00
	2010					9.5%					$ 8.00
	2010					10.0%					$ 12.00
	2010					11.0%					$ 25.00
OEM2-Average	2010					3.1%					$0.61
OEM2	2010					0.4%					$ -
	2010					0.9%					$ 0.10
	2010					1.9%					$ 0.20
	2010					2.3%					$ 0.33
	2010					2.4%					$ 0.38
	2010					3.1%					$ 0.60
	2010					3.6%					$ 0.76
	2010					4.0%					$ 0.85
	2010					4.1%					$ 0.88
	2010					4.5%					$ 0.98
	2010					4.8%					$ 1.09
	2010					5.0%					$ 1.17
OEM3-Average	2010					7.2%					$1.03
OEM3	2010					4.0%					$ 0.57
	2010					7.5%					$ 1.01
	2010					10.0%					$ 1.51
OEM4	2011					6.9%					$ 0.97
	2011					8.1%					$ 1.02
	2011					16.4%					$ 1.95

EPA and NHTSA scrutinized the various available studies in the literature as well as confidential information provided by several auto firms based on the kinds of factors described above for purposes of estimating the cost of mass-reduction in the 2017-2025 timeframe. We determined that there was wide variation across the studies with respect to costs estimates, applicability to the 2017-2025 time frame, and technical rigor. The mass cost curve that was developed this proposal is defined by the following equation:

Mass Reduction Direct Manufacturing Cost ($/lb) = 4.32 x Percentage of Mass Reduction

For example, this results in an estimated $173 cost increase for a 10% mass reduction of a 4,000lb vehicle (or $0.43/lb), and a $390 cost increase for 15% reduction on the same vehicle (or $0.65/lb).

Because of the wide variation in data used to select this estimated cost curve, the agencies have also conducted cost sensitivity studies in their respective RIAs using values of +/-40%. The wide variability in the applicability and rigor of the studies also provides justification for continued research in this field, such as the agency studies discussed below. The assessment of the current studies highlights the importance of these agency studies, as they are expected to be amongst the most comprehensive ever conducted in the literature, and to be more informative than other studies for estimating the cost of mass reduction for purposes of rulemaking.

The agencies consider this DMC to be applicable to the 2017MY and consider mass reduction technology to be on the flat portion of the learning curve in the 2017-2025MY timeframe. To estimate indirect costs for applied mass reduction of up to 15%, the agencies have applied a low complexity ICM of 1.24 through 2018 and 1.19 thereafter. To estimate indirect costs for applied mass reduction of 15% to 25%, the agencies have applied a medium complexity ICM of 1.39 through 2024 and 1.29 thereafter. To estimate indirect costs for applied mass reduction greater than 25%, the agencies believe it is appropriate to apply a high1 complexity ICM of 1.56 through 2024 and 1.35 thereafter.

The agencies seek detailed comment regarding options for realistically and appropriately assessing the degree of feasible mass reduction for vehicles in the rulemaking timeframe and the total costs to achieve that mass reduction. For example, the agencies seek comments on what practical limiting factors need to be considered when considering maximum feasible amount of mass reduction; the degree to which these limiting factors will impact the amount of feasible mass reduction (in terms of the percent of mass reduction); the best method(s) to assess an appropriate and feasible fleet-wide amount mass reduction amount (because each study mainly focuses on a single vehicle); etc. If commenters wish to submit additional studies for the agencies' consideration, it would assist the agencies if commenters could address how the studies also contribute to the agencies' understanding of the issues enumerated above. The agencies also note that we expect to refine our estimate of both the amount and the cost of mass reduction between the NPRM and the final rule based on the ongoing work described below.

How effective do the agencies estimate that mass reduction will be?

In the analysis for the MYs 2012-2016 final rule, NHTSA and EPA estimated that a 10 percent mass reduction with engine downsizing would result in a 6.5 percent reduction in fuel consumption while maintaining equivalent vehicle performance (*i.e.*, 0-60 mph time, towing capacity, etc.), consistent with estimates in the 2002 NAS report. For small amounts of mass reduction, such as the 1.5 percent used at vehicle refresh in NHTSA's modeling, no engine downsizing was used, so a 10 percent mass reduction without engine downsizing was assumed to result in a 3.5 percent reduction in fuel consumption. In this NPRM, both agencies have chosen to use the effectiveness value for mass reduction from EPA's lumped parameter model to maintain consistency. EPA's lumped parameter model-estimated mass reduction effectiveness is based on a simulation model developed by Ricardo, Inc. under contract to EPA. **The 2011 Ricardo simulation results show an effectiveness of 5.1 percent for every 10 percent reduction in mass. NHTSA has assumed that** for mass reduction less than 10 percent the effectiveness is 3.5 percent. For mass reduction greater than 10 percent, NHTSA estimates the effectiveness is 5.1 percent which avoids double counting benefits – because the effectiveness of engine downsizing is included in the effectiveness of the engine decision tree when applying engine downsizing, it should appropriately be removed from the mass reduction effectiveness value in the mass reduction decision tree. **EPA applies an effectiveness of 5.1 percent for every 10 percent mass reduction, and this scales linearly from 0 percent mass reduction, up to the maximum applied mass reduction for any given vehicle, which in this proposal is never larger than 20 percent.**

What additional studies are the agencies conducting to inform our estimates of mass reduction amounts, cost, and effectiveness?

In the MYs 2012-2016 final rule, the agencies stated that there are several areas concerning vehicle mass reduction and vehicle safety on which the agencies will focus their research efforts and undertake further study. Some studies focus on the potential safety effects of mass reduction through fleetwide analyses, and thus help to inform the agencies with regard to how much mass reduction might appropriately be deemed feasible in the rulemaking timeframe, while others focus on the cost and feasibility of reducing mass in specific vehicles. The results of all of these studies are currently expected to be available for the final rule, and should contribute significantly to informing the agencies' estimates of the costs and feasible amounts of mass reduction to be included in that analysis. The following is an update for the status of those studies.

The agencies and independent researchers have several vehicle level projects to determine the maximum potential for mass reduction in the MY 2017-2021 timeframe by using advanced materials and improved designs while continuing to meeting safety regulations and maintaining functionality of vehicles, and one study that will investigate the effects of resultant designs on fleet safety:

- NHTSA has awarded a contract to Electricore, with EDAG and George Washington University (GWU) as subcontractors, to study the maximum feasible amount mass reduction for a mid-size car – specifically, a Honda Accord. The study tears down a MY 2011 Honda Accord, studies each component and sub-system, and then redesigns each component and sub-system trying to maximize the amount of mass reduction with technologies that are considered feasible for 200,000 units per year production volume during the time frame of this rulemaking. Electricore and its sub-contractors are consulting industry leaders and experts for each component and sub-system when deciding which technologies are feasible. Electricore and its sub-contractors are also building detailed CAD/CAE/powertrain models to validate vehicle safety, stiffness, NVH, durability, drivability and powertrain performance. For OEM-supplied parts, a detailed cost model is being built based on a Technical Cost Modeling (TCM) approach developed by the Massachusetts Institute of Technology (MIT) Materials Systems Laboratory's research[99] for estimating the manufacturing costs of OEM parts. The cost will be broken down into each of the operations involved in the manufacturing, such as for a sheet metal part production by starting from blanking the steel coil, until the final operation to fabricate the component. Total costs are then categorized into fixed cost, such as tooling, equipment, and facilities; and variable costs such as labor, material, energy, and maintenance. These costs will be assessed through an interactive process between the product designer, manufacturing engineers and cost analysts. For OEM-purchased parts, the cost will be estimated by consultation with experienced cost analysts and Tier 1 system suppliers. This study will help to inform the agencies about the feasible amount of mass reduction and the cost associated with it. NHTSA intends to have this study completed and peer reviewed before July 2012, in time for it to play an integral role in informing the final rule.

- EPA has awarded a contract to FEV, with EDAG and Monroe & Associates, Inc. as subcontractors, to study the maximum feasible amount of mass reduction for a mid-size CUV (cross over vehicle) specifically, a Toyota Venza. The study tears down a MY 2010 vehicle, studies each component and sub-system, and then redesigns each component and sub-system trying to maximize the amount of mass reduction with technologies that are considered feasible for high volume production for a 2017 MY vehicle. FEV in coordination with EDAG is building detailed CAD/CAE/powertrain models to validate vehicle safety, stiffness, NVH, durability, drivability and powertrain performance to assess the safety of this new design. This study builds upon the low development (20% mass reduction) design in the 2010 Lotus Engineering study "An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program". This study will undergo a peer review. EPA intends to have this study completed and peer reviewed before July 2012, in time for it to play an integral role in informing the final rule.

- California Air Resources Board (CARB) has awarded a contract to Lotus Engineering, to study the maximum feasible amount mass reduction for a mid-size CUV (cross over vehicle) specifically, a Toyota Venza. The study will concentrate on the Body-in-White and closures in the high development design (40% mass reduction) in the Lotus

Engineering study cited above. The study will provide an updated design with crash simulation, detailed costing and manufacturing feasibility of these two systems for a MY2020 high volume production vehicle. This study will undergo a peer review. CARB intends to have this study completed and peer reviewed before July 2012, in time for it to play an integral role in informing the final rule.

- NHTSA has contracted with GWU to build a fleet simulation model to study the impact and relationship of light-weighted vehicle design and injuries and fatalities. This study will also include an evaluation of potential countermeasures to reduce any safety concerns associated with lightweight vehicles. NHTSA will include three light-weighted vehicle designs in this study: the one from Electricore/EDAG/GWU mentioned above, one from Lotus Engineering funded by California Air Resource Board for the second phase of the study, evaluating mass reduction levels around 35 percent of total vehicle mass, and one funded by EPA and the International Council on Clean Transportation (ICCT). This study will help to inform the agencies about the possible safety implications for light-weighted vehicle designs and the appropriate counter-measures,[vv] if applicable, for these designs, as well as the feasible amounts of mass reduction. All of these analyses are expected to be finished and peer-reviewed before July 2012, in time to inform the final rule.

Safety considerations in establishing CAFE/GHG standards along with discussion of NHTSA's February 25, 2011, mass-size-safety workshop at DOT headquarters, can be found in Section II.G of the preamble for this proposal. NHTSA plans to host additional workshops when the studies have reached a sufficient level of completion, to share the results with the public and seek public comments.

3.5 How did the agencies consider real-world limits when defining the rate at which technologies can be deployed?

3.5.1 Refresh and redesign schedules

During MYs 2017-2025 manufacturers are expected to go through the normal automotive business cycle of redesigning and upgrading their light-duty vehicle products, and in some cases introducing entirely new vehicles not in the market today. The MY 2017-2025 standards timeframe allows manufacturers the time needed to incorporate GHG reduction and fuel-saving technologies into their normal business cycle while considering the requirements of the MY 2012-2016 standards.. This is important because it has the potential to avoid the much higher costs that could occur if manufacturers need to add or change technology at times other than their scheduled vehicle redesigns. This time period also provides

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[vv] Countermeasures could potentially involve improved front end structure, knee bags, seat ramps, buckle pretensioners, and others.

manufacturers the opportunity to plan for compliance using a multi-year time frame, again consistent with normal business practice. Over these 9 model years, and the 5 prior model years that make up the 2012-2016 standards, there will be an opportunity for manufacturers to evaluate, presumably, every one of their vehicle platforms and models and add technology in a cost effective way to control GHG emissions and improve fuel economy. This includes all the technologies considered here and the redesign of the air conditioner systems in ways that will further reduce GHG emissions and improve fuel economy.

Because of the complexities of the automobile manufacturing process, manufacturers are generally only able to add new technologies to vehicles on a specific schedule; just because a technology exists in the marketplace or is made available, does not mean that it is immediately available for application on all of a manufacturer's vehicles. In the automobile industry there are two terms that describe when technology changes to vehicles occur: redesign and refresh (*i.e.*, freshening). Vehicle redesign usually refers to significant changes to a vehicle's appearance, shape, dimensions, and powertrain. Redesign is traditionally associated with the introduction of "new" vehicles into the market, often characterized as the "next generation" of a vehicle, or a new platform. Across the industry, redesign of models generally takes place about every 5 years. However, while 5 years is a typical design period, there are many instances where redesign cycles can be longer or shorter. For example, it has generally been the case that pickup trucks and full size vans have longer redesign cycles, while high-volume cars have shorter redesign cycles in order to remain competitive in the market. There are many other factors that can also affect redesign such as availability of capital and engineering resources and the extent of platform and component sharing between models, or even manufacturers.

Vehicle refresh usually refers to less extensive vehicle modifications, such as minor changes to a vehicle's appearance, a moderate upgrade to a powertrain system, or small changes to the vehicle's feature or safety equipment content. Refresh is traditionally associated with mid-cycle cosmetic changes to a vehicle, within its current generation, to make it appear "fresh." Vehicle refresh generally occurs no earlier than two years after a vehicle redesign or at least two years before a scheduled redesign. For the majority of technologies discussed today, manufacturers will only be able to apply them at a refresh or redesign, because their application would be significant enough to involve some level of engineering, testing, and calibration work.

Most vehicles would likely undergo two redesigns during this period. Even with the potential of multiple of refresh and redesign cycles, it is still likely that some of the more advanced and costly technologies (such as cooled boosted EGR engines, or advanced (P)HEVs) may not be able to be fully implemented within the timeframe of this rule. These limitations are captured in "phase-in caps," discussed in the next section, and "maximum technology penetration rates" within the modeling analysis.

The broad technology classes evaluated for purposes of this analysis are defined below and a brief discussion of the limiting factors considered are presented.

- Conventional Spark Ignition (SI) - This technology category includes all technologies, such as gasoline direct injection engines, cylinder deactivation, six and eight speed automatic and dual clutch transmissions, and start-stop micro-hybrid technology, that are not contained in other categories. Many of these technologies were anticipated as being available in the MYs 2012-2016 time frame in the recent NHTSA and EPA final rule, and it is expected manufacturers could expand production to all models by model year 2025. Conventional SI also includes turbocharged and downsized engines and turbocharged and downsized engines that include cooled EGR with additional levels of boost and a larger degree of engine downsizing than seen in the current light-duty gasoline fleet. These latter technologies are similar to the technologies that many OEMs indicated were underdevelopment and which they anticipate will be introduced into the market in the 2017-2025 time frame.

- Hybrid – While the agencies recognize there are many types of full-hybrids either in production or under development, for the purposes of this analysis we have specifically modeled the P2 type hybrid, as explained in section 3.4.3.6.3. While the agencies expect the proliferation of these vehicles to increase in this timeframe, the maximum technology penetration rate and phase-in caps are set at less than 100% in MY 2025 due to industry-wide engineering and capacity constraints, for converting the entire new vehicle fleet to strong hybrids (like P2 and others) in this time frame. As described these technologies (along with PHEVs and EVs) require a significant cost and complexity, and thus are not expected to be able to be fully phased into the 2017-2025 fleet like other more conventional (but advanced) engines.

- Plug-in Hybrid (PHEV) - This technology includes PHEV’s with a range of 20 and 40 miles. The maximum technology penetration rates and phase-in caps are set at less than 100% in MY 2025 due to the same general potential constraints as listed for the HEVs, but are lower for PHEVs due to the current status of the development of these advanced vehicles and the higher cost relative to HEVs. In addition, some consumers may have limited or no access to charging infrastructure, and for those consumers, the PHEV offers little benefit over an HEV at a higher cost. Further, we project (based on what we know today) that PHEV technology is not available to some vehicle types, such as large pickups. While it is technically possible to electrify such vehicles, there are tradeoffs in terms of cost, electric range, and utility that may reduce the appeal of the vehicle to a narrower market. However, the agencies are interested in promoting innovation to overcome these potential obstacles and are thus incentivizing more HEV and PHEV pickup trucks with credit flexibilities as described in the preamble for this proposed rule.

- Electric Vehicle (EV) - This technology includes vehicles with actual on-road ranges of 75, 100, and 150 miles. The actual on-road range was calculated using a projected 30% gap between two-cycle and on-road range. These vehicles are powered solely by electricity and are not powered by any liquid fuels. The maximum technology penetration rates and phase-in caps are set at less than 100% in MY 2025 due to the same general potential constraints as discussed for PHEVs. EVs have additional constraints due to limited infrastructure and range as well. Further, as with PHEVs, we assume that EV technology is not available to some vehicle types, such as large pickups. While it is possible to electrify such vehicles, there are tradeoffs in terms of cost, range, and utility that would reduce the appeal of the vehicle to a narrower market. These trade-offs are expected to reduce the market for other vehicle types as well, and for this analysis we have considered this in the development of the maximum technology penetration rates.

- Mass Reduction - This technology includes material substitution, smart design, and mass reduction compounding. NHTSA and EPA have conducted a thorough assessment of the levels of mass reduction that could be achieved which is both technologically feasible and which can be implemented in a safe manner for this joint federal NPRM (as described earlier in this Chapter).

3.5.2 Vehicle phase-in caps

GHG-reducing and fuel-saving technologies for vehicle applications vary widely in function, cost, effectiveness and availability. Some of these attributes, like cost and availability vary from year to year. New technologies often take several years to become available across the entire market. The agencies use phase-in caps to manage the maximum rate that the CAFE and OMEGA models can apply new technologies.

Phase-in caps are intended to function as a proxy for a number of real-world limitations in deploying new technologies in the auto industry. These limitations can include but are not limited to, engineering resources at the OEM or supplier level, restrictions on intellectual property that limit deployment, and/or limitations in material or component supply as a market for a new technology develops. Without phase-in caps, the models may apply technologies at rates that are not representative of what the industry is actually capable of producing, which would suggest that more stringent standards might be feasible than actually would be.

EPA applies the caps on an OEM vehicle platform basis for most technologies. For a given technology with a cap of x%, this means that x% of a vehicle platform can receive that technology. On a fleet average basis, since all vehicle platforms can receive x% of this technology, x% of a manufacturer’s fleet can also receive that technology. EVs and PHEVs are an exception to this rule. Unlike other technologies, which are applicable to all classes of vehicles, EPA only allows non-towing vehicle types to be electrified in the OMEGA model. As a result, the PHEV and EV cap was applied so that the average manufacturer could produce to the cap levels. Manufacturers that make fewer non-towing vehicles have a lower potential maximum production limit of EVs and PHEV, while those that make more non-towing vehicles have a higher potential maximum limit on EV and PHEV production.

NHTSA applies phase-in caps in addition to refresh/redesign cycles used in the CAFE model, which constrain the rate of technology application at the vehicle level so as to ensure a period of stability following any modeled technology applications, Unlike vehicle-level cycle settings, phase-in caps, defined on a percent per year basis, constrain technology application at the OEM level. As discussed above phase-in caps are intended to reflect a manufacturer's overall resource capacity available for implementing new technologies (such as engineering and development personnel and financial resources) thereby ensuring that resource capacity is accounted for in the modeling process. At a high level, phase-in caps and refresh/redesign cycles work in conjunction with one another to avoid the CAFE modeling process out-pacing an OEM's limited pool of available resources during the rulemaking time frame, especially in years where many models may be scheduled for refresh or redesign. This helps to ensure technological feasibility and economic practicability in determining the stringency of the standards.

Phase-in caps do not define market penetration rates and they do not define the rate at which a particular technology will be applied, rather they simply present an upper limit, or ceiling at which the agencies' computer models can apply new technologies to vehicles to raise their fuel economy and reduce their CO_2 emissions. Ultimately, phase-in caps are determined by the agencies using engineering judgment. However, there are several sources of information on technology penetration that the agencies consider in assigning phase-in caps to various technologies:

- Confidential OEM submissions indicate the rate at which an individual manufacturer can deploy a particular technology. Manufacturer information is especially helpful if multiple manufacturers indicate similar technology penetration rates. The agencies consider these CBI submissions along with other sources of information.
- Historical data from EPA's annual Fuel Economy Trends Report[100] is used to inform the agencies about typical historical rates of adoption of technologies. However, historical data does not necessarily indicate the rates of future technology penetration. Increased competition is driving faster vehicle redesigns and faster adoption of new technologies. On the other hand, some new technologies such as EVs are significantly more complex than most other historical technologies, which must also be considered in defining a phase-in rate.
- Trade press articles, company publications, press releases, and other reports often discuss new technologies, how quickly they will be deployed and manufacturing strategies that enable faster penetration rates. These articles provide a useful glimpse into how manufacturers are changing in order to become more competitive.

3.5.2.1 Trends Report and Industry Data

For over 30 years, EPA's Fuel Economy Trends report has tracked the fuel economy of light duty vehicles and the technology used by automakers to improve fuel economy. A particularly interesting aspect of the Trends data is how technology is adopted by the industry and how this changes over time. Trends data shows that industry-wide, it has typically taken up to 15-20 years for a technology to penetrate the entire fleet. Some technologies such as port fuel injection and variable valve timing start slowly and then rapidly progress. Others, like torque converter lockup and front wheel drive penetrate rapidly after their first appearance on the market. Figure 3-33, below shows these trends.

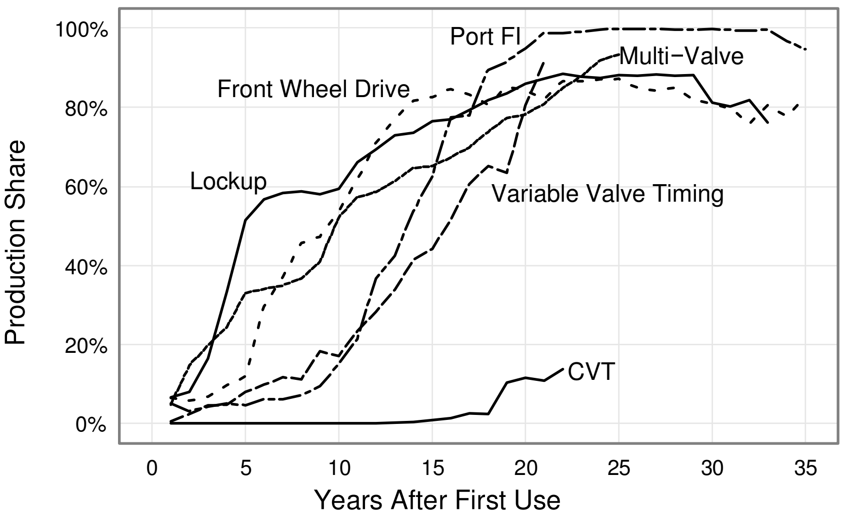

Figure 3-33 Technology Penetration After First Significant Use[101]

There are several cases where technologies have penetrated the fleet rapidly, sometimes beginning with significant market penetration, sometimes beginning with relatively small market penetration. For example, six speed automatic transmissions were in 7% of the industry-wide fleet in 2006 and by 2010, they were in 36% of the fleet, for an increase of 29% in 4 years[ww]. Port fuel injection went from about 12% of the fleet in 1984 to 88% in 1994. Front wheel drive, a technology that requires a complete change in vehicle architecture, increased from 9% in 1979 to 60% by 1988[102].

Recent academic literature has also used deployment rate data from the EPA Fuel Economy Trends Report, Wards Factory Installed data, and other sources to report to describe historical deployment rates of a variety of technologies. (DeCicco, 2010 and Zoepf, 2011). DeCicco, for example, cites conversion to fuel injection and front wheel drive in passenger cars as having seen maximum growth in adoption of 17% and 11% per year respectively.[103]

[ww] EPA staff calculated the penetration rate of 6-speed automatic transmissions from 2010 Trends data. Aggregated source data can be seen on page 54 of the 2010 Fuel Economy Trends Report.

Zoepf examines a broader array of automotive technologies and notes a span of maximum growth rates in passenger cars from 4% to nearly 24% per year with variance based on feature type.[104]

While these examples show that the industry is capable of adopting certain new technologies rapidly industry-wide, considering the rate of introduction of technology by individual OEMs shows that the pace of technology introduction can in some cases be even faster. Table 3-104 below shows how individual manufacturers can apply technologies rapidly to a large fraction of their fleet. Although not typical for most manufacturers and technologies, the data below shows that manufacturers have chosen to deploy some technologies very rapidly.

Table 3-104: Historical Phase-In Rates of Selected Technologies

Manufacturer	Technology	Technology Market Share Increase
General Motors	Lockup Transmission	1980-1982: 83% in 3 years
Ford	Fuel Injection	1983-1987: 91% in 5 years
Honda	Fuel Injection	1986-1990: 91% in 5 years
Chrysler	Fuel Injection	1988: 37% in 1 year
Toyota-cars only	Multi-Valve	1987-1989: 85% in 3 years
Nissan-cars only	Multi-Valve	1989-1990: 71% in 2 years
Toyota-cars only	Variable Valve Timing	2000-2003: 87% in 4 years
Ford	Multi-Valve	2004-2005: 36% in 2 years
Nissan	Continuously Variable Transmission	2007: 45% in 1 year
Volkswagen	Gasoline Direct Injection	2008: 52% in 1 year
Hyundai	Variable Valve Timing	2009: 48% in 1 year
General Motors	Variable Valve Timing	2006-2010: 75% in 5 years
General Motors	Gasoline Direct Injection	2010: 27% in 1 year

Often, a rapid application of technology is helped by having similar vehicle architecture, or by sharing major components such as engines or transmissions across multiple products. As discussed below, platform sharing combined with improvements in platform and manufacturing flexibility is expected to further enable faster implementation of new technologies.

3.5.2.2 The rate of technology adoption is increasing

The agencies recognize that new technologies may not achieve rapid deployment immediately and that small-scale production is a part of the technology learning process. To this end the phase-in caps distinguish between technologies that have been successfully applied in existing vehicles and those that under development but are anticipated on production vehicles in the near future.

The rate of technology adoption appears to be increasing as manufacturers increase model turnover and decrease the numbers of unique vehicle platforms. This facilitates a steady stream of new products, increased sales and optimized vehicle redesigns allowing and fuel consumption-reducing technologies to be applied to as many vehicles as possible. In today's globally competitive market, and certainly for the U.S., market share and competitiveness is strongly influenced by a manufacturer's ability to turn over their product line-up. Merrill Lynch's Car Wars Report[105] shows that replacement rate is speeding up and showroom age is dropping as manufacturers are striving to be more competitive in the market. Increased model turn-over creates more opportunity for manufacturers to deploy new technologies faster than in the past.

Zoepf, cited above, reports that the developmental time, from first production application to maximum growth rate, has been declining exponentially as manufacturers bring innovations to market progressively faster. Ellison et al. (1995)[106] indicate that U.S. and European automakers reduced overall product development time by more than a year in the 1990s. Ellison et al. point to the increased role that suppliers have had in product development process during the same time, potentially commoditizing innovations more quickly.

Vehicle platforms are the basic underpinnings of vehicles and are often shared across several unique products. By reducing the number of platforms, and making these platforms flexible, manufacturers can better deploy resources to serve a wider market with more products. Utilizing a modern, flexible platform architecture, a manufacturer can produce a sedan, wagon, minivan, and a crossover, or SUV on a single platform and all of these products can be assembled in a single vehicle assembly plant. Basic components can be developed and purchased at high volumes, while enabling the manufacturer to exploit what would otherwise be niche markets. This commonization of platforms does have the potential to increase the mass for lighter vehicle models within the platform because the platform needs to be designed for the more severe duty cycle of the SUV and/or larger engine. Volkswagen has recently launched a new platform called MQB, which will be used world-wide by up to 60 unique models from VW, Audi, Seat, and Skoda. This structure will replace 18 "engine mounting architectures" with just two.

> *It gives us the possibility to produce models from different segments and in varying sizes using the same basic front-end architecture," …. "We can go from a typical hatchback to a saloon, cabriolet and SUV with only detailed changes to the size of the wheel carriers." … it will be used on every model from the new Lupo all the way through to the next-generation Sharan.*[107]

One of the key enablers of this drive to reduce platforms and increase model turn-over is increased manufacturing flexibility.[108] For example, in 2004, Ford invested in flexible manufacturing technology for their Cleveland No. 1 engine plant. Although the plant was shut down for two years after this investment, Ford was able to retool and reopen the plant at a low cost to produce their new 3.5L EcoBoost turbocharged, direct injection engine as well as their 3.7L V6.[109] In their December, 2008 business plan submitted to Congress,[110] Ford further stated,

> *…nearly all of our U.S. assembly plants will have flexible body shops by 2012 to enable quick response to changing consumer demands and nearly half of our transmission and engine plants will be flexible, capable of manufacturing various combinations of transmission and engine families.*

Like VW, Ford is also striving to reduce their platforms and complexity. In Ford's 2008 business plan submitted to Congress, they stated that in addition to divesting themselves from certain luxury brands like Jaguar, Land Rover, Volvo, and Aston Martin, they were working to consolidate their vehicle platforms from 25 in 2005 to 9 by 2012. Having more vehicles per platform frees up resources to deploy new technologies across a greater number of vehicles more quickly and increases the rate at which new technologies can be introduced. We believe GM's recent restructuring will also enable faster vehicle redesigns and more rapid penetration rates in the 2010-plus time frame compared to the 1990s and 2000s. In the past seven years, GM has eliminated five brands (Saturn, Hummer, Saab, Pontiac, and Oldsmobile), significantly reducing the number of unique products and platforms the company needed to devote engineering resources to. GM has set a goal to halve its number of vehicle platforms by 2018 and boost manufacturing efficiency by 40%.[111]

3.5.2.3 Phase-in Rates Used in the Analysis

Table 3-105 below shows phase-in rates for the technologies used in the OMEGA model. OMEGA calculations are based on five year intervals, so phase-in caps are derived for model years 2016, 2021 and 2025. Table 3-106 shows phase-in rates for the technologies used in the CAFE model. The CAFE model calculations are annual, so phase in rates are derived for every year of the program. Where possible, phase-in rates for OMEGA and CAFE were harmonized, but there are some differences mainly where technologies differ between the agencies.

Most technologies are available at a rate of either 85% or 100% beginning in 2016. Some advanced technologies expected to enter the market in the near future such as EGR Boost follow a 3% annual cap increase from 2016 to 2021, then, approximately 10% from 2021 to 2025. Diesels follow an annual 3% increase in phase-in cap through 2025. Hybrids follow a 3% annual increase from 2016 to 2012, then 5% from 2021 to 2015. PHEVs and EVs follow a 1% annual cap increase.

Lower phase-in caps for Alternate Fueled Vehicles (AFVs) reflect additional investment in infrastructure that is required to achieve high levels of conversion to a new fuel type. These limited phase-in caps also reflect as yet unknown consumer responses to HEVs, PHEVs and BEVs.

Table 3-105 Phase-In Caps used in the OMEGA model

Technology	**2016**	**2021**	**2025**
Low Friction Lubricants	100%	100%	100%
Engine Friction Reduction - level 1	100%	100%	100%

Early Torque Converter lockup	100%	100%	100%
Aggressive Shift Logic - Level 1	100%	100%	100%
Improved Accessories - Level 1	100%	100%	100%
Low Rolling Resistance Tires - Level 1	100%	100%	100%
Low Drag Brakes	100%	100%	100%
VVT - Intake Cam Phasing	85%	100%	100%
VVT - Coupled Cam Phasing	85%	100%	100%
VVT - Dual Cam Phasing	85%	100%	100%
Cylinder Deactivation	85%	100%	100%
Variable Valve Lift - Discrete	85%	100%	100%
Variable Valve Lift - Continuous	85%	100%	100%
Conversion to DOHC	85%	100%	100%
Stoichiometric Gasoline Direct Injection (GDI)	85%	100%	100%
Turbocharging (18 bar BMEP) and Downsizing	85%	100%	100%
Continuously Variable Transmission	85%	100%	100%
6-speed Automatic Transmission	85%	100%	100%
6-speed Dual Clutch Transmission - dry & wet clutch	85%	100%	100%
Electric & Electric/Hydraulic Power Steering	85%	100%	100%
12V Stop-Start	85%	100%	100%
Secondary Axle Disconnect	85%	100%	100%
Aero Drag Reduction - Level 1	85%	100%	100%
Aggressive Shift logic - Level 2 (Shift Optimizer)	0%	100%	100%
8-speed Automatic Transmission	30%	80%	100%
8-speed Dual Clutch Transmission - dry & wet clutch	30%	80%	100%
Improved Accessories - Level 2	30%	80%	100%
Aero Drag Reduction - Level 2	30%	80%	100%
Low Rolling Resistance Tires - Level 2	0%	75%	100%
Engine Friction Reduction - level 2 (inc. low friction lubes - level 2)	0%	60%	100%
High Effiency Gearbox	0%	60%	100%
Turbocharging (24 bar BMEP) and Downsizing	15%	30%	75%
Cooled EGR	15%	30%	75%
P2 Hybrid Electric Vehicle (HEV)	15%	30%	50%
Turbocharging (27 bar BMEP) and Downsizing	0%	15%	50%
Conversion to Advanced Diesel	15%	30%	42%
Full Electric Vehicle (EV)	6%	11%	15%
Plug-in HEV	5%	10%	14%

Table 3-106 Phase-In Caps used in the CAFE Model

Technology	Abbr.	MY 2009	MY 2010	MY 2011	MY 2012	MY 2013	MY 2014	MY 2015	MY 2016	MY 2017	MY 2018	MY 2019	MY 2020	MY 2021	MY 2022	MY 2023	MY 2024	MY 2025
Low Friction Lubricants - Level 1	LUB1	30%	40%	50%	60%	70%	80%	90%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Engine Friction Reduction - Level 1	EFR1	30%	40%	50%	60%	70%	80%	90%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Low Friction Lubricants and Engine Friction Reduction - Level 2	LUB2_EFR2	0%	0%	0%	0%	0%	0%	0%	0%	12%	24%	36%	48%	60%	72%	84%	96%	100%
Variable Valve Timing (VVT) - Coupled Cam Phasing (CCP) on SOHC	CCPS	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Discrete Variable Valve Lift (DVVL) on SOHC	DVVLS	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Cylinder Deactivation on SOHC	DEACS	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Variable Valve Timing (VVT) - Intake Cam Phasing (ICP)	ICP	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Variable Valve Timing (VVT) - Dual Cam Phasing (DCP)	DCP	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Discrete Variable Valve Lift (DVVL) on DOHC	DVVLD	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Continuously Variable Valve Lift (CVVL)	CVVL	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Cylinder Deactivation on DOHC	DEACD	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Stoichiometric Gasoline Direct Injection (GDI)	SGDI	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Cylinder Deactivation on OHV	DEACO	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Variable Valve Actuation - CCP and DVVL on OHV	VVA	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Stoichiometric Gasoline Direct Injection (GDI) on OHV	SGDIO	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Turbocharging and Downsizing - Level 1 (18 bar BMEP)	TRBDS1_SD	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Turbocharging and Downsizing - Level 2 (24 bar BMEP)	TRBDS2_SD	0%	0%	0%	3%	6%	9%	12%	15%	18%	21%	24%	27%	30%	45%	60%	75%	75%
Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP)	CEGR1_SD	0%	0%	0%	3%	6%	9%	12%	15%	18%	21%	24%	27%	30%	45%	60%	75%	75%
Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP)	CEGR2_LD	0%	0%	0%	0%	0%	0%	0%	0%	3%	6%	9%	12%	15%	25%	35%	45%	50%
Advanced Diesel	ADSL_LD	0%	0%	0%	0%	3%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
6-Speed Manual/Improved Internals	6MAN	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
High Efficiency Gearbox (Manual)	HETRANSM	0%	0%	0%	0%	0%	0%	0%	0%	12%	24%	36%	48%	60%	72%	84%	96%	100%
Improved Auto. Trans. Controls/Externals	IATC	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
6-Speed Trans with Improved Internals (Auto)	NAUTO	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
6-speed DCT	DCT	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
8-Speed Trans (Auto or DCT)	8SPD	0%	0%	0%	0%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	100%	100%
High Efficiency Gearbox (Auto or DCT)	HETRANS	0%	0%	0%	0%	0%	0%	0%	0%	12%	24%	36%	48%	60%	72%	84%	96%	100%
Shift Optimizer	SHFTOPT	0%	0%	0%	0%	0%	0%	0%	0%	20%	40%	60%	80%	100%	100%	100%	100%	100%
Electric Power Steering	EPS	5%	20%	35%	50%	65%	80%	95%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Improved Accessories - Level 1	IACC1	5%	20%	35%	50%	65%	80%	95%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Improved Accessories - Level 2	IACC2	0%	0%	0%	0%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	100%	100%
12V Micro-Hybrid (Stop-Start)	MHEV	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Integrated Starter Generator	ISG	0%	0%	0%	3%	6%	9%	12%	15%	18%	21%	24%	27%	30%	35%	40%	45%	50%
Strong Hybrid - Level 1	SHEV1	0%	0%	0%	3%	6%	9%	12%	15%	18%	21%	24%	27%	30%	35%	40%	45%	50%
Conversion from SHEV1 to SHEV2	SHEV1_2	0%	0%	0%	3%	6%	9%	12%	15%	18%	21%	24%	27%	30%	35%	40%	45%	50%
Strong Hybrid - Level 2	SHEV2	0%	0%	0%	3%	6%	9%	12%	15%	18%	21%	24%	27%	30%	35%	40%	45%	50%
Plug-in Hybrid - 30 mi range	PHEV1	0%	0%	0%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%
Plug-in Hybrid	PHEV2	0%	0%	0%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%
Electric Vehicle (Early Adopter) - 75 mile range	EV1	0%	0%	0%	1%	2%	3%	4%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Electric Vehicle (Broad Market) - 150 mile range	EV4	0%	0%	0%	0%	0%	0%	0%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Fuel Cell Vehicle	FCV	0%	0%	0%	0%	0%	0%	0%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Mass Reduction - Level 1	MR1	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Mass Reduction - Level 2	MR2	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Mass Reduction - Level 3	MR3	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Mass Reduction - Level 4	MR4	0%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	100%	100%	100%	100%	100%
Mass Reduction - Level 5	MR5	0%	0%	0%	0%	0%	0%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Low Rolling Resistance Tires - Level 1	ROLL1	20%	35%	50%	65%	80%	95%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Low Rolling Resistance Tires - Level 2	ROLL2	0%	0%	0%	0%	0%	0%	0%	0%	15%	30%	45%	60%	75%	90%	100%	100%	100%
Low Drag Brakes	LDB	20%	35%	50%	65%	80%	95%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Secondary Axle Disconnect	SAX	15%	25%	35%	45%	55%	65%	75%	85%	95%	100%	100%	100%	100%	100%	100%	100%	100%
Aero Drag Reduction, Level 1	AERO1	30%	40%	50%	60%	70%	80%	90%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Aero Drag Reduction, Level 2	AERO2	0%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	100%	100%	100%	100%	100%

3.6 How are the technologies applied in the agencies' respective models?

Although both NHTSA and EPA are basing their fuel economy and emission modeling on the same baseline vehicle fleet and cost and effectiveness estimates for control technologies, differences in the CAFE and OMEGA models result in this common information being processed in different ways prior to its use in the respective models. With respect to the vehicle fleet, the CAFE Model evaluates the addition of technology to individual vehicle configurations or models, while the OMEGA model does so for vehicle platforms broken down further by engine size. The Volpe (or CAFE) Model evaluates technologies individually. This, coupled with the modeling of individual vehicle models, means that only the presence or absence of any particular technology needs to be indicated, as described above. OMEGA applies technology in combinations or packages. This, plus the grouping of individual vehicle models, requires that the total effectiveness of the technology already applied in the baseline fleet must be calculated and must be reflected as a percentage of the various technology packages available to be added to those vehicles.

With respect to the cost and effectiveness of technologies, as mentioned above, the CAFE Model applies technologies individually. It does this following certain specified pathways for several categories of technologies (*e.g.*, engine, transmission, accessories, etc.). The Volpe Model applies technology incrementally, so the effectiveness of each subsequent technology needs to be determined relative to the previous one. The same is true for cost. In addition, because of interaction in the effectiveness of certain technologies, herein referred to as the synergy/dis-synergy, any such interaction between the next technology on a specified pathway with those which have already been potentially applied in other pathways must be determined. For example, the incremental effectiveness of switching from a six-speed automatic transmission to a dual clutch transmission will depend on the level of engine technology already applied (*e.g.*, intake cam phasing on a port-fuel injected engine or a down-sized, turbocharged, direct injection engine).

EPA’s OMEGA model applies technologies in packages and according to a fixed sequence for any particular group of vehicles. This requires that the overall cost and effectiveness of each package be determined first, considering any and all dis-synergies which may exist. Then, the incremental cost and effectiveness of each subsequent package is determined relative to the prior one.

Thus, while the same baseline vehicle fleet and cost and effectiveness estimates for technologies are being used in both the CAFE and OMEGA models, the form of the actual inputs to the model will appear to be different. For more information on EPA’s and NHTSA’s unique approaches to modeling, please refer to each agency’s respective preliminary or draft RIA.

In order to estimate both technology costs and fuel consumption/CO_2 reduction estimates, it is necessary for each agency to describe the baseline vehicle characteristics from which the estimates can be compared. This “baseline” is different from the usage in Chapter 1 of this joint TSD. In Chapter 1, the baseline fleet is the projected fleet in MY 2025 before accounting for technologies needed to meet the MY 2016 CAFE standards and before accounting for changes in fleet composition attributable to that rule (those later steps accounted for independently by each agency in developing their separate reference fleets). In the present context, it indicates the vehicle types and technologies that will be used for comparison from a strict cost and effectiveness point of view. These baselines may be slightly different for the two agencies. For EPA, unless noted elsewhere, the baseline vehicle is defined as a vehicle with a port-fuel injected, naturally aspirated gasoline engine with fixed valve timing and lift. The baseline transmission is a 4-speed automatic, and the vehicle has no hybrid systems. For NHTSA, unless noted elsewhere, the baseline vehicle is the actual vehicle as it exists in the baseline fleet, because NHTSA models each unique vehicle separately.

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Chapter 4: **Economic and Other Assumptions Used in the Agencies' Analysis**

4.1 How the Agencies use the economic and other assumptions in their analyses

Improving new vehicles' fuel efficiency and reducing greenhouse gas (GHG) emissions provides direct benefits to their buyers and users by reducing fuel consumption and fuel costs throughout those vehicles' lifetimes, stimulating increased vehicle use through the fuel economy rebound effect, and often increasing vehicles' driving range so that they require less frequent refueling. At the same time, the reduction in fuel use that results from requiring higher fuel economy and reducing GHGs also produces wider benefits to the U.S. economy by lowering the cost of economic externalities that result from U.S. petroleum consumption and imports. This occurs because reducing U.S. oil consumption and imports reduces the global price of petroleum, lowers the potential costs from disruptions in the flow of oil imports, and potentially reduces federal outlays to secure imported oil supplies and cushion the U.S. economy against their potential interruption. Reducing fuel consumption and GHGs also lowers the economic costs of environmental externalities resulting from fuel production and use, including reducing the impacts on human health from emissions of criteria air pollutants, and reducing future economic damages from potential changes in the global climate caused by greenhouse gas emissions.

These social benefits are partly offset by the increase in fuel use that results from added vehicle use due to the fuel economy rebound effect, as well as by added costs from the increased congestion, crashes, and noise caused by increased vehicle use. They would also be offset by any loss in the utility that new vehicles provide to their buyers (and subsequent owners) if manufacturers include reductions in vehicles' performance, carrying capacity, or comfort as part of their strategies to comply with higher fuel economy requirements and GHG standards. However, the agencies' analyses supporting the proposed standards do not anticipate any such reductions in utility as being necessary, and the analysis seeks to include the costs to manufacturers of preserving vehicle capabilities.[a] For instance, the costs of engine downsizing include the costs of turbocharging the engine to maintain its performance. The total economic benefits from requiring higher fuel economy and reducing GHGs are likely to be substantial, and EPA and NHTSA have developed detailed estimates of the economic benefits from adopting more stringent standards.

This chapter discusses the common economic and other values used by both NHTSA and EPA in their rulemaking analyses. These inputs incorporate a range of forecast information, economic estimates, and input parameters. This chapter describes the sources that EPA and NHTSA have relied upon for this information, the rationale underlying each assumption, and the agencies' estimates of specific parameter values. These common values

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[a] Two exceptions – hybrid vehicles that may have some limited towing capacity, and electric vehicles – are discussed elsewhere.

are then used as inputs into each agency's respective modeling and other analyses of the economic benefits and costs of the EPA and NHTSA programs. While the underlying input values are common to both agencies, program differences, and differences in the way each agency assesses its program that result in differing benefits estimates. This issue is discussed further in Section I.C of the preamble to the joint rulemaking.

4.2 What assumptions do the agencies use in the impact analyses?

4.2.1 The on-road fuel economy "gap"

4.2.1.1 Definition and past use by EPA and NHTSA

In aggregate, actual fuel economy levels achieved by vehicles in on-road driving fall significantly short of their levels measured in the laboratory-like test conditions and two-cycle tests used under the CAFE program to determine the fuel economy ratings for different models for purposes of compliance with the CAFE and CO_2 standards. The test procedure used to determine compliance is highly controlled, and does not reflect real-world driving in a variety of ways – real-world driving tends to be more aggressive than the Federal Test Procedure (FTP) and Highway Fuel Economy Test (HFET) test cycles used to establish compliance with the GHG and CAFE regulations. Real world driving tends to include more stops and starts and more rapid acceleration/deceleration, and may include the use of technologies like air-conditioning that reduce fuel economy but that are not exercised on the test cycle.[1] There are also a number of elements that affect real-world achieved fuel economy which are not measured on the two cycle GHG/CAFE compliance test, such as wind resistance, road roughness, grade, temperature, and fuel energy content. The agencies' analyses for this proposal recognize this gap, and account for it by adjusting the fuel economy performance downward from its rated value. In December 2006, EPA adopted changes to its regulations on fuel economy labeling, which were intended to bring vehicles' label fuel economy levels seen by consumers shopping for new vehicles closer to their actual on-road fuel economy levels.[2]

Comparisons of on-road and CAFE fuel economy levels developed by EPA as part of its 2006 Final Rule implementing new fuel economy labeling requirements for new vehicles indicated that actual on-road fuel economy for light-duty vehicles average about 20 percent lower than compliance fuel economy ratings.[3] While there is great heterogeneity among individual drivers, as discussed in the referenced material, the 20 percent figure appears to represent an accurate average for modeling a fleet. For example, if the overall EPA fuel economy rating of a light truck is 20 MPG, the on-road fuel economy actually achieved by a typical driver of that vehicle is expected to be 16 mpg (20*.80). In its analysis supporting the Final Rule establishing CAFE standards for MY 2011, NHTSA employed EPA's revised estimate of this on-road fuel economy gap in its analysis of the fuel savings resulting from alternative fuel efficiency standards. EPA and NHTSA likewise employed this fuel economy gap for estimating fuel savings in the MYs 2012-2016 rulemaking and in the Interim Joint Technical Assessment Report (TAR) analysis for MYs 2017-2025.

An analysis conducted by NHTSA confirmed that EPA's estimate of a 20 percent gap between test and on-road fuel economy for the majority of vehicles is well-founded. NHTSA used data on the number of passenger cars and light trucks of each model year that were in service (registered for use) during each calendar year from 2000 through 2006; average fuel economy for passenger cars and light trucks produced during each model year; and estimates of average miles driven per year by cars and light trucks of different ages during each calendar year over that period. These data were combined to develop estimates of the usage-weighted average fuel economy that the U.S. passenger car and light truck fleets would have achieved during each year from 2000 through 2006 under test conditions.

Table 4-1 compares NHTSA's estimates of fleet-wide average fuel economy under test conditions for 2000 through 2006 to the Federal Highway Administration's (FHWA) published estimates of on-road fuel economy achieved by passenger cars and light trucks during each of those years. As it shows, FHWA's estimates of fuel economy for passenger cars ranged from 21-23 percent lower than NHTSA's estimates of its fleet-wide average value under test conditions over this period, and FHWA's estimates of fuel economy for light trucks ranged from 16-18 percent lower than NHTSA's estimates of its fleet-wide average value under test conditions. Thus, these results appear to confirm that the 20 percent on-road fuel economy gap represents a reasonable estimate for use in evaluating the fuel savings likely to result from more stringent fuel economy and CO_2 standards in MYs 2017-2025.

Table 4-1 Estimated Fleet-Wide Fuel Economy of Passenger Cars and Light Trucks Compared to Reported Fuel Economy

YEAR	PASSENGER CARS			LIGHT-DUTY TRUCKS		
	NHTSA Estimated Test MPG	FHWA Reported MPG	Percent Difference	NHTSA Estimated Test MPG	FHWA Reported MPG	Percent Difference
2000	28.2	21.9	-22.2%	20.8	17.4	-16.3%
2001	28.2	22.1	-21.7%	20.8	17.6	-15.5%
2002	28.3	22.0	-22.3%	20.9	17.5	-16.2%
2003	28.4	22.2	-21.9%	21.0	17.2	-18.0%
2004	28.5	22.5	-21.1%	21.0	17.2	-18.3%
2005	28.6	22.1	-22.8%	21.1	17.7	-16.3%
2006	28.8	22.5	-21.8%	21.2	17.8	-16.2%
Avg., 2000-2006	28.4	22.2	-22.0%	21.0	17.5	-16.7%

We are aware of two potential issues involved in these estimates. One, the estimates of total annual car and truck VMT are developed by the states and submitted to FHWA. Each state uses its own definition of a car and a truck. For example, some states classify minivans as cars and some as trucks. Thus, there are known inconsistencies with these estimates when evaluated separately for cars and trucks. Also, total gasoline consumption can be reasonably estimated from excise tax receipts, but separate estimates for cars and trucks are not available. We are not aware of the precise methodology used to develop the distinct on-road fuel economy estimates for cars and trucks developed by FHWA. We do not believe that they are based on direct measurements from substantial numbers of vehicles, as no such test programs were found by EPA during its fuel economy labeling rule in 2006. Also, the year-to-year consistency for both car and truck fuel economy implies some methodology other than direct measurement. For this reason, NHTSA and EPA are not using distinct on-road fuel economy gaps for cars and trucks, but one common value of 20 percent for both vehicle classes for purposes of estimating the fuel savings of the standards. This figure lies between the separate estimated for cars and light trucks reported in Table 4-1.

For purposes of the MYs 2012-2016 rulemaking, the TAR, and this current rulemaking for MYs 2017-2025, then, the agencies are assuming that the on-road fuel economy gap for liquid fuel is 20 percent. As in the TAR, the agencies assume that the overall energy shortfall for the electric drivetrain (for vehicles that have those instead of or in addition to gasoline engines) is 30 percent when driven on wall electricity. The 30 percent value was derived from the agencies' engineering judgment based on several data points. Foremost among these, during the stakeholder meetings conducted prior to the Interim Joint TAR, confidential business information (CBI) was supplied by several manufacturers which indicated that electrically powered vehicles had greater variability in their on-road energy consumption than vehicles powered by internal combustion engines. Second, data from EPA's 2006 analysis of the "five cycle" fuel economy label as part of the rulemaking discussed above potentially supported a larger on-road shortfall for vehicles with hybrid-electric drivetrains[4] And third, heavy accessory load, extreme (both high and low) temperatures, and aggressive driving have deleterious impacts of unknown magnitudes on battery performance. As a counterpoint, CBI provided by several other manufacturers suggested that the on-road/laboratory differential attributable to electric operation should approach that of liquid fuel operation in the future. Consequently, 30 percent was judged by the agencies to be a reasonable estimate for the Interim Joint TAR, and was carried into the current analysis.

The recent 2011 Fuel Economy labeling rule employs a 30% on-road shortfall for electric vehicles. [5] Under the labeling program, for gasoline vehicles, there are two methods for getting label values: full 5-cycle or derived 5-cycle. Full 5-cycle means all five cycles are tested, and bag MPG results are used in a set of formulae to determine label MPG. Derived 5-cycle involves testing on the FTP and Highway tests and adjusting those values using regression-based formulae, to get label MPG values. The derived 5-cycle adjustment results in an ever-increasing adjustment in percentage terms. However, the data on which the derived 5-cycle formulae are based ends at roughly 70 MPG, where the adjustment is about 70% or an on-road gap of 30% (assuming that the five cycle formula represents the real world). For labeling purposes, lacking any EVs or PHEVs (or any vehicles beyond 70 MPG) in the database at the time this adjustment was derived, the adjustment was set at 70% for MPG values beyond 70 MPG.

Electric vehicles are allowed and expected to use the derived 5-cycle method, which suggests that their on-road gap will be approximately 30% during the near future. Individual EVs may vary, and as additional data becomes available the agencies will consider whether the 30% average gap remains appropriate.

4.2.1.2 Considerations in Future Years

Looking forward to MYs 2017-2025, while the agencies do not forecast changes in most of the factors discussed above that contribute to the on-road gap in ways that would change our estimates, the agencies expect that two specific factors will change somewhat that could affect this analysis. Specifically, we anticipate changes in the energy content of fuels sold at retail as a result of the recent EPA Renewable Fuel Standard 2 (RFS2) rulemaking and E15 waiver decision,[6] as well as a change in reference air conditioning efficiency as a result of the recent MYs 2012-2016 EPA Light Duty Greenhouse Gas rulemaking.

4.2.1.2.1 Air Conditioning

Air conditioning is a significant contributor to the on-road efficiency gap. While the air conditioner is turned off during the FTP and HFET tests, in real world use drivers often use air conditioning in warm, humid conditions. The air conditioning compressor can also be engaged during “defrost” operation of the heating system.[7] In the MYs 2012-2016 rulemaking, the agencies estimated the average impact of an air conditioning system at approximately 14.3 grams over an SCO3 test for an average vehicle without any of the improved air conditioning technologies discussed in that rulemaking. For a 27 MPG (330 g CO_2/mile) vehicle, this is approximately 20 percent of the total estimated on-road gap, or about 4 percent of total fuel consumption.

In the MYs 2012-2016 rule, EPA estimated that 85 percent of MY 2016 vehicles would reduce their air conditioning-related CO_2 emissions by 40 percent through the use of advanced air conditioning efficiency technologies. Incorporating this change would reduce the average on-road gap by about 2 percent in the reference case.[b] However, as shown in Chapter 5 of the joint TSD air conditioning-related fuel consumption does not proportionally decrease as overall engine efficiency improves. Unlike most technologies in this rulemaking, which have a multiplicative reduction on fuel consumption and CO_2 emissions, the load due to air conditioning operation is relatively constant across engine efficiency and technology. As a consequence, as engine efficiency increases, air conditioning operation represents an increasing percentage of vehicular fuel consumption.[c] To some extent, these factors are expected to counterbalance, so the agencies therefore chose not to make an air conditioning-related adjustment to the on-road gap for this proposal.

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[b] 4% of the on-road gap x 40% reduction in air conditioning fuel consumption x 85% of the fleet = ~2%.

[c] As an example, the air conditioning load of 14.3 g/mile of CO2 is a smaller percentage (4.3%) of 330 g/mile than of 260 g/mile (5.4%).

4.2.1.2.2 Fuel Energy Content

Differences in fuel energy content between test conditions and real-world driving is another contributor to the on-road fuel economy gap. Two-cycle testing for CAFE and CO_2 compliance is based on “certification fuel” which contains no ethanol (also known as E0). The on-road fuel economy gap is estimated with reference to the difference in fuel energy content between certification fuel and 2004 retail gallons,[d] but this rule produces a reduction in petroleum based fuel consumption only.[e] Volumes of renewable fuels are statutorily fixed by the Renewable Fuel Standard, so the entirety of the energy savings will take place as reduced oil consumption. To estimate the petroleum fuel savings, we modify the on-road gap by the average difference in energy content between CY 2004 retail fuel used in the five cycle analysis and certification fuel. This results in an approximately 1% higher fuel economy than if no additional adjustment was made for fuel energy content, and corresponds to the greater energy content of certification gasoline as compared to 2004 retail gasoline.

$E0\ Fuel\ Economy\ =\ 2\ Cycle\ Fuel\ Economy * (1 - gap)\ *\ (E0\ BTU/Gallon)\ /\ (2004\ BTU/gallon))$Where:

Gap= 20%
E0 BTU/Gallon = 115,000
2004 BTU/Gallon = 113,912 (3.14% ethanol, 96.86% petroleum gasoline)

A related adjustment in fuel energy was made in order to “match” fuel savings to the fuel prices used in this analysis. As discussed below, the agencies use fuel prices from the Energy Information Administration’s (EIA) Annual Energy Outlook (AEO) 2011 reference case, which assume approximately 20 percent of the fuel pool by volume is ethanol.[f] By contrast, and as shown above, the gasoline savings from this rule are calculated as gallons of certification fuel, which is is more energy dense than ethanol blended market fuel. To appropriately apply the AEO prices on a dollar per btu basis, we adjust our certification fuel savings upwards by approximately 5% (the difference between the energy content of E15 retail fuel and certification) when monetizing the fuel savings. This adjustment more appropriately reflects AEO projections of motor gasoline energy prices.

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[d] The five cycle formula analysis is based on CY 2004 data.

[e] Ethanol contains approximately 76,000 British Thermal Units (Btu) per gallon as compared to petroleum gasoline (Indolene), which contains approximately 115,000 Btu. Thus, a 10 percent ethanol (E10) blend contains approximately 3.3 percent less energy than a gallon of E0, and an E15 blend contains approximately 5.1 percent less energy than a gallon of E0.

[f] EIA projects that ethanol replaces approximately 12 percent of the gasoline energy demand by 2035. This is greater than 20 percent of the gasoline pool by volume. For calculation of fuel savings for MYs 2017-2025, for this rulemaking, the agencies made the simplifying assumption that all retail gallons were E15.

4.2.2 Fuel prices and the value of saving fuel

Projected future fuel prices are a critical input into the preliminary economic analysis of alternative fuel efficiency and GHG standards, because they determine the value of fuel savings both to new vehicle buyers and to society. For this proposal, EPA and NHTSA relied on the most recent fuel price projections from the U.S. Energy Information Administration's (EIA) *Annual Energy Outlook* (AEO) for this analysis, the AEO 2011 Reference Case. The Reference Case forecasts inflation-adjusted (constant-dollar) retail gasoline and diesel fuel prices and represents the EIA's most up-to-date estimate of future prices for petroleum products. In the Preface to AEO 2011, the Energy Information Administration describes the reference case. They state that, "Projections by EIA are not statements of what will happen but of what might happen, given the assumptions and methodologies used for any particular scenario. The Reference case projection is a business-as-usual trend estimate, given known technology and technological and demographic trends. The agency has published annual forecasts of energy prices and consumption levels for the U.S. economy since 1982 in its AEOs. These forecasts have been widely relied upon by federal agencies for use in regulatory analysis and for other purposes. Since 1994, EIA's annual forecasts have been based upon the agency's National Energy Modeling System (NEMS), which includes detailed representation of supply pathways, sources of demand, and their interaction to determine prices for different forms of energy.

As compared to the gasoline prices used in the MYs 2012-2016 analysis, which relied on forecasts from AEO 2010, the AEO 2011 Reference Case fuel prices are largely similar. They are slightly higher through the year 2020, but slightly lower for most years after 2020 (when both are expressed in 2009 dollars). A comparison is presented below, Table 4-2.

Table 4-2 Gasoline Prices for Selected Years in AEO 2010 and 2011

(Presented in constant 2009$ and including all taxes)

	2015	2020	2030
AEO 2011	$3.13	$3.38	$3.64
AEO 2010	$3.10	$3.37	$3.71

The retail fuel price forecasts presented in AEO 2011 span the period from 2008 through 2035. Measured in constant 2009 dollars, the AEO 2011 Reference Case forecast of retail gasoline prices during calendar year 2017 is $3.25 per gallon, rising gradually to $3.71 by the year 2035 (these values include federal and state taxes). However, valuing fuel savings over the full lifetimes of passenger cars and light trucks affected by the standards proposed for MYs 2017-25 requires fuel price forecasts that extend through 2060, approximately the last year during which a significant number of MY 2025 vehicles will remain in service.[g] To obtain fuel price forecasts for the years 2036 through 2060, the agency assumes that retail fuel prices will continue to increase after 2035 at the average annual rate (0.7%) projected for 2017-2035 in the AEO 2011 Reference Case. The years between 2008 and 2016 were not included in the extrapolation due to the high volatility in the AEO projection for those years. This assumption results in a projected retail price of gasoline that reaches $4.16 in 2050.

The value of fuel savings resulting from improved fuel economy and reduced GHG emissions to buyers of light-duty vehicles is determined by the retail price of fuel, which includes federal, state, and any local taxes imposed on fuel sales. Total taxes on gasoline, including federal, state, and local levies, averaged $0.43 per gallon during 2008, while those levied on diesel averaged $0.46. Because fuel taxes represent transfers of resources from fuel buyers to government agencies, rather than real resources that are consumed in the process of supplying or using fuel, their value must be deducted from retail fuel prices to determine the value of fuel savings resulting from more stringent fuel efficiency and GHG standards to the U.S. economy.[8] When calculating the value of fuel saved by an individual driver, however, these taxes are included as part of the value of realized fuel savings. Over the entire period spanned by the agencies' analysis, this difference causes each gallon of fuel saved to be valued by about $0.36 (in constant 2009 dollars) more from the perspective of an individual vehicle buyer than from the overall perspective of the U.S. economy.[h]

In the estimates of costs and benefits presented in the preamble and in the agencies' RIAs, the agencies have included the full fuel savings over vehicles' expected lifetimes, discounted to their present values using both 3 and 7 percent discount rates. Additional discussion of this approach can be found in preamble Sections III.H and IV.

4.2.3 Vehicle Lifetimes and Survival Rates

The agencies' analysis of fuel savings and related benefits from adopting more stringent fuel economy and GHG standards for MYs 2017-2025 passenger cars and light trucks begin by estimating the resulting changes in fuel use over the entire lifetimes of affected cars and light trucks. The change in total fuel consumption by vehicles produced during each of these model years is calculated as the difference in their total lifetime fuel use over the entire lifetimes of these vehicles as compared to a reference case.

The first step in estimating lifetime fuel consumption by vehicles produced during a model year is to calculate the number of those vehicles expected to remain in service during

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[g] The agency defines the maximum lifetime of vehicles as the highest age at which more than 2 percent of those originally produced during a model year remain in service. In the case of light trucks, for example, this age has typically been 36 years for recent model years.

[h] For society, the fuel taxes represent a transfer payment. By contrast, an individual realizes savings from not paying the additional money.

each future calendar year after they are produced and sold.[i] This number is calculated by multiplying the number of vehicles originally produced during a model year by the proportion expected to remain in service at the age they will have reached during each subsequent calendar year, often referred to as a "survival rate."

The proportions of passenger cars and light trucks expected to remain in service at each age are drawn from a 2006 NHTSA study, and are shown in Table 4-3[9] Note that these survival rates were calculated against the pre-MY 2011 definitions of cars and light trucks, because the NHTSA study has not been updated since 2006. Because the agencies are unaware of a better data source, these values were used unchanged, and are the same values used in the MYs 2012-2016 rule and the interim Joint TAR. The rates are applied to vehicles based on their regulatory class (passenger car or light truck) regardless of fuel type or level of technology. Survival may vary by other factors, but data to support an investigation do not currently exist. Additionally, the survival rates are assumed to remain constant over time.

The survival and annual mileage estimates reported in this section's tables reflect the convention that vehicles are defined to be of age 1 during the calendar year that coincides with their model year. Thus for example, model year 2017 vehicles will be considered to be of age 1 during calendar year 2017. This convention is used in order to account for the fact that vehicles produced during a model year typically are first offered for sale in June through September of the preceding calendar year (for example, sales of a model year typically begin in June through September of the previous calendar year, depending on manufacturer). Thus, virtually all of the vehicles produced during a model year will be in use for some or all of the calendar year coinciding with their model year, and they are considered to be of age 1 during that year.[j]

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[i] Vehicles are defined to be of age 1 during the calendar year corresponding to the model year in which they are produced; thus for example, model year 2000 vehicles are considered to be of age 1 during calendar year 2000, age 1 during calendar year 2001, and to reach their maximum age of 26 years during calendar year 2025. NHTSA considers the maximum lifetime of vehicles to be the age after which less than 2 percent of the vehicles originally produced during a model year remain in service. Applying these conventions to vehicle registration data indicates that passenger cars have a maximum age of 26 years, while light trucks have a maximum lifetime of 36 years. *See*Lu, S., NHTSA, Regulatory Analysis and Evaluation Division, "Vehicle Survivability and Travel Mileage Schedules," DOT HS 809 952, 8-11 (January 2006). *Available at* http://www-nrd.nhtsa.dot.gov/Pubs/809952.pdf (last accessed Sept. 9, 2011).

[j] A slight increase in the fraction of new passenger cars remaining in service beyond age 10 has accounted for a small share of growth in the U.S. automobile fleet. The fraction of new automobiles remaining in service to various ages was computed from R.L. Polk vehicle registration data for 1977 through 2005 by the DOT's Center for Statistical Analysis.

Table 4-3 Survival Rates

VEHICLE AGE	ESTIMATED SURVIVAL FRACTION CARS	ESTIMATED SURVIVAL FRACTION LIGHT TRUCKS
1	0.9950	0.9950
2	0.9900	0.9741
3	0.9831	0.9603
4	0.9731	0.9420
5	0.9593	0.9190
6	0.9413	0.8913
7	0.9188	0.8590
8	0.8918	0.8226
9	0.8604	0.7827
10	0.8252	0.7401
11	0.7866	0.6956
12	0.7170	0.6501
13	0.6125	0.6042
14	0.5094	0.5517
15	0.4142	0.5009
16	0.3308	0.4522
17	0.2604	0.4062
18	0.2028	0.3633
19	0.1565	0.3236
20	0.1200	0.2873
21	0.0916	0.2542
22	0.0696	0.2244
23	0.0527	0.1975
24	0.0399	0.1735
25	0.0301	0.1522
26	0.0227	0.1332
27	0	0.1165
28	0	0.1017
29	0	0.0887
30	0	0.0773
31	0	0.0673
32	0	0.0586
33	0	0.0509
34	0	0.0443
35	0	0.0385
36	0	0.0334

4.2.4 VMT

The second step in estimating lifetime fuel use by the cars or light trucks produced during a future model year is to calculate the total number of miles that they will be driven during each year of their expected lifetimes. To estimate total miles driven, the number of cars and light trucks projected to remain in use during each future calendar year is multiplied by the average number of miles a surviving car or light truck is expected to be driven at the age it will have reached in that year. Estimates of average annual miles driven by Calendar Year 2001 cars and light trucks of various ages were developed by NHTSA from the Federal Highway Administration's 2001 National Household Travel Survey, and are reported in Table 4-4. These estimates represent the typical number of miles driven by a surviving light duty vehicle at each age over its estimated full lifetime. To determine the number of miles a typical vehicle produced during a given model year is expected to be driven at a specific age, the average annual mileage for a vehicle of that model year and age is multiplied by the corresponding survival rate for vehicles of that age.

Table 4-4 CY 2001 Mileage Schedules based on NHTS Data

VEHICLE AGE	ESTIMATED VEHICLE MILES TRAVELED CARS	ESTIMATED VEHICLE MILES TRAVELED LIGHT TRUCKS
1	14,231	16,085
2	13,961	15,782
3	13,669	15,442
4	13,357	15,069
5	13,028	14,667
6	12,683	14,239
7	12,325	13,790
8	11,956	13,323
9	11,578	12,844
10	11,193	12,356
11	10,804	11,863
12	10,413	11,369
13	10,022	10,879
14	9,633	10,396
15	9,249	9,924
16	8,871	9,468
17	8,502	9,032
18	8,144	8,619
19	7,799	8,234
20	7,469	7,881
21	7,157	7,565
22	6,866	7,288
23	6,596	7,055
24	6,350	6,871
25	6,131	6,739
26	5,940	6,663
27	0	6,648
28	0	6,648
29	0	6,648
30	0	6,648
31	0	6,648
32	0	6,648
33	0	6,648
34	0	6,648

35	0	6,648
36	0	6,648

4.2.4.1 Adjusting vehicle use for future fuel prices

The estimates of average annual miles driven by passenger cars and light trucks reported in Table 4-4 reflect the historically low gasoline prices that prevailed at the time the 2001 NHTS was conducted. Under the assumption that people tend to drive more as the cost of driving decreases, the higher fuel prices that are forecast for future years would be expected to reduce average vehicle use. For this rulemaking, the agencies updated the estimates of average vehicle use reported in Table 4-4 using the forecasts of future fuel prices reported in the AEO 2011 Reference Case. This adjustment accounts for the difference between the average retail price per gallon of fuel forecast during each calendar year over the expected lifetimes of model year 2017-25 passenger cars and light trucks, and the average price that prevailed when the NHTS was conducted in 2001.

Specifically, the elasticity of annual vehicle use with respect to fuel cost per mile corresponding to the 10 percent fuel economy rebound effect used in this analysis (*i.e.*, an elasticity of annual vehicle use with respect to fuel cost per mile driven of -0.10; see Section 4.2.5) was applied to the percentage change in cost-per-mile travel between each future year's vehicle and the cost per mile of a vehicle that was the same age in 2001. This computation adjusts the estimates of annual mileage by vehicle age derived from the 2001 NHTS to reflect the effect of higher fuel prices and changes in the fuel economies of new model year vehicles over time for each future calendar year of the expected lifetimes of model year 2017-25 cars and light trucks.

4.2.4.2 Ensuring consistency with growth in total vehicle use

The estimates of annual miles driven by passenger cars and light trucks at each age were also adjusted to reflect projected future growth in average use for vehicles of all ages. Increases in the average number of miles cars and trucks are driven each year have been an important source of historical growth in *total* car and light truck use, and are expected to be a continued source of future growth in total light-duty vehicle travel as well. As an illustration of the importance of growth in average vehicle use, the total number of miles driven by passenger cars increased 35 percent from 1985 through 2005, equivalent to a compound annual growth rate of 1.5 percent.[10] During that same time, however, the total number of passenger cars registered for in the U.S. grew by only about 0.3 percent annually.[k] Thus

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[k] A slight increase in the fraction of new passenger cars remaining in service beyond age 10 has accounted for a small share of growth in the U.S. automobile fleet. The fraction of new automobiles remaining in service to various ages was computed from R.L. Polk vehicle registration data for 1977 through 2005 by the agency's Center for Statistical Analysis.

growth in the average number of miles automobiles are driven each year accounted for the remaining 1.2 percent (= 1.5 percent - 0.3 percent) annual growth in total automobile use.[l]

Further, the AEO 2011 Reference Case forecasts of total car and light truck use and of the number of cars and light trucks in use suggest that their average annual use will continue to increase gradually from 2010 through 2035, as detailed in the following sections.[m]

In order to develop reasonable estimates of future growth in the average number of miles driven by cars and light trucks of all ages, the agencies calculated the rate of growth in the mileage schedules necessary for total car and light truck travel to increase at the rate forecast in the AEO 2011 Reference Case. The growth rate in average annual car and light truck use produced by this calculation is approximately 1 percent per year through 2030, and 0.5% per year from 2031-2050.[n] This growth was applied to the mileage figures reported in Table 4-4 (after adjusting them as described previously for future fuel prices and expected vehicle survival rates) to estimate average annual mileage during each calendar year analyzed and during the expected lifetimes of model year 2017-25 cars and light trucks[o]

The agencies made separate adjustments to vehicle use to account for projected increases in future fuel prices and for continued growth in average vehicle use during each future calendar year. Because the effects of both fuel prices and cumulative growth in average vehicle use differ for each year, these adjustments result in different VMT schedules for each future year. While the adjustment for future fuel prices generally *reduces* average mileage at each age from the values tabulated from the 2001 NHTS, the adjustment for reduced fuel consumption and the expected future growth in average vehicle use *increases* it. The net impact resulting from these two separate adjustments is continued growth over time in the average number of miles that vehicles of each age are driven, although at slower rates than those observed from 1985 – 2005. Observed aggregate VMT in recent years has actually declined, but it is unclear if the underlying cause is general shift in behavior or a response to a set of temporary economic conditions. The agencies' intend to consider new data on the VMT growth estimates as it becomes available, and the agencies request comment on this topic.

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[l] *See supra* note k below.

[m] The agencies note that VMT growth has slowed, and because the impact of VMT is an important element in our benefit estimates, we will continue to monitor this trend to see whether this is a reversal in trend or temporary slow down. See the 2009 National Household Travel Survey (http://nhts.ornl.gov/2009/pub/stt.pdf) and National transportation Statistics (http://www.bts.gov/publications/national_transportation_statistics/html/table_04_09.html)

[n] It was not possible to estimate separate growth rates in average annual use for cars and light trucks, because of the significant reclassification of light truck models as passenger cars discussed previously. For the final rulemaking, the agencies intend to review the relevant historic data and current AEO forecast and update these values if necessary.

[o] As indicated previously, a vehicle's age during any future calendar year is uniquely determined by the difference between that calendar year and the model year when it was produced.

4.2.4.3 Final VMT equation

The following equation summarizes in mathematical form the adjustments that are made to the values of average miles driven by vehicle age derived from the 2001 NHTS to derive the estimates of average miles driven by vehicles of each model year during future calendar years that are used in this analysis.

$$VMT_{calendar\ year\ \ x\ ,age\ y} = \left(V_y\right) * (1 + GR1)^{YS1} * (1 + G2)^{YS2} * (1 - \ R * (FCPM_{2001,y} - \ FCPM_{\ x,y})/FCPM_{2001,y}$$

Where:
V_y = Average miles driven in CY 2001 (from NHTSA analysis of 2001 NHTS data) by a vehicle of age $_y$ during 2001
GR1 = Growth Rate for average miles driven by vehicles of each age from 2001 to 2030
YS1 = Lesser of (Years since 2001) and (29).
GR2 = Growth Rate for average miles driven by vehicles of each age from 2030 to 2050
YS2 = Greater of (Years since 2030) and (0).
R= Magnitude of the rebound effect, expressed as an elasticity (-0.10)
$FCPM_{x,y}$ = Fuel cost per mile of a vehicle of age *y* in calendar year *x*

In turn, fuel cost per mile of an age y vehicle in calendar year x is determined by the following equation, which can be extended for any number of fuels:

$$FCPM_{Calendar\ year\ x} = EC_y * EP_x + GC_y * GP_x + DC_y * DP_x$$

Where:
EC_y= Electricity consumption of age *y* vehicle (in KWh) per mile
EP_x = Electricity Price (in $ per KWh) during calendar year *x*
GC_y = Gasoline Consumption of age *y* vehicle (in gallons) per mile
GP_x = Gasoline Price (in $ per gallon) during calendar year *x*
DC_y = Diesel Consumption of age *y* vehicle (in gallons) per mile
DP_x = Diesel Price (in $ per gallon) during calendar year *x*

The NHTSA and EPA models project slightly different fuel costs per mile for vehicles affected by the proposed standards, because of the different structures of the respective agencies' programs and the different technologies projected by each agency's model to be used by vehicle manufacturers to comply with each program. Over the entire lifetimes of those vehicles, however, the agencies' estimates of the number of miles they are expected to be driven differ by about 3% for cars and 1% for light trucks.[p] For comparison, Table 4-5

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[p] While the agencies' projections of VMT are highly similar both on average (~2-3% different depending on the MY) and for light trucks (~1% different), the passenger car VMT schedules have differences in part due to different treatment of vehicles reclassified from trucks to cars under the MY 2011 CAFE standards. For details,

presents the agencies' estimates of the average number of miles driven by model year 2021 and 2025 cars and light trucks at over their estimated average lifetimes.

Table 4-5 Survival Weighted Per-Vehicle Reference VMT used in the Agencies' analyses

	MY 2021		MY 2025	
	Cars	Light Trucks	Cars	Light Trucks
EPA	204,688	242,576	210,898	249,713
NHTSA	212,123	245,612	218,404	253,122

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see EPA's DRIA Chapter 4 and NHTSA's PRIA VIII.B. For the final rulemaking, the agencies intend to harmonize their assessment of these vehicles' use patterns

4.2.4.4 Comparison to other VMT Projections

As a check on their estimates of vehicle use, the agencies compared the forecasts of aggregate car and light truck VMT derived using the procedure described in preceding sections to the AEO 2011 reference case forecast of light duty VMT (see Figure 4-1). The aggregate VMT projected in this analysis is within 3% of the AEO 2011 Light Duty projections over the time period 2017-2035.[11] If AEO VMT is linearly extrapolated at the average growth rate of the period 2017-2035, the agencies' estimates remain within 3% of this projection through 2050. EPA's VMT comparison is shown in the chart below, but is indicative of both agencies' analysis.[q]

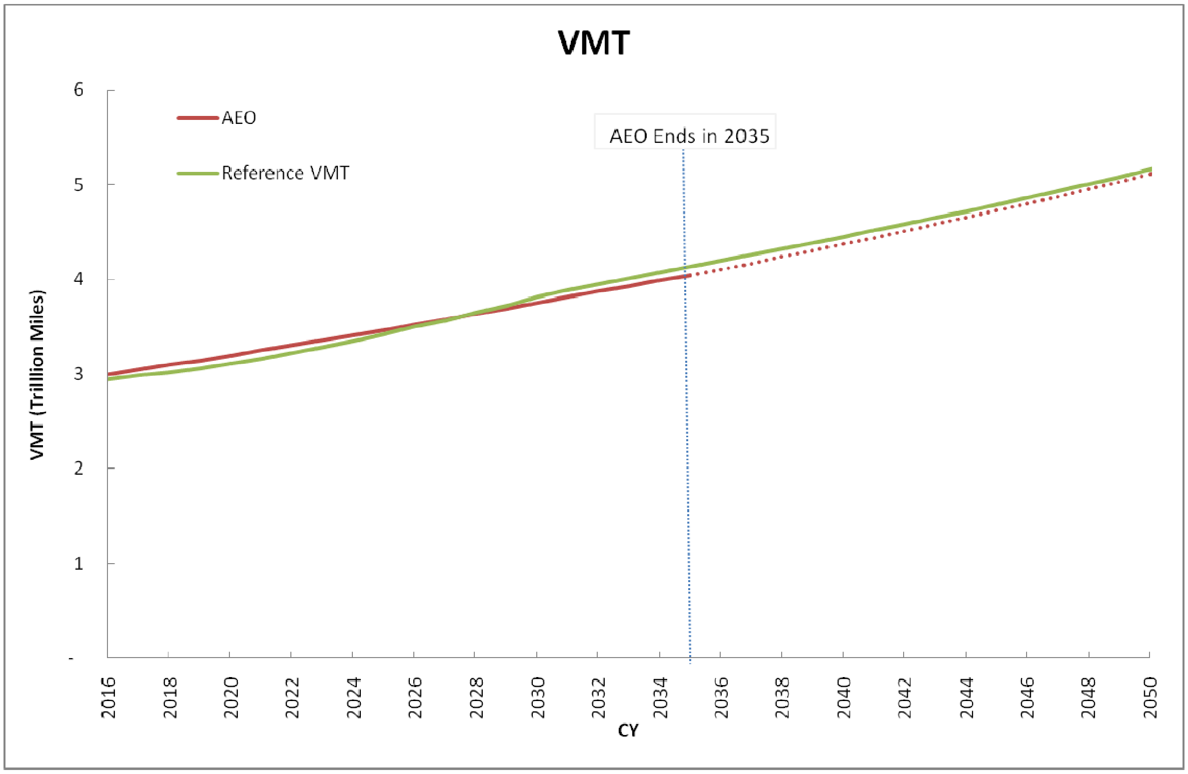

Figure 4-1 Comparison of AEO and Projected VMT

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[q] See note p above.

4.2.5 Accounting for the fuel economy rebound effect

The rebound effect refers to the increase in vehicle use that results if an increase in fuel efficiency lowers the cost per mile of driving, which can encourage people to drive slightly more. Because this additional driving consumes some fuel and increases emissions, it reduces fuel savings and increases emissions compared to those otherwise expected from the proposed standards. Thus the magnitude of the rebound effect is one of the determinants of the actual fuel savings and emission reductions that are likely to result from adopting stricter fuel economy or emissions standards, and is thus an important parameter affecting EPA's and NHTSA's evaluation of the proposed and alternative standards for future model years.

The rebound effect is measured directly by estimating the change in vehicle use, often expressed in terms of vehicle miles traveled (VMT), with respect to changes in vehicle fuel efficiency.[r] However, it is a common practice in the literature to measure the rebound effect by estimating the change in vehicle use with respect to the fuel cost per mile driven, which depends on both vehicle fuel efficiency and fuel prices.[s] When expressed as a positive percentage, these two parameters give the ratio of the percentage increase in vehicle use that results from a percentage increase in fuel efficiency or reduction in fuel cost per mile, respectively. For example, a 10 percent rebound effect means that a 10 percent decrease in fuel cost per mile is expected to result in a 1 percent increase in VMT.

The fuel economy rebound effect for light-duty vehicles has been the subject of a large number of studies since the early 1980s. Although these studies have reported a wide range of estimates of its exact magnitude, they generally conclude that a significant rebound effect occurs when the cost per mile of driving decreases.[t] The most common approach to estimating its magnitude has been to analyze household survey data on vehicle use, fuel consumption, fuel prices (often obtained from external sources), and other variables that influence travel demand . Other studies have relied on annual aggregate U.S. data. Finally, more recent studies have used annual data from individual states.[u]

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[r] Vehicle fuel efficiency is more often measured in terms of fuel consumption (gallons per mile) rather than fuel economy (miles per gallon) in rebound estimates.

[s] Fuel cost per mile is equal to the price of fuel in dollars per gallon divided by fuel economy in miles per gallon (or multiplied by fuel consumption in gallons per mile), so this figure declines when a vehicle's fuel efficiency increases.

[t] Some studies estimate that the long-run rebound effect is significantly larger than the immediate response to increased fuel efficiency. Although their estimates of the adjustment period required for the rebound effect to reach its long-run magnitude vary, this long-run effect could be more appropriate for evaluating the fuel savings and emissions reductions resulting from stricter standards that would apply throughout the lifetime of future model year vehicles.

[u] In effect, these studies treat U.S. states as a data "panel" by applying appropriate estimation procedures to data consisting of each year's average values of these variables for the separate states.

This section surveys these previous studies, summarizes recent work on the rebound effect,[12] and explains the basis for the 10 percent rebound effect EPA and NHTSA are using in this proposed rulemaking.

4.2.5.1 Summary of historical literature on rebound effect

It is important to note that a majority of the studies previously conducted on the rebound effect rely on data from the 1950-1990s. While these older studies provide valuable information on the potential magnitude of the rebound effect, studies that include more recent information (*e.g.*, data within the last decade) may provide more reliable estimates of how this proposal will affect future driving behavior. Therefore, the more recent studies have been described in more detail in Section 4.2.5.2 below.

Estimates based on aggregate U.S. vehicle travel data published by the U.S. Department of Transportation, Federal Highway Administration, covering the period from roughly 1950 to 1990, have found long-run rebound effects on the order of 10-30 percent. Some of these studies are summarized in the following table.

Table 4-6 Estimates of the Rebound Effect Using U.S. Aggregate Time-Series Data on Vehicle Travel[1]

AUTHOR (YEAR)	SHORT-RUN	LONG-RUN	TIME PERIOD
Mayo & Mathis (1988)	22%	26%	1958-84
Gately (1992)	9%	9%	1966-88
Greene (1992)	Linear 5-19% Log-linear 13%	Linear 5-19% Log-linear 13%	1957-89
Jones (1992)	13%	30%	1957-89
Schimek (1996)	5-7%	21-29%	1950-94

[1] Source: Sorrell and Dimitropolous (2007) table 4.6.

Table 4-7 Estimates of the Rebound Effect Using U.S. State Level Data[1]

AUTHOR (YEAR)	SHORT-RUN	LONG-RUN	TIME PERIOD
Haughton & Sarkar (1996)	9-16%	22%	1973-1992
Small and Van Dender (2005 and 2007a)	4.5% 2.2%	22.2% 10.7%	1966-2001 (at sample average) 1966-2001 (at 1997-2001 avg.)
Hymel, Small and Van Dender (2010)	4.7% 4.8%	24.1% 15.9%	1966-2004 1984-2004

[1] Source: Sorrell and Dimitropolous (2007) table 4.7 and the agencies' addition of recent work by Small and Van Dender (2007a) and Hymel, Small, and Van Dender (2010) discussed in section 4.2.5.2.

While studies using national (Table 4-6) and state level (Table 4-7) data have found relatively consistent long-run estimates of the rebound effect, household surveys display more variability (Table 4-8). There are several possible explanations for this larger variability. One explanation is that some of these studies do not include vehicle age as an explanatory variable, thus leading to omitted variable bias in some of their estimates.[13] Another explanation is that these studies consistently find that the magnitude of the rebound effect differs according to the number of vehicles a household owns, and the average number of vehicles owned per household differs among the surveys used to derive these estimates. Still another possibility is that it is difficult to distinguish the impact of residential density on vehicle use from that of fuel prices, since households with higher fuel prices are more likely to reside in urban areas.[14]

Table 4-8 Estimates of the Rebound Effect Using U.S. Survey Data[1]

AUTHOR (YEAR)	SHORT-RUN	LONG-RUN	TIME PERIOD
Goldberg (1996)	0%		CES 1984-90
Greene, Kahn, and Gibson (1999a)		23%	EIA RTECS 1979-1994
Pickrell & Schimek (1999)		4-34%	NPTS 1995 Single year
Puller & Greening (1999)	49%		CES 1980-90 Single year, cross-sectional
West (2004)	87%		CES 1997 Single year

[1] Source: Sorrell and Dimitropolous (2007) table 4.8 and the agencies' addition of Pickrell & Schimek (1999).

It is important to note that some of these studies actually quantify the price elasticity of gasoline demand (*e.g.*, Puller & Greening[15]) or the elasticity of VMT with respect to the price of gasoline (*e.g.*, Pickrell & Schimek), rather than the elasticity of VMT with respect to the fuel cost per mile of driving. The latter of these measures more closely matches the definition of the fuel economy rebound effect. In fact, none of the studies cited above estimate the direct measure of the rebound effect (*i.e.*, the increase in VMT attributed to an increase in fuel efficiency). This topic is discussed in more detail in Section 4.2.5.2.

Another important distinction among studies of the rebound effect is whether they assume that the effect is constant, or varies over time in response to the absolute levels of fuel costs, personal income, or household vehicle ownership. Most studies using aggregate annual data for the U.S. assume a constant rebound effect, although some of these studies test whether the effect can vary as changes in retail fuel prices or average fuel efficiency alter fuel cost per mile driven. Many studies using household survey data estimate significantly different rebound effects for households owning varying numbers of vehicles, with most finding that the rebound effect is larger among households that own more vehicles.[v],[w] Finally, one recent study using state-level data concludes that the rebound effect varies directly in response to changes in personal income and the degree of urbanization of U.S. cities, as well as fuel costs.

In order to provide a more comprehensive overview of previous estimates of the rebound effect, EPA and NHTSA reviewed 22 studies of the rebound effect conducted from 1983 through 2005. The agencies then performed a detailed analysis of the 66 separate estimates of the long-run rebound effect reported in these studies, which is summarized in Table 4-9 below.[x] As the table indicates, these 66 estimates of the long-run rebound effect range from as low as 7 percent to as high as 75 percent, with a mean value of 23 percent. Limiting the sample to 50 estimates reported in the 17 published studies of the rebound effect yields the same range, but a slightly higher mean estimate (24 percent).

The type of data used and authors' assumption about whether the rebound effect varies over time have important effects on its estimated magnitude. The 34 estimates derived from analysis of U.S. annual time-series data produce a mean estimate of 18 percent for the long-run rebound effect, while the mean of 23 estimates based on household survey data is considerably larger (31 percent), and the mean of 9 estimates based on state data (25 percent) is close to that for the entire sample. The 37 estimates assuming a constant rebound effect produce a mean of 23 percent, identical to the mean of the 29 estimates reported in studies that allowed the rebound effect to vary in response to fuel prices, vehicle ownership, or household income.

Table 4-9 Summary Statistics for Estimates of the Rebound Effect

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[v] Six of the household survey studies evaluated in Table 4-7 found that the rebound effects varies in relation to the number of household vehicles. Of those six studies, four found that the rebound effect rises with higher vehicle ownership, and two found that it declines.

[w] The four studies with rebound estimates that increase with higher household vehicle ownership: Greene & Hu; Hensher et al.; Wall et al.; and West & Pickrell. The two studies with rebound estimates that decrease with higher household vehicle ownership: Mannering and Winston; and Greene et al. (note that Greene et al. showed decreases in the rebound effect as households went from 1 to 2 and from 2 to 3 vehicles, then a slight increase from 3 to 4 vehicles; the rebound estimate for households with 4 vehicles was lower than for households with 2 vehicles).

[x] In some cases, NHTSA derived estimates of the overall rebound effect from more detailed results reported in the studies. For example, where studies estimated different rebound effects for households owning different numbers of vehicles but did not report an overall value, the agency computed a weighted average of the reported values using the distribution of households among vehicle ownership categories.

Category of Estimates	Number of Studies	Number of Estimates	Range		Distribution		
			Low	High	Median	Mean	Std. Dev.
All Estimates	22	66	7%	75%	22%	23%	14%
Published Estimates	17	50	7%	75%	22%	24%	14%
U.S. Time-Series Data	7	34	7%	45%	14%	18%	9%
Household Survey Data	13	23	9%	75%	31%	31%	16%
Pooled U.S. State Data	2	9	8%	58%	22%	25%	14%
Constant Rebound Effect (1)	15	37	7%	75%	20%	23%	16%
Variable Rebound Effect: (1)	10	29	10%	45%	23%	23%	10%

4.2.5.2 Summary of recent studies and analyses of the rebound effect

More recent studies since 2007 indicate that the rebound effect has decreased over time as incomes have generally increased and, until recently, fuel costs as a share of total monetary travel costs have generally decreased.[y] One theoretical argument for why the rebound effect should vary over time is that the responsiveness to the fuel cost of driving will be larger when it is a larger proportion of the total cost of driving. For example, as incomes rise, the responsiveness to the fuel cost per mile of driving will decrease if people view the time cost of driving – which is likely to be related to their income levels – as a larger component of the total cost.

Small and Van Dender combined time series data for each of the 50 States and the District of Columbia to estimate the rebound effect, allowing the magnitude of the rebound to vary over time.[16] For the time period from 1966-2001, their study found a long-run rebound effect of 22.2 percent, which is consistent with previously published studies. But for the most recent five year period (1997-2001), the long-run rebound effect decreased to 10.7 percent. Furthermore, when the authors updated their estimates with data through 2004, the long-run rebound effect for the most recent five year period (2000-2004) dropped to 6 percent.[17] Finally, when the Small methodology was used to project the future rebound effect, estimates of the rebound effect throughout 2010-2030 were below 6 percent given a range of future gasoline price and income projections.[18]

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[y] While real gasoline prices have varied over time, fuel costs (which reflect both fuel prices and fuel efficiency) as a share of total vehicle operating costs declined substantially from the mid-1970s until the mid-2000s when the share increased modestly (see Greene (2010)). Note that two studies discussed in this section, Small and Van Dender (2007) and Hymel, Small, and Van Dender (2010), find that the rebound effect is more strongly dependant on income than fuel costs. A third study, Greene (2010), did not directly test the effect of fuel cost on rebound, but found evidence supporting the strong effect from income. Although several studies have shown that the rebound effect rises with household vehicle ownership (see section 4.2.5.1), which has generally increased with income, these findings indicate that income has had a negative effect on rebound.

In 2010, Hymel, Small and Van Dender extended the Small and Van Dender model by adding congestion as an endogenous variable.[19] Although controlling for congestion significantly increased their estimates of the rebound effect, Hymel, Small and Van Dender also found that the rebound effect was declining over time. For the time period from 1966-2004, they estimated a long-run rebound effect of 24 percent, while for 2004 they estimated a long-run rebound effect of 13 percent.

Research conducted by David Greene in 2008-2009 under contract with EPA further appears to support the theory that the magnitude of the rebound effect is declining over time and may be as low as zero.[20] Over the entire time period analyzed (1966-2007), Greene found that fuel prices had a statistically significant impact on VMT, while fuel efficiency did not, which is similar to Small and Van Dender's prior finding. When Small and Van Dender tested whether the elasticity of vehicle travel with respect to the price of fuel was equal to the elasticity with respect to the rate of fuel consumption (gallons per mile), they found that the data could not reject this hypothesis. Therefore, Small and Van Dender estimated the rebound effect as the elasticity of travel with respect to fuel cost per mile. In contrast, Greene's research showed that the hypothesis of equal elasticities for gasoline prices and fuel efficiency can be rejected. In spite of this result, Greene also tested Small and Van Dender's formulation which allows the elasticity of fuel cost per mile to decrease with increasing per capita income. The results of estimation using national time series data confirmed the results obtained by Small and Van Dender using a time series of state level data. When using Greene's preferred functional form, the projected rebound effect is approximately 12 percent in 2007, and drops to 10 percent in 2010, 9 percent in 2016 and 8 percent in 2030.

Since there has been little variation in fuel efficiency in the data over time, isolating the impact of fuel efficiency on VMT can be difficult using econometric analysis of historical data. Therefore, studies that estimate the rebound effect using time-series data often examine the impact of gasoline prices on VMT, or the combined impact of both gasoline prices and fuel efficiency on VMT, as discussed above. However, these studies may overstate the potential impact of the rebound effect resulting from this proposal, if people are more responsive to changes in gasoline prices than to changes in fuel efficiency itself. Recent work conducted by Kenneth Gillingham included an estimate of the elasticity of VMT with respect to the price of gasoline of -0.17, while his corresponding estimate of the elasticity of VMT with respect to fuel economy was only 0.05.[21] While this research pertains specifically to California, this finding suggests that the common assumption that consumers respond similarly to changes in gasoline prices and changes in fuel efficiency may overstate the magnitude of the rebound effect. Additional research is needed in this area, and the agencies request comments and data on this topic.

Another question discussed by Gillingham is whether consumers actually respond the same way to an increase in the cost of driving compared to a decrease in the cost of driving. There is some evidence in the literature that consumers are more responsive to an increase in prices than to a decrease in prices. At the aggregate level, Dargay & Gately and Sentenac-Chemin have shown that demand for transportation fuel is asymmetric.[22,23] In other words, given the same size change in prices, the response to a decrease in gasoline price is smaller than the response to an increase in gasoline price. Gately has shown that the response to an increase in oil prices can be on the order of five times larger than the response to a price decrease.[24] Furthermore, Dargay & Gately and Sentenac-Chemin find evidence that consumers respond more to a large shock than a small, gradual change in fuel prices. Since these proposed standards would decrease the cost of driving gradually over time, it is possible that the rebound effect would be much smaller than some of the historical estimates included in the literature. Although these types of asymmetric responses have been noted at the aggregate level on oil and gasoline consumption, little research has been done on these same phenomena in the context of changes in vehicle fuel efficiency and the resulting rebound effect. More research in this area is also important, and the agencies invite comment on this aspect of the rebound effect.

4.2.5.3 NHTSA analysis of the rebound effect

To provide additional insight into the rebound effect for the purposes of this rulemaking, NHTSA developed several new estimates of its magnitude. These estimates were developed by estimating and testing several econometric models of the relationship between vehicle miles-traveled and factors that influence it, including household income, fuel prices, vehicle fuel efficiency, road supply, the number of vehicles in use, vehicle prices, and other factors.

As the 2007 study by Small and Van Dender pointed out, it is important to account for the effect of fuel prices when attempting to estimate the rebound effect. Failing to control for changes in fuel prices is likely to bias estimates of the rebound effect. Therefore, changes in fuel prices are taken into account in NHTSA's analysis of the rebound effect. Several different approaches were used to estimate the fuel economy rebound effect for light duty vehicles, many of which attempt to account for the endogenous relationship of fuel efficiency to fuel prices.

The results from each of these approaches are presented in **Table 4-10** below. The table reports the value of the rebound effect calculated over the entire period from 1950 through 2006, as well as for the final year of that period. In addition, the table presents forecasts of the average rebound effect between 2010 and 2030, which utilize forecasts of personal income, fuel prices, and fuel efficiency from EIA's AEO 2011 Reference Case.

The results of NHTSA's analysis are broadly consistent with the findings from previous research summarized above. The historical average long-run rebound effect is estimated to range from 16-30 percent, and comparing these estimates to its calculated values for 2006 (which range from 8-14 percent) gives some an indication that it is declining in magnitude. The forecast values of the rebound effect shown in the table also suggest that this decline is likely to continue through 2030, as they range from 4-16 percent.

Table 4-10 Summary of NHTSA Estimates of the Rebound Effect

Model	VMT Measure	Variables Included in VMT Equation	Estimation Technique	Rebound Effects:		
				1950-2006	2006	2010-2030*
Small-Van Dender single VMT equation	annual VMT per adult	fuel cost per mile, per Capita income, vehicle stock, road miles per adult, fraction of population that is adult, fraction of population living in urban areas, fraction of population living in urban areas with heavy rail, dummy variables for fuel rationing, time trend	OLS	33.0%	15.8%	8.0%
Small-Van Dender three-equation system	annual VMT per adult	fuel cost per mile, per Capita income, vehicle stock, road miles per adult, fraction of population that is adult, fraction of population living in urban areas, fraction of population living in urban areas with heavy rail, dummy variables for fuel rationing, time trend	3SLS	21.6%	5.8%	3.4%
Single-equation VMT model	annual VMT per adult	personal income, road miles per Capita, time trend	OLS	18.4%	11.7%	9.2%
Single-equation VMT model	annual VMT per vehicle	fuel cost per mile, personal income, road miles per Capita, time trend	OLS	17.6%	15.2%	15.7%
Single-equation VMT model	annual VMT per adult	fuel cost per mile, personal income, road miles per Capita, dummy variables for fuel	OLS	34.0%	20.8%	13.6%

4.2.5.4 Basis for rebound effect used by EPA and NHTSA in this rule

As the preceding discussion indicates, there is a wide range of estimates for both the historical magnitude of the rebound effect and its projected future value, and there is some evidence that the magnitude of the rebound effect appears to be declining over time. Nevertheless, NHTSA requires a single point estimate for the rebound effect as an input to its analysis, although a range of estimates can be used to test the sensitivity to uncertainty about its exact magnitude. Based on a combination of historical estimates of the rebound effect and more recent analyses conducted by EPA and NHTSA, an estimate of 10 percent for the rebound effect was used for this proposal (*i.e.*, we assume a 10 percent decrease in fuel cost per mile from our proposed standards would result in a 1 percent increase in VMT), with a range of 5-15 percent for use in NHTSA's sensitivity testing.

As Table 4-6, Table 4-7, Table 4-9, and Table 4-9 indicate, the 10 percent figure is on the low end of the range reported in previous research, and Table 4-10 shows that it is also below most estimates of the historical and current magnitude of the rebound effect developed by NHTSA. However, other recent research – particularly that conducted by Hymel, Small and Van Dender, Small and Van Dender, and Greene – reports persuasive evidence that the magnitude of the rebound effect is likely to be declining over time, and the forecasts developed by NHTSA and reported in Table 4-10 also suggest that this is likely to be the case. Furthermore, for the reasons described in section 4.2.5.2, historical estimates of the rebound effect may overstate the magnitude of a change in a small, gradual decrease in the cost of driving due to our proposed standards. Finally, new research by Gillingham suggests that consumers may be more responsive to changes in gasoline prices than to changes in fuel efficiency, and that the rebound effect that occurs when consumers purchase more efficient vehicles as a result of a policy may be on the order of 6 percent.

As a consequence, the agencies concluded that a value on the low end of the historical estimates reported in Table 4-6, Table 4-7, Table 4-8, and Table 4-9 is likely to provide a more reliable estimate of its magnitude during the future period spanned by the agencies' analyses of the impacts of this proposal. The 10 percent estimate lies within the 10-30 percent range of estimates for the historical rebound effect reported in most previous research, and at the upper end of the 5-10 percent range of estimates for the future rebound effect reported in the recent studies by Small and Greene. As Table 4-10 shows, it also lies within the 3-16 percent range of forecasts of the future magnitude of the rebound effect developed by NHTSA in its recent research. In summary, the 10 percent value was not derived from a single point estimate from a particular study, but instead represents a reasonable compromise between historical estimates of the rebound effect and forecasts of its projected future value.

4.2.6 Benefits from increased vehicle use

The increase in vehicle use from the rebound effect provides additional benefits to their drivers and occupants, since it is likely to take the form of more frequent trips or travel to more distant but desirable destinations. In either case, it provides benefits to drivers and their passengers by improving their access to social and economic opportunities away from home. As evidenced by their decisions to make more frequent or longer trips when improved fuel economy reduces their costs for driving, the benefits from this additional travel exceed the costs drivers and passengers incur in making those more frequent or longer trips.

The agencies' analyses estimate the economic benefits from increased rebound-effect driving as the sum of the additional fuel costs drivers incur, plus the consumer surplus they receive from the additional accessibility it provides.[z] The benefits that drivers and passengers receive from additional travel are sufficient to offset these increased fuel costs, and to generate consumer surplus – that is, benefits over and above these higher costs. It should be noted that the consumer surplus benefits representing a small fraction of total benefits from increased vehicle use.

4.2.7 Added costs from increased vehicle use

While it provides some benefits to drivers, increased vehicle use associated with the rebound effect also contributes to increased traffic congestion, motor vehicle accidents, and highway noise. Depending on how the additional travel is distributed over the day and on where it takes place, additional vehicle use can contribute to traffic congestion and delays by increasing traffic volumes on facilities that are already heavily traveled. These added delays impose higher costs on drivers and other vehicle occupants in the form of increased travel time and operating expenses. Because drivers do not take these added costs into account in deciding when and where to travel, they must be accounted for separately as a cost of the added driving associated with the rebound effect.

Increased vehicle use due to the rebound effect may also increase the costs associated with traffic accidents. Drivers may take account of the potential costs they (and their passengers) face from the possibility of being involved in an accident when they decide to make additional trips. However, they probably do not consider all of the potential costs they impose on occupants of other vehicles and on pedestrians when accidents occur. Thus any increase in these "external" accident costs must be considered as another cost of additional rebound-effect driving. Like increased delay costs, any increase in these external accident costs caused by added driving is likely to depend on the traffic conditions under which it takes place, since accidents are more frequent in heavier traffic (although their severity may be reduced by the slower speeds at which heavier traffic typically moves).

Finally, added vehicle use from the rebound effect may also increase traffic noise. Noise generated by vehicles causes inconvenience, irritation, and potentially even discomfort to occupants of other vehicles, to pedestrians and other bystanders, and to residents or occupants of surrounding property. Because these effects are unlikely to be taken into account by the drivers whose vehicles contribute to traffic noise, they represent additional externalities associated with motor vehicle use. Although there is considerable uncertainty in measuring their value, any increase in the economic costs of traffic noise resulting from added vehicle use must be included together with other increased external costs from the rebound effect.

To estimate the increased external costs caused by added driving due to the rebound effect, EPA and NHTSA rely on estimates of congestion, accident, and noise costs caused by

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[z] The consumer surplus provided by added travel is estimated as one-half of the product of the decline in fuel cost per mile and the resulting increase in the annual number of miles driven.

automobiles and light trucks developed previously by the Federal Highway Administration.[25] NHTSA employed these estimates previously in its analysis accompanying the MY 2011 final rule, and the agencies jointly applied them in the MYs 2012-2016 rulemaking, and the agencies continue to find them appropriate for this NPRM. The values are intended to measure the increases in costs (or "marginal" external costs) from added congestion, property damages and injuries in traffic accidents, and noise levels caused by automobiles and light trucks that are borne by persons other than their drivers and occupants.

Updated to 2009 dollars, FHWA's "Middle" estimates for marginal congestion, accident, and noise costs caused by automobile use amount to 5.7 cents, 2.4 cents, and 0.1 cents per vehicle-mile (for a total of 8.2 cents per mile), while those for pickup trucks and vans are 5.1 cents, 2.7 cents, and 0.1 cents per vehicle-mile (for a total of 7.9 cents per mile).[26, aa] These costs are multiplied by the mileage increases attributable to the rebound effect to yield the estimated increases in congestion, accident, and noise externality costs during future years.

4.2.8 Petroleum and energy security impacts

The proposed standards for MYs 2017-2025 will reduce fuel consumption and GHG emissions in light-duty vehicles, which will result in improved fuel efficiency and, in turn, help to reduce U.S. petroleum imports. A reduction of U.S. petroleum imports reduces both financial and strategic risks caused by potential sudden disruptions in the supply of imported petroleum to the U.S. This reduction in the expected future economic costs associated with these risks provides a measure of value of improved U.S. energy security resulting from lower petroleum imports. This section summarizes the agencies' estimates of U.S. oil import reductions and energy security benefits of the proposed Program. Additional discussion of this issue can be found in Section III.H.6 and Section IV of the preamble.

4.2.8.1 Impact on U.S. petroleum imports

In 2010, U.S. petroleum import expenditures represented 14 percent of total U.S. imports of all goods and services, and this figure rose to 18 percent by April of 2011.[27,28] In 2010, the United States imported 49 percent of the petroleum it consumed[29], while the transportation sector accounted for 71 percent of total U.S. petroleum consumption[30]. These figures compare to approximately 37 percent of U.S. petroleum supplied by imports and 55 percent of total petroleum consumed by the nation's transportation sector during 1975.[31]

[aa] The Federal Highway Administration's estimates of these costs agree closely with some other recent estimates. For example, recent published research conducted by Resources for the Future (RFF) estimates marginal congestion and external accident costs for increased light-duty vehicle use in the U.S. to be 3.5 and 3.0 cents per vehicle-mile in year-2002 dollars. *See* Ian W.H. Parry and Kenneth A. Small, "Does Britain or the U.S. Have the Right Gasoline Tax?" Discussion Paper 02-12, Resources for the Future, 19 and Table 1 (March 2002). *Available at* http://www.rff.org/rff/Documents/RFF-DP-02-12.pdf (last accessed Sept. 9, 2011).

Requiring improved fuel economy and lower-GHG vehicle technology in the U.S. is expected to lower U.S. petroleum imports.

Based on analysis of historical and projected future variation in U.S. petroleum consumption and imports, EPA and NHTSA estimate that approximately 50 percent of the reduction in fuel consumption resulting from adopting improved GHG emission and fuel efficiency standards is likely to be reflected in lower U.S. imports of refined fuel, while the remaining 50 percent is expected to be reflected in reduced domestic fuel refining.[bb] Of this latter figure, 90 percent is anticipated to reduce U.S. imports of crude petroleum for use as a refinery feedstock, while the remaining 10 percent is expected to reduce U.S. domestic production of crude petroleum.[cc] Thus, on balance, each gallon of fuel saved as a consequence of this proposed rule is anticipated to reduce total U.S. imports of petroleum by 0.95 gallons.[dd]

4.2.8.2 Background on U.S. energy security

U.S. energy security is broadly defined as protecting the U.S. economy against circumstances that threaten significant short- and long-term increases in energy costs or interruptions in energy supplies. Most discussions of U.S. energy security focus on the economic costs of U.S. dependence on oil imports, and particularly on U.S. reliance on oil imported from potentially unstable sources. In addition, oil exporters have the ability to raise the price of oil by exerting monopoly power through the mechanism of a cartel, the Organization of Petroleum Exporting Countries (OPEC). These factors contribute to the vulnerability of the U.S. economy to episodic oil supply shocks and price spikes. In 2010, total U.S. imports of crude oil, including those from OPEC nations as well as other sources, were $269 billion (in 2009$)[32] (see Figure 4-2).

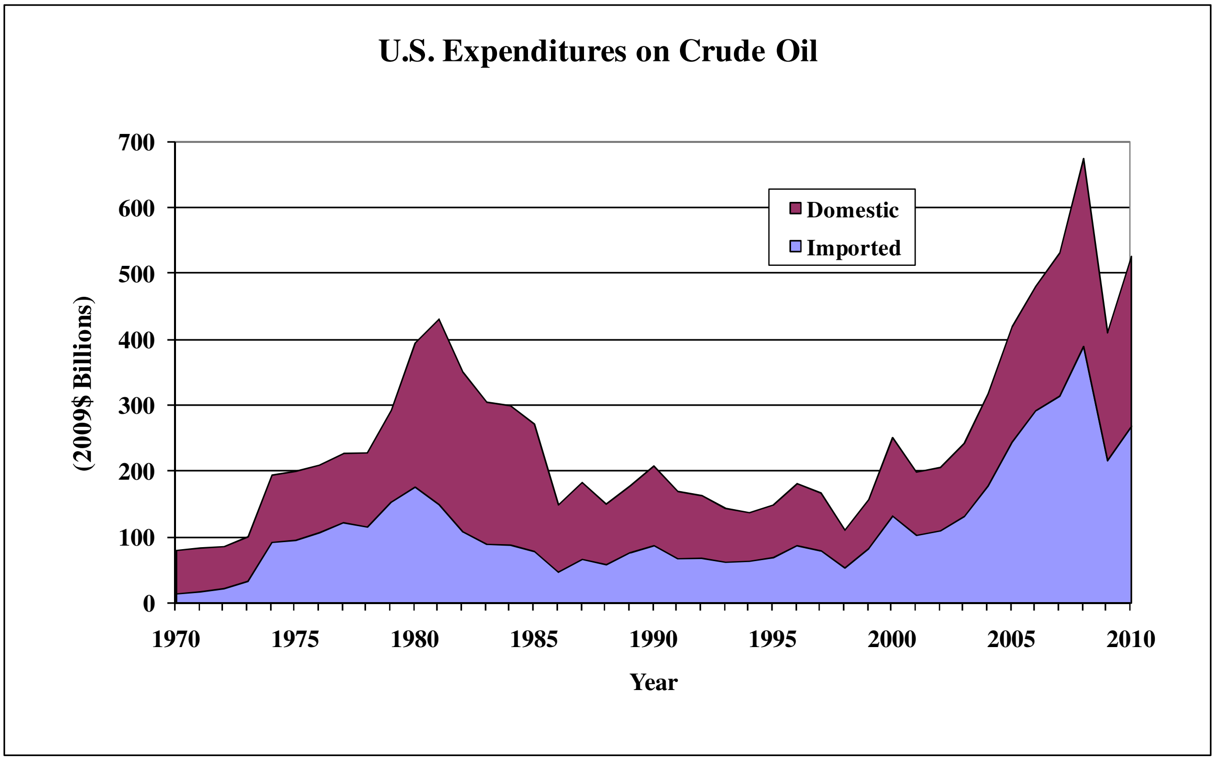
Figure 4-2 U.S. Expenditures on Crude Oil from 1970 through 2010[ee]

[bb] Differences in forecasted annual U.S. imports of crude petroleum and refined products among the Reference, High Oil Price, and Low Oil Price scenarios analyzed in EIA's Annual Energy Outlook 2011 range from 35-74 percent of differences in projected annual gasoline and diesel fuel consumption in the U.S. These differences average 53 percent over the forecast period spanned by AEO 2011.

[cc] Differences in forecasted annual U.S. imports of crude petroleum among the Reference, High Oil Price, and Low Oil Price scenarios analyzed in EIA's Annual Energy Outlook 2011 range from 67-104 percent of differences in total U.S. refining of crude petroleum, and average 90 percent over the forecast period spanned by AEO 2011.

[dd] This figure is calculated as $0.50 + 0.50*0.9 = 0.50 + 0.45 = 0.95$.

[ee] Source for historical data: EIA Annual Energy Review, various editions. For recent historical and forecasted data: EIA Annual Energy Outlook (AEO) 2011 Reference Case.



One effect of the EPA/NHTSA joint proposal (as well as the 2012-2016 light-duty vehicle standards and the 2014-2018 standards for medium- and heavy-duty vehicles and engines) will be to reduce consumption of transportation fuels in the U.S. This will in turn reduce U.S. oil imports, which lowers both financial and strategic risks associated with potential disruptions in supply or sudden increases in the price of petroleum. For this proposed rule, an "oil import premium" approach is utilized to estimate energy security-related costs of importing petroleum into the U.S. Specifically, the oil import premium measures the expected economic value of costs that are not reflected in the market price of petroleum, and that are expected to change in response to an incremental change in the level of U.S. oil imports.

4.2.8.3 Methodology used to estimate U.S. energy security benefits

In order to understand the energy security implications of reducing U.S. oil imports, EPA has worked with Oak Ridge National Laboratory (ORNL), which has developed approaches for evaluating the social costs and energy security implications of oil use. The energy security estimates provided below are based upon a methodology developed in a peer-reviewed study entitled, "*The Energy Security Benefits of Reduced Oil Use, 2006-2015*," completed in March 2008. This study is included as part of the docket for this proposal.[33]

When conducting this recent analysis, ORNL considered the full cost of importing petroleum into the U.S. The full economic cost is defined to include two components in addition to the purchase price of petroleum itself. These are: (1) the higher costs for oil imports resulting from the effect of U.S. import demand on the world oil price and on OPEC market power (*i.e.*, the "demand" or "monopsony" costs); and (2) the risk of reductions in U.S. economic output and disruption of the U.S. economy caused by sudden disruptions in the supply of imported oil to the U.S. (*i.e.*, macroeconomic disruption and adjustment costs). Costs associated with maintaining a U.S. military presence to help secure stable oil supply from potentially vulnerable regions of the world were not included in this analysis, because attributing costs for military operations to specific missions or activities is difficult (as discussed further below).

For this analysis, ORNL estimated energy security premiums by incorporating the most recent available AEO 2011 Reference Case oil price forecasts and market trends. Energy security premiums for the years 2020, 2025, 2030, and 2035 and beyond are presented in Table 4-11, as well as a breakdown of the components of the energy security premiums for each of these years.[ff] The oil security premium rises over the future as a result of changing factors such as the world oil price, global supply/demand balances, U.S. oil imports and consumption, and U.S. GDP (i.e., the size of economy at risk to oil shocks). The principal factor is steadily rising world oil prices, but other effects interact. From 2020 to 2030, the macroeconomic disruption and adjustment component rises by 17% by 2030 and then stabilizes, over a period where projected average real world oil prices rise 15%. U.S. oil import quantities fall by 3% but total domestic oil consumption still rises by 3% despite higher prices. Looked at another way, U.S. GDP, the size of the economy potentially at risk to oil shocks, grows 30%, while the value share of oil in GDP stays high, declining only 9% by 2030.

The components of the energy security premiums and their values are discussed below. Section III.H.7 of the preamble contains a detailed discussion of how the monopsony and macroeconomic disruption/adjustment components were treated for this analysis.

Table 4-11 Energy Security Premiums in Selected Years (2009$/Barrel)

[ff] AEO 2011 forecasts energy market trends and values only to 2035. The energy security premium estimates post-2035 were assumed to be the 2035 estimate.

	Monopsony	Macroeconomic Disruption/Adjustment Costs	Total Mid-Point
2020	$11.12 ($3.78 - $21.21)	$7.10 ($3.40 - $10.96)	$18.22 ($9.53 - $29.06)
2025	$11.26 ($3.78 - $21.48)	$7.77 ($3.84 - $12.32)	$19.03 ($9.93 - $29.75)
2030	$10.91 ($3.74 - $20.47)	$8.32 ($4.09 - $13.34)	$19.23 ($10.51 - $29.02)
2035+	$10.11 ($3.51 - $18.85)	$8.60 ($4.41 - $13.62)	$18.71 ($10.30 - $28.20)

4.2.8.4 Monopsony Effect

The first component of the full economic costs of importing petroleum into the U.S. follows from the effect of U.S. import demand on the world oil price over the long-run. Because the U.S. is a sufficiently large purchaser of foreign oil supplies, it exercises "monopsony power" in the global petroleum market. This means that increases in U.S. petroleum demand can cause the world price of crude oil to rise, and conversely, that reduced U.S. petroleum demand can reduce the world price of crude oil. Since this component of the energy security premium is a transfer between the U.S. and oil exporting countries, it is excluded from the benefit estimates of these proposed rules. See more discussion of this topic in Section 4.2.8.7.

Thus, one benefit of reducing U.S. oil purchases, due both to reductions in overall energy consumption in transportation and substitution of transportation fuels derived from non-petroleum sources, is the potential decrease in the total dollar value of U.S. crude oil purchases. Because lower U.S. oil purchases reduce the price paid for each barrel, the decline in the dollar value of U.S. petroleum purchases exceeds the savings that would result if the global price for oil remained unchanged. The amount by which it does so – which reflects the effect of U.S. monopsony power over the world oil price – represents the demand or monopsony effect of reduced U.S. petroleum consumption.

This demand or monopsony effect can be readily illustrated with an example. If the U.S. imports 10 million barrels per day at a world oil price of $50 per barrel, its total daily bill for oil imports is $500 million. If a decrease in U.S. imports to 9 million barrels per day causes the world oil price to drop to $49 per barrel, the daily U.S. oil import bill drops to $441 million (9 million barrels times $49 per barrel). While the world oil price declines by only $1, the resulting decrease in oil purchases equals $59 million per day ($500 million minus $441 million). This is equivalent to an incremental savings of $59 for each barrel by which U.S. oil imports decline ($59 million per day divided by 1 million barrels per day), or $10 more than the newly-decreased world price of $49 per barrel.

This additional $10 per barrel reduction in the “monopsony premium” represents the incremental external benefits to the U.S. associated with the reduction in import payments beyond the savings that would occur if prices remained unchanged. Of course, this additional benefit arises only to the extent that reduction in U.S. oil imports actually affects the world oil price. ORNL estimates this component of the energy security benefit in 2025 to be $11.26 /barrel by which U.S. petroleum imports are reduced, with a range of $3.78 - $21.48/barrel.

4.2.8.5 Macroeconomic Disruption and Adjustment Effect

The second component of the oil import premium, the “macroeconomic disruption and adjustment cost premium”, arises from the effect of U.S. oil imports on the expected cost of disruptions in oil supply and resulting increases in oil prices. A sudden increase in oil prices triggered by a disruption in world oil supplies has two main effects: (1) it increases the costs of oil imports in the short run, further expanding the transfer of U.S. wealth to foreign producers, and (2) it can lead to macroeconomic contraction, dislocation and losses in Gross Domestic Product (GDP). ORNL estimates the composite estimate of these two factors that comprise the macroeconomic disruption/adjustment costs premium to be $7.77 /barrel in 2025, with a range of $3.84 – 12.32/barrel of imported oil reduced. This component of the energy security premium is included in the agencies’ estimate of the benefits of the proposed rules. See more discussion of how the agencies account for the energy security benefits of the proposed rules in Section 4.2.8.7.

During oil price shocks, the higher price of imported oil causes increased payments for imports from the U.S to oil exporters. This increased claim on U.S. economic output is a loss to the U.S. that is separate from and additional to any reduction in economic output due to the shock. The increased oil payments during shocks are counted as a loss to the degree that the expected price increase is not anticipated and internalized by oil consumers.

Secondly, macroeconomic losses during price shocks reflect both losses in aggregate economic output and “allocative” losses. The former are reductions in the level of output that the U.S. economy can produce by fully utilizing its available resources, while the latter stem from temporary dislocation and underutilization of available resources due to the shock, such as labor unemployment and idle plant capacity. The aggregate output effect, a reduction in “potential” economic output, will persist as long as the price for oil remains elevated. Thus its magnitude depends on the extent and duration of any disruption in the world supply of oil, since these factors determine the extent of the resulting increase in prices for petroleum products, as well as whether and how rapidly these prices return to their pre-disruption levels.

In addition to the aggregate contraction, there are “allocative” or “adjustment” costs associated with dislocations in energy markets. Because supply disruptions and resulting price increases occur suddenly, empirical evidence shows they also impose additional costs on businesses and households for adjusting their use of petroleum and other productive factors more rapidly than if the same price increase had occurred gradually. Dislocation effects include the unemployment of workers and other resources during the time period required for their inter-industry or interregional reallocation, as well as pauses in capital investment due to uncertainty. These adjustments temporarily reduce the level of economic output that can be achieved even below the "potential" output level that would ultimately be reached once the economy's adaptation to higher petroleum prices was complete. The additional costs imposed on businesses and households for making these adjustments reflect their limited ability to adjust prices, output levels, and their use of energy, labor and other inputs quickly and smoothly in response to rapid changes in prices for petroleum products.

Since future disruptions in foreign oil supplies are an uncertain prospect, each of the disruption cost components must be weighted by the probability that the supply of petroleum to the U.S. will actually be disrupted. Thus, the "expected value" of these costs – the product of the probability that a supply disruption will occur and the sum of costs from reduced economic output and the economy's abrupt adjustment to sharply higher petroleum prices – is the relevant measure of their magnitude. Further, when assessing the energy security value of a policy to reduce oil use, only the *change* in these expected costs from potential disruptions that results from the policy is relevant. The expected costs of disruption may change from lowering the normal (*i.e.*, pre-disruption) level of domestic petroleum use and imports, from any induced alteration in the likelihood or size of disruption, or from altering the short-run flexibility in substituting other energy sources or inputs for petroleum use.

In summary, the steps needed to calculate the disruption or security premium are: (1) determine the likelihood of an oil supply disruption in the future; (2) assess the likely impacts of a potential oil supply disruption on the world oil price; (3) assess the impact of the oil price shock on the U.S. economy (in terms of import costs and macroeconomic losses); and (4) determine how these costs are likely to change with the level of U.S. oil imports. The reduction in the expected value of costs and other macroeconomic losses that results from lower oil imports represents the macroeconomic and adjustment cost portion of the oil import premium.

4.2.8.6 Cost of existing U.S. energy security policies

The last often-identified component of the full economic costs of U.S. oil imports is the costs to the U.S. taxpayers of existing U.S. energy security policies. The two primary components of this cost are likely to be (1) the expenses associated with maintaining a U.S. military presence – in part to help secure a stable oil supply – in potentially unstable regions of the world; and (2) costs for maintaining the U.S. Strategic Petroleum Reserve (SPR). The SPR is the largest stockpile of government-owned emergency crude oil in the world. Established in the aftermath of the 1973-74 oil embargo, the SPR provides the U.S. a response option should price increases triggered by a disruption in commercial oil supplies threaten the U.S. economy. It also allows the U.S. to meet part of its International Energy Agency obligation to maintain emergency oil stocks, and it provides a national defense fuel reserve.

The agencies recognize that potential national and energy security risks exist due to the possibility of tension over oil supplies. Much of the world's oil and gas supplies are located in countries facing social, economic, and demographic challenges, thus making them even more vulnerable to potential local instability. For example, in 2010 just over 40 percent of world oil supply came from OPEC nations, and this share is not expected to decline in the AEO 2011 projections through 2030. Approximately 28 percent of global supply is from Persian Gulf countries alone. As another measure of concentration, of the 137 countries/principalities that export either crude oil or refined petroleum product, the top 12 have recently accounted for over 55 percent of exports.[gg] Eight of these countries are members of OPEC, and a 9th is Russia.[hh] In a market where even a 1-2 percent supply loss raises prices noticeably, and where a 10 percent supply loss could lead to a significant price shock, this regional concentration is of concern. Historically, the countries of the Middle East have been the source of eight of the ten major world oil disruptions[34] with the 9th originating in Venezuela, an OPEC member.

Because of U.S. dependence on oil, the military could be called on to protect energy resources through such measures as securing shipping lanes from foreign oil fields. To maintain such military effectiveness and flexibility, the Department of Defense identified in the Quadrennial Defense Review that it is "increasing its use of renewable energy supplies and reducing energy demand to improve operational effectiveness, reduce greenhouse gas emissions in support of U.S. climate change initiatives, and protect the Department from energy price fluctuations."[35] The Department of the Navy has also stated that the Navy and Marine Corps rely far too much on petroleum, which "degrades the strategic position of our country and the tactical performance of our forces. The global supply of oil is finite, it is becoming increasingly difficult to find and exploit, and over time cost continues to rise."[36]

In remarks given to the White House Energy Security Summit on April 26, 2011, Deputy Security of Defense William J. Lynn, III noted the direct impact of energy security on military readiness and flexibility. According to Deputy Security Lynn, "Today, energy technology remains a critical element of our military superiority. Addressing energy needs must be a fundamental part of our military planning."[37]

Thus, to the degree to which the proposed rules reduce reliance upon imported energy supplies or promotes the development of technologies that can be deployed by either consumers or the nation's defense forces, the United States could expect benefits related to national security, reduced energy costs, and increased energy supply. These benefits are why President Obama has identified this program as a key component for improving energy efficiency and putting America on a path to reducing oil imports in the Blueprint for a Secure Energy Future.[38]

[gg] Based on data from the CIA, combining various recent years, https://www.cia.gov/library/publications/the-world-factbook/rankorder/2176rank.html.

[hh] The other three are Norway, Canada, and the EU, an exporter of product.

Although the agencies recognize that there clearly is a benefit to the United States from reducing dependence on foreign oil, the agencies have been unable to calculate the monetary benefit that the United States will receive from the improvements in national security expected to result from this program. In contrast, the other portion of the energy security premium, the U.S. macroeconomic disruption and adjustment cost that arises from U.S. petroleum imports, is included in the energy security benefits estimated for this program. To summarize, the agencies have included *only* the macroeconomic disruption portion of the energy security benefits to estimate the monetary value of the total energy security benefits of this program. The agencies have calculated energy security in very specific terms, as the reduction of both financial and strategic risks caused by potential sudden disruptions in the supply of imported petroleum to the U.S. Reducing the amount of oil imported reduces those risks, and thus increases the nation's energy security.

Potential savings in U.S. military costs are excluded from the analysis performed by ORNL, because their attribution to particular missions or activities is difficult. Most military forces serve a broad range of security and foreign policy objectives. Attempts to attribute some share of U.S. military costs to oil imports are further complicated challenged by the need to estimate how those costs vary with incremental variations in U.S. oil imports. Similarly, while the costs for building and maintaining the SPR are more clearly related to U.S. oil use and imports, these costs have not varied historically in response to changes in U.S. oil import levels. Thus while the influence of the SPR on oil price increases resulting from a disruption of U.S oil imports is reflected in the ORNL estimate of the macroeconomic and adjustment cost component of the oil import premium, potential changes in the cost of maintaining the SPR associated with variation in U.S petroleum imports are excluded.

4.2.8.7 Total Energy Security Benefits

Much of the literature on the energy security for the last two decades has routinely combined the monopsony and the macroeconomic disruption components when calculating the total value of the energy security premium. However, in the context of using a global social cost of carbon (SCC) value, the question arises: how should the energy security premium be measured from a global perspective? Monopsony benefits largely represent a reduction in payments by consumers of petroleum products in the United States to foreign oil producers that result from a decrease in the world oil price as the U.S. decreases its petroleum consumption.

Although a reduction in these payments clearly represents a benefit to the U.S. when considered from a domestic perspective, it represents an exactly offsetting loss to petroleum-producing countries. Given the purely redistributive nature of this monopsony effect when viewed from a global perspective, it is excluded in the energy security benefits calculations for this program. In contrast, the other portion of the energy security premium, the U.S. macroeconomic disruption and adjustment cost that arises from U.S. petroleum imports, does not have offsetting impacts outside of the U.S., and is thus included in the energy security benefits estimated for this program. Thus, the agencies have included only the macroeconomic disruption portion of the energy security benefits to estimate the monetary value of the total energy security benefits of this program.

The energy security analysis conducted for this proposal estimates that the world price of oil will fall modestly in response to lower U.S. demand for refined fuel. One potential result of this decline in the world price of oil would be an increase in the consumption of petroleum products, particularly outside the U.S. In addition, other fuels could be displaced from the increasing use of oil worldwide. For example, if a decline in the world oil price causes an increase in oil use in China, India, or another country's industrial sector, this increase in oil consumption may displace natural gas usage. Alternatively, the increased oil use could result in a decrease in coal used to produce electricity. An increase in the consumption of petroleum products particularly outside the U.S., could lead to a modest increase in emissions of greenhouse gases, criteria air pollutants, and airborne toxics from their refining and use. However, lower usage of, for example, displaced coal would result in a decrease in greenhouse gas emissions. Therefore, any assessment of the impacts on GHG emissions from a potential increase in world oil demand would need to take into account the impacts on all portions of the global energy sector. The agencies' analyses have not attempted to estimate these effects.

4.2.9 Air pollutant emissions

Car and light truck use, fuel refining, and fuel distribution and retailing also generate emissions of certain criteria air pollutants, including carbon monoxide (CO), hydrocarbon compounds (usually referred to as "volatile organic compounds," or VOC), nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), and sulfur dioxide (SO_2). Emissions of most of these pollutants are associated with the number of vehicle miles driven, rather than with the quantity of fuel consumed. Sulfur dioxide is an exception, as described below. While reductions in fuel refining and distribution that result from lower fuel consumption will reduce emissions of criteria pollutants, additional vehicle use associated with the rebound effect will increase emissions of most of these pollutants.

Thus the net effect of stricter fuel efficiency and GHG standards on total emissions of each criteria pollutant depends on the relative magnitudes of reduced emissions during fuel refining and distribution, and increases in emissions from vehicle use. Because the relationship between emission rates (emissions per gallon refined of fuel or mile driven) in fuel refining and vehicle use is different for each criteria pollutant, the net effect of increases in fuel efficiency and GHG standards on total emissions of each pollutant differs.

4.2.9.1 Emissions of criteria air pollutants

For the analysis of criteria emissions over the lifetime of the model years covered by this rule, EPA and NHTSA estimate the increases in emissions of each criteria air pollutant from additional vehicle use by multiplying the increase in total miles driven by cars and light trucks of each model year and age by their estimated emission rates per vehicle-mile of each pollutant. These emission rates differ between cars and light trucks as well as between gasoline and diesel vehicles, and both their values for new vehicles and the rates at which they increase with age and accumulated mileage can vary among model years. With the exception of SO_2, the agencies calculated the increase in emissions of these criteria pollutants from added car and light truck use by multiplying the estimated increases in vehicle use during each year over their expected lifetimes by per-mile emission rates appropriate to each vehicle type, fuel used, model year, and age as of that future year.

As in the MY 2012-2016 rulemaking, the relevant emission rates were estimated by U.S. EPA using the most recent version of the Motor Vehicle Emission Simulator (MOVES2010a).[39] The MOVES model assumes that the per-mile rates at which these pollutants are emitted are determined by EPA regulations and the effectiveness of after-treatment of engine exhaust emissions, and are thus unaffected by changes in car and light truck fuel economy. The MOVES modeling conducted for this proposal is assuming RFS2 volumes of renewable fuel volumes in both the "reference case" and the control case.[ii] The emission analysis assumed a 10% ethanol fuel supply.[jj]As a consequence, the downstream impacts of required increases in fuel economy on emissions of these pollutants from car and light truck use are determined entirely by the increases in driving that result from the fuel economy rebound effect.

Emission factors in the MOVES database are expressed in the form of grams per vehicle-hour of operation. To convert these emission factors to grams per mile, MOVES was run for the year 2050, and was programmed to report aggregate emissions from vehicle start, running, brake and tirewear and crankcase exhaust operations. EPA analysts selected the year 2050 in order to generate emission factors that were representative of lifetime average emission rates for vehicles meeting the agency's Tier 2 emission standard.[kk] Separate estimates were developed for each vehicle type and model year, as well as for each state and month, in order to reflect the effects of regional and temporal variation in temperature and other relevant variables on emissions.

The MOVES emissions estimates were then summed to the model year level and divided by total distance traveled by vehicles of that model year in order to produce per-mile emission factors for each pollutant. The resulting emission rates represent average values across the nation, and incorporate typical variation in temperature and other operating conditions affecting emissions over an entire calendar year. These national average rates also

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[ii] The agencies assume 100 percent E10 in both the reference and control cases, which is a simplifying assumption that is appropriate to the level of detail necessary for this proposal's analysis.

[jj] More discussion on fuel supply and this rule is in Preamble Section III.F

[kk] Because all light-duty emission rates in MOVES2010a are assumed to be invariant after MY 2010, a calendar-year 2050 run produced a full set of emission rates that reflect anticipated deterioration in the effectiveness of vehicles' emission control systems with increasing age and accumulated mileage for post-MY 2010 vehicles.

reflect county-specific differences in fuel composition, as well as in the presence and type of vehicle inspection and maintenance programs.[ll]

Emission rates for the criteria pollutant SO_2 were calculated by using average fuel sulfur content estimates supplied by EPA, together with the simplifying assumption that the entire sulfur content of fuel is emitted in the form of SO_2. These calculations assumed that national average gasoline and diesel sulfur levels would remain at current levels.[mm] Therefore, unlike many other criteria pollutants, sulfur dioxide emissions from vehicle use decline in proportion to the decrease in fuel consumption.

Emissions of criteria air pollutants also occur during each phase of fuel production and distribution, including crude oil extraction and transportation, fuel refining, and fuel storage and transportation. The reduction in emissions during each of these phases depends on the extent to which fuel savings result in lower imports of refined fuel, or in reduced domestic fuel refining. To a lesser extent, they also depend on whether reductions in domestic gasoline refining are reflected in reduced imports of crude oil or in reduced domestic extraction of petroleum.

Both EPA's and NHTSA's analyses assume that reductions in imports of refined fuel would reduce criteria pollutant emissions during fuel storage and distribution only. Reductions in domestic fuel refining using imported crude oil as a feedstock are assumed to reduce emissions during fuel refining, storage, and distribution, because each of these activities would be reduced. Finally, reduced domestic fuel refining using domestically-produced crude oil is assumed to reduce emissions during all phases of fuel production and distribution.[nn]

EPA estimated the reductions in criteria pollutant emissions from producing and distributing fuel that would occur under alternative fuel efficiency and GHG standards using emission rates obtained from Argonne National Laboratories' Greenhouse Gases and Regulated Emissions in Transportation (GREET) model.[40] The GREET model provides separate estimates of air pollutant emissions that occur in four phases of fuel production and distribution: crude oil extraction, crude oil transportation and storage, fuel refining, and fuel

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[ll] The national mix of fuel types includes county-level market shares of conventional and reformulated gasoline, as well as county-level variation in sulfur content, ethanol fractions, and other fuel properties. Inspection/maintenance programs at the county level account for detailed program design elements such as test type, inspection frequency, and program coverage by vehicle type and age.

[mm] These are 30 and 15 parts per million (ppm, measured on a mass basis) for gasoline and diesel respectively, which produces emission rates of 0.17 grams of SO_2 per gallon of gasoline and 0.10 grams per gallon of diesel.

[nn] In effect, this assumes that the distances crude oil travels to U.S. refineries are approximately the same regardless of whether it travels from domestic oilfields or import terminals, and that the distances that gasoline travels from refineries to retail stations are approximately the same as those from import terminals to gasoline stations.

distribution and storage.[oo] EPA modified the GREET model to change certain assumptions about emissions during crude petroleum extraction and transportation, as well as to update its emission rates to reflect adopted and pending EPA emission standards. EPA also incorporated emission factors for the air toxics estimated in this analysis: benzene, 1,3-butadiene, acetaldehyde, acrolein, and formaldehyde. The resulting emission factors are shown in Table 4-12.

[oo] Emissions that occur during vehicle refueling at retail gasoline stations (primarily evaporative emissions of volatile organic compounds, or VOCs) are already accounted for in the “tailpipe” emission factors used to estimate the emissions generated by increased light truck use. GREET estimates emissions in each phase of gasoline production and distribution in mass per unit of gasoline energy content; these factors are then converted to mass per gallon of gasoline using the average energy content of gasoline.

Table 4-12 Emissions by Stage of Fuel Production and Distribution (grams/million Btu)

Pollutant	Fuel Type	Petroleum Extraction & Transportation[1]	Refinery Energy Use Upstream Emissions	Petroleum Refining On-Site	Petroleum Refining[2]	Fuel Transport, Storage, Distribution[3]
CO	Conventional Gasoline	4.908	0.928	5.596	6.525	0.748
	Reformulated Gasoline	4.908	0.908	5.662	6.571	0.768
	Low Sulfur Diesel	4.908	0.800	5.103	5.903	0.780
VOC	Conventional Gasoline	3.035	0.602	2.560	3.162	42.91
	Reformulated Gasoline	3.035	0.627	2.584	3.211	42.92
	Low Sulfur Diesel	3.035	0.552	2.511	3.063	1.261
NOx	Conventional Gasoline	14.91	3.328	14.442	17.771	3.691
	Reformulated Gasoline	14.91	3.288	14.575	17.863	3.786
	Low Sulfur Diesel	14.91	2.895	12.972	15.866	3.570
SOx	Conventional Gasoline	3.926	4.398	9.678	14.076	0.886
	Reformulated Gasoline	3.926	4.422	9.922	14.344	0.909
	Low Sulfur Diesel	3.926	3.893	9.187	13.080	0.840
PM2.5	Conventional Gasoline	0.645	1.442	1.789	3.231	0.155
	Reformulated Gasoline	0.645	1.487	1.838	3.325	0.159
	Low Sulfur Diesel	0.645	1.309	1.635	2.943	0.133
Air Toxics						
1,3-Butadiene	Conventional Gasoline	0.0017	0.0003	0.0014	0.0017	0.0001
	Reformulated Gasoline	0.0017	0.0003	0.0014	0.0018	0.0001
	Low Sulfur Diesel	0.0017	0.0003	0.0014	0.0017	0.0001
Acetaldehyde	Conventional Gasoline	0.0002	0.0000	0.0002	0.0002	0.0046
	Reformulated Gasoline	0.0002	0.0000	0.0002	0.0002	0.0047
	Low Sulfur Diesel	0.0002	0.0000	0.0002	0.0002	0.0044
Acrolein	Conventional Gasoline	0.0001	0.0000	0.0001	0.0001	0.0006
	Reformulated Gasoline	0.0001	0.0000	0.0001	0.0001	0.0006
	Low Sulfur Diesel	0.0001	0.0000	0.0001	0.0001	0.0006
Benzene	Conventional Gasoline	0.0313	0.0062	0.0264	0.0326	0.0787
	Reformulated Gasoline	0.0313	0.0064	0.0264	0.0328	0.0788
	Low Sulfur Diesel	0.0313	0.0058	0.0264	0.0322	0.0015
Formaldehyde	Conventional Gasoline	0.0050	0.0010	0.0042	0.0052	0.0326
	Reformulated Gasoline	0.0050	0.0010	0.0042	0.0052	0.0335
	Low Sulfur Diesel	0.0050	0.0009	0.0042	0.0051	0.0316

[1] The petroleum extraction and transport emission factors are only applied to domestic crude oil.

[2] Refinery emissions factors are applied to domestic refineries, whether refining domestic or imported crude.

[3] Fuel transport, storage, and distribution emission factors represent domestic emissions and are applied to all finished fuel, whether refined domestically or internationally.

The agency converted these emission rates from the mass per fuel energy content basis on which GREET reports them to mass per gallon of fuel supplied using the estimates of fuel energy content reported by GREET. The resulting emission rates were applied to both EPA's and NHTSA's estimates of fuel consumption under alternative fuel efficiency standards to develop estimates of total emissions of each criteria pollutant during fuel production and distribution. The assumptions about the effects of *changes* in fuel consumption on domestic and imported sources of fuel supply discussed above were then employed to calculate the effects of reductions in fuel use from alternative fuel efficiency and GHG standards on changes in domestic emissions of each criteria pollutant throughout the fuel supply and distribution process.

Electricity emission factors were derived from EPA's Integrated Planning Model (IPM). EPA uses IPM to analyze the projected impact of environmental policies on the electric power sector in the 48 contiguous states and the District of Columbia. Developed by ICF Consulting, Inc. and used to support public and private sector clients, IPM is a multi-regional, dynamic, deterministic linear programming model of the U.S. electric power sector. It provides forecasts of least-cost capacity expansion, electricity dispatch, and emission control strategies for meeting energy demand and environmental, transmission, dispatch, and reliability constraints. IPM can be used to evaluate the cost and emissions impacts of proposed policies to limit emissions of sulfur dioxide (SO2), nitrogen oxides (NOx), carbon dioxide (CO2), and mercury (Hg) from the electric power sector.

Among the factors that make IPM particularly well suited to model multi-emissions control programs are (1) its ability to capture complex interactions among the electric power, fuel, and environmental markets; (2) its detail-rich representation of emission control options encompassing a broad array of retrofit technologies along with emission reductions through fuel switching, changes in capacity mix and electricity dispatch strategies; and (3) its capability to model a variety of environmental market mechanisms, such as emissions caps, allowances, trading, and banking.

For this analysis, EPA derived national emission factors from an IPM version 4.10 run for the "Proposed Transport Rule .[41]" IPM provided national emission totals and power generation totals for VOC, CO, NOx, PM2.5, and SO_2 in 2015, 2020, 2030, 2040 and 2050. EPA divided these sums to derive national average emission factors, and interpolated in intermediate years. Emissions factors for air toxics were derived from the 2002 National Emission Inventory in conjunction with the IPM estimates. The emission factors for electricity was adjusted upwards by six percent in order to properly capture the feedstock gathering that occurs upstream of the powerplant.[pp] Feedstock gathering includes the gathering, transporting, and preparing fuel for electricity generation. This adjustment factor is consistent with those discussed in the MY 2012-2016 Final Rule.[qq]

This analytic method makes the simplifying assumption that the electricity generation due to this rulemaking produces emissions at the national average level. EPA plans to further

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[pp] The factor of 1.06 to account for GHG emissions associated with feedstock extraction, transportation, and processing is based on Argonne National Laboratory's The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8c.0, available at http://www.transportation.anl.gov/modeling_simulation/GREET/). EPA Docket EPA-HQ-OAR-2009-0472.

[qq] MY 2012-2016 Final Rule, Section III.2.C

examine the implications of this assumption in the final rulemaking, as discussed in Section III.C.

The agencies account for all electricity consumed by the vehicle. For calculations of GHG emissions from electricity generation, the total energy consumed from the battery is divided by 0.9 to account for charging losses, and by 0.93 to account for losses during transmission. Both values were discussed in the MYs 2012-2016 rule as well as the Interim Joint TAR, and are unchanged from those analyses. The estimate of charging losses is based upon engineering judgment and manufacturer Confidential Business Information (CBI). The estimate of transmission losses is consistent, although not identical to the 8% estimate used in GREET, as well as the 6% estimate in eGrid 2010.[42,43] The upstream emission factor is applied to total electricity production, rather than simply power consumed at the wheel. [rr]

The derived set of electricity emission factors was employed by both agencies.

Finally, EPA and NHTSA calculated the *net* changes in domestic emissions of each criteria pollutant by summing the increases in its emissions projected to result from increased vehicle use, electricity production, and the reductions in emissions anticipated to result from lower domestic fuel refining and distribution.[ss] As indicated previously, the effect of adopting improved fuel efficiency and GHG standards on total emissions of each criteria pollutant depends on the relative magnitudes of the resulting reduction in emissions from fuel refining and distribution, and the increase in emissions from additional vehicle use.

4.2.9.2 Estimated values of reducing PM-related emissions in the model year analysis

The agencies' analysis of $PM_{2.5}$-related benefits over the lifetime of specific model years uses a "benefit-per-ton" method to estimate selected $PM_{2.5}$-related health benefits. These $PM_{2.5}$-related benefit-per-ton estimates provide the total monetized human health benefits (the sum of premature mortality and premature morbidity) of reducing one ton of directly emitted $PM_{2.5}$, or one ton of a pollutant that contributes to secondarily-formed $PM_{2.5}$ (such as NOx, SOx, and VOCs) from a specified source.

Ideally, the human health benefits would be estimated based on changes in ambient $PM_{2.5}$ concentrations and population exposure, as determined by complete air quality and exposure modeling. However, conducting such detailed modeling was not possible within the timeframe for this proposal. Note that EPA will conduct full-scale photochemical air quality

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[rr] By contrast, consumer electricity costs would not include the power lost during transmission. While consumers indirectly pay for this lost power through higher rates, this power does not appear on their electric meter.

[ss] All emissions from increased vehicle use are assumed to occur within the U.S., since fuel efficiency standards would apply only to vehicles produced for sale in the U.S.

modeling for selected future calendar years as part of the air quality analysis it conducts for the final rule.

Due to analytical limitations, the estimated benefit-per-ton values do not include comparable benefits related to reductions in other ambient concentrations of criteria pollutants (such as ozone, NO_2 or SO_2) or toxic air pollutants, nor do they monetize all of the potential health and welfare effects associated with $PM_{2.5}$ or the other criteria pollutants. As a result, monetizing PM-related health impacts alone underestimates the benefits associated with reductions of the suite of non-GHG pollutants that would be reduced by the proposed standards.

The dollar-per-ton estimates used to monetize reductions in emissions that contribute to ambient concentrations of $PM_{2.5}$ are provided in Table 4-13.

Table 4-13 Benefits-per-ton Values (2009$) Derived Using the American Cancer Society Cohort Study for PM-related Premature Mortality (Pope et al., 2002)[a]

Year[c]	All Sources[d]		Stationary (Non-EGU) Sources[e]		Mobile Sources	
	SO_X	VOC	NO_X	Direct PM2.5	NO_X	Direct PM2.5
Estimated Using a 3 Percent Discount Rate[b]						
2015	$29,000	$1,200	$4,800	$230,000	$5,000	$280,000
2020	$32,000	$1,300	$5,300	$250,000	$5,500	$300,000
2030	$38,000	$1,600	$6,300	$290,000	$6,600	$360,000
2040	$44,000	$1,900	$7,500	$340,000	$7,900	$430,000
Estimated Using a 7 Percent Discount Rate[b]						
2015	$27,000	$1,100	$4,400	$210,000	$4,600	$250,000
2020	$29,000	$1,200	$4,800	$220,000	$5,000	$280,000
2030	$34,000	$1,400	$5,700	$260,000	$6,000	$330,000
2040	$40,000	$1,700	$6,800	$310,000	$7,200	$390,000

[a] The benefit-per-ton estimates presented in this table are based on an estimate of premature mortality derived from the ACS study (Pope et al., 2002). If the benefit-per-ton estimates were based on the Six-Cities study (Laden et al., 2006), the values would be approximately 245% (nearly two-and-a-half times larger). See below for a description of these studies.

[b] The benefit-per-ton estimates presented in this table assume either a 3 percent or 7 percent discount rate in the valuation of premature mortality to account for a twenty-year segmented cessation lag.

[c] Benefit-per-ton values were estimated for the years 2015, 2020, and 2030. For intermediate years, such as 2017 (the year the standards begin), we interpolated exponentially. For years beyond 2030 (including 2040), EPA and NHTSA extrapolated exponentially based on the growth between 2020 and 2030.

[d] Note that the benefit-per-ton value for SOx is based on the value for Stationary (Non-EGU) sources; no SOx value was estimated for mobile sources. The benefit-per-ton value for VOCs was estimated across all sources.

[e] Non-EGU denotes stationary sources of emissions other than electric generating units (EGUs).

As Table 4-13 indicates, EPA projects that the per-ton values for reducing emissions of criteria pollutants from both vehicle use and stationary sources such as fuel refineries and storage facilities will increase over time.[tt] These projected increases reflect rising income levels, which are assumed to increase affected individuals' willingness to pay for reduced exposure to health threats from air pollution. They also reflect future population growth and increased life expectancy, which expands the size of the population exposed to air pollution in both urban and rural areas, especially in older age groups with the highest mortality risk.[44,uu]

For certain $PM_{2.5}$-related pollutants (such as direct $PM_{2.5}$ and NOx), EPA estimates different per-ton values for reducing mobile source emissions than for reductions in emissions of the same pollutant from stationary sources such as fuel refineries and storage facilities. These reflect differences in the typical geographic distributions of emissions of each pollutant by different sources, their contributions to ambient levels of $PM_{2.5}$, and resulting changes in population exposure. EPA and NHTSA apply these separate values to its estimates of changes in emissions from vehicle use and from fuel production and distribution to determine the net change in total economic damages from emissions of those pollutants.

The benefit per-ton technique has been used in previous analyses, including the 2012-2016 Light-Duty Greenhouse Gas Rule,[45] the Ozone National Ambient Air Quality Standards (NAAQS) RIA,[46] the Portland Cement National Emissions Standards for Hazardous Air Pollutants (NESHAP) RIA,[47] and the final NO_2 NAAQS.[48] Table 4-14 shows the quantified and monetized $PM_{2.5}$-related co-benefits that are captured in these benefit-per-ton estimates, and also lists other effects that remain un-quantified and are thus excluded from the estimates.

Table 4-14 Human Health and Welfare Effects of $PM_{2.5}$

Pollutant / Effect	Quantified and Monetized in Primary Estimates	Un-quantified Effects Changes in:
$PM_{2.5}$	Adult premature mortality Bronchitis: chronic and acute Hospital admissions: respiratory and cardiovascular Emergency room visits for asthma Nonfatal heart attacks (myocardial infarction) Lower and upper respiratory illness Minor restricted-activity days Work loss days Asthma exacerbations (asthmatic population) Infant mortality	Subchronic bronchitis cases Low birth weight Pulmonary function Chronic respiratory diseases other than chronic bronchitis Non-asthma respiratory emergency room visits Visibility Household soiling

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[tt] As we discuss in the emissions chapter of EPA's DRIA (Chapter 4), the rule would yield emission reductions from upstream refining and fuel distribution due to decreased petroleum consumption.

[uu] For more information about EPA's population projections, please refer to the following: http://www.epa.gov/air/benmap/models/BenMAPManualAppendicesAugust2010.pdf (See Appendix K)

Consistent with the NO_2 NAAQS,[vv] the benefits estimates utilize concentration-response functions as reported in the epidemiology literature. Readers interested in reviewing the complete methodology for creating the benefit-per-ton estimates used in this analysis can consult the Technical Support Document (TSD)[49] accompanying the final ozone NAAQS RIA. Readers can also refer to Fann et al. (2009)[50] for a detailed description of the benefit-per-ton methodology.[ww]

As described above, national per-ton estimates were developed for selected pollutant/source category combinations. The per-ton values calculated therefore apply only to tons reduced from those specific pollutant/source combinations (*e.g.*, NO_2 emitted from mobile sources; direct PM emitted from stationary sources). Our estimate of total $PM_{2.5}$ benefits is therefore based on the total direct $PM_{2.5}$ and $PM_{2.5}$–related precursor emissions (NOx, SOx, and VOCs) controlled from each source and multiplied by the respective per-ton values of reducing emissions from that source.

The benefit-per-ton coefficients in this analysis were derived using modified versions of the health impact functions used in the PM NAAQS Regulatory Impact Analysis. Specifically, this analysis uses the benefit-per-ton estimates first applied in the Portland Cement NESHAP RIA, which incorporated concentration-response functions directly from the epidemiology studies, without any adjustment for an assumed threshold. Removing the threshold assumption is a key difference between the method used in this analysis to estimate PM co-benefits and the methods used in analyses prior to EPA's Portland Cement NESHAP.[xx] As a consequence, the benefit-per-ton estimates used in this analysis include

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[vv] Although we summarize the main issues in this chapter, we encourage interested readers to see benefits chapter of the NO2 NAAQS for a more detailed description of recent changes to the PM benefits presentation and preference for the no-threshold model.

[ww] The values included in this report are different from those presented in the article cited above. Benefits methods change to reflect new information and evaluation of the science. Since publication of the June 2009 article, EPA has made two significant changes to its benefits methods: (1) We no longer assume that a threshold exists in PM-related models of health impacts, which is consistent with the findings reported in published research; and (2) We have revised the Value of a Statistical Life to equal $6.3 million (year 2000$), up from an estimate of $5.5 million (year 2000$) used in the June 2009 report. Please refer to the following website for updates to the dollar-per-ton estimates: http://www.epa.gov/air/benmap/bpt.html

[xx] Based on a review of the current body of scientific literature, EPA estimates PM-related mortality without applying an assumed concentration threshold. EPA's Integrated Science Assessment for Particulate Matter (U.S. Environmental Protection Agency. 2009. Integrated Science Assessment for Particulate Matter (Final Report). EPA-600-R-08-139F. National Center for Environmental Assessment – RTP Division. December), which was reviewed by EPA's Clean Air Scientific Advisory Committee (U.S. Environmental Protection Agency - Science Advisory Board. 2009. Review of EPA's Integrated Science Assessment for Particulate Matter (First External Review Draft, December 2008). EPA-COUNCIL-09-008. May.; U.S. Environmental Protection Agency Science Advisory Board . 2009. Consultation on EPA's Particulate Matter National Ambient Air Quality Standards: Scope and Methods Plan for Health Risk and Exposure Assessment. EPA-COUNCIL-09-009. May), concluded that the scientific literature consistently finds that a no-threshold log-linear model most adequately portrays the PM-mortality concentration-response relationship while recognizing potential uncertainty about the exact shape of the concentration-response function. This assumption is incorporated into the calculation of the PM-related benefits-per-ton values.

incremental benefits of reductions in $PM_{2.5}$ concentrations down to their lowest modeled levels. This approach is also consistent with EPA's analysis of the 2012-2016 Light-Duty Vehicle Greenhouse Gas rule.

Reductions in PM-related mortality provide the majority of the monetized value in each benefit-per-ton estimate. Typically, the premature mortality-related effect coefficients that underlie the benefits-per-ton estimates are drawn from epidemiology studies that examine two large population cohorts: the American Cancer Society cohort (Pope et al., 2002)[51] and the Harvard Six Cities cohort (Laden et al., 2006).[52] The concentration-response (C-R) function developed from the extended analysis of American Cancer Society (ACS) cohort, as reported in Pope et al. (2002), has previously been used by EPA to generate its primary benefits estimate. The extended analysis of the Harvard Six Cities cohort, as reported by Laden et al (2006), was published after the completion of the Staff Paper for the 2006 $PM_{2.5}$ NAAQS and has been used as an alternative estimate in the $PM_{2.5}$ NAAQS RIA and $PM_{2.5}$ co-benefits estimates in analyses completed since the $PM_{2.5}$ NAAQS.

These studies provide logical choices for anchor points when presenting PM-related benefits because, while both studies are well designed and peer-reviewed, there are strengths and weaknesses inherent in each. Although this argues for using both studies to generate benefits estimates, due to the analytical limitations associated with this analysis, EPA and NHTSA have chosen to use the benefit-per-ton value derived from the ACS study. The agencies note that benefits would be approximately 245 percent (or nearly two-and-a-half times) larger if the per-ton benefit values based on the Harvard Six Cities were used instead.

As is the nature of benefits analyses, assumptions and methods evolve over time to reflect the most current interpretation of the scientific and economic literature. For a period of time (2004-2008), EPA's Office of Air and Radiation (OAR) valued mortality risk reductions using a value of statistical life (VSL) estimate derived from a limited analysis of some of the available studies. OAR arrived at a VSL using a range of $1 million to $10 million (2000$) consistent with two meta-analyses of the wage-risk literature.

The $1 million value represented the lower end of the interquartile range from the Mrozek and Taylor (2002)[53] meta-analysis of 33 studies. The $10 million value represented the upper end of the interquartile range from the Viscusi and Aldy (2003)[54] meta-analysis of 43 studies. The mean estimate of $5.5 million (2000$) was also consistent with the mean VSL of $5.4 million estimated in the Kochi et al. (2006)[55] meta-analysis. However, the Agency neither changed its official guidance on the use of VSL in rulemakings nor subjected the interim estimate to a scientific peer-review process through the Science Advisory Board (SAB) or other peer-review group.

Until updated guidance is available, EPA determined that a single, peer-reviewed estimate applied consistently best reflects the Science Advisory Board Environmental Economics Advisory Committee (SAB-EEAC) advice it has received. Therefore, EPA has decided to apply the VSL that was vetted and endorsed by the SAB in the Guidelines for Preparing Economic Analyses (U.S. EPA, 2000)[56] while they continue efforts to update their guidance on this issue.[yy] This approach calculates a mean value across VSL estimates derived from 26 labor market and contingent valuation studies published between 1974 and 1991. The mean VSL across these studies is $6.3 million (2000$). The dollar-per-ton estimates used in this analysis are based on this revised VSL.[zz]

The benefit-per-ton estimates are subject to a number of assumptions and uncertainties.

- They do not reflect local variability in population density, meteorology, exposure, baseline health incidence rates, or other local factors that might lead to an overestimate or underestimate of the actual benefits of controlling fine particulates in specific locations. Please refer to Chapter 6.3 of EPA's DRIA for the description of the agency's quantification and monetization of PM- and ozone-related health impacts for the proposal.
- This analysis assumes that all fine particles, regardless of their chemical composition, are equally potent in causing premature mortality. This is an important assumption, because $PM_{2.5}$ produced via transported precursors emitted from stationary sources may differ significantly from direct $PM_{2.5}$ released from engines and other industrial sources. At the present time, however, no clear scientific grounds exist for supporting differential effects estimates by particle type.
- This analysis assumes that the health impact function for fine particles is linear within the range of ambient concentrations under consideration. Thus, the estimates include health benefits from reducing fine particles in areas with varied initial concentrations of $PM_{2.5,}$ including both regions that are in attainment with fine particle standard and those that do not meet the standard, down to the lowest modeled concentrations.
- There are several health benefits categories that EPA and NHTSA were unable to quantify due to limitations associated with using benefits-per-ton estimates, several of which could be substantial. Because NO_X and VOC emissions are also precursors to ozone, changes in NO_X and VOC would also impact ozone formation and the health effects associated with ozone exposure. Benefits-per-ton estimates for ozone do not exist due to issues associated with the complexity of the atmospheric air chemistry and nonlinearities associated with ozone formation. The PM-related benefits-per-ton estimates also do not include any human welfare or ecological benefits. Please refer to Chapter 6.3 of EPA's PRIA for a description of the unquantified co-pollutant benefits associated with this rulemaking.

[yy] In the update of the Economic Guidelines (U.S. EPA, 2011), EPA retained the VSL endorsed by the SAB with the understanding that further updates to the mortality risk valuation guidance would be forthcoming in the near future. The update of the Economic Guidelines is available on the Internet at http://yosemite.epa.gov/ee/epa/eed.nsf/pages/Guidelines.html/$file/Guidelines.pdf.

[zz] This value differs from the Department of Transportation's most recent estimate of the value of preventing transportation-related fatalities, which is $6.1 million when expressed in today's (2011) dollars.

As mentioned above, emissions changes and benefits-per-ton estimates alone are not a good indication of local or regional air quality and health impacts, as the localized impacts associated with the rulemaking may vary significantly. Additionally, the atmospheric chemistry related to ambient concentrations of $PM_{2.5}$, ozone and air toxics is very complex. Full-scale photochemical modeling is therefore necessary to provide the needed spatial and temporal detail to more completely and accurately estimate the changes in ambient levels of these pollutants and their associated health and welfare impacts. For the final rule, EPA will conduct a national-scale air quality modeling analysis in 2030 to analyze the impacts of the standards on $PM_{2.5}$, ozone, and selected air toxics.

4.2.10 Reductions in emissions of greenhouse gases

Emissions of carbon dioxide and other greenhouse gases (GHGs) occur throughout the process of producing and distributing transportation fuels, as well as from fuel combustion itself. By increasing fuel efficiency and thus reducing the volume of fuel consumed by passenger cars and light trucks, the proposed standards will reduce GHG emissions generated by fuel use, as well as throughout the fuel supply cycle. Lowering these emissions is likely to slow the projected pace and reduce the ultimate extent of future changes in the global climate, thus reducing future economic damages that changes in the global climate are otherwise expected to cause. Further, by reducing the probability that climate changes with potentially catastrophic economic or environmental impacts will occur, lowering GHG emissions may also result in economic benefits that exceed the resulting reduction in the expected future economic costs caused by gradual changes in the earth's climatic systems. Quantifying and monetizing benefits from reducing GHG emissions is thus an important step in estimating the total economic benefits likely to result from establishing improved fuel efficiency and GHG standards.

4.2.10.1 Estimating reductions in GHG emissions

NHTSA estimates emissions of carbon dioxide (CO_2) from passenger car and light truck use by multiplying the number of gallons of each type of fuel (gasoline and diesel) they are projected to consume with each alternative CAFE standard in effect by the quantity or mass of CO_2 emissions released per gallon of fuel consumed. EPA directly calculates CO_2 emissions from the projected CO_2 emissions of each vehicle. This calculation assumes that the entire carbon content of each fuel is ultimately converted to CO_2 emissions during the combustion process. The weighted average CO_2 content of certification gasoline is estimated to be 8,887 grams per gallon, while that of diesel fuel is estimated to be approximately 10,200 grams per gallon. For details, please see EPA's DRIA and NHTSA's PRIA.

Although carbon dioxide emissions account for nearly 95 percent of total GHG emissions that result from fuel combustion during vehicle use, emissions of other GHGs are potentially significant as well because of their higher "potency" as GHGs than that of CO_2 itself. EPA and NHTSA estimated the increases in emissions of methane (CH_4) and nitrous oxide (N_2O) from additional vehicle use by multiplying the increase in total miles driven by cars and light trucks of each model year and age by emission rates per vehicle-mile for these

GHGs. These emission rates, which differ between cars and light trucks as well as between gasoline and diesel vehicles, were estimated by EPA using MOVES 2010a.

The MOVES model assumes that the per-mile rates at which cars and light trucks emit these GHGs are determined by the efficiency of fuel combustion during engine operation and chemical reactions that occur during catalytic after-treatment of engine exhaust, and are thus independent of vehicles' fuel consumption rates. Thus MOVES emission factors for these GHGs, which are expressed per mile of vehicle travel, are assumed to be unaffected by changes in fuel economy.

Much like criteria pollutants, emissions of GHGs occur during each phase of fuel production and distribution, including crude oil extraction and transportation, fuel refining, and fuel storage and transportation. Emissions of GHGs also occur in generating electricity, which the agencies' analysis anticipates will account for an increased share of energy consumption in the model years that would be subject to the proposed rules. The agencies' analyses assume that reductions in fuel consumption would reduce global GHG emissions during all four phases of fuel production and distribution.[aaa] Unlike criteria pollutants, the agencies report both domestic and international reductions in GHG emissions. EPA derived GHG emission rates corresponding to producing and distributing fuel from Argonne National Laboratories' Greenhouse Gases and Regulated Emissions in Transportation (GREET) model.[57][bbb]

As with the non-GHGs, EPA derived national CO_2 emission factors from the IPM version 4.10 run for the "Proposed Transport Rule.[58]" This case features almost no change in the CO2 emission factors from powerplants between 2012 and 2050 (approximately 1%). A similar methodology was used for CO2 as with the criteria pollutants. N2O and CH4 emissions, which are not readily available from IPM, were calculated from eGrid 2007, and scaled according to the growth in CO_2. These non-CO_2 emissions are a small fraction of the emissions from power plants, as shown below in Table 4-15.

Table 4-15 Calender Year 2025 GHG Emission Rates for Electricity

POLLUTANT	CY 2025 ELECTRICITY (g/kWh)
CO_2	539
CH_4	0.01
N_2O	0.01
CO_2eq	541
CO2eq adjusted for	574

[aaa] The four stages are crude oil extraction, crude oil transportation and storage, fuel refining, and fuel distribution and storage

[bbb] This version of the model was modified, and is discussed in section 4.2.9.1

feedstock gathering	

Increases in emissions of non-CO_2 GHGs are converted to equivalent increases in CO_2 emissions using estimates of the Global Warming Potential (GWP) of methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFC-134a).[ccc] These GWPs are one way of accounting for the higher radiative forcing capacity and differing lifetimes of methane and nitrous oxide when they are released into the earth's atmosphere, measured relative to that of CO_2 itself. Because these gases differ in atmospheric lifetimes, their relative damages are not constant over time. Impacts other than temperature change also vary across gases in ways that are not captured by GWP. For instance, CO_2 emissions, unlike methane and other greenhouse gases, contribute to ocean acidification. Methane contributes to health and ecosystem effects arising from increases in tropospheric ozone, while damages from methane emissions are not offset by the positive effect of CO_2 fertilization. Noting these caveats, the CO_2 equivalents of increases in emissions of these gases are then added to the increases in emissions of CO_2 itself to summarize the effect of the total increase in CO_2-equivalent GHG emissions from vehicle use. However, only the CO_2 emissions were monetized for purposes of valuing benefits of the rule, as discussed in the next section.

4.2.10.2 Economic benefits from reducing GHG emissions

NHTSA and EPA have taken the economic benefits of reducing CO_2 emissions (or avoiding damages from increased emissions) into account in developing the proposed GHG and CAFE standards and in assessing the economic benefits of the proposed standards. Specifically, NHTSA and EPA have assigned dollar values to reductions in carbon dioxide (CO_2) emissions using estimates of the global "social cost of carbon" (SCC). The SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change. The SCC is expressed in constant dollars per additional metric ton of CO_2 emissions occurring during a specific year, and is higher for

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[ccc] As in the MYs 2012-2016 rules and in the recent MD and HD rulemakings, the global warming potentials (GWP) used in this proposal are consistent with the 100-year time frame values in the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). At this time, the 1996 IPCC Second Assessment Report (SAR) 100-year GWP values are used in the official U.S. greenhouse gas inventory submission to the United Nations Framework Convention on Climate Change (per the reporting requirements under that international convention, which were last updated in 2006) . N_2O has a 100-year GWP of 298 and CH4 has a 100-year GWP of 25 according to the 2007 IPCC AR4.

more distant future years because the damages caused by an additional ton of emissions increase with larger concentrations of CO_2 in the earth's atmosphere.

The estimates used in this analysis were developed through an interagency process that included EPA, DOT/NHTSA, and other executive branch entities, and concluded in February 2010. The interagency group focused on global SCC values because emissions of CO_2 involve a global externality: greenhouse gases contribute to damages around the world wherever they are emitted. Consequently, to address the global nature of the climate change problem, the SCC must incorporate the full (global) damages caused by GHG emissions. Furthermore, climate change occurs over very long time horizons and represents a problem that the United States cannot solve independently. The February 2010 SCC Technical Support Document (SCC TSD) provides a complete discussion of the SCC estimates and the methods used to develop them.[59]

We first used these SCC estimates in the benefits analysis for the final joint EPA/DOT Rulemaking to establish 2012-2016 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; see the rule's preamble for discussion about application of the SCC (75 FR 25324; 5/7/10). We have continued to use these estimates in other rulemaking analyses, including the Greenhouse Gas Emission Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles (76 FR 57106; 9/15/11). Finally, see also preamble Section III.H.5-6, Section IV.C.3.l, EPA RIA Chapter 7.2, and NHTSA RIA VIII.C for discussion about the application of new SCC estimates to this proposed rule. The SCC estimates corresponding to assumed values of the discount rate are shown below in Table 4-16.

Table 4-16 Social Cost of of CO_2, 2017 – 2050[a] (in 2009 dollars)

Year	Discount Rate and Statistic			
	5% Average	3% Average	2.5% Average	3% 95th percentile
2017	$6.36	$25.59	$40.94	$78.28
2020	$7.01	$27.10	$42.98	$83.17
2025	$8. 53	$30.43	$47.28	$93.11
2030	$10.05	$33.75	$51.58	$103.06
2035	$11.57	$37.08	$55.88	$113.00
2040	$13.09	$40.40	$60.19	$122.95
2045	$14.63	$43. 34	$63.59	$131.66
2050	$16.18	$46.27	$66.99	$140.37

[a] The SCC values apply to emissions occurring during each year shown (in 2009 dollars), and represent the present value of future damages as of the year shown.

As Table 4-16 shows, the SCC estimates selected by the interagency group for use in regulatory analyses range from somewhat more than $6 to about $78 (in 2009 dollars) for emissions occurring in the year 2017. The first three estimates are based on the average SCC estimated using different models and reflect discount rates of 5, 3, and 2.5 percent, respectively. The fourth value is included to represent the possibility of higher-than-expected impacts from accumulation of GHGs in the earth's atmosphere, and the consequently larger economic damages. For this purpose, the interagency group elected to use the SCC value for the 95th percentile at a 3 percent discount rate.

The value that the interagency group centered its attention on is the average SCC estimate at a 3 percent discount rate, or more than $25 per metric ton in 2017. To capture the uncertainties involved in regulatory impact analysis, however, the group emphasized the importance of considering the full range of estimated SCC values. As the table shows, the SCC estimates rise over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change; for example, the central value increases from over $25 per ton of CO_2 in 2017 to almost $34 per ton of CO_2 by 2030.

Reductions in CO_2 emissions that are projected to result from lower fuel consumption, refining, and distribution during each future year are multiplied by the appropriate SCC estimates for that year, to determine the range of total economic benefits from reduced emissions during that year. For internal consistency, these annual benefits are discounted back to net present value terms using a discount rate that is consistent with that used to develop each SCC estimate.

Finally, the SCC estimates presented in this analysis exclude the value of changes in non-CO_2 GHG emissions expected under this program as discussed above in section 4.2.10.1. The interagency group did not estimate the social costs of non-CO2 GHG emissions when it developed the current social cost of CO2 values. Although we have not monetized changes in non-CO_2 GHGs, the value of any increases or reductions should not be interpreted as zero.

4.2.11 The Benefits due to reduced refueling time

No direct estimates of the value of extended vehicle range are readily available, so the agencies instead calculate the reduction in the required annual number of refueling cycles due to improved fuel economy, and assess the economic value of the resulting benefits. Chief among these benefits is the time that owners save by spending less time both in search of fueling stations and in the act of pumping and paying for fuel.

The agencies calculate the economic value of those time savings by applying DOT-recommended values of travel time savings to our estimates of how much time is saved.[60] The value of travel time depends on average hourly valuations of personal and business time, which are functions of total hourly compensation costs to employers. The total hourly compensation cost to employers, inclusive of benefits, in 2009$ is $29.37.[ddd] Table 4-17 demonstrates the agencies' approach to estimating the value of travel time ($/hour) for both urban and rural (intercity) driving. This approach relies on the use of DOT-recommended weights that assign a lesser valuation to personal travel time than to business travel time, as well as weights that adjust for the distribution between personal and business travel.

[ddd] Total hourly employer compensation costs for 2009 (average of quarterly observations). See http://www.bls.gov/ect/. NHTSA previously a value of $25.50 for the total hourly compensation cost (*see*, *e.g.*, 75 FR at 25588, fn. 619) during 2008 expressed in 2007$. This earlier figure is deprecated by the availability of more current economic data.

Table 4-17 Estimating the Value of Travel Time For Urban and Rural (Intercity) Travel ($/hour)[eee]

Urban Travel			
	Personal travel	**Business Travel**	**Total**
Wage Rate ($/hour)	$29.37	$29.37	-
DOT-Recommended Value of Travel Time Savings, as % of Wage Rate	50%	100%	-
Hourly Valuation (=Wage Rate * DOT-Recommended Value)	$14.69	$29.37	-
% of Total Urban Travel	94.4%	5.6%	100%
Hourly Valuation (Adjusted for % of Total Urban Travel)	$13.86	$1.64	**15.50**
Rural (Intercity) Travel			
	Personal travel	**Business Travel**	**Total**
Wage Rate ($/hour)	$29.37	$29.37	-
DOT-Recommended Value of Travel Time Savings, as % of Wage Rate	70%	100%	-
Hourly Valuation (=Wage Rate * DOT-Recommended Value)	$20.56	$29.37	-
% of Total Rural Travel	87.0%	13.0%	100%
Hourly Valuation (Adjusted for % of Total Rural Travel)	$17.89	$3.82	**21.71**

The estimates of the hourly value of urban and rural travel time ($15.50 and $21.71, respectively) shown in Table 4-17 must be adjusted to account for the nationwide ratio of urban to rural driving. By applying this adjustment (as shown in Table 4-18), an overall estimate of the hourly value of travel time – independent of urban or rural status – may be produced. Note that up to this point, all calculations discussed assume only one adult

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[eee] Time spent on personal travel during rural (intercity) travel is valued at a greater rate than that of urban travel. There are several reasons behind the divergence in these values: 1) time is scarcer on a long trip; 2) a long trip involves complementary expenditures on travel, lodging, food, and entertainment, since time at the destination is worth such high costs.

occupant per vehicle. To fully estimate the average value of vehicle travel time, the agency must account for the presence of additional adult passengers during refueling trips. The agencies apply such an adjustment as shown in Table 4-18; this adjustment is performed separately for passenger cars and for light trucks, yielding occupancy-adjusted valuations of vehicle travel time during refueling trips for each fleet.

Table 4-18 Estimating the Value of Travel Time for Light-Duty Vehicles ($/hour)

	Unweighted Value of Travel Time ($/hour)	**Weight (% of Total Miles Driven)[fff]**	**Weighted Value of Travel Time ($/hour)**
Urban Travel	$15.50	66.5%	$10.31
Rural Travel	$21.71	33.5%	$7.27
Total	--	100.0%	$17.58

	Passenger Cars	**Light Trucks**
Average Vehicle Occupancy During Refueling Trips (persons)[ggg]	1.21	1.23
Weighted Value of Travel Time ($/hour)	$17.58	$17.58
Occupancy-Adjusted Value of Vehicle Travel Time During Refueling Trips ($/hour)	**$21.27**	**$21.62**

NHTSA estimated the amount of refueling time saved using (preliminary) survey data gathered as part of our 2010-2011 National Automotive Sampling System's Tire Pressure Monitoring System (TPMS) study.[hhh] The study was conducted at fueling stations nationwide, and researchers made observations regarding a variety of characteristics of thousands of individual fueling station visits from August, 2010 through April, 2011.[iii]

[fff] Weights used for urban vs. rural travel are computed using cumulative 2009 estimates of urban vs. rural miles driven provided by the Federal Highway Administration. *Available at* http://www.fhwa.dot.gov/policyinformation/travel_monitoring/tvt.cfm (last accessed 07/18/2011).

[ggg] National Automotive Sampling System 2010-2011 Tire Pressure Monitoring System (TPMS) study. See next page for further background on the TPMS study. TPMS data are preliminary at this time and rates are subject to change pending availability of finalized TPMS data. Average occupancy rates shown here are specific to refueling trips, and do not include children under 16 years of age.

[hhh] TPMS data are preliminary and not yet published. Estimates derived from TPMS data are therefore preliminary and subject to change. Observational and interview data are from distinct subsamples, each consisting of approximately 7,000 vehicles. For more information on the National Automotive Sampling System and to access TPMS data when they are made available, see http://www.nhtsa.gov/NASS.

[iii] The data collection period for the TPMS study ranged from 08/10/2010 to 04/15/2011.

Among these characteristics of fueling station visits is the total amount of time spent pumping and paying for fuel. From a separate sample (also part of the TPMS study), researchers conducted interviews at the pump to gauge the distances that drivers travel in transit to and from fueling stations, how long that transit takes, and how many gallons of fuel are being purchased.

For purposes of this analysis of the proposed standards, the NHTSA focused on the interview-based responses in which respondents indicated the primary reason for the refueling trip was due to a low reading on the gas gauge.[jjj] This restriction was imposed so as to exclude distortionary effects of those who refuel on a fixed (*e.g.*, weekly) schedule and may be unlikely to alter refueling patterns as a result of increased driving range. The relevant TPMS survey data on average refueling trip characteristics are presented below in Table 4-19.

Table 4-19 Average Refueling Trip Characteristics for Passenger Cars and Light Trucks

	Gallons of Fuel Purchased	**Round-Trip Distance to/from Fueling Station (miles)**	**Round-Trip Time to/from Fueling Station (minutes)**	**Time to Fill and Pay (minutes)**	**Total Time (minutes)**
Passenger Cars	9.8	0.97	2.28	4.10	6.38
Light Trucks	13.0	1.08	2.53	4.30	6.83

As an illustration of how we estimate the value of extended refueling range, assume a small light truck model has an average fuel tank size of approximately 20 gallons, and a baseline actual on-road fuel economy of 24 mpg. TPMS survey data indicate that drivers who indicated the primary reason for their refueling trips was a low reading on the gas gauge typically refuel when their tanks are 35 percent full (*i.e.,* 13.0 gallons as shown in Table 4-19, with 7.0 gallons in reserve). By this measure, a typical driver would have an effective driving range of 312 miles (= 13.0 gallons x 24 mpg) before he or she is likely to refuel. Increasing this model's actual on-road fuel economy from 24 to 25 mpg would therefore extend its effective driving range to 325 miles (= 13.0 gallons x 25 mpg). Assuming that the truck is driven 12,000 miles/year,[kkk] this 1 mpg improvement in actual on-road fuel economy reduces

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[jjj] Approximately 60 percent of respondents indicated "gas tank low" as the primary reason for the refueling trip in question.

[kkk] Source of annual vehicle mileage: U.S. Department of Transportation, Federal Highway Administration, 2009 National Household Travel Survey (NHTS). See http://nhts.ornl.gov/2009/pub/stt.pdf (table 22, p.48). 12,000 miles/year is an approximation of a light duty vehicle's annual mileage during its initial decade of use (the

the expected number of refueling trips per year from 38.5 (= 12,000 miles per year / 312 miles per refueling) to 36.9 (= 12,000 miles per year / 325 miles per refueling), or 1.6 refuelings per year. If a typical fueling cycle for a light truck requires a total of 6.83 minutes, then the annual value of time saved due to that 1 mpg improvement would amount to $3.94 (= (6.83/60) x $21.62 x 1.6).

In the analysis, we repeat this calculation for each future calendar year that light-duty vehicles of each model year affected by the alternative standards considered in this rule would remain in service. The resulting cumulative lifetime valuations of time savings account for both the reduction over time in the number of vehicles of a given model year that remain in service and the reduction in the number of miles (VMT) driven by those that stay in service. We also adjust the value of time savings that will occur in future years both to account for expected annual growth in real wages and to apply a discount rate to determine the net present value of time saved.[lll] A final adjustment is made to account for evidence from the TPMS study which suggests that 40 percent of refueling trips are for reasons other than a low reading on the gas gauge; it is therefore assumed that only 60 percent of the theoretical refueling time savings will be realized, as we assume that owners who refuel on a fixed schedule will continue to do.The assumption that the 40 percent of refueling trips that occur for reasons other than a low reading on the gas gauge will not realize a refueling time savings may be a conservative assumption. Results are calculated separately for a given model year's fleet of passenger cars and that year's fleet of light trucks. Valuations of both fleets' benefits are then summed to determine the benefit across all light-duty vehicles.

Since a reduction in the expected number of annual refueling trips leads to a decrease in miles driven to and from fueling stations, we can also calculate the value of consumers' fuel savings associated with this decrease. As shown in Table 4-19, the typical incremental round-trip mileage per refueling cycle is 1.08 miles for light trucks and 0.97 miles for passenger cars. Going back to the earlier example of a light truck model, a decrease of 1.6 in the number of refuelings per year leads to a reduction of 1.73 miles driven per year (= 1.6 refuelings x 1.08 miles driven per refueling). Again, if this model's actual on-road fuel economy was 24 mpg, the reduction in miles driven yields an annual savings of approximately 0.07 gallons of fuel (= 1.73 miles / 24 mpg), which at $3.44/gallon[mmm] results in a savings of $0.25 per year to the owner. Note that this example is illustrative only of the approach the agencies uses to quantify this benefit; in practice, the value of this benefit is

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period in which the bulk of benefits are realized). The VOLPE model estimates VMT by model year and vehicle age, taking into account the rebound effect, secular growth rates in VMT, and fleet survivability; these complexities are omitted in the above example for simplicity.

[lll] A 1.1 percent annual rate of growth in real wages is used to adjust the value of travel time per vehicle ($/hour) for future years for which a given model is expected to remain in service. This rate is supported by a BLS analysis of growth in real wages from 2000 – 2009. See http://www.bls.gov/opub/ted/2011/ted_20110224.htm.

[mmm] Estimate of $3.44/gallon is in 2009$. This figure is an average of forecasted cost per gallon (including taxes, as individual consumers consider reduced tax expenditures to be savings) for motor gasoline for years 2017 to 2027. Source of price forecasts: U.S. Energy Information Administration, Annual Energy Outlook 2011 (April 2011 release). See http://www.eia.gov/forecasts/aeo/source_oil.cfm.

modeled using fuel price forecasts for each year the given fleet will remain in service, and unlike the above example excludes fuel taxes from the computation of the total social benefit, as taxes are transfer payments.

The annual savings to each consumer shown in the above example may seem like a small amount, but the reader should recognize that the valuation of the cumulative lifetime benefit of this savings to owners is determined separately for passenger car and light truck fleets and then aggregated to show the net benefit across all light-duty vehicles – which is much more significant at the macro level. Calculations of benefits realized in future years are adjusted for expected real growth in the price of gasoline, for the decline in the number of vehicles of a given model year that remain in service as they age, for the decrease in the number of miles (VMT) driven by those that stay in service, and for the percentage of refueling trips that occur for reasons other than a low reading on the gas gauge; a discount rate is also applied in the valuation of future benefits. The agencies considered using this direct estimation approach to quantify the value of this benefit by model year, however the value of this benefit is implicitly captured in the separate measure of overall valuation of fuel savings, and therefore direct estimates of this benefit are not added to net benefits calculations.

We note that there are other benefits resulting from the reduction in miles driven to and from fueling stations, such as a reduction in greenhouse gas emissions – CO_2 in particular, reductions in evaporative emissions from refuelings, and reduced wear on vehicles. However, estimates of the values of these benefits indicate that both are extremely minor in the context of the overall valuation of benefits associated with gains in vehicle driving range, so quantitative valuations of these additional benefits are not included within this analysis.

It is important to note that manufacturers' decisions regarding vehicles' fuel tank sizes are integral to the realized value of this benefit. In MY 2010, fuel tanks were sized such that average driving range of passenger cars was 410 miles and of light trucks was 430 miles. At vehicle redesign, manufacturers typically redesign fuel tanks based on changes in vehicle design and the allowable space for the fuel tank. At redesign, manufacturers consider driving range, cargo and passenger space (utility), mass targets, safety, and other factors. As fuel economy improves, manufacturers may opt at the time of vehicle redesign to downsize vehicles' fuel tanks as a mass-reduction strategy and to maintain a target maximum range consistent with previous models. Downsizing the fuel tank offers the potential for moderate mass reduction[nnn] at a small cost savings. It is also possible for manufacturers to reduce the effective size of their fuel tanks by changing the length of the fill tube, which does not require redesign of the tank itself. In determining the maximum feasible amount of mass reduction and the cost curves developed for mass reduction, the agencies used an assumption that fuel tanks would be resized to maintain range. If a manufacturer did not downsize the fuel tank to

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[nnn] For example, for a vehicle with a 15 gallon fuel tank and a 400 mile range, increasing fuel economy by 50% and downsizing the fuel tank to maintain range would enable a mass reduction of approximately 32 pounds based on the reduction in the amount of fuel alone. If the fuel tank was not downsized, the range of the vehicle would increase to 600 miles.

maintain range, it could incur higher costs for compliance than the agencies projections because the manufacturer may need to employ other higher cost technologies to achieve the small incremental change in fuel economy and GHG improvements attributed to the reduction in the mass of the fuel tank. If manufacturers elect to reduce fuel tank size in response to improved fuel economy to maintain range, the value of the refueling time savings benefit will be reduced because the number of trips to the gasoline station would not be reduced as much as estimated. Reductions to fuel tank size will not eliminate the value of the refueling time savings benefit, however, unless they are performed annually to maintain a constant range. Also, the reduced time for refueling and reduction in evaporative emissions would be unchanged. The agencies believe that annual refreshes of fuel tank size during the years in-between model redesigns are unlikely; therefore, while downsizing fuel tanks would decrease the realized value of the refueling time savings benefit, it would not eliminate it, assuming that fuel economy rises in those interim years.

The agencies considered past trends to evaluate potential outcomes with regard to the refueling time savings benefit. Fuel tank sizes by broad vehicle class has been nearly flat over the past 20 years, with average light truck fuel tank volume slightly decreasing in recent years, and average passenger car fuel tank volume slightly increasing in size in recent years. These changes, less a gallon change in average fuel tanks size over twenty years, are slight.

Tank sizes for popular passenger cars and light trucks in recent model years typically allow for maximum driving ranges of between 300 and 500 miles. In MY 2010, the average driving range for light trucks was approximately 430 miles, while the average driving range for cars was 410 miles, and the average range for the combined fleet was approximately 420 miles (Figure 4-3). This compares to average ranges of 390 miles (trucks), 360 miles (cars) and 370 miles (fleet) in MY 1990. While the linear trend shows a small increase in range (5-10%) over this time period, the factors discussed above preclude drawing simple conclusions about the relationship between increases in average fuel economy and changes in fuel tank size. As an example – in MY 2010, greater proportional sales of I4 sedans were seen as compared to previous years. Since I4 and V6 sedan typically share the fuel tank component, the 2009/2010 spike in range (corresponding to the dip in fuel consumption in the previous chart) may or may not be a lasting increase, depending on manufacturer’s redesign choices.

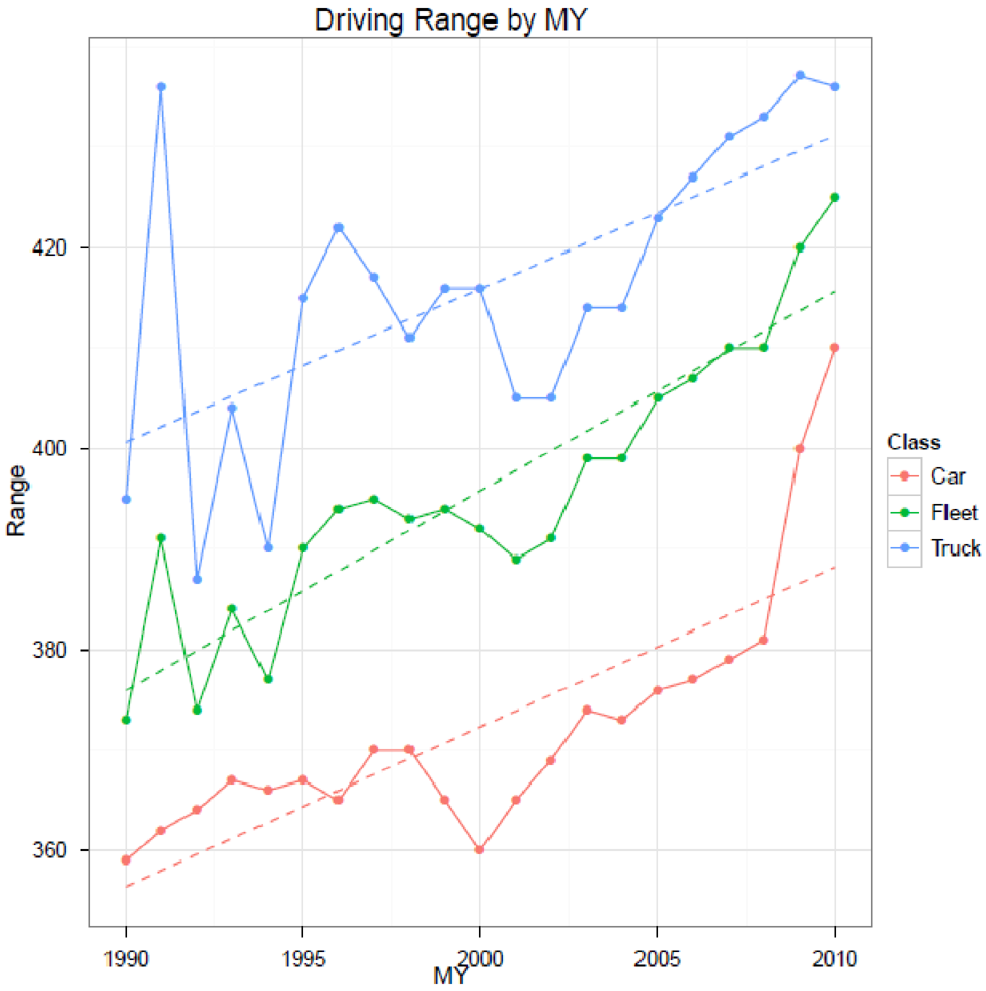

Figure 4-3 Driving range by MY

The agencies seek comment on the method and assumptions being used to estimate the refueling benefit.

4.2.12 Discounting future benefits and costs

Discounting future fuel savings and other benefits is intended to account for the reduction in their value to society when they are deferred until some future date, rather than received immediately. The discount rate expresses the percent decline in the value of these benefits – as viewed from the current perspective – for each year they are deferred into the future. In evaluating the benefits from alternative increases in fuel economy and GHG standards for MY 2017-2025 passenger cars and light trucks, EPA and NHTSA consider discount rates of both 3 and 7 percent per year.

Three percent may be the appropriate rate for discounting future benefits from increased fuel economy and GHG standards because most or all of vehicle manufacturers' costs for complying with improved fuel economy and GHG standards are likely to be reflected in higher sales prices for their new vehicle models. By increasing sales prices for new cars and light trucks, GHG and CAFE regulations will thus primarily affect vehicle purchases and other private consumption decisions.

Both economic theory and OMB guidance on discounting indicate that the future benefits and costs of regulations that mainly affect private consumption should be discounted at the consumption rate of time preference.61 OMB guidance indicates that savers appear to discount future consumption at an average real (that is, adjusted to remove the effect of inflation) rate of about 3 percent when they face little risk about its likely level, which makes it a reasonable estimate of the consumption rate of time preference.62 Thus EPA and NHTSA have employed the 3 percent rate to discount projected future benefits and costs resulting from improved fuel economy and GHG standards for MY 2017-2025 passenger cars and light trucks.

Because there is some uncertainty about the extent to which vehicle manufacturers will be able to recover their costs for complying with improved fuel economy and GHG standards by increasing vehicle sales prices, however, the use of a higher percent discount rate may also be appropriate. OMB guidance indicates that the real economy-wide opportunity cost of capital is the appropriate discount rate to apply to future benefits and costs when the primary effect of a regulation is "…to displace or alter the use of capital in the private sector," and estimates that this rate currently averages about 7 percent.63 Thus the agencies estimate net present values using both 3 and 7 percent discount rates.

One important exception to these values are the rates used to discount benefits from reducing CO_2 emissions from the years in which reduced emissions occur, which span the lifetimes of model year 2017-2025 cars and light trucks, to their present values. In order to ensure consistency in the derivation and use of the SCC estimates of the unit values of reducing CO_2 emissions, the total benefits from reducing those emissions during each future year are discounted using the same rates that were used to derive the alternative values of reducing each ton of CO_2 emissions (2.5, 3.0, and 5.0 percent).

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Chapter 5: Air Conditioning, Off-Cycle Credits, and Other Flexibilities

5.1 Air conditioning technologies and credits

5.1.1 Overview

Air conditioning (A/C) is virtually standard equipment in new cars and trucks, as over 95% of the new cars and light trucks in the United States are equipped with mobile air conditioning (or MAC) systems. Given the large penetration of A/C in today's light duty vehicle fleet, its impact on the amount of energy consumed is significant. In the 2012-2016 Light-Duty Greenhouse Gas Rule, EPA structured the rule to allow vehicle manufacturers' to generate credits for improved air conditioner systems in complying with the CO_2 fleetwide average standards. EPA is proposing to continue with and expand upon these provisions the result being that manufacturers could generate credits for improved performance of both direct (A/C leakage) and indirect (tailpipe emissions attributable to A/C use) A/C emissions.

Through model years 2012-2016, the EPA expects that manufacturers will take advantage of the A/C credits offered (for reduced leakage and improved efficiency) in the previous rule in order to help come into compliance with the standards. EPA estimated that there would be significant penetration of A/C technologies to gain credits, and this was reflected in the stringency of the standards.[a] Consistent with the fleet definitions from Chapter 1 of the joint TSD, the base level of A/C technologies in 2008 forms the A/C "baseline", and the A/C technologies projected to penetrate to the fleet in 2016 is referred to as the A/C "reference". For this 2017-2025 rule the EPA is proposing to maintain the crediting program starting from the baseline (MY 2008). The credits should continue to the present rule since without them, a manufacturer utilizing credits in 2016 could suddenly find in 2017 that the stringency of the standards are artificially increased due to discontinued A/C credits.[b] In this chapter, A/C credits are accounted from the baseline (though there are some changes to the credit program), while costs are accounted from the reference. Any additional A/C credits projected for 2017-2025 are reflected in the stringency of the standards as described in Section III.C.1 of the proposed preamble. EPA in coordination NHTSA is proposing for this 2017-2025 rule to allow manufacturers to include fuel consumption reductions related to improvements in A/C system efficiency (indirect) in their CAFE calculations. In the 2012 to 2016 rule, EPA and NHTSA did not allow manufacturers to include reductions in fuel consumption resulting from A/C operation (indirect) in the CAFE

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[a] NHTSA will also be referencing these efficiency improving A/C technologies in their rule, but they will be referred to as "fuel consumption improvements" instead of credits. For the purpose of this document, the term "credit" can be considered synonymous with the phrase "fuel consumption improvement" wherever efficiency-improving A/C technologies are discussed.

[b] Put another way, the 2016 GHG standards would remain even if there were no new 2017-2025 standards and A/C credits would also continue. Thus, if the AC credits were removed or significantly changed from these (perpetuated) post-2016 standards, the stringency of those standards would effectively be increased.

calculations. As was the case in the 2012 to 2016 rule, the agency is not proposing to provide credit for reductions in HFC leakage. A discussion of how this change will be implemented is provided in this chapter.

A/C is different from the other technologies described in Chapter 3 of the joint TSD in several ways. First, most of the technologies described earlier directly affect the efficiency of the engine, transmission, and vehicle systems. As such, these systems are almost always active while the vehicle is moving down the road or being tested on a dynamometer for the fuel economy and emissions test drive cycles. A/C, on the other hand, is a parasitic load on the engine that only burdens the engine when the vehicle occupants demand it. Since it is not tested as a part of the fuel economy and emissions test drive cycles – with the exception of the SC03 cycle - it is referred to as an "off-cycle" effect. There are many other off-cycle loads that can be switched on by the occupant that affect the engine; these include lights, wipers, stereo systems, electrical defroster/defogger, heated seats, power windows, etc. However, these electrical loads individually amount to a very small effect on the engine (although together they can be significant). The A/C system (by itself) adds a significant load on the engine, resulting in increased fuel consumption, or "indirect" CO_2 emissions.

There are two mechanisms by which A/C systems contribute to the emissions of greenhouse gases. The first is through direct leakage of the refrigerant into the air. The hydrofluorocarbon (HFC) refrigerant compound currently used in all recent model year vehicles is R-134a (also known as 1,1,1,2-Tetrafluoroethane, or HFC-134a). Based on the higher global warming potential of HFCs, a small leakage of the refrigerant has a greater global warming impact than a similar amount of emissions of some other mobile source GHGs. R-134a has a global warming potential (GWP) of 1,430. This means that 1 gram of R-134a has the equivalent global warming potential of 1,430 grams of CO2 (which has a GWP of 1). In order for the A/C system to take advantage of the refrigerant's thermodynamic properties and to exchange heat properly, the system must be kept at high pressures even when not in operation. Typical static pressures can range from 50-80 psi depending on the temperature, and during operation, these pressures can get to several hundred psi. At these pressures leakage can occur through a variety of mechanisms. The refrigerant can leak slowly through seals, gaskets, and even small failures in the containment of the refrigerant. Through normal use, the rate of leakage may also increase due to wear on the system components. Leakage may also increase more quickly through rapid component deterioration such as during vehicle accidents, maintenance or end-of-life vehicle scrappage (especially when refrigerant capture and recycling programs are less efficient). Small amounts of leakage can also occur continuously even in extremely "leak-tight" systems by permeating through hose membranes and seals. This last mechanism is not dissimilar to fuel permeation through porous fuel lines (and seals). Manufacturers may be able to reduce these leakage emissions through the implementation of technologies/designs such as leak-tight, non-porous, durable components. The global warming impact of leakage emissions also can be addressed by using alternative refrigerants, such as HFO-1234yf, R-744 (CO2), HFC-152a (R-152a), or other refrigerants under development with lower global warming potentials. Refrigerant emissions can also occur during maintenance and at the end of the vehicle's life (as well as emissions during the initial charging of the system with refrigerant), and these emissions are already addressed by the CAA Title VI stratospheric ozone program, as described below.[c]

The second mechanism by which vehicle A/C systems contribute to GHG emissions is through the consumption of additional fuel required to provide power to the A/C system and from carrying around the weight of the A/C system hardware year-round. These indirect emissions result from the additional fuel which is required to provide power to the A/C system (and the additional fuel is converted into CO_2 by the engine during combustion). These increased emissions due to A/C operation can be reduced by increasing the overall efficiency of the vehicle's A/C system, as described below. EPA does not plan to address modifications to the weight of the A/C system, since the incremental increase in CO_2 emissions and fuel consumption due to carrying the A/C system is directly measured during the normal federal test procedure, and is thus already accounted for in the CO_2 tailpipe standard.

EPA's analysis from the MY 2012-2016 rule indicates that A/C-related indirect emissions represent about 3.9% of the total greenhouse gas emissions from cars and light trucks. In this document, EPA will separate the discussion of these two categories of A/C-related emissions because of the fundamental differences in the emission mechanisms and the methods of emission control. Refrigerant leakage control is akin in many respects to past EPA fuel evaporation control programs (in that containment of a fluid is the key feature), while efficiency improvements are more similar to the vehicle-based control of CO_2 using the technologies described in chapter 3 of the joint TSD in that emission reductions would be achieved through specific hardware and controls.

5.1.2 Air Conditioner Leakage

5.1.2.1 Impacts of Refrigerant Leakage on Greenhouse Gas Emissions

There have been several studies in the literature which have attempted to quantify the emissions (and impact) of air conditioner HFC emissions from light duty vehicles. In this section, several of these studies are discussed. These inventories and impacts form the basis for the air conditioner environmental credits, and in this proposal, we are using the same emissions inventory and analysis method for refrigerant leakage as we did in the 2012-2016 rule as described in section 5.1.2.2.3.

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[c] Even if A/C systems utilize a "low-GWP" refrigerant, such as HFO-1234yf (GWP = 4), emissions is still a concern. First, as refrigerant leaks from the system, once the refrigerant level drops to 40 to 50 percent of its normal capacity, the operating efficiency of the system will degrade, resulting in an increase in fuel consumption due to A/C use, and an increase in indirect emissions, Second, if systems do leak refrigerant at an excessive rate, there is a higher probability that someone will unlawfully recharge the system with a cheaper, and higher-GWP refrigerant, resulting in increased direct emissions.

Based on measurements from 300 European vehicles (collected in 2002 and 2003), Schwarz and Harnisch estimate that the average HFC direct leakage rate from modern A/C systems was 53 g/yr.[1] This corresponds to a leakage rate of 6.9% per year. This was estimated by extracting the refrigerant from recruited vehicles and comparing the amount extracted to the amount originally filled (as per the vehicle specifications). The fleet and size of vehicles differs from Europe and the United States, therefore it is conceivable that vehicles in the United States could have a different leakage rate. The authors measured the average charge of refrigerant at initial fill to be about 747 grams (it is somewhat higher in the U.S. at 770g), and that the smaller cars (684 gram charge) emitted less than the higher charge vehicles (883 gram charge). Moreover, due to the climate differences, the A/C usage patterns also vary between the two continents, which may influence leakage rates.

Vincent et al., from the California Air Resources Board estimated the in-use refrigerant leakage rate to be 80 g/yr.[2] This is based on consumption of refrigerant in commercial fleets, surveys of vehicle owners and technicians. The study assumed an average A/C charge size of 950 grams and a recharge rate of 1 in 16 years (lifetime). The recharges occurred when the system was 52% empty and the fraction recovered at end-of-life was 8.5%.

5.1.2.1.1 Emission Inventory

The EPA publishes an inventory of greenhouse gases and sinks on an annual basis. The refrigerant emissions numbers that are used in the present analysis are from the Vintaging model, which is used to generate the emissions included in this EPA inventory source. The HFC refrigerant emissions from light duty vehicle A/C systems was estimated to be 61.8 Tg CO_2 equivalent in 2005 by the Vintaging model.[3,d] In 2005, refrigerant leakage accounted for about 5.1% of total greenhouse gas emissions from light duty sources. From a vehicle standpoint, the Vintaging model assumes that 42% of the refrigerant emissions are due to direct leakage (or “regular” emissions), 49% for service and maintenance (or “irregular” emissions), and 9% occurs at disposal or end-of-life as shown in the following table. These are based on assumptions of the average amount of chemical leaked by a vehicle every year, how much is lost during service of a vehicle (from professional service center and do-it-yourself practices), and the amount lost at disposal. These numbers vary somewhat over time based on the characteristics (e.g. average charge size and leakage rate) of each “vintage” of A/C system, assumptions of how new A/C systems enter the market, and the number of vehicles disposed of in any given year.

Table 5-1 Light Duty Vehicle HFC-134a Emissions in 2005 from Vintaging Model - HFC Emissions Multiplied by 1430 GWP to Convert to CO_2 Equivalent

Emission Process	HFC emissions (metric tons)	Fraction of total

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[d] EPA reported the MVAC emissions at 56.6 Tg CO_2 EQ, using a GWP of 1300. This number has been adjusted using a GWP of 1430.

Leakage	18,151	0.42
Maintenance/servicing	21,176	0.49
Disposal/end-of-life	3,890	0.09
Total	43,217	1.0

5.1.2.1 Alternative Refrigerants

Leakage emissions can also be reduced with the use of refrigerants other than R-134a, which has a global warming potential (GWP) of 1430. To address future GHG regulations in the Europe Union and the State of California, air conditioning systems which use alternative refrigerants are under serious development, and have been demonstrated in prototypes by vehicle manufacturers and A/C component suppliers. The European Union has enacted regulations which require the use of refrigerants with a GWP less than 150. Phase-in of these EU regulations began with new vehicle platforms in 2011, and will be completely phased-in for all vehicles by 2017. Some of the alternative refrigerants under development by manufacturers and A/C component suppliers include HFO-1234yf, CO_2, HFC-152a, and low-GWP blends of existing refrigerants. The air conditioning component and refrigerant manufacturers, as well as automotive manufacturers, are actively studying the performance, efficiency, safety, and cost of these alternative refrigerants.

HFO-1234yf, with a GWP of 4, is a leading candidate as an alternative to R-134a refrigerant. For example, General Motors has selected HFO1234yf for use in certain model year 2013 vehicles.[4] While the performance and efficiency of A/C systems using HFO-1234yf can be equivalent to those using HFC-134a, the higher cost of implementing this refrigerant – estimated at $67 per vehicle in model year 2016 (see section 5.1.4) – is causing the industry to consider other solutions which are lower-cost.

A so-called "natural refrigerant" under consideration is CO_2, which has a GWP of 1. While this refrigerant is environmentally neutral from a GWP perspective (i.e. relative to a CO_2 baseline), and is currently used in some commercial refrigeration units, its use in automotive applications is challenging due to the higher operating pressure of CO_2 systems, where the peak pressure can be as high as 2000 PSI, compared to the peak pressure in HFC-134a systems of around 450 PSI. Several European auto manufacturers have successfully developed CO_2 A/C systems, but none have been produced for use in new vehicles at this time. An A/C system which uses CO_2 is estimated to cost $139 to $209 more than an equivalent HFC-134a system; however, the cost of the refrigerant itself is expected to be considerably less than HFO-1234yf.[5]

HFC-152a (1,1-difluoroethane) is a flammable refrigerant with a GWP of 120 and an ASHRAE flammability designation of Class 2. Given the flammability of this refrigerant, we expect that manufacturers would either need to design their A/C systems with a secondary loop or with directed relief valves to mitigate safety concerns within the cabin area, and to comply with the use conditions at 40 CFR Part 82 Subpart G Appendix B. With a secondary loop design, the evaporator is not located inside the passenger cabin area, but inside a chiller in an underhood location, where a secondary fluid (such as an ethylene glycol-water mixture) is circulated to transfer heat from the cabin to the chiller. This approach requires additional system components (chiller, pump, reservoir, and plumbing for secondary loop), which adds an estimated 12 lbs. of mass to the vehicle.[6] With the directed relief valve design, the refrigerant within the A/C system is vented and ducted to the atmosphere by opening high and low-side relief valves when a leak is detected.[7] The advantage of the directed relief valve approach (relative to a secondary loop) is that fewer components are needed, potentially minimizing the mass and cost of the system.

Other alternative refrigerants which may be used in the future may include low-GWP blends. Recent studies have shown that the low-GWP refrigerant blends AC5 and AC6 from the chemical manufacturer Mexichem, have performance and efficiency characteristics which are similar to HFC-134a under high-load (maximum cooling) conditions, and slightly reduced performance and efficiency under low-load conditions. These mildly-flammable (similar to HFO-1234yf) refrigerant blends, being comprised of several different refrigerant components, have zeotropic properties. This means that the fraction of each component in the gas and liquid phases is not constant, and varies with temperature and pressure within the system.[8] Zeotropic behavior may result in mal-distribution of the refrigerant within the evaporator and condenser, which negatively affects system efficiency, especially at low loads.[9] However, it is believed that optimization of evaporator and condenser design can improve the load-load efficiency. These blends may be similar enough in performance and in their physical characteristics to HFC-134a and HFO-1234yf that they may be used in current production A/C systems designs with relatively minor modifications

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We expect that stakeholders in the automotive A/C industry will continue to study and develop low-GWP refrigerant solutions in order to minimize the direct and indirect impact of A/C-related emissions. With the statutory requirements for low-GWP refrigerants in the European Union, which began in model year 2011 for new vehicles designs, we expect that one or more of these low-GWP solutions will be available for at least 20% of the U.S. vehicle fleet by model year 2017, and that an additional 20% of the fleet can adopt the alternative refrigerant in each subsequent model year. EPA expects that manufacturers would be changing over to alternative refrigerants at the time of complete vehicle redesign, which occurs about every 5 years, though in confidential meetings, some manufacturers/suppliers have informed EPA that it may be possible to modify the hardware for some alternative refrigerant systems between redesign periods.

5.1.2.2 A/C Leakage Credit

The level to which each technology can reduce leakage can be estimated using the SAE Surface Vehicle Standard J2727 – HFC-134a Mobile Air Conditioning System Refrigerant Emission Chart. While this standard was developed for leakage of HFC-134a refrigerant, it is also applicable to the alternative refrigerant HFO-1234yf, and may be applicable to other low-GWP refrigerants as well. To convert J2727 chart emission (leak) rates from HFC-134a to HFO-1234yf leakage rates, the result is multiplied by the ratio of the molecular weights of the two refrigerants, or 114 divided by 102.

The J2727 standard was developed by SAE and the cooperative industry and government IMAC (Improved Mobile Air Conditioning) program using industry experience, laboratory testing of components and systems, and field data to establish a method for calculating leakage. With refrigerant leakage rates as low as 10 g/yr, it would be exceedingly difficult to measure such low levels in a test chamber (or shed). Since the J2727 method has been correlated to "mini-shed", or SAE J2763, results (where A/C components are tested for leakage in a small chamber, simulating real-world driving cycles), the EPA considers this method to be an appropriate surrogate for vehicle testing of leakage.[10] It is also referenced by the California Air Resources Board in their Environmental Performance Label regulation and the State of Minnesota in their GHG reporting regulation.[11,12]

5.1.2.2.1 Why Is EPA Relying on a Design-Based Approach to Quantify Leakage?

As in the 2012-2016 rule, EPA will continue to use a design-based method for quantifying refrigerant leakage from A/C systems. In the time since the 2012 rule was finalized, the Agency was not informed of any new approaches or methods for measuring actual refrigerant leak rates. While EPA generally prefers performance testing for emissions, a feasible method for measuring refrigerant emissions accurately from a vehicle is not available, and we are proposing for MY 2017-2025 a continuation of the SAE J2727-based approach adopted in the 2012-2016 rule. EPA believes that the SAE J2727 method, as discussed below, is an appropriate method for quantifying the expected yearly refrigerant leakage rate from A/C systems.

5.1.2.2.2 How Would Leakage Credits Be Calculated?

For model years 2017 through 2025, the A/C credit available to manufacturers will be calculated based on how much a particular vehicle's annual leakage value is reduced compared to an average MY 2008 vehicle with baseline levels of A/C technology, and will be calculated using a method drawn directly from the updated SAE J2727 approach (for details on these updates, see 5.1.2.2.2.2). By scoring the minimum leakage rate possible on the J2727 components enumerated in the rule (expressed as a measure of annual leakage), a manufacturer can generate the maximum A/C credit (on a gram per mile basis). To avoid backsliding on leakage rates when using low-GWP refrigerants, where manufacturers could choose less costly sealing technologies and/or materials, EPA is proposing a disincentive credit for "high leak" on alternative refrigerant systems. The maximum value for this high leak disincentive credit (or HiLeakDisincentive) is 1.8 g/mi for cars and 2.1 g/mi for trucks, with lower amounts possible for leakage rates between the minimum leakage score (MinScore) and the average impact (AvgImpact). The terms used for calculating the A/C Leakage Credit as well as the HiLeakDisincentive are discussed later in this section.

The A/C credit available to manufacturers will be calculated based on the reduction to a vehicle's yearly leakage rate, using the following equation:

Equation 5-1 Credit Equation

$$\text{A/C Leakage Credit} = (\text{MaxCredit}) * [\,1 - (\S 86.166\text{-}12\ \text{Score} / \text{AvgImpact}^{e}) * (\text{GWPRefrigerant} / 1430)] - \text{HiLeakDisincentive}$$

where the HiLeakDisincentive is determined in accordance with one of the following three conditions:

- HiLeakDisincentive = MaxHiLeakDisincentive, or 1.8 g/mi for cars and 2.1 g/mi for trucks, if the Score > AvgImpact
- HiLeakDisincentive = MaxHiLeakDisincentive * (Score – MinScore)/(AvgImpact – MinScore), if MinScore < Score ≤ AvgImpact
- HiLeakDisincentive = 0 g/mi, if Score ≤ MinScore

There are four significant terms to the credit equation. Each is briefly summarized below, and is then explained more thoroughly in the following sections. Please note that the values of many of these terms change depending on whether HFC-134a or an alternative refrigerant is used. The values are shown in Table 5-2, and are documented in the following sections.

- "MaxCredit" is a term for the maximum amount of credit entered into the equation before constraints are applied to terms. The maximum credits that could be generated by a manufacturer is limited by the choice of refrigerant and by assumptions regarding maximum achievable leakage reductions. Some of these values may have changed since the 2012-2016 rule.
- "Score" is the leakage score of the A/C system as measured according to the §86.166-12 calculation in units of g/yr, where the minimum score which is deemed feasible is fixed.
- "AvgImpact" is a term which represents the annual average impact of A/C leakage.
- "MinScore" is the lowest leak score that EPA projects is possible, when starting from a baseline, or AvgImpact, system. The MinScore represents a 50% reduction in leakage from the baseline levels based on the feasibility analysis detailed below.
- "GWPRefrigerant" is the global warming potential for direct radiative forcing of the refrigerant as defined by EPA (or IPCC).
- "HiLeakDisincentive" is a term for the disincentive credit deducted for low-GWP alternative refrigerant systems which have a leakage rate greater than the minimum leakage score of 8.3 g/year for cars, and 10.4 g/year for trucks. The maximum Disincentive is 1.8 g/mile for cars, and 2.1 g/mile for trucks. HiLieakDisincentive is

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[e] Section 86.166-12 sets out the individual component leakage values based on the SAE value.

zero for systems where the GWP of the refrigerant is >150, this is to prevent leakage-only credits from having this disincentive.

Table 5-2 Components of the A/C Credit Calculation

	HFC-134a		Lowest-GWP Refrigerant (GWP=1)	
	Cars	Trucks	Cars	Trucks
MaxCredit equation input (grams/mile CO_2 EQ)	12.6	15.6	13.8	17.2
A/C credit maximum (grams/mile CO_2 EQ)[a]	6.3	7.8	13.8	17.2
§86.166-12 Score MinScore (grams HFC/year)	8.3	10.4	8.3	10.4
Avg Impact (grams HFC/year)	16.6	20.7	16.6	20.7

[a] With electric compressor, value increases to 9.5 and 11.7 for cars and trucks, respectively.

5.1.2.2.2.1 **Max Credit Term**

In order to determine the maximum possible credit on a gram per mile basis, it was necessary to determine the projected real world HFC emissions per mile. This calculation is done exactly the same as it was done for the 2012-2016 final rule. Because HFC is a leakage type emission, it is largely disconnected from vehicle miles traveled (VMT).[f] Consequently, the total HFC inventory (in 2016) was calculated, and then calculated the relevant VMT. The quotient of these two terms is the HFC contribution per mile.

Consistent with the methodology presented in the 2012-2016 rule, the HFC emission inventories were estimated from a number of existing data sources. The per-vehicle per-year HFC emission of the current vehicle fleet was determined using averaged 2005 and 2006 registration data from the Transportation Energy Databook (TEDB) and 2005 and 2006 mobile HFC leakage estimates from the EPA Emissions and Sinks report described above.[3,13] The per-vehicle per-year emission rates were then adjusted to account for the new definitions of car and truck classes by increasing the car contribution proportionally by the percentage of former trucks that are reclassified as cars.[g] This inventory calculation assumes that the leakage rates and charge sizes of future fleets (absent any standards) are equivalent to the fleet present in the 2005/2006 reference years. Preliminary EPA analysis indicates that this may increasingly overstate the future HFC inventory, as charge sizes are decreasing, though more is discussed on this topic below.

The per-vehicle per-year average emission rate was then scaled by the projected vehicle fleet in each future year (using the fleet predicted in the emissions analysis) to

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[f] In short, leakage emissions occur even while the car is parked, so the connection to a gram/mile credit is not straightforward. However, HFC emissions must be converted to a gram/mile basis in order to create a relevant credit.

[g] Many of these “older” references still use the old definition of car and truck. The new definitions do not apply until model year 2011.

estimate the HFC emission inventory if no further controls were enacted on the fleet. After dividing the 2016 inventory by total predicted VMT in 2016, an average per mile HFC emission rate ("base rate") was obtained.

The base rate is an average in-use number, which includes both old vehicles with significant leakage, as well as newer vehicles with very little leakage. The new vehicle leakage rate is discussed in section 5.1.2.3, while deterioration is discussed in section 5.1.2.5.

- Max Credit with Conventional Refrigerant (HFC-134a)
  Two adjustments were made to the base rate in order to calculate the Maximum HFC credit with conventional refrigerant. First, EPA has determined that 50% leakage prevention is the maximum potentially feasible prevention rate in the timeframe of this rule (see section 5.1.2.3). Some leaks will occur and are expected, regardless of prevention efforts. The accuracy of the J2727 approach (as expressed in §86.112), as a design based test, decreases as the amount of expected leakage diminishes. 50% of the base rate is therefore set as the maximum potential leakage credit for improvements to HFC leakage using conventional refrigerant.

  Second, EPA expects that improvements to conventional refrigerant systems will affect both leakage and service emissions, but will not affect end of life emissions. EPA expects that reductions in the leakage rate from A/C systems will result in fewer visits for maintenance and recharges. This will have the side benefit of reducing the emissions leftover from can heels (leftover in the recharge cans) and the other releases that occur during maintenance. However, as disposal/end of life emissions will be unaffected by the leakage improvements (and also are subject to control under the rules implementing Title VI of the CAA), the base rate was decreased by a further 9% (Table 5-1).

- Max Credit with Alternative Refrigerant
  Emission reductions greater than 50% are possible with alternative refrigerants. As an example, if a refrigerant with a GWP of 0 were used, it would be possible to eliminate all refrigerant GHG emissions. In addition, for alternative refrigerants, the EPA believes that vehicles with reduced GWP refrigerants should get credit for end of life emission reductions. Thus, the maximum credit with alternative refrigerant is about 9% higher than twice the maximum leakage reduction.

As discussed above, EPA recognizes that substituting a refrigerant with a significantly lower GWP will be a very effective way to reduce the impact of all forms of refrigerant emissions, including maintenance, accidents, and vehicle scrappage.

The A/C Leakage Credits that will be available will be a function of the GWP of the alternative refrigerant as well as of leakage, with the largest credits being available for refrigerants with GWPs at or approaching a value of 1, while also maintaining a low leakage rate. For a hypothetical alternative refrigerant with a GWP of 1 (e.g., CO_2 as a refrigerant), effectively eliminating leakage as a GHG concern, our credit calculation method could result in maximum credits equal to total average emissions, or credits of 13.8 and 17.2 g/mi CO_2eq for cars and trucks, respectively, as incorporated into the A/C Leakage Credit formula above as the "MaxCredit" term.

A final adjustment was made to each credit to account for the difference between real-world HFC emissions and test-cycle CO_2 emissions. It has been shown that the tests currently used for CAFE certification represents an approximately 20% gap from real world fuel consumption and the resulting CO_2 emissions.[14] Because the credits from direct a/c improvements are taken from a real world source, and are being traded for an increase in fuel consumption due to increased CO_2 emissions, the credit was multiplied by 0.8 to maintain environmental neutrality (Table 5-3).

Table 5-3 HFC Credit Calculation for Cars and Trucks Based on a GWP of 1430

	HFC Inventory (MMT CO_2 EQ)	VMT (Billions of Miles)	Total HFC EmissionsPer Mile (CO_2 EQ Gram/mile)	HFC Leakage and Service EmissionsPer Mile (CO_2 EQ Gram/mile)	Maximum Credit w/ alternative refrigerant (Adjusted for On-road gap & including end of life)	Maximum Credit w/o alternative refrigerant (50% of Adjusted HFC & excluding end of life)
Car	27.4	1,580	17.2	15.5	13.8	6.3
Truck	30.4	1,392	21.5	19.6	17.2	7.8
Total	57.8	2,972	18.6	16.9	14.9	6.8

5.1.2.2.2.2 Section 86.166-12, implementing the J2727 Score Term

The J2727 score is the SAE J2727 yearly leakage estimate of the A/C system as calculated according to the J2727 procedure. In the time since the 2012-2016 Light-Duty GHG Rule, there have been several refinements to the J2727 procedure which EPA will propose to incorporate into the EPA regulations. First, a provision was made for system joints where 100 percent of the joints are leak test with helium and a mass-spectrometer leak detector. If the joints pass this leak test, they can be considered to have a leakage factor equivalent to that of a seal washer, which is next to the lowest factor possible for system joints. Second, a requirement was added to use SAE J2064 hose permeation test results in place of the discrete values for various hose material and construction types that was provided in previous versions of the J2727 test method. By using the test chamber results for refrigerant permeation through hoses, a more representative leakage estimate for the overall system is achieved. The minimum J2727 score for cars and trucks is a fixed value, and the section below describes the derivation of the minimum leakage scores that can be achieved using the J2727 procedure.

To calculate a J2727 score and credit for the alternative refrigerant HFO-1234yf, all values relevant to the credit calculations, as well as the J2727 score, shall be adjusted to account for the higher molecular weight of this refrigerant. In contrast to the studies discussed in section 5.1.2.5 which examines the HFC emission rate of the in-use fleet (which includes vehicles at all stages of life), the SAE J2727 estimates leakage from new vehicles. In the development of J2727, two relevant studies were assessed to quantify new vehicle emission rates. In the first study, measurements from relatively new (properly functioning and manufactured) Japanese-market vehicles were collected. This study was based on 78 in-use vehicles (56 single evap, 22 dual evap) from 7 Japanese auto makers driven in Tokyo and Nagoya from April, 2004 to December, 2005. The study also measured a higher emissions level of 16 g/yr for 26 vehicles in a hotter climate (Okinawa). This study indicated the leakage rate to be close to 8.6 g/yr for single evaporator systems and 13.3 g/yr for dual evaporator systems.[15] A weighted (test) average gives 9.9 g/yr. In the second study, emissions were measured on European-market vehicles up to seven years age driven from November, 2002 to January, 2003.[16] The European vehicle emission rates were slightly higher than the Japanese fleet, but overall, they were consistent. The average emission rate from this analysis is 17.0 g/yr with a standard deviation of 4.4 g/yr. European vehicles, because they have smaller charge sizes, likely understate the leakage rate relative to the United States. To these emission rates, the J2727 authors added a factor to account for occasional defective parts and/or improper assembly and to calibrate the result of the SAE J2727 calculation with the leakage measured in the vehicle and component leakage studies.

We adjust this rate up slightly by a factor proportional to the average European refrigerant charge to the average United States charge (i.e. 770/747 from the Vintaging model and Schwarz studies respectively). The newer vehicle emission rate is thus 18 g/yr for the average newer vehicle emissions (average for car and truck).

To derive the minimum score, the 18 gram per year rate was used as a ratio to convert the gram per mile emission impact into a new vehicle gram per year for the test. The car or truck direct a/c emission factor (gram per mile) was divided by the average emission factor (gram per mile) and then multiplied by the new vehicle average leakage rate (gram per year)

Equation 5-2 – J2727 Minimum Score

J2727 Minimum Score = Car or truck average pre control emissions (gram per mile)/ Fleet average pre-control emissions (grams per mile) x New vehicle annual leakage rate (grams per year) x Minimum Fraction

By applying this equation, the minimum J2727 score is fixed at 8.3 g/yr for cars and 10.4 g/yr for trucks. This corresponds to a total fleet average of 18 grams per year, with a maximum reduction fraction of 50%.

The GWP Refrigerant term in Equation 1 allows for the accounting of refrigerants with lower GWP (so that this term can be as low as zero in the equation), which is why the same minimum score is kept regardless of refrigerant used. It is technically feasible for the

J2727 Minimum score to be less than the values presented in the table. But this will usually require the use of an electric compressor (see below for technology description).

5.1.2.2.2.3 **AvgImpact Term**

AvgImpact is the average annual impact of A/C leakage, which is 16.6 and 20.7 g/yr for cars and trucks respectively. This was derived using Equation 2, but by setting the minimum fraction to one.

5.1.2.2.2.4 **GWPRefrigerant Term**

This term is relates to the global warming potential (GWP) of the refrigerant as documented by EPA. A full discussion of GWP and its derivation is too lengthy for this space, but can be found in many EPA documents.[4c] This term is used to correct for refrigerants with global warming potentials that differ from HFC-134a.

5.1.2.2.2.5 **HiLeakDisincentive**

The EPA is proposing to add (compared to the 2012-2016 formula) a disincentive to the leakage credit formula for systems which use a low GWP refrigerant, but “backslide” on low leakage levels. As stated above, low leakage levels provide an environmental benefit by maintaining the charge of the system. This has two advantageous effects. First, it preserves the efficiency of the system. Reduced refrigerant charge levels can reduce overall efficiency, especially if the compressor starts “short-cycling”. Also, since lubrication is combined with refrigerant, the shortage of lubrication can wear out the compressor and cause it to seize and malfunction. CARB testing has shown that preserving the refrigerant charge level in an A/C system results in improved system efficiency.[17] Second, by reducing the leak rate of the low GWP system, the probability that the new system will run out of charge will be minimized. When a system runs out of charge, vehicle owners can either drive without A/C, or have a professional recharge the system, or recharge the system themselves. The latter are called “do-it-yourself-ers” (DIYers). It is entirely possible that DIYers (and some repair shops) may refill the system with the old refrigerant, R-134a, in order to save on costs. Due to the demand from the legacy fleet, refill canisters of R-134a must be available to the market for many years to come (so it will be available to DIYers). It is highly probable that the cost of HFO-1234yf (for example) will exceed R-134a for the foreseeable future, therefore there is an economic incentive to “tamper” with the A/C system and refill with the older, cheaper refrigerant. Since the thermodynamic properties of the two refrigerants are similar, HFO-1234yf systems should function with R-134a, although with some reduced effectiveness, and in some systems may lead to long term damage.[h] Unfortunately, the extent to which this will occur is impossible to predict. EPA is proposing this disincentive credit in order to maintain low refrigerant leakage emissions and to reduce the potential for leakage of high GWP refrigerants from systems which have been improperly recharged by DIY-ers. Thus, EPA

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[h] Based on discussions with vehicle manufacturers.

believes that there are real, but unquantifiable, benefits for a leakage disincentive credit, and we are proposing that this (Max)HiLeakDisincentive be 1.8 g/mi for cars and 2.1 g/mi for trucks. The EPA believes that these numbers strike a balance in that it is a large enough incentive to maintain low leakage levels, but it is not too large as to diminish incentive to switch to an alternative refrigerant.

5.1.2.2.3 Why are the credits different from the 2010 Technical Assessment Report?

The 2010 Technical Assessment report employed a different methodology for calculating the HFC credit, which resulted in significantly fewer credits available for A/C leakage (approximately 40% less). The TAR analysis decreased the average charge size and leakage assumed in its analysis of future model years as compared to the 2012-2016 final rule. In the present rule, we maintain the 2012-2016 credit value. EPA chose this approach for both technical and policy reasons.

Like any inventory, the refrigerant inventory produced by the Vintaging model has uncertainties associated with it. This is especially true given that we do not know how many “high emitters” exist in the U.S. fleet. A high emitter is a vehicle that rapidly leaks HFC, but is also continually recharged. A typical light duty vehicle may require recharge approximately every seven years (see section 5.1.2.5). However, the owner of a high emitter may continually charge their systems each summer, thereby increasing the overall average emissions of the fleet. In the 2009-2010 study of the leakage rates from 70 in-use heavy duty vehicles, the California Air Resources Board found a relatively high prevalence of high emitting vehicles. Of the 70, 5 had leakage rates that were greater than one-half a charge per year, while seven additional vehicles had annualized leakage rates greater than one-quarter charge per year.[i] These values could potentially be used to recalculate the HFC inventories from the TAR and recalculate the leakage credit.

EPA considered the lower inventory discussed in the TAR as well as the CARB study when determining the leakage credit for this rule. While there is ultimately a mass balance between HFC produced and HFC leaked, this balance is not closed on an annual basis, and is difficult to directly verify. Given the counterbalancing factors, EPA made the policy decision to maintain continuity with the 2012-2016 FRM analysis, and is proposing to incorporate this level of the credit in the standard setting process. A reduction in A/C credits (in 2017 compared to 2016 for example) would artificially increase the stringency of the standard for those manufacturers who generated leakage (and alternative refrigerant) credits in 2016 as a means of compliance. With little lead time, these manufacturers would need to add other technologies to their fleet in order to close the gap their compliance target created by a reduction in the maximum potential A/C credit. Alternately, the stringency of the 2017 standards would have to be relaxed, and in some cases may even be less stringent than 2016 standards if this adjustment is made. Given the need for stability for the standards (and stringencies), EPA is “freezing” the credit assessment based on that presented in the 2012-2016 rule, and also presented again above.

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[i] While the Vintaging model assumes an average annualized leakage rate of 18% + 43% at end of life, it assumes that the MAC unit only lasts 12 years. Actual MACs, particularly those that are recharged, may last longer.

5.1.2.3 Technologies That Reduce Refrigerant Leakage and their Effectiveness

In this section, the analysis used in the 2012-2016 rule is again applied to the baseline technology levels and the effectiveness for leakage-reducing technologies. For the 2012-2016 rule, EPA conducted an analysis to determine the historic leakage emission rate for motor vehicle A/C systems, and it was estimated in section 5.1.2.2.2.2 that the A/C systems in new vehicles would leak refrigerant at an average rate of 18 g/yr – a value which EPA believes represented the types of A/C components and technologies in use prior to MY 2007. EPA believes, through utilization of the leakage-reducing technologies described below, that it will be possible for manufacturers to reduce refrigerant leakage 50%, relative to the 18 g/yr baseline level.[18] EPA also believes that all of these leakage-reducing technologies are currently available, and that manufacturers will use these technologies to generate credits under provisions of the 2012-2016 rule, as well as under the proposed provisions of this rule.

In describing the technologies below, only the relative effectiveness figures are presented, as the individual piece costs are not known. The EPA only has costs of complete systems based on the literature, and the individual technologies are described below.

5.1.2.3.1 Baseline Technologies

The baseline technologies assumed for A/C systems which have an average annual leak rate of 18 g/yr are common to many mass-produced vehicles in the United States. In these mass-produced vehicles, the need to maintain A/C system integrity (and the need to avoid the customer inconvenience of having their A/C system serviced due to loss of refrigerant) is often balanced against the cost of the individual A/C components. For manufacturers seeking improved system reliabilty, components and technologies which reduce leakage (and possibly increased cost) are selected, whereas other manufacturers may choose to emphasize lower system cost over reliabilty, and choose components or technologies prone to increased leakage. In EPA's baseline scenario, the following assumptions were made concerning the definition of a baseline A/C system:

- all flexible hose material is rubber, without leakage-reducing barriers or veneers, of approximately 650 mm in length for both the high and low pressure lines
- all system fittings and connections are sealed with a single o-rings
- the compressor shaft seal is a single-lip design
- one access port each on the high and low pressure lines
- two of the following components: pressure switch, pressure relief valves, or pressure transducer
- one thermostatic expansion valve (TXV)

The design assumptions of EPA baseline scenario are also similar to the sample worksheet included in SAE's surface vehicle standard J2727 – (R) HFC-134a Mobile Air Conditioning System Refrigerant Emission Chart.[10] In the J2727 emission chart, it is the baseline technologies which are assigned the highest leakage rates, and the inclusion of improved components and technologies in an A/C system will reduce this annual leakage rate, as a function of their effectiveness relative to the baseline. EPA considers these 'baseline' technologies to be representative of recent model year vehicles, which, on average, can experience a refrigerant loss of 18 g/yr. However, depending on the design of a particular vehicle's A/C system (e.g. materials, length of flexible hoses, number of fittings and adaptor plates, etc.), it is possible to achieve a leakage score much higher (i.e. worse) than 18 g/yr. According to manufacturer data submitted to the State of Minnesota, 19% of 2009 model year vehicles have a J2727 refrigerant score greater than 18 g/yr, with the highest-scoring vehicle reporting a leakage rate of 30.1 g/yr.[19] For the 2010 model year, the average J2727 leakage score reporting database was 14.0 g/yr for cars, and 14.8 g/yr for trucks, but this is simply the average result of all vehicles in the database, and does not reflect sales weighting of the leakage scores nor does it eliminate identical models (vehicles with different brands or nameplates, but identical with respect to the A/C system design and components) when calculating the average score.

Here again, the 18g/yr baseline is maintained at the 2012-2016 rule levels for both technical and policy reasons. As mentioned earlier, there is great uncertainty in the leakage emissions from vehicles. The J2727 scoring system, which is calibrated to in-use emissions from properly functioning vehicles, does not include high emitters. EPA considers J2727 to be a surrogate for in-use emissions, and not necessarily an accurate representation of real-world emissions. Thus to maintain continuity with 2016 standards (and credits), EPA is "freezing" the baseline assumption of leakage rate from the fleet.

5.1.2.3.2 Flexible Hoses

The flexible hoses on an automotive A/C system are needed to isolate the system from engine vibration and to allow for the engine to roll within its mounts as the vehicle accelerates and decelerates. Since the compressor is typically mounted to the engine, the lines going to-and-from the compressor (i.e. the suction and pressure lines) must be flexible, or unwanted vibration would be transferred to the body of the vehicle (or other components), and excessive strain on the lines would result. It has been industry practice for many years to manufacture these hoses from rubber, which is relatively inexpensive and durable. However, rubber hoses are not impermeable, and refrigerant gases will eventually migrate into the atmosphere. To reduce permeation, two alternative hose material can be specified. The first material, is known as a standard 'veneer' (or 'barrier') hose, where a polyamide (polymer) layer - which has lower permeability than rubber - is encased by a rubber hose. The barrier hose is similar to a veneer hose, except that an additional layer of rubber is added inside the polyamide layer, creating three-layer hose (rubber-polyamide-rubber). The second material is known as 'ultra-low permeation', and can be used in a veneer or barrier hose design. This ultra-low permeation hose is the most effective at reducing permeation, followed by the standard veneer or barrier hose. Permeation is most prevalent during high pressure conditions, thus it is even more important that these low permeable hoses are employed on the high pressure side, more so than on the low pressure side.

According to J2727, standard barrier veneer hoses have 25% the permeation rate of rubber hose, and ultra low permeable barrier veneer hoses have 10% the permeation rate (as compared to a standard baseline rubber hose of the same length and diameter). However, manufacturers will be required to use actual SAE J2064 hose permeation data, instead of the discrete values provided for various hose material and construction types in previous versions of the J2727 method.

5.1.2.3.3 System Fittings and Connections

Within an automotive A/C system and the various components it contains (e.g. expansion valves, hoses, rigid lines, compressors, accumulators, heat exchangers, etc.), it is necessary that there be an interface, or connection, between these components. These interfaces may exist for design, manufacturing, assembly, or serviceability reasons, but all A/C systems have them to some degree, and each interface is a potential path for refrigerant leakage to the atmosphere. In SAE J2727 emission chart, these interfaces are described as fittings and connections, and each type of fitting or connection type is assigned an emission value based on its leakage potential; with a single O-ring (the baseline technology) having the highest leak potential; and a metal gasket having the lowest. In between these two extremes, a variety of sealing technologies, such as multiple o-rings, seal washers, and seal washers with o-rings, are available to manufacturers for the purpose of reducing leakage. It is expected that manufacturers will choose from among these sealing technology options to create an A/C system which offers the best cost-vs-leakage rate trade-off for their products.

The relative effectiveness of the fitting and connector technology is presented in Table 5-4. For example, the relative leakage factor of 125 for the baseline single O-ring is 125 times more "leaky" than the best technology - the metal gasket.

Table 5-4 Effectiveness of Fitting and Connector Technology

Fitting or Connector	Relative Leakage
Single O-ring	125
Single Captured O-ring	75
Multiple O-ring	50
Seal Washer	10
Seal Washer with O-ring	5
Metal Gasket	1
100% Helium Leak Test	10

5.1.2.3.4 Compressor Shaft Seal

A major source of refrigerant leakage in automotive A/C systems is the compressor shaft seal. This seal is needed to prevent pressurized refrigerant gasses from escaping the compressor housing. As the load on the A/C system increases, so does the pressure, and the leakage past the seal increases as well. In addition, with a belt-driven A/C compressor, a side load is placed on the compressor shaft by the belt, which can cause the shaft to deflect slightly. The compressor shaft seal must have adequate flexibility to compensate for this deflection, or movement, of the compressor shaft to ensure that the high-pressure refrigerant does not leak past the seal lip and into the atmosphere. When a compressor is static (not running), not only are the system pressures lower, the only side load on the compressor shaft is that from tension on the belt, and leakage past the compressor shaft is at a minimum. However, when the compressor is running, the system pressure is higher and the side load on the compressor shaft is higher (i.e. the side load is proportional to the power required to turn the compressor shaft) - both of which can increase refrigerant leakage past the compressor shaft seal. It is estimated that the rate of refrigerant leakage when a compressor is running can be 20 times that of a static condition.[20] Due to the higher leakage rate under running conditions, SAE J2727 assigns a higher level of impact to the compressor shaft seal. In the example shown in the August 2008 version of the J2727 document, the compressor is responsible for 58% of the system refrigerant leakage, and of that 58%, over half of that leakage is due to the shaft seal alone (the remainder comes from compressor housing and adaptor plate seals). To address refrigerant leakage past the compressor shaft, manufacturers can use multiple-lip seals in place of the single-lip seals.

5.1.2.4 Technical Feasibility of Leakage-Reducing Technologies

EPA believes that the leakage-reducing technologies discussed in the previous sections are available to manufacturers today, are relatively low in cost, and that their feasibility and effectiveness have been demonstrated by the SAE IMAC teams. EPA also believes – as has been demonstrated in the J2727 calculations submitted by manufacturers to the State of Minnesota – that reductions in leakage from 18 g/yr to 9 g/yr are possible (e.g. the 2009 Saturn Vue has a reported leakage score of 8.5 g/yr). In addition to generating credit for reduced refrigerant leakage, some manufacturers are likely to, within the timeframe of this rulemaking, choose to introduce alternative refrigerant systems, such as HFO-1234yf.

EPA also believes that the alternative refrigerant HFO1234yf will be more commonplace within the timeframe of this rule. EPA projects that because of the significant credit potential from alternative refrigerants, that the new vehicle fleet will completely switch to the new refrigerant by model year 2021. More detailed discussion of this can be found in Section III of the Preamble.

5.1.2.5 Leakage Controls in A/C Systems

In order to determine the cost savings from the improvements to the leakage system, it may be necessary to project the point at which the vehicle will require servicing and an additional refrigerant charge.

There are two mechanisms of leakage that are modeled: the “normal” leakage that results in annual refrigerant loss, and the “avoidable” leakage which results in total refrigerant loss due to failure of the A/C components (e.g. evaporator, condenser, or compressor). This analysis is developed to help us estimate the costs of the A/C leakage reductions. It is especially needed to determine the period over which the discounted cost savings should be applied.[j]

Normal refrigerant leakage occurs throughout all components of the A/C system. Hoses, fittings, compressors, etc all wear with age and exposure to heat (temperature changes), vibration, and the elements. It is assumed that the system leakage rates decrease (proportionally) as the base leakage rates are decreased with the use of improved parts and components. The base leakage rate is modeled as a linear function, such that the (new vehicle) leakage rate is 18 g/yr at age zero and 59 g/yr at the "average" age of 5 years old. The 18 gram leakage rate for new vehicles has been documented in section 5.1.2.2.2.2, while the 59 gram mid-life leakage rate is drawn from the Vintaging model and is documented below.

The Vintaging model assumes a constant leakage + servicing emission rate of 18% per year for modern vehicles running with HFC-134a refrigerant. As the emission rates do not change by age in vintaging, the emission rate is the average rate of loss over the vehicle's life.

Applying the percentages in Table 5-1, this corresponds to a leakage rate of 7.6% (59 grams) per year and a servicing loss rate of 8.8% (68 grams) per year averaged over the vehicle's life. The model assumes an average refrigerant charge of 770 grams for vehicles sold in 2002 or later and does not currently assume that these charge sizes will change in the future; however, the model may be updated as new information becomes available. The resulting vehicle emission rates are presented in Table 5-5.

Table 5-5 Annual In-Use Vehicle HFC-134a Emission Rate from Vintaging Model

Emission Process	Leak rate (%/year)	Leak rate (g/year)
Leakage	7.6%	59
Servicing/maintenance	8.8%	68

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[j] Air conditioning leakage controls are the only technology in this rule that have an assumed deterioration that affects the effectiveness of the technology. This is partly because sufficient data is not available for many of the technologies in chapter 3 of the TSD. More important, it is not expected that deterioration of powertrain technologies will lead to emissions increases on the scale of those seen when criteria pollutant technologies deteriorate. The deterioration from the latter can increase emissions by factors of 10 or even 100 or more. Similarly, air conditioning leakage technologies can and do deteriorate, contributing to significantly higher emissions over time. For this reason, a deterioration model is proposed below. This model only applies for leakage, and not for indirect CO_2 (tailpipe) emissions due to A/C. For the latter, a partly functioning system may lead to somewhat higher emissions, but when it finally fails, it is one of the few technologies where the emissions are no longer relevant, i.e. an A/C system that no longer functions no longer emits indirect emissions.

The average leakage emissions rate of 59-68 g/yr is higher with Schwarz's European[1] study and lower than CARB's study,[2] and thus is within the range of results in the literature.

This model is presented in Figure 5-1 with the assumption that the average vehicle (A/C system) last about 10 years. Technically, the assumption is that the A/C system lasts 10 years and not the vehicle per se. Inherent in this assumption is that the vehicle owner will not repair the A/C system on an older vehicle due to the expensive nature of most A/C repairs late in life relative to the value of the vehicle. It is also assumed for the analysis in this section that the refrigerant requires a recharge when the state of charge reaches 50%. This deterioration/leakage model approach can be used to estimate the cost of maintenance savings due to low leak technologies (from refills) as well as the benefits of leakage controls, though we have not accounted for maintenance savings or expenses in this rule.

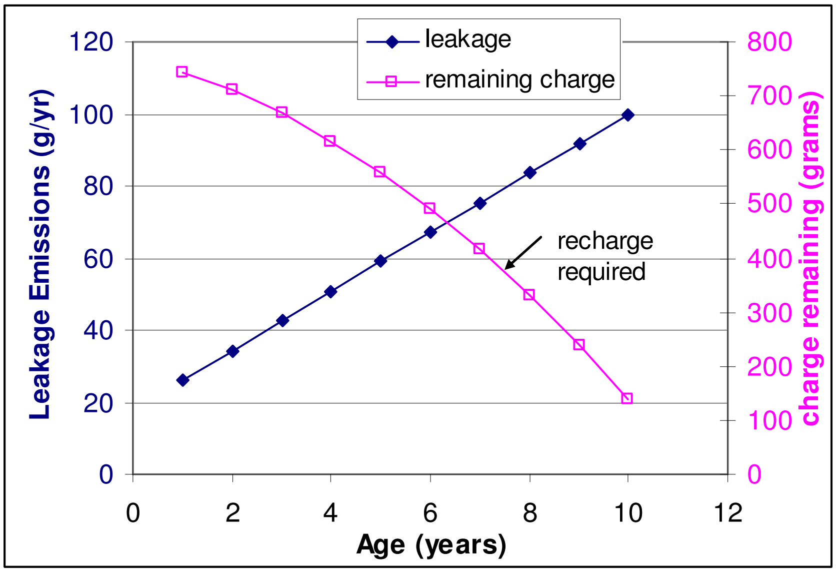

Figure 5-1 Deterioration Rate of Refrigerant Leakage

Figure 5-2 shows how the leakage rates vary with age as the initial leakage rates are decreased to meet new standards (with improved components and parts). The deterioration lines of the lower leakage rates were determined by applying the appropriate ratio to the 17 g/yr base deterioration rate. Figure 5-3 shows the refrigerant remaining, which includes a line indicating when a recharge is required (50% charge remaining out of an initial charge of 770g). So a typical vehicle meeting a leakage score of 8.5 g/yr (new) will not require a recharge until it is about 12 years old.

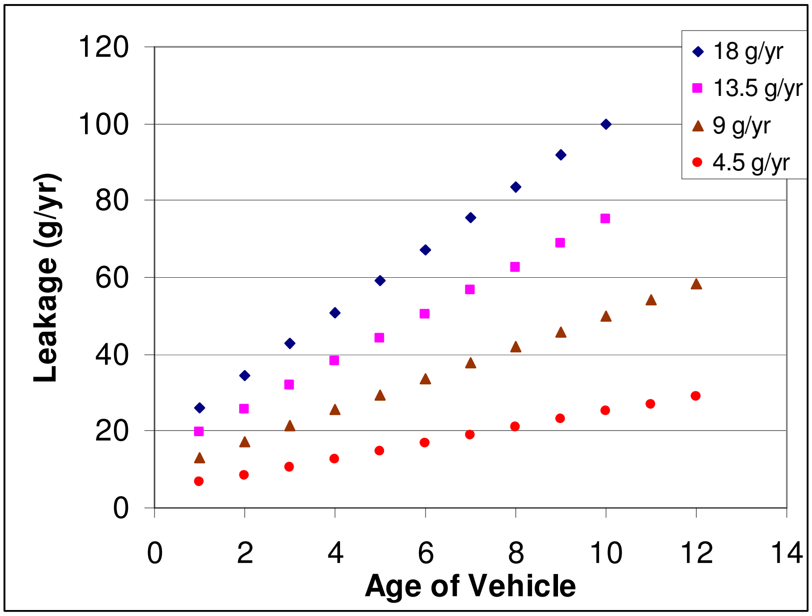

Figure 5-2 A/C Refrigerant Leakage Rate for Different Technologies as Vehicles Age

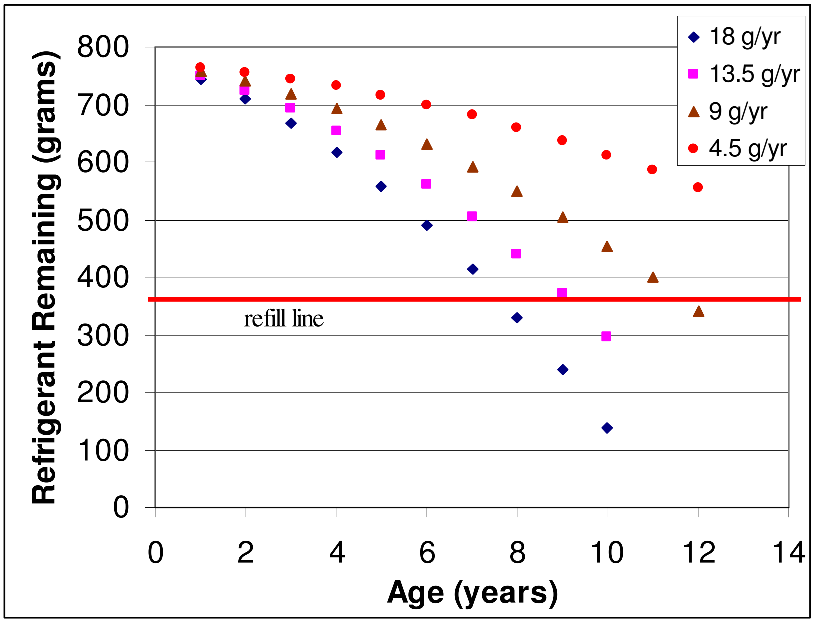

Figure 5-3 A/C Refrigerant Remaining in a Typical System as Vehicles Age and Deteriorate

5.1.2.6 Other Benefits of improving A/C Leakage Performance

The EPA is assuming that a reduction in leakage emissions from new vehicles will also improve the leakage over the lifetime of the vehicle. There is ample evidence to show that A/C systems that leak more also have other problems that occur (especially with the compressor) due to the lack of oil circulating in the system. Thus, it is expected that an A/C system which utilizes leak-reducing components and technologies should, on average, last longer than one which does not.

A European study conducted in 2001 (by Schwarz) found that the condenser is the component most likely to fail and result in a total leak.[21] The study also found that compressor component was most likely the culprit when other malfunctions were present (other than total loss). A more recent (and larger) study found that condensers required replacement at half the rate of a compressor (10% vs 19% of the entire part replacement rate), and that evaporators and accumulators failed more often.[16] The same study also found that many of the repairs occurred when the vehicles were aged 5-10 years. Both these studies indicate that the condenser and compressor are among the major causes of failure in an A/C system. Leakage reductions in the system are expected to greatly reduce the incidence of compressor repair, since one of the main root causes of compressor failure is a shortage of lubricating oil, which originates from a shortage of refrigerant flowing through the system (and it is a refrigerant-oil mixture which carries lubricating oil to the compressor).[22]

Monitoring of refrigerant volume throughout the life of the A/C system may provide an opportunity to circumvent some previously described failures specifically related to refrigerant loss. Similar to approaches used today by the engine on-board diagnostic systems (OBD) to monitor engine emissions, a monitoring system that informed the vehicle operator of a low refrigerant level could potentially result in significant reductions in A/C refrigerant emissions due to component failure(s) by creating an opportunity for early repair actions. While most A/C systems contain sensors capable of detecting the low refrigerant pressures which result from significant refrigerant loss, these systems are generally not designed to inform the vehicle operator of the refrigerant loss, and that further operation of the unrepaired system can result in additional component damage (e.g. compressor failure). Electronic monitoring of the refrigerant may be achieved by using a combination of existing A/C system sensors and new software designed to detect refrigerant loss before it progresses to a level where component failure is likely to occur.

EPA requested comment in the 2012-2016 NPRM on allowing additional leakage credits for systems that monitor the leak levels, especially where manufacturers are willing to warrant such systems. Presently, the EPA is not aware if any such technology exists to accurately monitor refrigerant levels, as the technical challenges are high. As a result, there were no manufacturers who expressed interest in this credit, and the EPA did not finalize such credits. For this 2017-2025 NPRM, EPA is again requesting comments on allowing these credits again, in the hopes of encouraging innovative technologies to monitor leakage levels.

5.1.3 CO_2 Emissions and Fuel Consumption due to Air Conditioners

As stated above, for model years 2012 to 2016, EPA provided credits for the use of A/C technologies that improve efficiency and achieve reductions in indirect CO2 emissions related to A/C use. These credits were not previously applicable to the CAFE program fuel economy calculations. For this proposal, the agencies are proposing that the A/C indirect credits be applicable to both the greenhouse gas and fuel economy calculations.

5.1.3.1 Impact of Air Conditioning Use on Fuel Consumption and CO_2 Emissions

Three studies have been performed in recent years which estimate the impact of A/C use on the fuel consumption of motor vehicles in the United States. In the first study, the National Renewable Energy Laboratory (NREL) and the Office of Atmospheric Programs (OAP) within EPA have performed a series of A/C related fuel use studies.[23,24] The energy needed to operate the A/C compressor under a range of load and ambient conditions was based on testing performed by Delphi, an A/C system supplier. They used a vehicle simulation model, ADVISOR, to convert these loads to fuel use over the EPA's FTP test cycle. They developed a personal "thermal comfort"-based model to predict the percentage of drivers which will turn on their A/C systems under various ambient conditions. Overall, NREL estimated A/C use to represent 5.5% of car and light truck fuel consumption in the U.S.

In the second study, the California Air Resources Board (ARB) estimated the impact of A/C use on fuel consumption as part of their GHG emission rulemaking.[25] The primary technical analysis utilized by ARB is summarized in a report published by NESCCAF for ARB. The bulk of the technical work was performed by two contractors: AVL Powertrain Engineering and Meszler Engineering Services. This work is founded on that performed by NREL-OAP. Meszler used the same Delphi testing to estimate the load of the A/C compressor at typical ambient conditions. The impact of this load on onroad fuel consumption was estimated using a vehicle simulation model developed by AVL - the CRUISE model - which is more sophisticated than ADVISOR. These estimates were made for both the EPA FTP and HFET test cycles. (This is the combination of test cycle results used to determine compliance with NHTSA's current CAFE standards.) NREL's thermal comfort model was used to predict A/C system use in various states and seasons.

The NESCCAF results were taken from Table 3-1 of their report and are summarized in Table 5-6.[26]

Table 5-6 CO_2 Emissions Over 55/45 FTP/HFET Tests and From A/C Use (g/mi) Based on the NESCCAF study

	Small Car	Large Car	Minivan	Small Truck	Large Truck
55/45 FTP/HFET	278	329	376	426	493
Indirect A/C Fuel Use (g/mi CO_2)	16.8	19.1	23.5	23.5	23.5

Total	294.8	348.1	399.5	449.5	516.5
Indirect A/C Fuel Use	5.7%	5.5%	5.9%	5.2%	4.6%

NESCCAF estimated that nationwide, the average impact of A/C use on vehicle fuel consumption ranged from 4.6% for a large truck or SUV, to 5.9% for a minivan. The total CO_2 emissions were determined using a 55%/45% weighting of CO_2 emissions from EPA FTP and HFET tests plus A/C fuel use (hereafter referred to simply as FTP/HFET). For the purposes of this analysis of A/C system fuel use, the percentage of CO_2 emissions and fuel use are equivalent, since the type of fuel being used is always gasoline.[k]

In the 2012-2016 rule, there was a third analysis presented along with a thorough comparison of these studies. While not repeated here, it was estimated that the impact of A/C on onroad fuel consumption was 3.9% based on a combination of the results from these studies. This resulted in an average impact of 14.3g/mi (independent of car or truck type) and hence a maximum of 5.7 g/mi credit, identical for car and truck (based on a 40% improvement feasibility). For this rule, EPA has conducted a new analysis, which supports the results achieved in the 2012-2016 final rule, though there is now a distinction made between cars and trucks as it relates to A/C efficiency impacts (and credits).

5.1.3.2 Updated Analysis of Efficiency Impacts

In the Light-Duty GHG final rule for model years 2012 through 2016, EPA estimated that the average CO_2 emission increase due to A/C use would be 14.3 g/mi, as mentioned earlier, taking into account both manual and automatic climate control systems with market penetrations of 62% and 38%, respectively. For this study of the A/C compressor load impact on vehicle fuel economy, EPA relied on comparisons of measured fuel economy over two warmed up bags (or phases) of the FTP test (without A/C operating) and the SC03 test (A/C emissions test). EPA had based its estimates on testing of over 600 production vehicles. These test results were combined with the Phoenix study, where the A/C compressor on-time was estimated to be 23.9% for manual climate control systems and 35% for automatic climate control systems. For more technical details, one can refer to the Regulatory Impact Analysis for the model year 2012 to 2016 final rule.

For this proposed rule for model years 2017 through 2025, EPA has developed a more robust and systematic method of estimating vehicle CO_2 emissions related to A/C usage. This method is based on a sophisticated, newly-developed EPA vehicle simulation tool. The next few paragraphs provide an overview of the vehicle simulation tool and describe how this approach improves on the earlier analysis. More detailed descriptions about the vehicle simulation tool and its use for the A/C indirect impact analysis are in Chapter 2 of the EPA Draft Regulatory Impact Analysis.

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[k] Because NESCCAF estimated A/C fuel use nationwide, while ARB focused on that in California, the NESCCAF and EPA methodologies and results are compared below.

Over the past year, EPA has developed full vehicle simulation capabilities in order to support regulations and vehicle compliance by quantifying the effectiveness of different technologies with scientific rigor over a wide range of engine and vehicle operating conditions. This in-house simulation tool has been developed for modeling a wide variety of light, medium, and heavy duty vehicle applications over various driving cycles. In order to ensure transparency of the models and free public access, EPA has developed the tool in MATLAB/Simulink environment with the completely open source code. To support these simulation capabilities in part, EPA is upgrading its testing infrastructure (such as engine test cells, vehicle dynamometers, Portable Emissions Measurement Systems, and a battery laboratory) at the National Vehicle and Fuel Emissions Laboratory in Ann Arbor, Michigan. This testing infrastructure provides necessary data to calibrate and validate vehicle simulations, such as engine fuel maps, engine torque maps, vehicle aerodynamic parameters, battery, electrical component parameters, etc.

EPA's first application of the vehicle simulation tool was for purposes of heavy-duty vehicle compliance and certification. For the model years 2014 to 2018 final rule for medium and heavy duty trucks, EPA created the "Greenhouse gas Emissions Model" (GEM), which is used both to assess Class 2b-8 vocational vehicle and Class 7/8 combination tractor GHG emissions and fuel efficiency and to demonstrate compliance with the vocational vehicle and combination tractor standards, see 40 CFR sections 1037.520 and 1037.810. This GEM documentation is also currently in publication.[27]

For light-duty vehicles, EPA has developed a conventional (non-hybrid) vehicle simulation tool and used it to estimate indirect A/C CO_2 emissions. These estimates are used, in turn, to quantify the maximum amount of indirect A/C credit (i.e. the maximum credit potential). As mentioned previously, the tool is based on MATLAB/Simulink and is a forward-looking full vehicle model that uses the same physical principles as other commercially available vehicle simulation tools (e.g. Autonomie, AVL-CRUISE, GT-Drive, etc.) to derive the governing equations. These governing equations describe steady-state and transient behaviors of each of electrical, engine, transmission, driveline, and vehicle systems, and they are integrated together to provide overall system behavior during transient conditions as well as steady-state operations. Chapter 2 of the Draft Regulatory Impact Analysis provides more details on this light-duty vehicle simulation tool used for estimating indirect A/C impact on fuel consumption.

In the light-duty vehicle simulation tool, there are four key system elements that describe the overall vehicle dynamics behavior and the corresponding fuel efficiency: electrical, engine, transmission, and vehicle. The electrical system model consists of parasitic electrical load and A/C blower fan, both of which were assumed to be constant. The engine system model is comprised of engine torque and fueling maps. For estimating indirect A/C impact on fuel consumption increase, two engine maps were used: baseline and EGR boost engines. These engine maps were obtained by reverse-engineering the vehicle simulation results provided by Ricardo Inc. For the transmission system, a Dual-Clutch Transmission (DCT) model was created and used along with the gear ratios and shifting schedules used for the earlier Ricardo simulation work. For the vehicle system, four vehicles were modeled:

small, mid, large size passenger vehicles, and a light-duty pick-up truck. The transient behavior and thermodynamic properties of the A/C system was not explicitly simulated, in favor of a simpler approach of capturing the compressor load based on national average ambient conditions. We believe this simplification is justified since the goal is to capture the behavior on the average of a fleet of vehicles (not the behavior of an individual make or model).

In order to properly represent average load values to the engine caused by various A/C compressors and vehicle types, EPA has adopted power consumption curves of A/C systems, published by an A/C equipment supplier, Delphi.[28,29] Also, in an effort to characterize an average A/C compressor load in the presence of widely varying environmental conditions in the United States, EPA has adopted data from the National Renewable Energy Laboratory (NREL) to estimate environmental conditions associated with typical vehicle A/C usage.[30,31,32] Based on the NREL data, EPA selected an A/C power consumption curve as a function of engine speed that was acquired by Delphi at 27°C and 60% relative humidity as a representative average condition. This power consumption curve data was taken from a fixed displacement compressor with a displacement volume of 210 cc. Thus, the curve includes the effect of compressor cycling as well as non-summer defrost/defog usage. In order to associate each vehicle type with the appropriate A/C compressor displacement, EPA scaled the curve based on the displacement volume ratio. For determining indirect A/C impact on fuel consumption increase, EPA estimated A/C compressor sizes of 120 cc, 140 cc, 160 cc, and 190 cc for small, medium, large passenger vehicles, and light-duty pick-up truck, respectively. By applying the displacement volume ratios to the 210 cc power consumption curve, EPA created A/C load curves for four vehicle types, as shown in Figure 5-4.

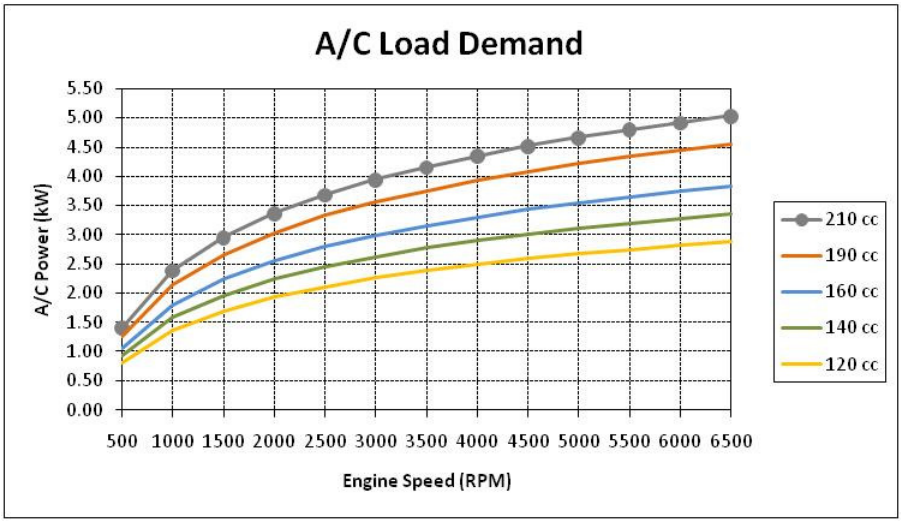


Figure 5-4 Representative A/C Compressor Load Curves

With these A/C compressor load curves, EPA ran full vehicle simulations based on the following matrix. In this matrix, the baseline engine represents a typical Spark-Ignition (SI), Port-Fuel Injection (PFI), Naturally-Aspirated (NA) engine equipped with a Variable Value

Actuation (VVA) technology. In this technology, the valve timing (both intake and exhaust) is continuously varied over a wide range of engine operating conditions in order to result in optimal engine breathing efficiency. On the other hand, the EGR boost engine uses turbocharging and cooled EGR to increase engine's Brake Mean Effective Pressure (BMEP) level while managing combustion and exhaust temperatures. This engine usually has a peak BMEP of 25 to 30 bar, which supports significant downsizing (e.g. about 50%) compared to the baseline engines. Table 5-7 provides simulation results over SC03 driving cycle with an EGR boost engine for various vehicle classes.

- Small, medium, large cars, and pick-up truck
- FTP, Highway, and SC03 cycles
- Baseline and EGR boost engines
- A/C off and A/C on

Table 5-7 Vehicle Simulation Results on CO_2 Emissions over SC03 Cycle with EGR Boost Engine

SC03 Cycle		Small Car	Medium Car	Large Car	Truck
CO_2 with A/C off	[g/mi]	196.4	235.7	293.7	472.4
CO_2 Increase with A/C on	[g/mi]	11.7	12.0	13.8	17.2
Total CO_2 with A/C	[g/mi]	208.1	247.7	307.5	489.6
Indirect A/C Fuel Use	[%]	5.6	4.8	4.5	3.5

EPA ran the SC03 cycle simulations instead of FTP/Highway combined cycle simulations so that the simulation results would represent the actual A/C cycle test. EPA also assumed the EGR boost engine during vehicle simulations because EGR boost engine better represents engine technology more likely to be implemented in model years 2017 to 2025 and because the A/C impact on CO_2 increase in the EGR boost engine is similar to that in the baseline engine as shown in Table 5-7 and Table 5-8. Details of this analysis which showed impact of A/C usage on fuel consumption is independent of engine technology are provided in the next section. Moreover, EPA assumed 38% of a market penetration for automatic climate control systems as well as 23.9% and 35.0% of A/C on-time for manual and automatic climate control systems, respectively. These are the same assumptions made in the 2012-2016 rule.[33] In order to come up with overall impact of A/C usage on CO_2 emissions for passenger cars, the simulation results for cars shown in Table 5-7 were sales-weighted for each year from 2017 to 2025. For the end result, the impact of A/C usage was estimated at 11.9 CO_2 g/mile for cars and 17.2 CO_2 g/mile for trucks. This corresponds to an impact of approximately 14.0 CO_2 g/mile for the (2012) fleet, which is comparable to the 2012-2016 final rule result, but still lower than the two studies by NREL and NESCCAF cited above.

5.1.3.2.1 Effect of Engine Technology on Fuel Consumption by A/C System

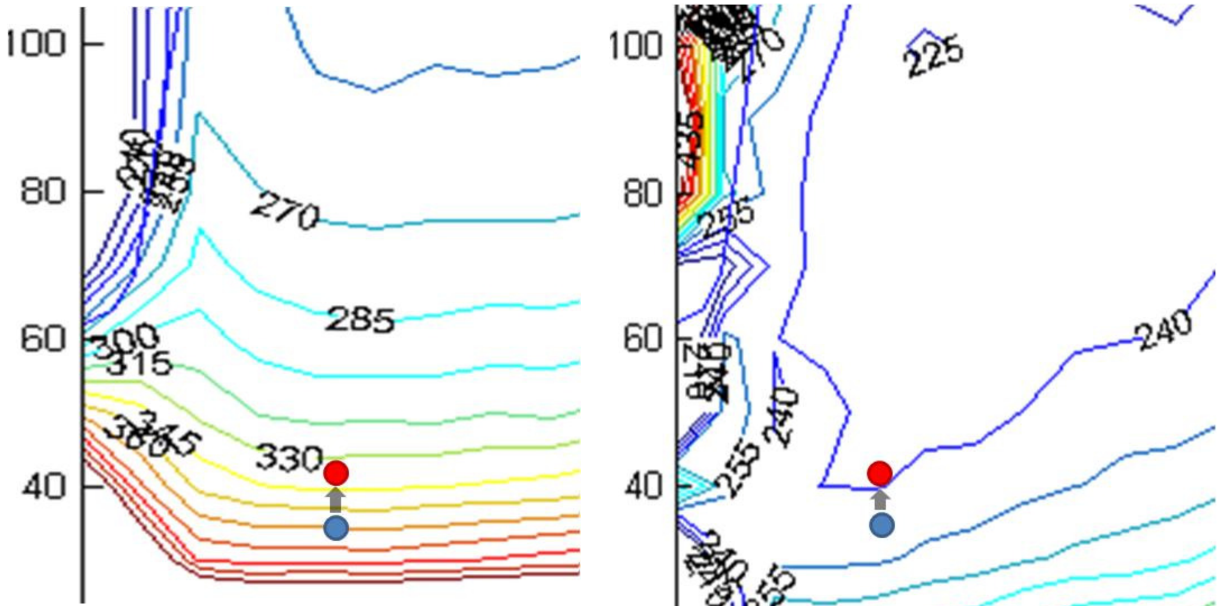
In order to continue to maintain the credit levels from the 2012-2016 rule, EPA had to first demonstrate that the fuel economy and CO_2 emissions due to A/C was relatively insensitive to the engine technologies that may be expected to be prevalent in the future. If for example, more efficient engines are able to run the A/C system more efficiently such that the incremememental increase in emissions due to A/C decreased compared to the base engines, then credits for the same A/C technologies must decrease over time as engines become more efficient. This would correspond to a decrease in credits proportional (or multiplicative) to the increase in efficiency of the engine. Conversely, if the incremental increase in emissions due to A/C remained relatively constant, then the credits available for A/C efficiency should also remain stable. This would correspond to the credits (A/C impact) being additive to the base emissions rate, thus being independent of engine efficiency). The EPA based the hypothesis on the latter assumption.

In order to prove out this hypothesis, EPA carried out vehicle simulations for several cases, including two engine technologies: baseline and EGR boost engines (a surrogate for a future advanced efficient engine). Table 5-8 shows the vehicle simulation results of CO_2 emissions over the SC03 driving cycle when baseline engines are used, as opposed to the advanced EGR boost engines. By comparing the values of CO_2 increase with A/C on in Table 5-7 and Table 5-8, it is evident that the impact of A/C usage on fuel consumption is not very dependent on the engine technologies. In fact, the difference in the CO_2 increase with A/C on (2nd row in table) between the emissions from the baseline and EGR boost engines is less than 10% for all vehicle classes.

Table 5-8 Vehicle Simulation Results on CO_2 Emissions over SC03 Cycle with Baseline Engine

SC03 Cycle		Small Car	Medium Car	Large Car	Truck
CO_2 with A/C off	[g/mi]	259.3	348.0	425.4	628.1
CO_2 Increase with A/C on	[g/mi]	11.3	11.1	12.5	16.2
Total CO_2 with A/C	[g/mi]	270.6	359.1	437.9	644.3
Indirect A/C Fuel Use	[%]	4.2	3.1	2.9	2.5

Figure 5-5 depicts zoomed-in BSFC maps for baseline and EGR boost engines. The circles on these maps represent average operating conditions of the engines over the FTP (city) drive cycle. The blue circle represents a simulated average operating condition without A/C while the red circle represents an average operating condition with A/C. As can be seen in the figure, the engines operate at higher load levels when the A/C is on.



(a) Baseline Engine (b) EGR Boost Engine

Figure 5-5 Average Engine Operating Conditions with A/C Off and A/C On over Fueling Maps for Baseline and EGR Boost Engines

For the baseline engine case, the engine efficiency improves significantly (375 g/kW-h to almost 330 g/kW-h) as it moves along the BSFC surface, whereas the improvement is much less for the EGR boost engine as it moves from approximately 250 g/kW-h to 240 g/kW-h. However, the large improvement in engine efficiency for the baseline engine is offset by the fact that the engine itself is less efficient than the EGR boost engine. Conversely, the small efficiency improvement for the EGR boost engine is compensated by the fact that the engine is much more efficient than the baseline engine. As a result, the CO_2 increase seen by both engines due to A/C usage becomes similar between the two different technologies. This result allows us to approximate the A/C impact on vehicle fuel consumption as an additive effect rather than a multiplicative effect since it is independent of engine technologies. For the same reason, it also means that A/C credits for a given technology can remain constant over time, which will greatly simplify the progression of future credits.[1]

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[1] It also means that the last row in the above two tables are a bit misleading as A/C impact should not be quantified as a fraction of the total emissions, but rather an additive increment. The numbers are left onto the tables for comparison purposes to studies in the literature that use this convention.

5.1.3.3 Technologies That Improve Efficiency of Air Conditioning and Their Effectiveness

Most of the excess load on the engine comes from the compressor, which pumps the refrigerant around the system loop. Significant additional load on the engine may also come from electrical or hydraulic fan units used for heat exchange across the condenser and radiator. The controls that EPA and NHTSA believe manufacturers would use to generate credits for improved A/C efficiency and to improve fuel efficiency in the CAFE program through the use of an adjustment in calculated fuel economy would focus primarily, but not exclusively, on the compressor, electric motor controls, and system controls which reduce load on the A/C system (e.g. reduced 'reheat' of the cooled air and increased of use recirculated cabin air). EPA and NHTSA are proposing a program that will result in improved efficiency of the A/C system (without sacrificing passenger comfort) while improving the fuel efficiency of the vehicle, which has a direct impact on CO_2 emissions.

The cooperative IMAC program described above has demonstrated that average A/C efficiency can be improved by 36.4% (compared to an average MY 2008 baseline A/C system), when utilizing "best-of-best" technologies.[34] EPA and NHTSA consider a baseline A/C system contains the following components and technologies; internally-controlled fixed displacement compressor (in which the compressor clutch is controlled based on 'internal' system parameters, such as head pressure, suction pressure, and/or evaporator outlet temperature); blower and fan motor controls which create waste heat (energy) when running at lower speeds; thermostatic expansion valves; standard efficiency evaporators and condensers; and systems which circulate compressor oil throughout the A/C system. These baseline systems are also extraordinarily wasteful in their energy consumption because they add heat to the cooled air out of the evaporator in order to control the temperature inside the passenger compartment. Moreover, many systems default to a fresh air setting, which brings hot outside air into the cabin, rather than recirculating the already-cooled air within the cabin.

The IMAC program indicates that improvements can be accomplished by a number of methods related only to the A/C system components and their controls including: improved component efficiency, improved refrigerant cycle controls, and reduced reheat of the cooled air. The program EPA and NHTSA are proposing will encourage the reduction of A/C CO_2 emissions from cars and trucks by up to 42% from current baseline levels through a CO2 credit and fuel economy improvement system. EPA and NHTSA believe that the component efficiency improvements demonstrated in the IMAC program, combined with improvements in the control of the supporting mechanical and electrical devices (i.e. engine speeds and electrical heat exchanger fans), can go beyond the IMAC levels and achieve a total efficiency improvement of 42% through incremental improvements beyond that shown in the study due to the long lead time before 2017. The following sections describe the technologies the agencies believe manufacturers can use to attain these efficiency improvements.

Based on the new vehicle simulation research conducted by the EPA described above, the EPA believes that the impact of A/C on average CO_2 emissions amounts to 11.9 CO_2 g/mile for cars and 17.2 CO_2 g/mile for trucks (0.001339 / 0.001935 gallons of gasoline per mile car/truck improvement) and that these results are relatively insensitive to the engine and transmission efficiency improvements expected to be seen during the rule timeframe. A 42% improvement on this emissions rate leads to the maximum credit opportunity of 5.0 g CO2/mi for cars and 7.2 g CO2/mi for trucks (-0.000563 / -0.000810 gallons per mile car/truck improvement). This compares to the 5.7 g/mi (identical for cars and trucks) finalized in the 2012-2016 final rule. When cars and trucks are combined, the new final rule maximum credits are consistent (on a fleet level) with those finalized in the previous rule, though for cars the credits are now somewhat diminished and for trucks increased. The agencies believe that the modification of these credits for this rule is justified given the simulation work conducted, which shows that A/C emissions tends to be larger for the larger vehicles (and trucks tend to be larger than passenger cars).

5.1.3.3.1 Reduced Reheat Using a Externally-Controlled, Variable-Displacement Compressor

The term ‘external control’ of a variable-displacement compressor is defined as a mechanism or control strategy where the displacement of the compressor adjusted electronically, based on the temperature setpoint and/or cooling demand of the A/C system control settings inside the passenger compartment. External controls differ from ‘internal controls’ that internal controls adjust the displacement of the compressor based on conditions within the A/C system, such has head pressure, suction pressure, or evaporator outlet temperature. By controlling the displacement of the compressor by external means, the compressor load can be matched to the cooling demand of the cabin. With internal controls, the amount of cooling delivered by the system may be greater than desired, at which point the cooled cabin air is then ‘reheated’ to achieve the desired cabin comfort. It is this reheating of the air which results reduces the efficiency of the A/C system – compressor power is consumed to cool air to a temperature less than what is desired.

Reducing reheat through external control of the compressor is a very effective strategy for improving A/C system efficiency. The SAE IMAC team determined that an annual efficiency improvement of 24.1% was possible using this technology alone.[34] The agencies estimate that additional improvements to this technology are possible (e.g. the increased use of recirculated cabin air), and that when A/C control systems and components are fully developed, calibrated, and optimized to particular vehicle’s cooling needs, an efficiency improvement of 42% can be achieved, compared to the baseline system.

5.1.3.3.2 Reduced Reheat Using a Externally-Controlled, Fixed-Displacement or Pneumatic Variable-Displacement Compressor

When using a fixed-displacement or pneumatic variable-displacement compressor (which controls the stroke, or displacement, of the compressor based on system suction pressure), reduced reheat can be realized by disengaging the compressor clutch momentarily to achieve the desired evaporator air temperature. This disengaging, or cycling, of the compressor clutch must be externally-controlled in a manner similar to that described in 2.3.2.1. The agencies believe that a reduced reheat strategy for fixed-displacement and pneumatic variable-displacement compressors can result in an efficiency improvement of 20%. This lower efficiency improvement estimate (compared to an externally-controlled variable displacement compressor) is due to the thermal and kinetic energy losses resulting from cycling a compressor clutch off-and-on repeatedly.

5.1.3.3.3 Defaulting to Recirculated Cabin Air

In ambient conditions where air temperature outside the vehicle is much higher that the air inside the passenger compartment, most A/C systems draw air from outside the vehicle and cool it to the desired comfort level inside the vehicle. This approach wastes energy because the system is continuously cooling the hotter outside air instead of having the A/C system draw its supply air from the cooler air inside the vehicle (also known as recirculated air, or 'recirc'). By only cooling this inside air (i.e. air that has been previously cooled by the A/C system), less energy is required, and A/C Idle Tests conducted by EPA indicate that an efficiency improvement of 35-to-40% improvement is possible under the conditions of this test. A mechanically-controlled door on the A/C system's air intake typically controls whether outside air, inside air, or a mixture of both, is drawn into the system. Since the typical 'default' position of this air intake door is outside air (except in cases where maximum cooling capacity is required, in which case, many systems automatically switch this door to the recirculated air position), EPA and NHTSA are specifying that, as cabin comfort and de-fogging conditions allow, an efficiency credit be granted if a manufacturer defaults to recirculated air whenever the outside ambient temperature is greater than 75°F. To maintain the desired quality inside the cabin (in terms of freshness and humidity), EPA believes some manufacturers will control the air supply in a 'closed-loop' manner, equipping their A/C systems with humidity sensors or fog sensors (which detect condensation on the inside glass), allowing them to adjust the blend of fresh-to-recirculated air and optimize the controls for maximum efficiency. Vehicles with closed-loop control of the air supply (i.e. sensor feedback is used to control the interior air quality) will qualify for a 1.7 g/mi CO_2 credit and a 0.000124 gal/mi fuel consumption improvement. Vehicles with open-loop control (where sensor feedback is not used to control interior air quality) will qualify for a 1.1 g/mi CO_2 credit and a 0.000124 gal/mi fuel consumption improvement. We believe that the closed-loop control system will be inherently more efficient than the open-loop control system because the former can maximize the amount to recirculation to achieve a desired air quality and interior humidity level, whereas the latter will use a fixed 'default' amount of recirculated air which provides the desired air quality under worst case conditions (e.g. maximum number of passengers in the vehicle).

Electric drive vehicles such as HEVs, PHEVs and EVs may require some fraction of the A/C cooling capacity to control the battery temperature under hot conditions. PHEVs are most likely to require A/C cooling because their batteries have higher current requirements for all-electric driving than HEVs, and much less battery mass and energy storage than pure EVs. Some electrified vehicles today, such as the Nissan Leaf, cool their batteries with outside air, while others, such as the Toyota Prius and Ford Fusion Hybrid, use cooled cabin air, and the Chevrolet Volt is an example of a vehicle which uses a refrigerant loop to cool the battery. With the increased penetration of these electrified vehicles, it is possible that there will be some loss of efficiency of the A/C system (especially as it relates to cabin air recirculation). Vehicles which use cabin air to cool the battery must discharge this heated air outside the vehicle, rather than recirculating it through the climate control system. Currently, EPA does not account for this A/C efficiency loss in the credit menu. EPA and NHTSA request comments on the technical merits or applicability of accounting for this loss of efficiency within the crediting and fuel economy improvement scheme.

5.1.3.3.4 Improved Blower and Fan Motor Controls

In controlling the speed of the direct current (DC) electric motors in an air conditioning system, manufacturers often utilize resistive elements to reduce the voltage supplied to the motor, which in turn reduces its speed. In reducing the voltage however, these resistive elements produce heat, which is typically dissipated into the air ducts of the A/C system. Not only does this waste heat consume electrical energy, it contributes to the heat load on the A/C system. One method for controlling DC voltage is to use a pulsewidth modulated (PWM) controller on the motor. A PWM controller can reduce the amount of energy wasted, and based on Delphi estimates of power consumption for these devices, EPA and NHTSA believe that when more efficient speed controls are applied to either the blower or fan motors, an overall improvement in A/C system efficiency of 15% is possible.[35]

5.1.3.3.5 Internal Heat Exchanger

An internal heat exchanger (IHX), which is alternatively described as a suction line heat exchanger, transfers heat from the high pressure liquid entering the evaporator to the gas exiting the evaporator, which reduces compressor power consumption and improves the efficiency of the A/C system. In the 2012-2016 rule, we considered that IHX technology would be required with the changeover to an alternative refrigerant such as HFO-1234yf, as the different expansion characteristics of that refrigerant (compared to R-134a) would necessitate an IHX. The agencies believe that a 20% improvement in efficiency relative to the baseline configuration can be realized if the system includes an IHX, and a 1.1 g/mi credit and a 0.000124 gal/mi fuel consumption improvement for an IHX.

5.1.3.3.6 Improved-Efficiency Evaporators and Condensers

The evaporators and condensers in an A/C system are designed to transfer heat to and from the refrigerant – the evaporator absorbs heat from the cabin air and transfers it to the refrigerant, and the condenser transfer heat from the refrigerant to the outside ambient air. The efficiency, or effectiveness, of this heat transfer process directly effects the efficiency of the overall system, as more work, or energy, is required if the process is inefficient. A method for measuring the heat transfer effectiveness of these components is to determine the Coefficient of Performance (COP) for the system using the industry-consensus method described in the SAE surface vehicle standard J2765 – Procedure for Measuring System COP of a Mobile Air Conditioning System on a Test Bench.[36] The bench test based engineering analysis that a manufacturer will submit at time of certification. We will consider the baseline component to be the version which a manufacturer most recently had in production on the same vehicle or a vehicle in a similar EPA vehicle classification. The design characteristics of the baseline component (e.g. tube configuration/thickness/spacing and fin density) are to be documented in an engineering analysis and compared to the improved components, along with data demonstrating the COP improvement. This same engineering analysis can be applied to evaporators and condensers on other vehicles and models (even if the overall size of the heat exchanger is different), as long as the design characteristics of the baseline and improved components are the same. If these components can demonstrate a 10% improvement in COP versus the baseline components, EPA and NHTSA estimate that a 20% improvement in overall system efficiency is possible.

5.1.3.3.7 Oil Separator

The oil present in a typical A/C system circulates throughout the system for the purpose of lubricating the compressor. Because this oil is in contact with inner surfaces of evaporator and condenser, and a coating of oil reduces the heat transfer effectiveness of these devices, the overall system efficiency is reduced.[37] It also adds inefficiency to the system to be "pushing around and cooling" an extraneous fluid that results in a dilution of the thermodynamic properties of the refrigerant. If the oil can be contained only to that part of the system where it is needed – the compressor – the heat transfer effectiveness of the evaporator and condenser will improve. The overall COP will also improve due to a reduction in the flow of diluent. The SAE IMAC team estimated that overall system COP could be improved by 8% if an oil separator was used. EPA and NHTSA believe that if oil is prevented from prevented from circulating throughout the A/C system, an overall system efficiency improvement of 10% can be realized. Whether the oil separator is a standalone component or is integral to the compressor design, manufacturers can submit an engineering analysis to demonstrate the effectiveness of the oil separation technology.

5.1.3.4 Technical Feasibility of Efficiency-Improving Technologies

EPA and NHTSA believe that the efficiency-improving technologies discussed in the previous sections are available to manufacturers today, are relatively low in cost, and their feasibility and effectiveness has been demonstrated by the SAE IMAC teams and various industry sources. The agencies also believe that when these individual components and technologies are fully designed, developed, and integrated into A/C system designs, manufacturers will be able to achieve the estimated reductions in CO_2 emissions and generate appropriate A/C Efficiency Credits, which are discussed in the following section.

5.1.3.5 A/C Efficiency Test Procedures

For model years 2014 to 2016, we are proposing three options for qualifying for A/C efficiency credits: 1) running the A/C Idle Test, as described in the 2012-2016 final rule, and demonstrating compliance with the CO_2 threshold requirements, 2) running the A/C Idle and demonstrating compliance with engine displacement adjusted CO_2 threshold requirements, and 3) running a newly-developed A/C test and reporting the test results. For model years 2017-2025, we are proposing that the A/C Idle Test requirement be eliminated, and that the newly-developed A/C test be used to quantify the A/C-related fuel consumption of new vehicles with efficiency-improving technologies, relative to a baseline vehicle, without these technologies. All of these options continue to rely on the credit menu described below. These options are described in detail in this section.

In the 2012-2016 final rule, manufacturers were required, starting in MY 2014, to demonstrate the efficiency of a vehicle's A/C system by running an A/C Idle Test. If a vehicle met the emissions threshold of 14.9 g/min CO_2 or lower on this test, a manufacturer was eligible to receive full credit for efficiency-improving hardware or controls installed on that vehicle. The vehicle would be able to receive A/C credits based on a menu of technologies. A revised version of this technology menu is described below. For vehicles with a result between 14.9 g/min and 21.3 g/min, a downward adjustment factor was applied to the eligible credit amount, with vehicles testing higher than 21.3 g/min receiving zero credits. The details of this idle test can be found in the 2012-2016 final rule. See 75 FR at 25426-27.

In order to establish the value of this threshold for the 2012-2016 final rule, the EPA conducted an extensive laboratory testing program to measure the amount of additional CO_2 a vehicle generated on the Idle Test due to A/C use. The results of this test program are summarized in Table 5-9, and represent a wide cross-section of vehicle types in the U.S. market. The average A/C CO_2 result from this group of vehicles is the value against which results from vehicle testing will be compared. The EPA conducted laboratory tests on over 60 vehicles representing a wide range of vehicle types (e.g. compact cars, midsize cars, large cars, sport utility vehicles, small station wagons, and standard pickup trucks).

Table 5-9 Summary of A/C Idle Test Study Conducted by EPA at the National Vehicle Fuel and Emissions Laboratory

Vehicle Makes Tested	19
Vehicle Models Tested	29
Model Years Represented (number of vehicles in each model year)	1999 (2), 2006 (21), 2007 (39)
EPA Size Classes Represented	Minicompact, Compact, Midsize, and Large Cars Sport Utility Vehicles Small Station Wagons Standard Pickup Trucks
Total Number of A/C Idle Tests	62
Average A/C CO_2 (g/min)	21.3
Standard Deviation of Test Results ($\underline{+}$ g/min)	5.8

The majority of vehicles tested were from the 2006 and 2007 model years and their A/C systems are representative of the 'baseline' technologies, in terms of efficiency (i.e. to EPA's knowledge, these vehicles do not utilize any of the efficiency-improving technologies described in the credit menu finalized for the 2012-2016 rule). For the 2012-2016 rule, EPA attempted to find a correlation between the A/C CO_2 results and a vehicle's interior volume, footprint, and engine displacement, but found it to be minimal, as there is significant "scatter" in the test results. This scatter is generally not test-to-test variation, but scatter amongst the various vehicle models and types. This original analysis covered a wide range of vehicle size classes and vehicle types: from compact cars to light-duty trucks, some of which did not have readily-available SAE and CAFE interior volume numbers (i.e. the interior volume for small station wagons and pickup trucks had to be inferred from other published sources). Due to the variability in the data, EPA chose a constant threshold value for the Idle Test performance, which provided access to the credit menu.

Since the previous rule, manufacturers have had the opportunity to run the idle test on a wide variety of vehicles and have discovered that even though there may be a small correlation between engine displacement and the idle test result, the trend was important enough that small vehicles had higher A/C idle emissions and were more inclined to fail to meet the threshold for the Idle Test than larger vehicles were. Specifically, vehicles with smaller displacement engines had a higher Idle Test result than those with larger displacement engines, even within the same vehicle platform.[38] This was causing some small vehicles with advanced A/C systems to fail the Idle Test. The load placed on the engine by the A/C system did not seem to be consistent, and in certain cases, larger vehicles perform better than smaller ones on the A/C idle test.

When the EPA test data is sorted according to engine displacement, the relationship between engine displacement and idle test result are somewhat apparent, though there is significant variability as is evident in Figure 5-6. The threshold value from the 2012-2016 rule is included in the figure for comparison purposes.

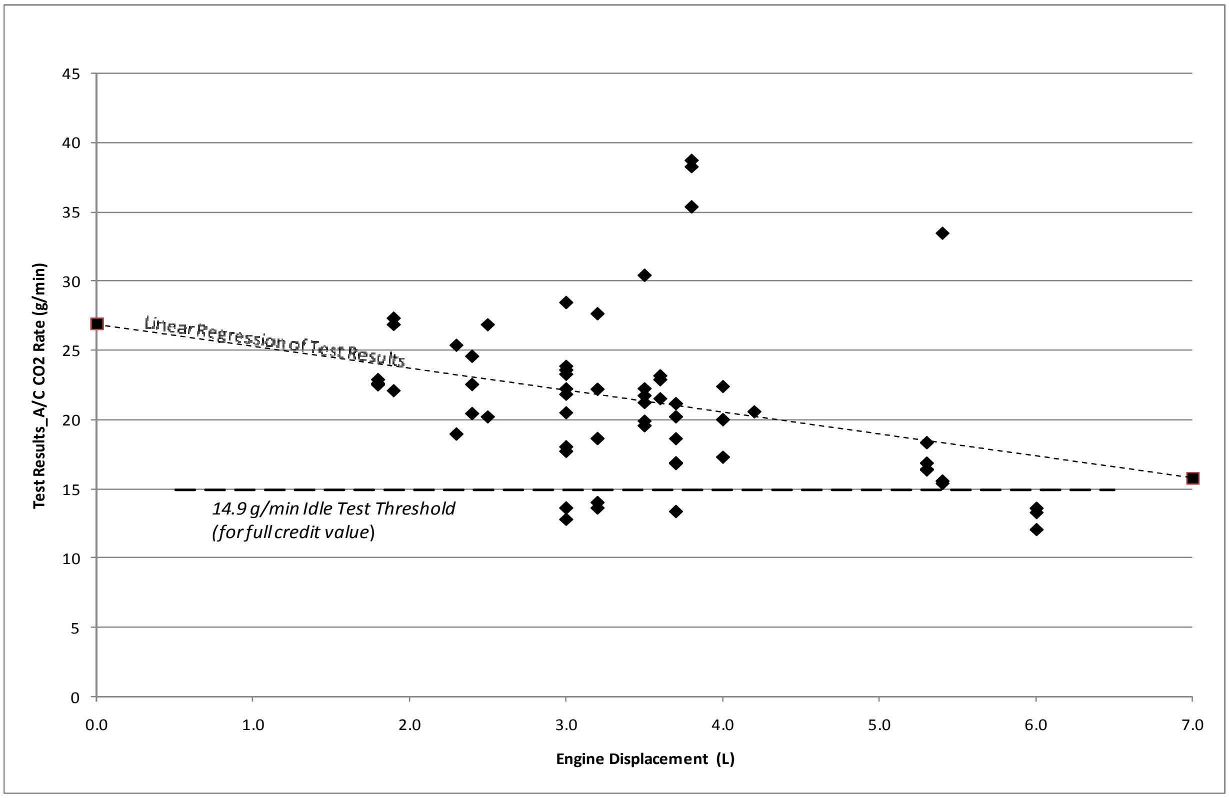

Figure 5-6 Relationship Between EPA A/C Idle Test Results and Engine Displacement.

One factor which may explain part of this observed phenomenon is that the brake-specific fuel consumption (bsfc) of a smaller displacement engine is generally lower at idle than that of a larger displacement engine. At the idle condition, without A/C load applied, a smaller engine is generally more efficient (i.e. has a lower bsfc) than a larger engine, in terms of how well it converts fuel heat energy into power. When additional load from the A/C system is added to the small displacement engine, the bsfc does not improve as dramatically as it does on a larger displacement engine, and if both the small- and large-displacement engines require a similar amount of engine power to run the A/C system, the larger engine will move from a "less-efficient" to "more-efficient" operating condition, whereas the smaller engine remains relatively flat, in terms of bsfc. The result is that a larger displacement engine uses less fuel to run the A/C system, relative to a smaller displacement engine, because its baseline condition (A/C off) is "less-efficient", and the incremental amount of fuel used is lower. The slope of the linear regression line for this data set is -1.58 g/min/L, with a zero intercept of 26.9 g/min.[m]

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[m] The R^2 for this fit is 0.09 reflecting the scatter and variability of the data. The slope is statistically significant at the 2% confidence level (Significance F) indicating that the slope is statistically significant.

In the 2012-2016 final rule, the EPA chose a threshold of 30% improvement on the Idle Test as the threshold for accessing the credit menu (the justification and feasibility argument is presented again below). This corresponded to a 6.4 g/min reduction from the average Idle Test result (or 14.9 g/min in the previous rule). In this rule, EPA is proposing to maintain the 6.4g/min gap between the average emissions (equation of the line) and the threshold. Equation 5-3 results in an idle test threshold which is scaled according to engine displacement, in liters. The threshold equation is overlaid on the data in Figure 5-7. Using this equation, the idle test threshold for a 1.2L engine for example (to receive full credit) would be 18.6 g/min for a 6.0L engine the threshold would be 11.0 g/min.

Equation 5-3 – A/C Idle Test Threshold

$$Idle\ Test\ Threshold = 20.5 - 1.58\ x\ (Engine\ Displacement)$$

Even though the idle test may not fully capture the effect of each and every technology, we believe that the test does reflect the overall efficiency of the vehicle's A/C system under a commonly encountered operating condition. When the Idle Test is combined with a displacement-adjusted "threshold", the EPA believes that this test is an appropriate criteria for a gaining access to A/C efficiency credits, at least until a new transient cycle can replace the Idle Test.

We believe that part of the variation in the EPA's A/C idle test results evident in the figure above, was due to the type of components a manufacture choose to use in a particular vehicle. Components such as compressors are shared across vehicle model types (e.g. a compressor may be 'over-sized' for one application, but the use of a common part amongst multiple model types results in a cost savings to the manufacturer), rather than being designed for one particular cabin size. Some of the variation may also be due to the amount of cooling capacity a vehicle has at idle. For instance, if the cooling capacity (or cooling performance) of a particular vehicle was less-than-optimal at idle (due to factors such as limitations of the compressor design, pulley ratio, or packaging), this vehicle could produce below-average A/C CO_2 results, because the amount of energy required by the compressor would be lower. Yet at higher engine and/or vehicle speeds, this same vehicle may have cooling capacity typical of other vehicles. Therefore, a test which is limited to one area of A/C operation is limited in its ability to determine overall A/C system efficiency.

Some of this variation between vehicle models may also be due to the efficiency of the fan(s) which draw air across the condenser – since an external fan is not placed in front of the vehicle during the A/C Idle Test, it is the vehicle's radiator fan which is responsible for rejecting heat from the condenser (and some models may do this more efficiently than others). In this case, EPA believes that an SC03-type test – run in a full environmental chamber with a "road-speed" fan on the front of the vehicle – would be a better measure of how a vehicle's A/C system performs under transient conditions, and any limitations the system may have at idle could be counter-balanced by improved performance and efficiency elsewhere in the drive cycle. However, since idle is significant part of real-world and FTP drive cycles (idle represents 18% of the FTP), EPA believes that the focus in this rulemaking on A/C system efficiency under idle conditions is still justified. EPA acknowledges that there are limitations to the Idle Test, however we have determined that it is still a valid tool evaluating the efficiency of a vehicle's A/C system under some of the conditions encountered in daily vehicle use until a more appropriate test procedure is developed. Moreover, we continue believe that a performance test is strongly preferred in order to assure that efficiency-improving technologies are implemented properly and that the vehicle's A/C system operates in an efficient manner under idle conditions.

Since the 2012-2016 final rule, EPA has received a number of idle test results from several manufacturers. Testing by Ford, General Motors, and Chrysler has shown that there are some significant limitations to the idle test procedure. As mentioned above, there was significant test-to-test variability noted, and many vehicles – especially those with smaller displacement engines – failed to meet the required test threshold (14.9 g/min) to qualify for A/C credits – even when such vehicles are equipped with a significant number of efficiency-improving technologies listed in the menu. These tested vehicles were from upcoming model years and had a variety of air conditioner components and controls strategies (from among the technologies described above and in the menu) implemented. The results are shown in the Table 5-10 and are printed with permission from the manufacturers.

Table 5-10 A/C Idle Test Results from Various Manufacturers

Engine Displacement (liters)	A/C Idle Test Result (gCO_2/min)
1.4	19.4
2.0	22.4
2.0	20.0
2.4	28.0
2.4	18.3
3.5	12.0
3.6	24.0
3.6	16.0
5.7	26.0

The test-to-test variability observed by the manufacturers was significant, and is likely due to high dilution of the exhaust sample (exhaust mass flow is low at idle), which results in greater measurement error, as there is less CO_2 present for sampling than there would be under normal operating conditions. Furthermore, fluctuations in cell ambient conditions (e.g. temperature and humidity), or in the way the driver is positioned in the seat, make accurate test-to-test comparisons of the results difficult to achieve. In Figure 5-7, these new data points from the manufacturers are overlaid onto the idle test data collected in support of the 2012-2016 final rule by the EPA. Most of the EPA vehicles tested over the past two years did not contain a significant amount of efficient air conditioner components (off of the menu list). The manufacturer data is largely consistent with the EPA data. The data support the notion that it might be more appropriate to use an increasing function of emissions as a function of engine displacement for a threshold, rather than the flat function we finalized in the 2012-2016 rule.

The test cells on which an Idle Tests are conducted are typically the same cells which are used for FTP testing for criteria pollutants, where the allowable ambient temperature is 68-to-86 °F, and there is no humidity specification. Since there are normal, seasonal fluctuations in humidity level for this type of test cell, controlling the ambient conditions to those specified in the Idle Test procedure is difficult. EPA is proposing that the allowable ambient air temperature condition be modified from to 75 ± 2 °F on average to 73-to-80°F on average, and the ambient humidity within the test cell be modified from 50 ± 5 grains of water per pound of dry air to 40-to-60 grains of water per pound of dry air. EPA is requesting comment on whether these modifications to the Idle Test ambient conditions are sufficient, and whether the requirements for allowable instantaneous temperature and humidity conditions need to be modified as well.

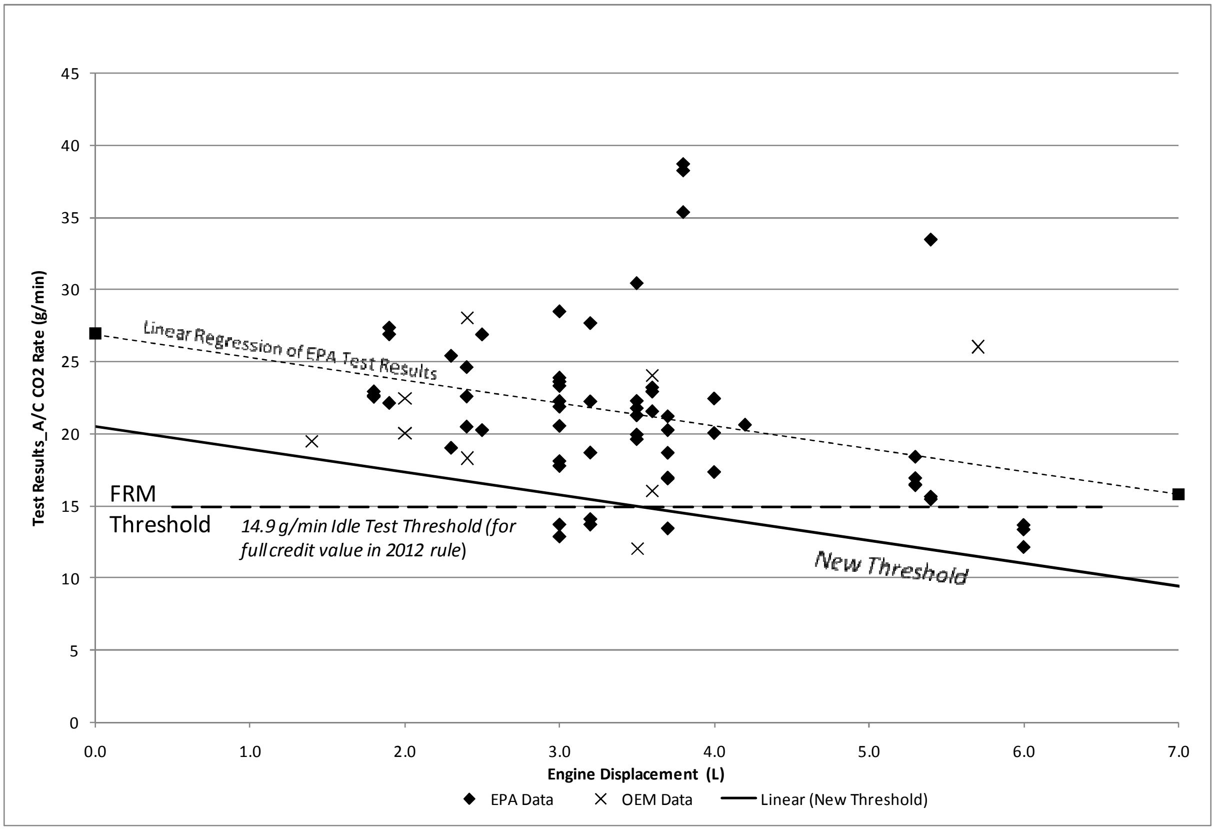

Figure 5-7 EPA A/C Idle Test Results with Results from Various Manufacturers

With the revised threshold, it is still possible for a vehicle test to have some A/C technologies but still fail to meet the threshold for the credit menu. For the present rule, the EPA is proposing to continue a gradual decrease in credits for vehicles that fail to meet the threshold. To qualify for the full credit, it will be necessary for each vehicle certified to achieve an A/C CO_2 result less than or equal to the threshold function (which is 30% less than the average value observed in the EPA testing). EPA chose the 30% improvement over the "average" value to drive the fleet of vehicles toward A/C systems which approach or exceed the efficiency of best-in-class vehicles. EPA test results on three vehicle size classes (large car, SUV, and pickup truck) indicate that significant reductions in fuel consumption can be achieved by simply switching A/C control from outside air (OSA) to recirculated cabin air. As shown in Table 5-11, the percentage reduction in the CO_2 and fuel consumption due to A/C use was greater than 30% in all three cases.

Table 5-11 Effect of Outside Air and Recirculated Cabin Air on A/C Idle Test Results (EPA Testing)

Vehicle Type	A/C CO2 Result (g/min)		Change in A/C CO2 w/Recirc (%)
	w/Outside Air	*w/Recirc Cabin Air*	
Large Car	25.9	14.0	-45.9
SUV	17.4	11.4	-34.5
Pickup Truck	14.1	9.0	-36.2

EPA believes this approach will cause manufacturers to tailor the size of A/C components and systems to the cooling needs of a particular vehicle model and focus on the overall efficiency of their A/C systems. EPA believes this approach strikes a reasonable balance between avoiding granting credits for improvements which would occur in any case, and encouraging A/C efficiency improvements which would not otherwise occur. However, as explained above, to avoid having an all-or-nothing threshold on the Idle Test to qualify for credits, EPA is proposing to allow some amount of credit as long as the Idle Test performance remains better than the best fit regression obtained from EPA testing. A multiplier would be applied to the credits (based on the menu) such that if the difference between the Idle Test result and the threshold value (hereafter referred to as the "gap") at the vehicle's engine displacement is greater than 6.4g/min, then the multiplier would be 1.0, if the gap is 0.0 g/min or less, then the multiplier would be 0.0, the multiplier in between would follow a linear function as shown in the following figure. The EPA is also proposing that manufacturers have the option of using these threshold adjustments as early as MY 2014.

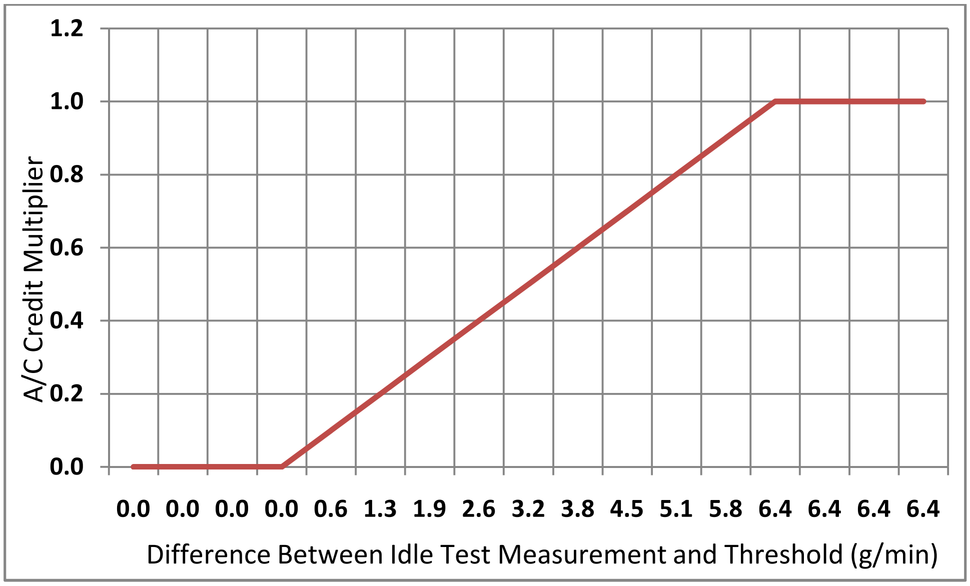

Figure 5-8 EPA A/C Credit Multiplier as a Function of the Difference Between Idle Test Measured and Threshold at any given engine displacement

EPA continues to recognize the limitations of the idle test applicable to MY 2014-2016 vehicles. The primary disadvantage is that the test does not capture the majority of the driving or ambient conditions in the real world when the A/C is in operation, and thus may only encourage the technologies that improve idle performance under narrow temperature conditions. Another limitation is that the idle test can never quantify the incremental improvement of a given technology to generate an actual credit (without a menu). In order to generate a credit value a more complex test procedure is required that can do an "A" to "B" comparison, where B is with the technology and A is without. There were comments from a number of stakeholders reiterating some of these limitations. The remainder of this section describes this effort. The test procedure has evolved since the concepts described in the 2012-2016 final rule.

In preparation for this 2017-2025 proposal, EPA has initiated studies and continues to engage with manufacturers, component suppliers, SAE, and CARB in developing a procedure for determining A/C system efficiency and credits. This effort also explores the applicability and appropriateness of a test method or procedure which combines the results of test-bench, modeling/simulation, and chassis dynamometer testing into a quantitative metric for quantifying A/C system (fuel) efficiency. The goal of this exercise is the development of a reliable, accurate, and verifiable assessment and testing method while also minimizing a manufacturer's testing burden. This effort is still underway and may not even be complete in time for the final rule, however much progress has been made on the chassis dynamometer test procedure.

The EPA, in cooperation with automotive manufacturers and CARB, initiated the development of a new A/C test procedure – one which would be capable (in part) of detecting the effect of more efficient A/C components and controls strategies during a transient drive cycle (rather than just idle). This new test procedure, known as "AC17", should more accurately reflect the impact that A/C use (and in particular, efficiency-improving components and control strategies), has on tailpipe CO2 emissions.

The new AC17 test has four elements: a pre-conditioning cycle, a 30-minute solar soak period; Bag 1 is an SC03 drive cycle at 77 °F (to capture the "pull-down" portion of A/C operation); and Bag 2 is a highway fuel economy cycle (to capture the "steady-state" portion of A/C operation). The test cycle is first run with the A/C on (Bags 1 and 2) and then re-run with the A/C off (Bags 3 and 4). The A/C-related CO_2 emissions are the difference between the A/C on and A/C off test results. Initially, EPA is proposing that emissions from first and second bags be weighted equally, and that these results would be used to calculate the grams per mile emissions due to A/C use. We are requesting comment on whether this weighting is appropriate for quantifying the typical effect of A/C use on tailpipe emissions. EPA believes that this new test cycle will be able to capture improvements in all areas related to efficient operation of a vehicle's A/C system: solar control; efficiency improving components; and efficient control strategies. Below is a depiction of the new test cycle, which is still in draft form. To assure consistent results for the fuel consumption effect of operating the A/C system, the test is always run in a warm condition, where an EPA Urban Dynamometer Driving Schedule (UDDS) cycle is run at the start of the test sequence, with the A/C off and the solar lamps on. Immediately following this precondition phase, the engine is turned off and the vehicle soaks for 30 minutes with the solar lamps on. At the conclusion of the solar soak, the “pull-down” (rapid cool-down of cabin temperature) phase begins. This phase utilizes the existing SC03 drive cycle to simulate dynamic, urban driving conditions. Finally, the highway fuel economy test cycle, or HFET, is used to simulate a “steady-state” driving condition, while the A/C system is maintaining the cabin temperature. Each element of this proposed cycle exercises modes of operation seen in everyday use where cabin cooling is needed. By running the vehicle through each of these conditions with and without the A/C system operating, we seek to understand the effect that soak, pull-down, and steady-state conditions have on the fuel consumption for a particular A/C system design or technology. The total time required to run this test on a single vehicle is approximately 4 hours (including A/C on/off). EPA is taking comment on all aspects of this test procedure. In particular, we are asking for comment on the appropriateness of using the AC17 test to evaluate new efficiency-improving technologies, with the goals of: quantifying the impact of a technology on A/C-related emissions and fuel consumption; establishing a value for the amount of credit a particular technology can generate; and ultimately, adding the technology to the list of efficiency-improving technologies (see Table 5-12).

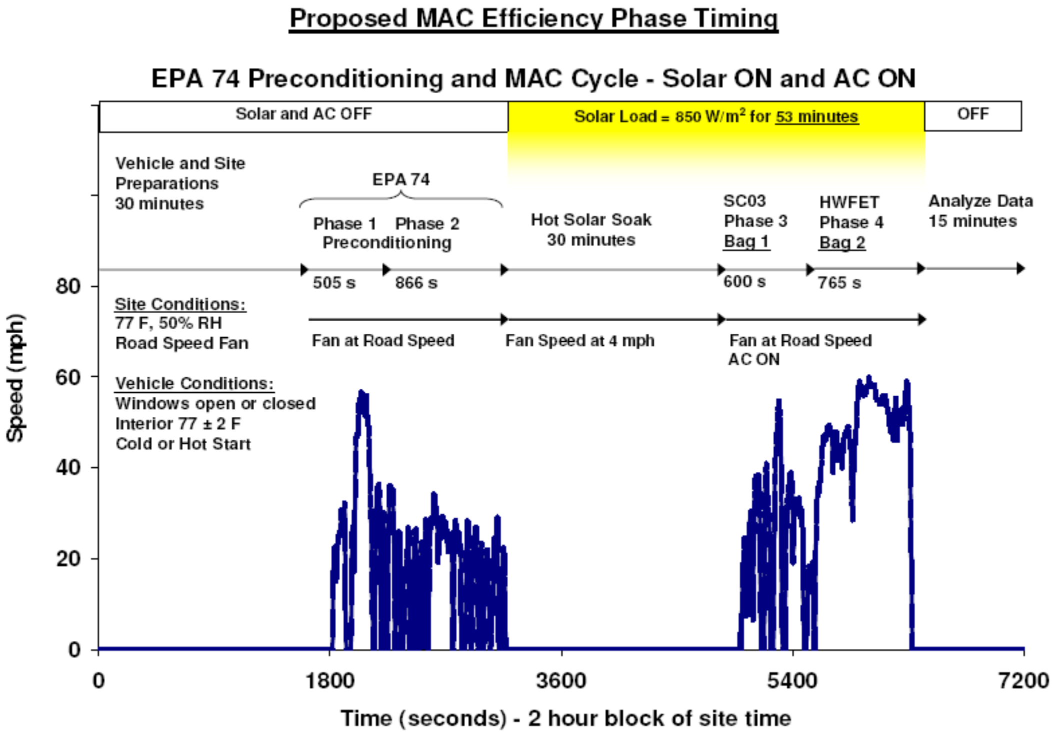

Figure 5-9 Proposed A/C Test

EPA is also seeking comment on the ambient conditions and system control settings proposed for this test. The proposed ambient temperature is 77± 2 °F average, and 77± 5 °F instantaneous, with a humidity level in the test cell of 69 ± 5 grains of water per pound of dry air average, and 69 ± 10 grains instantaneous. The ambient temperature and humidity conditions for the AC17 test were chosen because we believe that they represent a common operating condition for A/C use: extremely high temperatures, such as the 95 °F condition specified for today's SC03 test, while encountered in certain parts of the United States, wouldn't demonstrate the impact that technologies such as variable displacement compressors have on system efficiency under lower cooling demand conditions. The proposed control settings for the "A/C ON" portions of the test (Phases 3 and 4 in Figure 5-9) are different for systems with automatic and manual climate controls. Automatic systems will be set to a 72 °F target temperature, with blower (or fan) speed and vent location controlled by the automatic mode. Manual systems will set the temperature selector to full cold, blower speed at its highest setting, and the air supply set to "recirculated air" for the first 185 seconds of Phase 3. At the first idle of Phase 3 (186 to 204 seconds), the blower speed will be set to achieve 6 volts at the motor, temperature selector will be set to provide 55 °F at the center dash outlet, and the air supply set to "outside air". The recommended temperature selector and and blower control positions for manual systems will be identified by the manufacturer.

EPA is taking comment on the proposed option which allows manufacturers to replace the A/C Idle Test threshold requirement, which starts in MY 2014, with a reporting-only AC17 test requirement for generating Efficiency Credits. In MYs 2014-2016, to demonstrate that a vehicle's A/C system is delivering the efficiency benefits of the new technologies, manufacturers will have the option to run the AC17 test procedure on each vehicle platform which incorporates the new, credit-generating technologies, and report the results from all 4 phases of the test to EPA In addition to reporting the test results, EPA is proposing to require that manufactures provide information about each test vehicle and its A/C system (e.g. vehicle class, model type, curb weight, engine size, transmission type, interior volume, climate control type, refrigerant type, compressor type, and evaporator/condenser characteristics). We are seeking comment on whether this new test and reporting requirement approach is appropriate for generating and verifying A/C Efficiency Credits. In addition, we are seeking comment on whether the list of vehicle and A/C system information to be provided by the manufacturers is sufficient.

EPA further proposes that for model years 2017 to 2025, the A/C Idle Test and threshold requirement be eliminated, and be replaced with the AC17 test. For 2017 and beyond, manufacturers would run the AC17 test to validate the performance of a vehicle's A/C technology, relative to a baseline vehicle which does not incorporate the efficiency-improving technologies for which credit is being generated. The baseline vehicle is one with characteristics which are similar to the new vehicle, only it is not equipped with efficiency-improving technologies, or they are de-activated (e.g. forced cabin air recirculation). Presumably, this baseline vehicle would be from the same platform but a prior (re)design. We recognize that it may not be possible to find a baseline vehicle which is identical (in terms of powertrain characteristics, as well as aerodynamic and parasitic losses) to the new vehicle. However, as we described in section 5.1.3 of this Joint TSD and Chapter 2 of the RIA, based on the simulated behavior of A/C systems in a variety of vehicles, we believe that the fuel used to operate the A/C system is largely dependent on the compressor size and cooling capacity of the system, and much less dependent on engine displacement or efficiency. As such, we believe that it is technically appropriate for manufacturers to compare vehicles from different generations of redesign cycles in order to demonstrate that their efficient A/C systems can provide CO_2 and fuel consumption reductions commensurate to the amount of credit that a particular vehicle can generate. If the AC17 test result with the new technology demonstrates an emission reduction which is greater than or equal to the maximum credit potential (5g/mi for cars and 7.2 g/mi for trucks), full credit will be generated based on the menu (below). However if the test result is less than the maximum credit potential, partial credit can still be generated, in proportion to how far away the result is from the expected result. (As noted above, the agencies used the simulation tool to determine the maximum credit potential for indirect A/C credits.)

The AC17 testing would first be required on the highest-production-volume vehicle model from each platform for which credits are generated. Because the new A/C test requires significant amount of time for each test (nearly 4 hours) and must be run in SC03-capable facilities, EPA believes that it is appropriate to limit the number of vehicles a manufacturer must test in any given model year by limiting the testing to one vehicle per platform. For the purpose of the AC17 test and generating efficiency credits, a platform would be defined as a group of vehicles which have common body floor pan, chassis, and powertrain (e.g. engine and transmission) characteristics. The credits generated using the AC17 approach would carry forward to subsequent model years, unless there is a significant change in either the platform design or A/C system components or control strategies. EPA recognizes that a single platform designation may encompass a larger group of fuel economy label classes or car lines (40 CFR §600.002-93), such as passenger cars, compact utility vehicles, and station wagons. And in cases where there are multiple A/C system variants within a platform - such as component designs, control strategies (e.g. manual or automatic), or number of evaporators - EPA is proposing that manufacturers would run the AC17 test on one of these variants in each subsequent model year, where applicable, until all variants have been tested. In addition, EPA is proposing the manufacturers provide detailed information about the A/C systems in vehicles tested, both baseline and new, as well as a plot with the interior temperature of both vehicles, to confirm that there is equivalent or better cooling system performance in the new vehicle configuration. EPA is proposing that interior temperature be measured at three locations: outlet of the center duct on the dash panel and behind the driver and passenger seat headrests. For the headrest locations, the temperature measuring devices shall be 30 millimeters behind the headrest and 330 millimeters below the roof. EPA requests comment on the new test, its use as an optional method of validating the function of A/C efficiency-improving technologies, and the appropriate weighting of each phase of the AC17 test.

EPA is taking comment on whether the AC17 test is appropriate for estimating the effectiveness of new efficiency-improving A/C technologies, and whether this test could be used to add new technologies and credit values to the list described in the next section. EPA is also seeking comment on an option starting in 2017 to use the AC17 test with a performance threshold (rather than a comparison to a baseline vehicle test, in order to access the menu (similar to the role the idle test plays prior to 2017). Lastly, EPA is seeking comment on an option starting in 2017 to use the actual results of the AC17 comparison to a baseline to determine the credits without the use of the credit menu. This credit would still subject to the maximum car and truck efficiency credits.

5.1.3.6 A/C Efficiency Credits and Quantification of Credits

The EPA and NHTSA believe that it is possible to identify the A/C efficiency-improving components and control strategies most-likely to be utilized by manufacturers and are proposing to assign a CO_2 ‘credit’ and fuel economy improvement value to each. In addition, the agencies recognize that to achieve the maximum efficiency benefit, some components can be used in conjunction with other components or control strategies. Therefore, the system efficiency synergies resulting from the grouping of three or more individual components are additive, and will qualify for a credit commensurate with their overall effect on A/C efficiency. A list of these technologies – and the credit associated with each – is shown in Table 5-12. If more than one technology is utilized by a manufacturer for a given vehicle model, the A/C credits can be added, but the maximum credit possible is limited to 5.0 g/mi for cars (equivalent to 0.000563 gal/mi) and 7.2 g/mi (equivalent to 0.000810 gal/mi) for trucks. More A/C related credits are discussed in the off-cycle credits section of this chapter.

Table 5-12 Efficiency-Improving A/C Technologies and Credits

Technology Description	A/C CO_2 Emission and Fuel Consumption Reduction	Car A/C Credit and Ajustment (g/mi $CO_2$and gal/mi)	Truck A/C Credit and Improvement (g/mi CO_2 and gal/mi)*
Reduced reheat, with externally-controlled, variable-displacement compressor	30%	1.5 (*30% of 5.0 g/mi impact*) / 0.000169	2.2 (*30% of 7.2 g/mi impact*) / 0.000248
Reduced reheat, with externally-controlled, fixed-displacement or pneumatic variable displacement compressor	20%	1.0 / 0.000113	1.4 / 0.000158
Default to recirculated air with closed-loop control of the air supply (sensor feedback to control interior air quality) whenever the outside ambient temperature is 75 °F or higher (although deviations from this temperature are allowed if accompanied by an engineering analysis)	30%	1.5 / 0.000169	2.2 / 0.000248
Default to recirculated air with open-loop control of the air supply (no sensor feedback) whenever the outside ambient temperature is 75 °F or higher (although deviations from this temperature are allowed if accompanied by an engineering analysis)	20%	1.0 / 0.000113	1.4 / 0.000156
Blower motor control which limit wasted electrical energy (e.g. pulsewidth modulated power controller)	15%	0.8 / 0.000090	1.1 / 0.000124
Internal heat exchanger (or suction line heat exchanger)	20%	1.0 / 0.000113	1.4 / 0.000156
Improved evaporators and condensers (with engineering analysis on each component indicating a COP improvement greater than 10%, when compared to previous design)	20%	1.0 / 0.000113	1.4 / 0.000156
Oil Separator (internal or external to compressor)	10%	0.5 / 0.000056	0.7 / 0.000079

* This factor is a gasoline conversion from CO_2 using 8887 g/CO_2 per mpg, NHTSA is proposing to set this constant independent of fuel. NHTSA seeks comment on setting fuel specific improvement factors, especially as it related to dual fuel vehicles (FFVs for example).

Even though EPA is proposing a design based A/C credit program that introduces some minor revisions to what was finalized for the MY 2012-2016 rule, EPA continues to believe that a full performance based test procedure is the most appropriate way for quantifying A/C credits. Performance based procedures propose no limits on the technological choices made by a manufacturer to improve efficiency. Design based standards by their very nature choose technologies that are "winners" and "losers", thus potentially stifling innovation and unique solutions. Ideally, performance based standards would be the most appropriate method of quantifying A/C credits, however there are many challenges to accurately quantifying a small incremental decrease in emissions and fuel consumption compared to a relatively large tailpipe emissions and fuel consumption rate. For example, it would be nearly impossible to distinguish and measure the impact of a 0.5g/mi improvement in tailpipe emissions due to an improved oil separator system incremental to a tailpipe 250g/mi test procedure result. The 0.5g/mi increment would be well within the noise of a test measurement or test-to-test variability. Even if a number of the technologies were to be packaged together to account for a 5.0g/mi improvement, this is still only 2% of the tailpipe emissions value and still may be within test-to-test variability. The other major challenge to quantifying credits is that it is not practical (from a compliance standpoint) to measure the CO_2 emissions from a vehicle with and without a series of technologies that include hardware and software integrated in a complex fashion. This could only be done with an "A" to "B" comparison where the "B" condition includes the technologies and the "A" condition does not. Such A to B test comparisons require the manufacture of a prototype vehicle that is in all respects identical to the certified vehicle with the exception that the technologies being evaluated are removed. This would be impossible to do for every vehicle certified for a fuel economy test. It would even be prohibitive for a single vehicle demonstration for each manufacturer. This might only be practical on a single vehicle research level program as was done in the IMAC study. The proposed comparison of the AC17 test result to the baseline vehicle with the older technology will likely give an "A" to "B" comparison that is "close" based on the vehicle simulation results presented above, however, a more direct comparison is likely to give even more accurate quantification of credits such that the menu may no longer be required. Also a baseline comparison is more challenging to do with vehicle models that do not have a predecessor (a completely new model).

The IMAC study successfully demonstrated that there are methods by which the efficacy of technologies can be measured. In the IMAC study, the efficiency of A/C components were measured on a test bench where the conditions can be precisely controlled. Test bench measurements are, by their nature, much more repeatable than chassis dynamometer tests. They can also easily be used to do A to B comparisons of technology effectiveness since components can be relatively easily swapped out. The limitations of test bench measurements primarily lie in the fact that they cannot capture the impact of the component integration into the vehicle. The test bench only measures the efficiency of the A/C components, it cannot account for the controls strategy (for example), such as forced recirculation, not defaulting to reheat, and smart cycling of fixed displacement compressors. Another disadvantage of test benches are that there are few such facilities available in the United States and typical OEMs do not possess such extensive test benches as they do not manufacture A/C components.

One option to circumvent the limitations of both the test bench and the chassis tests are to merge the two in a combined test procedure that will utilize the strengths of each to supplement the weaknesses of the other. The test bench can generate the A to B comparison portion of the credit on the hardware changes, while the chassis test generates the A to B comparison of the (software) controls strategy changes.

An A/C test bench typically measures the efficiency of a system by measuring its Coefficient of Performance (COP). The COP of a heat pump is the ratio of the change in heat at the output to the supplied work (also equivalent to the SEER seasonal energy efficiency ratio rating on a residential A/C unit).[n] The IMAC procedure employed the SAE procedure J2765 in order to bench test systems in a fashion that reflects national average A/C usage. This test procedure could be used to generate the efficiency of any production A/C system. The challenge lies in the comparison to the baseline "A" system for the A to B comparison. This could be done either with a defined hardware baseline system or a typical baseline COP value agreed upon by the industry. The EPA requests comment on how to define this baseline system.

Combining the bench test together with a chassis test requires a model, simulation or some calculation procedure (algorithm) to convert the test bench results to fuel economy and GHG emissions. There are a number of options for this model. The Lifecycle Climate Performance or LCCP model (also known as SAE J2766), developed by General Motors in partnership with SAE, NREL, EPA, is one such model, and was utilized for the IMAC project. While the LCCP model took into account many factors concerning lifecycle emissions and fuel use (including the energy needed to manufacture a particular refrigerant), it may be possible to employ a portion that model, and only discern the effect of the A/C system efficiency of annualized fuel use due to A/C operation. Since the LCCP model uses the results of SAE J2765 bench testing as an input, EPA is seeking comment on the feasibility of using a simplified version of this model for quantifying the efficiency of A/C system designs and components. Another option is for the test bench to produce charts like the one in Figure 5-4. This can then be used as an input into EPA's vehicle simulation tool. Whatever the method, such a series of models can convert a system COP into a change in fuel economy and CO_2 emissions from the hardware changes in an A/C system. The controls strategy changes in the menu will have to be measured with an A to B comparison on the chassis dynamometer test procedure described above. To do this, the manufacturer would test a vehicle with a baseline controls strategy compared with a modified more efficient strategy.

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[n] According to the second law of thermodynamics, the COP of a real heat pump system is limited to the Carnot cycle efficiency, which is the ratio of the low Temperature to the difference between the high and low temperatures (in Kelvin).

Though the EPA has not yet conducted a test program to test the feasibility of this concept, combining the results from the bench and dynamometer tests should give a quantitative assessment of the credits from an improved A/C system compared to a baseline system.

Due to the relative complexity (and expense) of this demonstration, it would only be practical for a manufacturer to do this for only a small number of vehicle and A/C configurations in any given year. The EPA has met with a few manufacturers, and they have informed the EPA that on any single vehicle platform, the A/C systems usually share similar configurations. Most full line manufacturers only have a handful of vehicle platforms (in order to save on engineering and manufacturing costs). Therefore, this compliance demonstration should only have to be conducted infrequently on a vehicle platform or A/C system redesign. Based on the limited number of platforms and the relative infrequency of redesigns, EPA expects that any manufacturer may only be required to do a compliance demonstration of A/C credits perhaps one or two times per year on average in order to generate credits.

The EPA requests comment on all aspects of this combined performance based test procedure in order to generate A/C credits without a the credit menu in contrast to the new vehicle AC17 comparison to the older baseline vehicle with the credit menu.

5.1.4 Air Conditioner System Costs

Air Conditioner Systems – These technologies include improved hoses, connectors and seals for leakage control. They also include improved compressors, expansion valves, heat exchangers and the control of these components for the purposes of improving tailpipe CO2 emissions and fuel economy as a result of A/C use. The GHG and fuel economy effectiveness is unchanged from estimates used for 2016 model year vehicles in the 2012-2016 final rule.

In the 2012-2016 rule, EPA estimated the DMC of direct/leakage reduction A/C controls at $17 (2007$) and for indirect/efficiency improvement controls at $53 (2007$). These DMCs become $18 (2009$) and $54 (2009$), respectively, when converted to 2009 dollars for this analysis. EPA continues to consider those DMCs to be applicable in the 2012MY and continues to consider the technologies to be on the flat portion of the learning curve. For this proposal, the 2012-2016 rule technologies represent the reference case in terms of controls and costs. We have applied to those DMCs low complexity ICMs of 1.24 through 2018 then 1.19 thereafter to generate the indirect costs for this reference case. The resultant reference case costs are shown in Table 5-15.

New for this proposal are additional costs for indirect/efficiency improvement control as those 2012-2016MY vintage systems penetrate to the entire fleet, and new costs associated with the alternative refrigerant—both the alternative refrigerant itself and the system changes to accommodate that refrigerant. For the first of these—indirect controls—the agencies have estimated the DMC at $15 (2009$) applicable in the 2017MY. The agencies consider this technology to be on the flat portion of the learning curve and have used a low complexity

ICM of 1.24 through 2018 then 1.19 thereafter. For the alternative refrigerant, the agencies have estimated a DMC of $67 (2009$) applicable in the 2016MY. The agencies consider this technology to be on the steep portion of the learning curve because it is only now starting to be used in a limited number of vehicles. For this technology, the agencies have used a low complexity ICM of 1.24 through 2022 then 1.19 thereafter. For the alternative refrigerant system costs (i.e., the hardware changes necessary to accommodate the alternative refrigerant), the agencies have estimated a DMC of $15 applicable in the 2016MY The agencies consider this technology to be on the flat portion of the learning curve and have used a low complexity ICM of 1.24 through 2018 then 1.19 thereafter. The resultant control case costs are shown in Table 5-16.

Note that these costs are expected to be incurred consistent with our estimated ramp up of manufacturer use of A/C credits. For example, the direct credit for low GWP refrigerant use is 13.8 g/mi in MYs 2017-2025, but we estimate that the average credit earned by manufacturers would be 5.5 g/mi on cars in MY 2018 and 5.8 g/mi on trucks in that MY. Table 5-13 shows the credits by MY as we estimate they will be used for both cars and truck. Table 5-14 then shows how we have used these estimated credits to scale A/C-related costs by MY for both cars and trucks. The percentages shown in Table 5-14 are included in the costs shown in Table 5-15 and Table 5-16.

The total A/C related costs are shown in Table 5-17.

Table 5-13 Projected Average Estimated Use of A/C Credits

		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Car	Direct (Leakage) Credit if All R-134a AC	5.4	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
	Direct Credit for Low GWP AC	0.0	2.8	5.5	8.3	11.0	13.8	13.8	13.8	13.8	13.8
	Indirect Credit	4.8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	Total Credit	10.2	12.8	14.3	15.8	17.3	18.8	18.8	18.8	18.8	18.8
Truck	Direct (Leakage) Credit if All R-134a AC	6.6	7.0	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
	Direct Credit for Low GWP AC	0.0	0.0	5.8	10.3	13.8	17.2	17.2	17.2	17.2	17.2
	Indirect Credit	4.8	5.0	6.5	7.2	7.2	7.2	7.2	7.2	7.2	7.2
	Total Credit	11.5	12.0	17.5	20.6	22.5	24.4	24.4	24.4	24.4	24.4

Table 5-14 Scaling of A/C Costs to Estimated Use of Credits

		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
2012-2016 Rule (reference case)											
CAR	Leakage Reduction	5.4/6.3 =85%	5.4/6.3 =85%	5.4/6.3 =85%	5.4/6.3 =85%	5.4/6.3 =85%	5.4/6.3 =85%	5.4/6.3 =85%	5.4/6.3 =85%	5.4/6.3 =85%	5.4/6.3 =85%
	Low GWP Refrigerant & Hardware	0.0/13.8 =0%	0.0/13.8 =0%	0.0/13.8 =0%	0.0/13.8 =0%	0.0/13.8 =0%	0.0/13.8 =0%	0.0/13.8 =0%	0.0/13.8 =0%	0.0/13.8 =0%	0.0/13.8 =0%
	Efficiency Improvements	4.8/5.0 =97%	4.8/5.0 =97%	4.8/5.0 =97%	4.8/5.0 =97%	4.8/5.0 =97%	4.8/5.0 =97%	4.8/5.0 =97%	4.8/5.0 =97%	4.8/5.0 =97%	4.8/5.0 =97%
TRUCK	Leakage Reduction	6.6/7.8 =85%	6.6/7.8 =85%	6.6/7.8 =85%	6.6/7.8 =85%	6.6/7.8 =85%	6.6/7.8 =85%	6.6/7.8 =85%	6.6/7.8 =85%	6.6/7.8 =85%	6.6/7.8 =85%
	Low GWP Refrigerant	0.0/17.2 =0%	0.0/17.2 =0%	0.0/17.2 =0%	0.0/17.2 =0%	0.0/17.2 =0%	0.0/17.2 =0%	0.0/17.2 =0%	0.0/17.2 =0%	0.0/17.2 =0%	0.0/17.2 =0%
	Efficiency Improvements	4.8/7.2 =47%	4.8/7.2 =47%	4.8/7.2 =47%	4.8/7.2 =47%	4.8/7.2 =47%	4.8/7.2 =47%	4.8/7.2 =47%	4.8/7.2 =47%	4.8/7.2 =47%	4.8/7.2 =47%
2017-2025 Proposal (control case)											
CAR	Leakage Reduction		1-85% =15%	1-85% =15%	1-85% =15%	1-85% =15%	1-85% =15%	1-85% =15%	1-85% =15%	1-85% =15%	1-85% =15%
	Low GWP Refrigerant & Hardware		2.8/13.8 =20%	5.5/13.8 =40%	8.3/13.8 =60%	11.0/13.8 =80%	13.8/13.8 =100%	13.8/13.8 =100%	13.8/13.8 =100%	13.8/13.8 =100%	13.8/13.8 =100%
	Efficiency Improvements		1-97% =3%	1-97% =3%	1-97% =3%	1-97% =3%	1-97% =3%	1-97% =3%	1-97% =3%	1-97% =3%	1-97% =3%
TRUCK	Leakage Reduction		1-85% =15%	1-85% =15%	1-85% =15%	1-85% =15%	1-85% =15%	1-85% =15%	1-85% =15%	1-85% =15%	1-85% =15%
	Low GWP Refrigerant		0.0/17.2 =0%	5.8/17.2 =34%	10.3/17.2 =60%	13.8/17.2 =80%	17.2/17.2 =100%	17.2/17.2 =100%	17.2/17.2 =100%	17.2/17.2 =100%	17.2/17.2 =100%
	Efficiency Improvements		1-47% =53%	1-47% =53%	1-47% =53%	1-47% =53%	1-47% =53%	1-47% =53%	1-47% =53%	1-47% =53%	1-47% =53%

Table 5-15 Costs of A/C Controls in the Reference Case (2012-2016 Final Rule) (2009$)

Car/ Truck	Cost type	A/C Technology	2017	2018	2019	2020	2021	2022	2023	2024	2025
Car	DMC	Leakage reduction	$13	$13	$13	$13	$12	$12	$12	$12	$11
	DMC	Efficiency improvement	$46	$45	$44	$43	$42	$41	$40	$40	$39
	IC	Leakage reduction	$4	$4	$3	$3	$3	$3	$3	$3	$3
	IC	Efficiency improvement	$13	$13	$10	$10	$10	$10	$10	$10	$10
	TC	Leakage reduction	$17	$17	$16	$15	$15	$15	$15	$14	$14
	TC	Efficiency improvement	$58	$57	$54	$53	$52	$51	$50	$50	$49
Truck	DMC	Leakage reduction	$13	$13	$13	$13	$12	$12	$12	$12	$11
	DMC	Efficiency improvement	$32	$31	$30	$30	$29	$29	$28	$27	$27
	IC	Leakage reduction	$4	$4	$3	$3	$3	$3	$3	$3	$3
	IC	Efficiency improvement	$9	$9	$7	$7	$7	$7	$7	$7	$7
	TC	Leakage reduction	$17	$17	$16	$15	$15	$15	$15	$14	$14
	TC	Efficiency improvement	$40	$40	$37	$37	$36	$36	$35	$34	$34

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 5-16 Costs of A/C Controls in the Control Case (2017-2025 Proposal) (2009$)

Car/ Truck	Cost type	A/C Technology	2017	2018	2019	2020	2021	2022	2023	2024	2025
Car	DMC	Leakage reduction	$2	$2	$2	$2	$2	$2	$2	$2	$2
	DMC	Low GWP refrigerant	$13	$21	$32	$34	$41	$40	$39	$38	$37
	DMC	Low GWP refrigerant hardware	$3	$6	$8	$11	$14	$13	$13	$13	$13
	DMC	Efficiency improvement	$1	$1	$1	$1	$1	$1	$1	$1	$1
	IC	Leakage reduction	$1	$1	$1	$1	$1	$1	$1	$1	$1
	IC	Low GWP refrigerant	$3	$6	$10	$13	$16	$16	$13	$13	$13
	IC	Low GWP refrigerant hardware	$1	$1	$2	$2	$3	$3	$3	$3	$3
	IC	Efficiency improvement	$0	$0	$0	$0	$0	$0	$0	$0	$0
	TC	Leakage reduction	$3	$3	$3	$3	$3	$3	$3	$3	$3
	TC	Low GWP refrigerant	$17	$28	$42	$47	$57	$56	$52	$50	$49
	TC	Low GWP refrigerant hardware	$4	$7	$10	$13	$16	$16	$16	$16	$15
	TC	Efficiency improvement	$2	$2	$2	$2	$2	$2	$2	$2	$2
Truck	DMC	Leakage reduction	$1	$2	$2	$2	$2	$2	$2	$2	$2

	DMC	Low GWP refrigerant	$0	$18	$32	$34	$41	$40	$39	$38	$37
	DMC	Low GWP refrigerant hardware	$0	$5	$8	$11	$14	$13	$13	$13	$13
	DMC	Efficiency improvement	$1	$10	$15	$14	$14	$14	$14	$13	$13
	IC	Leakage reduction	$0	$1	$1	$1	$1	$1	$1	$1	$1
	IC	Low GWP refrigerant	$0	$5	$10	$13	$16	$16	$13	$13	$13
	IC	Low GWP refrigerant hardware	$0	$1	$2	$2	$3	$3	$3	$3	$3
	IC	Efficiency improvement	$0	$3	$3	$3	$3	$3	$3	$3	$3
	TC	Leakage reduction	$1	$3	$3	$3	$3	$3	$3	$3	$3
	TC	Low GWP refrigerant	$0	$24	$42	$47	$57	$56	$52	$50	$49
	TC	Low GWP refrigerant hardware	$0	$6	$10	$13	$16	$16	$16	$16	$15
	TC	Efficiency improvement	$1	$13	$18	$18	$18	$17	$17	$17	$16

DMC=Direct manufacturing cost; IC=Indirect cost; TC=Total cost

Table 5-17 Total Costs for A/C Control Used in This Proposal (2009$)

Car/ Truck	Cost type	Case	2017	2018	2019	2020	2021	2022	2023	2024	2025
Car	TC	Reference	$75	$74	$69	$68	$67	$66	$65	$64	$63
	TC	Control	$25	$40	$56	$65	$78	$76	$72	$70	$69
	TC	Both	$100	$114	$126	$133	$145	$142	$137	$134	$132
Truck	TC	Reference	$57	$56	$53	$52	$51	$50	$50	$49	$48
	TC	Control	$2	$46	$73	$81	$94	$92	$87	$85	$84
	TC	Both	$60	$102	$126	$133	$145	$142	$137	$134	$132
Fleet	TC	Both	$85	$110	$126	$133	$145	$142	$137	$134	$132

TC=Total cost

5.2 Off-Cycle Technologies and Credits

EPA employs a five-cycle test methodology to evaluate fuel economy for fuel economy labeling purposes. For GHG and CAFE compliance, EPA uses the established two-cycle (city, highway or correspondingly FTP, HFET) test methodology. EPA recognizes that there are technologies that provide real-world GHG benefits to consumers, but that the benefit of some of these technologies is not represented on the two-cycle test. Therefore, EPA is continuing the off-cycle credit program from the 2012-2016 rule with some changes such as providing manufacturers with a list of pre-approved technologies for which EPA can quantify a default value that would apply unless the manufacturer demonstrates to EPA that a different value for its technology is appropriate. This list is similar to the menu driven approach described in the previous section on A/C efficiency credits. With recent meetings with vehicle manufacturers, the EPA received comments that the public regulatory process for generating off-cycle credits was too cumbersome to utilize frequently if at all, and that the burden of proof to demonstrate a small incremental improvement on top of a large tailpipe measurement was impractical. This is similar to the argument described above for quantifying air conditioner improvements. These same manufacturers believed that such a process could stifle innovation and fuel efficient technologies from penetrating into the vehicle fleet. For this purpose, the EPA is proposing a menu with a number of technologies that the agency believes will show real-world CO_2 and fuel economy benefits which can be reasonably quantified a priori. The estimates of these credits were largely determined from research, analysis and simulations, rather from full vehicle testing, which would have been cost and time prohibitive.

In the 2012-2016 rule, EPA required that off-cycle technologies be innovative in nature. Manufacturers insisted that “innovative” is not a term that can have an exact definition and have it applied to a technology. They also informed EPA that there may be technologies that are quite old, but are utilized off-cycle and obtain real-world benefits. The EPA agrees with these comments and are proposing to amend the 2012-2016 rules to no longer requiring that off-cycle technologies be “innovative”.

The agencies are not proposing to adjust the stringency of the proposed 2017-2025 standards based on the off-cycle credit menu (with two limited exceptions for certain stop start technologies and for certain aerodynamic improvements, as described in section III.C.5.b.i of the preamble). There are a number of reasons for this. First, the agencies have very little technical information on these technologies. The analysis presented below is based on a limited amount of data and an engineering analysis for each technology. Some of the analysis includes more detailed vehicle simulation however the activity (or usage profiles) may have a fair amount of uncertainty. Second, the agencies have virtually no data on the cost, development time necessary, manufacturability, etc of these technologies. The agencies thus cannot project that some of these technologies are feasible within the 2017-2025 timeframe. Third, the agencies have no data on what the rates of penetration of these technologies would be during the rule timeframe. Fourth, as off-cycle technologies, they (by definition) typically do not affect the measurement of the 2-cycle fuel economy test procedure; therefore it may be incompatible to adjust a 2-cycle standard. It is still justifiable to grant credits toward a 2-cycle test as the technologies should still have a real-world benefit.

Some technologies provide a benefit on five-cycle testing, but show less benefit on two cycle testing. In order to quantify the emissions impacts of these technologies, EPA will simply subtract the two-cycle benefit from the five-cycle benefit for the purposes of assigning credit values for this pre-approved list. Other technologies, such as more efficient lighting, show no benefit over any test cycle. In these cases, EPA will estimate the average amount of usage using MOVES[o] data if possible and use this to calculate a duty-cycle-weighted benefit (or credit). In the 2012-2016 rule, EPA stated a technology must have "real world GHG reductions not significantly captured on the current 2-cycle tests…" For this proposal, EPA is modifying this requirement to allow technologies as long as the incremental benefit in the real-world is significantly better than on the 2-cycle test.

EPA is requesting comment on all aspects of the off-cycle credit menu derivation described below.

5.2.1 Reducing or Offsetting Electrical Loads

The EPA test cycles do not require that all electrical components to be turned on during testing. Headlights, for example, are always turned off during testing. Turning the headlights on during normal driving will add an additional load on the vehicle's electrical system and will affect fuel economy. More efficient electrical systems or technologies that offset electrical loads will have a real world impact on fuel economy but are not captured in the EPA test cycles. Therefore, the EPA believes that technologies that reduce or offset electrical loads related to the operation or safety of the vehicle deserve consideration for off cycle credits.

To evaluate technologies that reduce or offset electrical loads, the EPA conducted an analysis of the reduction in emissions corresponding to a general reduction of electrical demand in a vehicle. Using EPA's full vehicle simulation tool described in EPA's draft RIA, the agency evaluated the change in fuel consumption for a 100W reduction in electrical load for a typically configured vehicle. The impact of this load reduction was modeled on both the combined FTP/Highway cycles, and over the 5-cycle drive tests. The results of this analysis form the basis for a consistent methodology that the EPA applied to several technologies to determine the appropriate off-cycle credits for those technologies.

For the vehicle simulation, EPA assumed that high-efficiency alternators will be prevalent in most vehicles within the 2017-2025 timeframe of this rule, thus the simulation includes a high-efficiency alternator. Figure 5-4 below shows a sample efficiency map of a high-efficiency alternator. Based on this map, the EPA assumed a global average alternator efficiency of 65% for use in its modeling calculations.

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[o] MOVES is EPA's MOtor Vehicle Emissions Simulator. This model contains (in its database) a wide variety of fleet and activity data as well as national ambient temperature conditions.

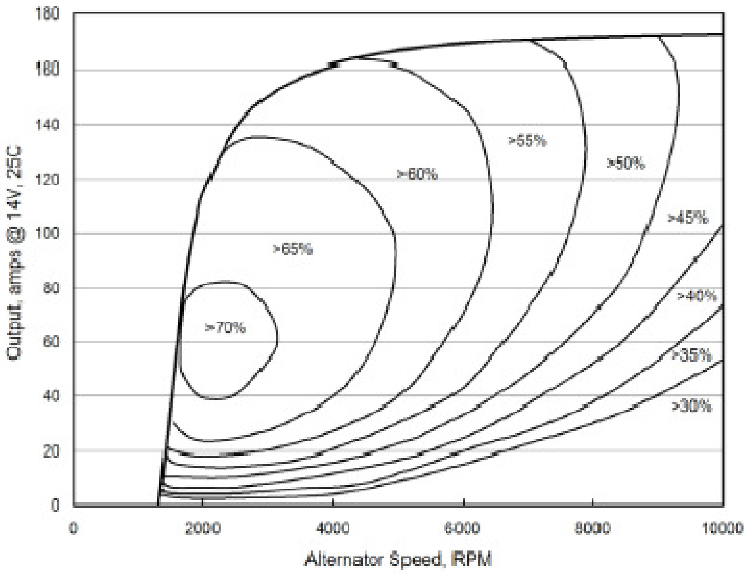


Figure 5-10: Alternator efficiency map (Delco-Remy, 2008[39])

Table 5-18 below shows the results of the simulation for four vehicle classes. Reducing the electrical load on a vehicle by 100W will result in an average of 3.0 g/mile reduction in CO_2 emissions over the course of a combined FTP/Highway test cycle, or 3.7 g/mile over a 5-cycle test. A 100W reduction in electrical load yields a reduction in required engine power of roughly 0.15 kW (=0.1 kW / 65%), or 1-2% over the FTP/HWFE test cycles.

Driving Cycle		Small Car [g/mile]	Mid-Sized Car [g/mile]	Large Car [g/mile]	Pick-up Truck [g/mile]	Average
FTP/Highway	100W Load Reduction	160.8	188.0	245.7	414.7	
	Baseline	164.0	190.8	248.8	417.9	
	Difference	3.2	2.8	3.0	3.2	3.0
5-Cycle	100W Load Reduction	221.2	252.8	325.9	539.0	
	Baseline	225.0	256.2	329.5	542.8	
	Difference	3.8	3.4	3.6	3.9	3.7

Table 5-18: Simulated GHG reduction benefits of 100W reduction in electrical load over FTP/HW and 5-cycle tests

To determine the off-cycle benefit of certain 100W electrical load reduction technologies, the benefit of the technology on the FTP/Highway cycles (2-cycle test) is subtracted from the benefit of the technology on the 5-cycle test. This determines the actual benefit of the technology not realized in the 2-cycle test methodology and in this case is 3.7 g/mi minus 3.0 g/mi, or 0.7 g/mi. However other technologies that exhibit efficiencies off-cycle, but on neither the 5-cycle, nor the 2-cycle test can have their benefits as credits without subtraction. An example of this is provided later.

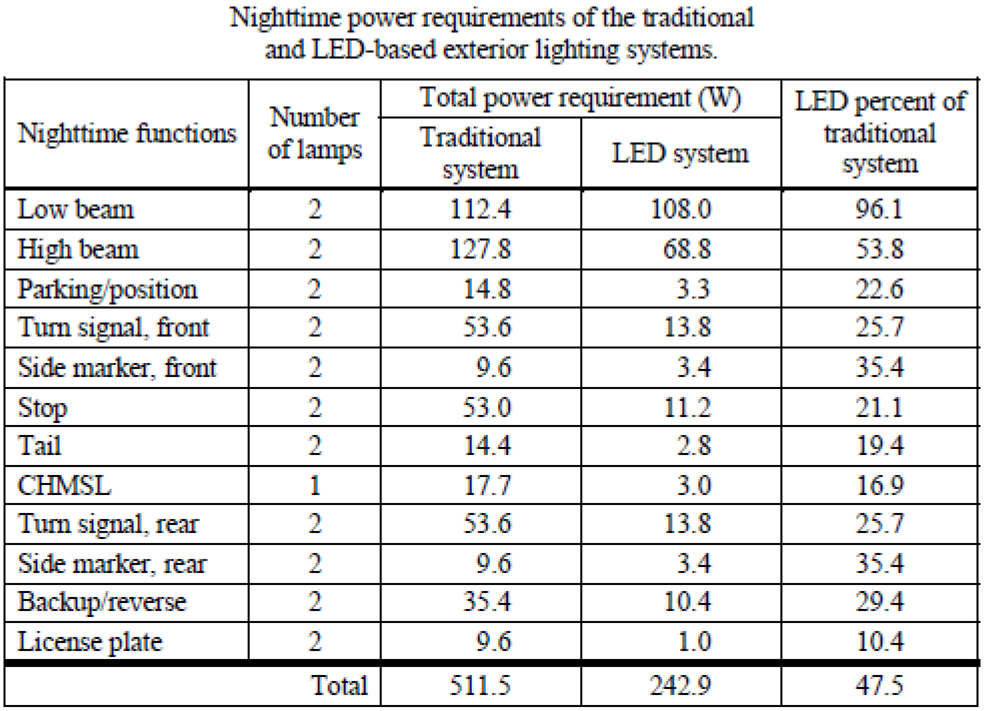
5.2.1.1 High Efficiency Exterior Lights

The current EPA test procedures are performed with vehicle lights (notably, headlights) turned off. Because of this, improvement to the efficiency of a vehicle's headlights is not captured in the existing test procedures and is appropriately addressed through the off-cycle crediting scheme.

As with residential light bulbs, the technology available for vehicle lighting has changed significantly in recent years. Vehicle manufacturers are commonly using advanced technology LEDs in taillights and offering new light producing technologies for headlights. If these technologies require less energy to operate, they will improve the overall fuel economy of the vehicle and will be eligible for an off-cycle credit.

Select trade press articles suggest that high-efficiency LEDs would save approximately 75% of the energy consumption of conventional headlamps. However, Schoettle, et al[40], studied the effects of high-efficiency LED lighting and found that this estimate, for the vehicle as a system, to be on the high side. Table 5-10 provides a summary (excerpted from that study) of average lighting power requirements for both baseline and high efficiency lights for late-model vehicles.

Table 5-19: Average power requirement for various lights on a late-model vehicle for traditional and LED systems (Schoettle, et al)



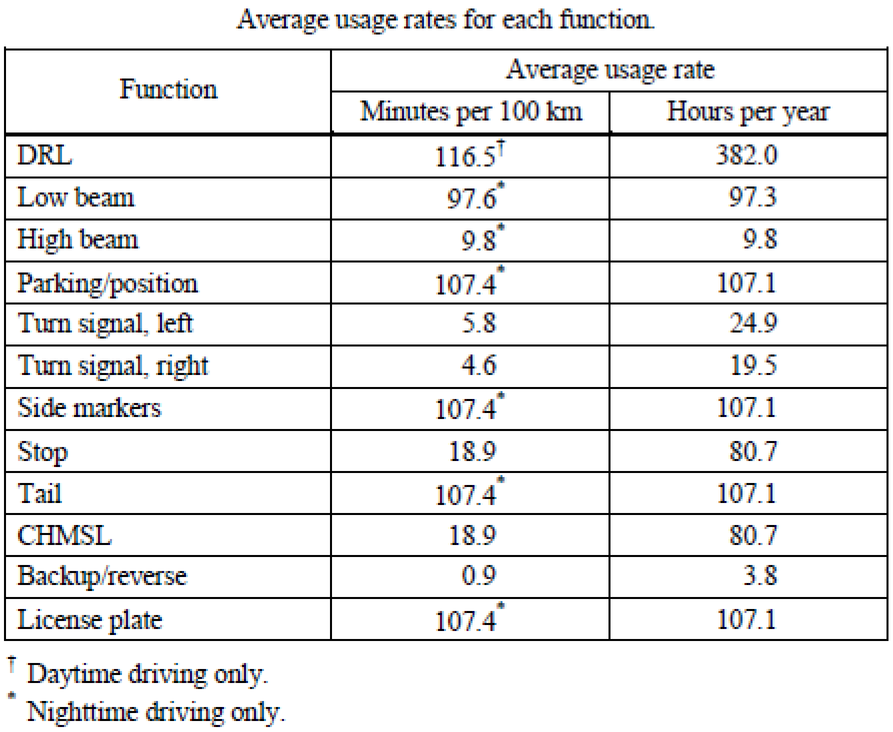
Nighttime power requirements of the traditional and LED-based exterior lighting systems.

Nighttime functions	Number of lamps	Total power requirement (W) Traditional system	Total power requirement (W) LED system	LED percent of traditional system
Low beam	2	112.4	108.0	96.1
High beam	2	127.8	68.8	53.8
Parking/position	2	14.8	3.3	22.6
Turn signal, front	2	53.6	13.8	25.7
Side marker, front	2	9.6	3.4	35.4
Stop	2	53.0	11.2	21.1
Tail	2	14.4	2.8	19.4
CHMSL	1	17.7	3.0	16.9
Turn signal, rear	2	53.6	13.8	25.7
Side marker, rear	2	9.6	3.4	35.4
Backup/reverse	2	35.4	10.4	29.4
License plate	2	9.6	1.0	10.4
	Total	511.5	242.9	47.5

Usage rates were also provided by Schoettle et al, and are reproduced below in Table 5-11. Using this data, headlight operation at night is split into 91% low beam operation and

9% high beam operation. The parking/position, side markers, tail lights and license plate light are all considered to be on 100% of nighttime driving. Turn signals are estimated to be in operation for 5% of all driving. Off-cycle credit for braking lights is considered negligible, because vehicle braking is as prevalent on the 2-cycle test, if not more, than over the 5-cycle test.

Table 5-20: Usage rates for various lighting components on a late-model vehicle (Schoettle, et al)



Average usage rates for each function.

Function	Average usage rate	
	Minutes per 100 km	Hours per year
DRL	116.5†	382.0
Low beam	97.6*	97.3
High beam	9.8*	9.8
Parking/position	107.4*	107.1
Turn signal, left	5.8	24.9
Turn signal, right	4.6	19.5
Side markers	107.4*	107.1
Stop	18.9	80.7
Tail	107.4*	107.1
CHMSL	18.9	80.7
Backup/reverse	0.9	3.8
License plate	107.4*	107.1

† Daytime driving only.
* Nighttime driving only.

A simple activity-weighted average of the aforementioned categories yields an average nighttime power consumption (for the categories in question) of roughly 180W for a baseline vehicle and 120 W for a vehicle with high efficiency lights. The calculations for the lights are shown in Table 5-21, below.

Table 5-21: EPA calculations of High Efficiency Light Savings Potential (Nighttime Driving)

Lighting Component	Baseline W	High Eff W	night use %	savings %
Low beam	112.4	108.0	91%	4%
High beam	127.8	68.8	9%	46%
Parking/position	14.8	3.3	100%	78%
Turn signal, front	53.6	13.8	5%	74%
Side marker, front	9.6	3.4	100%	65%
Stop	53.0	11.2	8%	79%
Tail	14.4	2.8	100%	81%
CHMSL	17.7	3.0	8%	83%
Turn signal, rear	53.6	13.8	5%	74%
Side marker, rear	9.6	3.4	100%	65%
Backup/reverse	35.4	10.4	1%	71%
License plate	9.6	1.0	100%	90%
Totals (rounded)	**180**	**120**		**33%**

Assuming that a set of standard exterior lights are replaced with high-efficiency LEDs, it would represent approximately a 60W savings during nighttime driving, and that nighttime driving represents approximately 50% of nationwide VMT (based Schoettle et al), the savings in the above example would amount to the equivalent of 30W averaged over all driving. Based on the GHG savings for a 100W electrical load reduction (presented in section 5.2.1) and scaling to 30W, EPA estimates that high-efficiency LEDs would be eligible for a credit of approximately 1.1 CO_2 g/mile. To be eligible for the credit, manufacturers must include high efficiency lights for all components listed in Table 5-21 with the exception of headlights (low and high beam).

The 60W savings shown above largely excludes headlights (low and high beam) due to their relatively small weighting in the averaged power savings estimate. Additionally, informal discussions with lighting suppliers indicate that the savings potential of headlights is highly variable and application-dependent. EPA and NHTSA believe there may be significant GHG savings due to high efficiency headlights, and seek comment on the savings potential for high efficiency headlights.

LEDs used for decorative or accent lighting is not eligible for the credit as they are considered optional accessories or “features”. Additionally, daytime running lights (DRLs) are not required by law, therefore EPA considers them an optional accessory and ineligible for off-cycle credits. EPA seeks comment on the application of the credit to daytime running lights.

5.2.1.2 Engine Heat Recovery

The combustion process that powers most of today’s vehicles results in a significant amount of exhaust heat. Most of this heat leaves the engine in the form of waste hot exhaust gasses which are expelled from the vehicle through the exhaust system, or through hot coolant which cycles from the engine to the radiator for expulsion. Recapturing some portion of this wasted heat energy and using it to offset the electrical requirements of the vehicle will lead to improved fuel efficiency.

Regardless of the design of the heat recovery system, whether it is exhaust or coolant based, the EPA assumes that any recovered energy will be in the form of electricity and will be used to recharge the vehicle's battery (primarily for HEVs or PHEVs). This is consistent with currently proposed designs. EPA expects that engine heat recovery systems will provide some benefit on the two-cycle tests; therefore the off-cycle credit will be based on the difference between the two-cycle and five-cycle tests. From Table 5-18, this difference is 0.7 g/mile per 100W of electric load reduction. For every 100W of thermoelectric device capacity, the vehicle off-cycle credit will be 0.7 g/mile.

5.2.1.3 Solar Roof Panels

Manufacturers are beginning to offer the option to put solar cells on the roof of a vehicle. The solar roof option on the new Toyota Prius is an example. The initial implementation of this idea has been limited to cabin ambient temperature control (see thermal/solar load control below), but manufacturers have raised the possibility of using roof top solar cells to charge PHEV, and EV batteries and provide energy to operate the vehicle, increasing the vehicle's all electric range. This electrical energy cannot be accounted for on the current EPA cycles. Only PHEV and EVs are eligible for this credit.

Using engineering judgment, the EPA estimates that vehicles with a solar roof would be parked in sunlight on average four hours a day, and that the solar panels will be 50W capable. The EPA also assumes that the solar cells will produce 50% of their rated power of 50W (due to the solar angle, parking conditions, weather conditions, etc.) with a battery efficiency of 80%. A vehicle with this configuration could save up to 80 Wh/day of electrical energy. The EPA seeks comments on these assumptions and requests more data to refine these numbers.

Using an assumption (based on MOVES) of 1 hour/day average vehicle usage, this yields an avoided electrical load of (on average) 80W. A reduction of 80W in electrical load represents a reduction potential (for large batteries) of approximately 2.7-3.1 g/mi for a 50W-capable solar roof panel. These reductions are subject to revision based on changes to key assumptions (such as maximum potential electrical consumption rate during vehicle operation, solar cell efficiency and exposure rates). EPA will also consider scaling this credit for solar roof panels that provide more or less power than 50W.

5.2.2 Active Aerodynamic Improvements

The aerodynamics of a vehicle plays an important role in determining fuel economy. Improving the aerodynamics of a vehicle reduces drag forces that the engine must overcome to propel the vehicle, resulting in lower fuel consumption. The aerodynamic efficiency of a vehicle is usually captured in a coast down test that is used to determine the dynamometer parameters used during both the two-cycle and five-cycle tests. This section discusses active aerodynamic technologies that are activated only at certain speeds to improve aerodynamic efficiency while preserving other vehicle attributes or functions. Two examples of active aerodynamic technologies are active grill shutters and active ride height control. Active aerodynamic features can change the aerodynamics of the vehicle according to how the vehicle is operating, and the benefit of these vehicle attributes may not be fully captured during the EPA test cycles.

EPA is proposing to limit credits to active aerodynamic systems only (not passive). The reason for this is that passive systems are too difficult to define and isolate as a technology. For example, the aerodynamic drag on the vehicle is highly dependent on the vehicle shape, and the vehicle shape is (in turn) highly dependent on the design characteristics for that brand and model. EPA feels that it would be inappropriate to grant off-cycle credits for vehicle aesthetic and design qualities that are passive and fundamentally inherent to the vehicle.

To evaluate technologies that reduce aerodynamic drag, the EPA conducted an analysis of the reduction in emissions corresponding to a general reduction of aerodynamic drag on a vehicle. Using EPA's full vehicle simulation tool described in EPA's draft RIA, the agency evaluated the change in fuel consumption for increasing reductions in aerodynamic drag for a typically configured vehicle. The results of this analysis form the basis for a consistent methodology that the EPA applied to technologies that provide active aerodynamic improvements.

Vehicle aerodynamic properties impact both the combined FTP/Highway and 5-cycle tests. However, these impacts are larger at higher speeds and have a larger impact on the 5-cycle tests. By their nature of being "active" technologies, EPA understands that active aerodynamic technologies will not be in use at all times. While deployment strategies for different active aerodynamic technologies will undoubtedly vary by individual technology, the impact of these technologies will mostly be realized at high speeds. Since aerodynamic loading is highest at higher speeds, EPA expects that active aerodynamic technologies will generally be in use at high speeds, and that the5-cycle tests will capture the additional real world benefits not quantifiable with the FTP/Highway test cycles due to the higher speed in the US06 cycle. Active aero may also depend on weather conditions. For example, active aerodynamics may operate less in hot weather when air cooling is required to exchange heat at the condenser. Also, active grill shutters may need to stay open during snowy conditions in order to prevent them from freezing shut (potentially causing component failure).

Using EPA's full vehicle simulation tools, the impact of reducing aerodynamic drag was simulated on both the combined FTP/Highway cycles and the 5-cycle drive tests. To determine the fuel savings per amount of aerodynamic drag reduction, the fuel savings on the FTP/Highway test cycle was subtracted from the fuel savings on the 5-cycle tests. This is consistent with the approach taken for other technologies. Table 5-22 shows the results of the vehicle simulation. Also, Figure 5-11 represents this GHG reduction metrics in a graphical form. These results assume that the active aerodynamics affects the coefficient of drag only, which is currently assumed to be constant over a wide range of vehicle operating speed. However, if the coefficient of aerodynamic drag is assumed to be vehicle speed dependent, then a different relationship could result.

Table 5-22: Simulated Maximum GHG Reduction Benefits of Active Aerodynamic Improvements

Reduction in Aerodynamic Drag (C_d)	Car Reduction in Emissions (g/mile)	Truck Reduction in Emissions (g/mile)
1%	0.2	0.3
2%	0.4	0.6
3%	0.6	1.0
4%	0.8	1.3
5%	0.9	1.6
10%	1.9	3.2

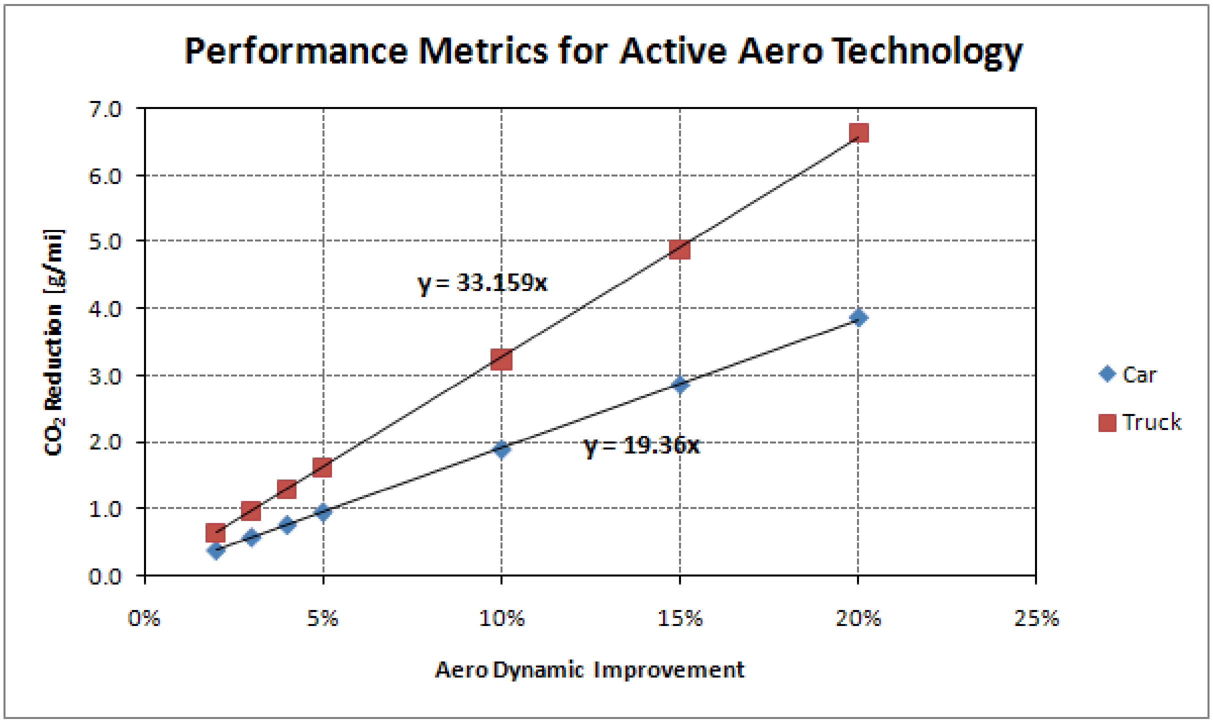


Figure 5-11 Simulated GHG Reduction Benefits of Active Aerodynamic Improvements

One example of an active aerodynamic technology is active grill shutters. This technology is a new innovation that is beginning to be installed on vehicles to improve aerodynamics. Nearly all vehicles allow air to pass through the front grill of the vehicle to flow over the radiator and into the engine compartment. This flow of air is important to prevent overheating of the engine (and for proper functioning of the A/C system), but it creates a significant drag on the vehicle and is not always necessary. Active grill shutters close off the area behind the front grill so that air does not pass into the engine compartment when additional cooling is not required by the engine. This reduces the drag of the vehicle, reduces CO_2 emissions, and increases fuel economy. When additional cooling is needed by the engine, the shutters open until the engine is sufficiency cooled.

Based on manufacturer data, active grill shutters provide a reduction in aerodynamic drag (C_d) from 0 to5% when deployed. EPA expects that most other active aerodynamic technologies will provide a reduction of drag in the same range as active grill shutters. EPA also expects that active aerodynamic technologies may not always be available during all operating conditions. Active grill shutters, for example, may not be usable in very cold temperatures due to concerns that they could freeze in place and cause overheating. Control and calibration issues, temperature limitations, air conditioning usage, and other factors may limit the usage of grill shutters and other active aerodynamic technologies. Therefore, EPA is proposing to provide a credit for active aerodynamic technologies that any of these technologies will achieve an aerodynamic drag of at least 3% improvement. The proposed credit will be 0.6 g/mile for cars and 1.0 g/mile for trucks, in accordance with the simulation results in Table 5-22. It is conceivable that some systems can achieve better performance. Manufacturers may apply for greater credit for better performing systems through the normal application process described in Section III.C of the preamble.

5.2.3 Advanced Load Reductions

The final category of off-cycle credits includes technologies that reduce engine loads by using advanced vehicle controls. These technologies range from enabling the vehicle to turn off the engine at idle, to reducing cabin temperature and thus A/C loading when the vehicle is restated. Because the benefit of these technologies is not fully captured on the combined two cycle tests, EPA has evaluated each technology and developed off-cycle credits for each technology individually.

5.2.3.1 Engine Start-Stop (Idle Off)

Engine start-stop technologies enable a vehicle to turn off the engine when the vehicle comes to a rest, and then quickly restart the engine when the driver applies pressure to the accelerator pedal. The benefit of this system is that it largely eliminates fuel consumption at idle. The EPA FTP (city) test does contain short periods of idle, but not as much idle as is often encountered in real world driving. HEV and PHEVs can also idle-off and are thus eligible for this credit. EVs and FCVs do not have engines and thus are not eligible for this credit.

Based on a MOVES estimate that 13.5% of all driving (in terms of vehicle hours operating) nationwide is at idle, and compared to a 9% idle rate for the combined (two-cycle) test, idle-off could theoretically approach an extra 50% of the existing benefit seen on the FTP/HWFE test. Vehicle simulation data was used to quantify the amount of fuel consumed in idle conditions over the FTP and HFET test across a range of vehicle classes. For each vehicle class reviewed, a FTP-HFET combined fuel consumption was calculated and compared to total fuel consumption during the combined test. The ratio of idle fuel to total fuel represents a maximum theoretical fuel consumption, and hence GHG emissions, that could be reduced by eliminating idling[P]. Table 5-23 shows this below:

	Standard Car	Large Car	Large MPV	Full size Truck
Total FTP fuel consumption (g)	1044	1276	1412	1868
FTP fuel consumed at idle (g)	68	71	69	97
Total HWFE fuel consumption (g)	675	862	970	1240
HWFE fuel consumed at idle (g)	0.0	0.0	0.0	0.0
FTP-HWFE combined fuel consumption (g)	878	1090	1213	1585
FTP-HWFE combined fuel consumed at idle (g)	37	39	38	53
potential % GHG reduction benefit	**4.2%**	**3.6%**	**3.1%**	**3.4%**
% FTP idle time	16%	16%	16%	16%
% HWFE idle time	0%	0%	0%	0%
FTP-HWFE combined % idle time	9%	9%	9%	9%
Real-world % idle time (via MOVES)	13.5%	13.5%	13.5%	13.5%
Real-world % GHG reduction benefit	**6.3%**	**5.3%**	**4.6%**	**5.0%**
Off-cycle GHG benefit	**2.1%**	**1.7%**	**1.5%**	**1.6%**
Assumed GHG for advanced vehicle (g/mi)	165	235	255	365
Off-cycle GHG benefit	**3.4**	**4.1**	**3.9**	**6.0**

Table 5-23: Calculation of Off-Cycle Credit for Stop Start Technologies

Based on this data, EPA suggests that idle-off technology is theoretically capable of providing 3.8 g/mi credit for passenger vehicles and up to 6.0 g/mi for trucks. However, cold and hot ambient conditions will prevent idle-off in all cases. The percentage of nationwide VMT driven above a 45 °F ambient temperature is approximately 75%. Therefore, EPA and NHTSA propose 75% of the theoretical savings above will be appropriate for an idle off credit; this equates to 2.9 g/mi for passenger vehicles and 4.5 g/mi for trucks. Electric heater circulation pump credits, described below, may be added to this credit.

[P] Note that aggressive fuel cutoff upon vehicle decelerations are technically possible and could increase the total amount of avoided "idle" fuel consumption; at the same time, the idle-off enable conditions might reduce the total idle avoidance. Given the accuracy level of this methodology, EPA assumes these caveats to cancel each other out.

5.2.3.2 Electric Heater Circulation Pump

Conventional vehicles use engine coolant circulated by the engine's water pump to provide heat to the cabin during operation in cold ambient conditions. Since the coolant is only circulated when the engine is running, very little heat is available to the cabin occupants if the engine is stopped during idle in vehicles equipped with stop-start. Stop-start equipped vehicles generally disable the feature during cold ambient temperatures to ensure cabin heat is always available. However, stop-start operation can be expanded to much colder ambient if a means of continuing to circulate coolant during idle stop is employed. An electric heater circulation pump takes the place of the engine's water pump to continue circulating hot coolant through the heater core when the engine is stopped during a stop-start event. Stop Start, HEV, and PHEVs are only eligible for this credit.

Because the engine does not generate any more heat when it is shut off during idle, the amount of heat available to be moved to the cabin is limited by the thermal mass of the engine. The heater core acts like a radiator to remove heat from the engine and deliver it to the cabin. After some period of time, depending on engine mass, ambient temperature, and desired cabin temperature, the coolant temperature would drop to a level where comfort would not be maintained and the engine could cool off to a point where cold start features would be needed (which increase fuel consumption). The stop-start control system would turn the engine back on before either of these conditions are reached. The coolant circulation pump is electrically powered and therefore uses some energy when in use.

EPA evaluated the effectiveness of this system using the same approach that was used for start stop technology. Based on MOVES data, the percentage of nationwide VMT below 45 °F is 25%. EPA assumes that vehicles with start stop systems will have to keep the engine running for cabin heat if the ambient temperature is less than 45 °F, unless the vehicle also has an electric heater circulation system. Therefore, a vehicle with both systems can utilize the start stop technology 25% more of the time. Based on the maximum credit of 3.8 g/mi and 6.0 g/mi calculated in the previous section, the credit available for an electric heater circulation pump is 1.0 g/mi for passenger vehicles and 1.5 g/mi for trucks. EPA determined that the electrical draw on the pump itself is small enough to be negligible in this calculation.

5.2.3.3 Active Transmission Warm-Up

When a vehicle is started and operated at cold ambient temperatures, there is additional drag on drivetrain components due to cold lubricants becoming more viscous which increases fuel consumption and GHG emissions. This effect is more pronounced at colder temperatures and diminishes as the vehicle warms up. Components affected by this additional drag include the engine, torque converter, transmission, transfer case, differential, bearings and seals. Some components, such as the transmission, can take a long time to warm to operating temperature. Automakers sometimes delay the application of very effective fuel-saving measures such as torque converter lockup in order to help the transmission reach operating temperature more quickly.

Active Transmission warm-up uses waste heat from a vehicle's exhaust system to warm the transmission oil to operating temperature quickly using a heat exchanger in the exhaust system. This heat exchanger loop must have a means of being selectable, so that the transmission fluid is not overheated under hot operating conditions. In cold temperatures, the exhaust heat warms the transmission fluid much more quickly than if the vehicle relies on passive heating alone. Other methods of heating the fluid can be implemented using electric heat for example, but these are not included in this analysis because of the additional energy consumption that would likely eliminate most of the benefit. This technology could also be used for other driveline fluids such as axle and differential lubricant on rear-wheel-drive vehicles or even engine oil, but only transmission fluid warming is considered here.

There is a lot of variability in which components are affected by cold temperatures and for how long due to the type of vehicle and how it is operated. Active transmission warm-up applied to a conventional front-wheel-drive vehicle will warm the transmission, torque converter, and differential lubricants because in most cases these components share the same lubricant. On a rear-wheel-drive vehicle such as a truck, active transmission warm-up would only affect the transmission and torque converter. The rear axle and differential lubricant, and the transfer case and front axle and differential lubricants in a four-wheel-drive vehicle would not be heated. Additionally, a vehicle operated under a heavy load will tend to warm these lubricants more quickly with or without active heating.

Using Ricardo modeling data and environmental data from EPA's MOVES model, EPA calculated the estimated benefit of active transmission warm-up. The Ricardo data indicates that there is a potential to improve GHG emissions by 7% at 20 °F if the vehicle is fully warm. EPA assumed that given that this technology only affects the transmission (and differential on a FWD vehicle) and that the technology does take some time to warm the transmission fluid, one third of this benefit would be available, or 2.3%. EPA then assumed the benefit would decay in a linear fashion to 0% at 72 °F.

Using MOVES data, EPA calculated the weighted average VMT at temperatures below about 70-80 °F, where the two-cycle FTP testing is conducted. These temperatures were arranged in 10 °F bins and a temperature and VMT-weighted benefit of 1.8 gpm was calculated for a midsize car. No benefit is assumed during the FTP, so nothing is subtracted from this result. EPA believes an off-cycle benefit of 1.8 grams/mile is possible using active transmission warm-up.

5.2.3.4 Active Engine Warm-Up

Like active transmission warm-up, active engine warm-up uses waste heat from a vehicle's exhaust system to warm targeted parts of the engine, reducing drag and increasing fuel economy. EPA assumed that of the 7% emission reduction available due to active drive train warming, that one third would be available for actively warming the transmission. EPA also assumes that another one third would be available for active engine warm-up, resulting in a possible 1.8 grams/mile off-cycle benefit. Active engine warm-up test data provided by manufacturers resulted in the calculation of a similar emission reduction.

5.2.3.5 Thermal (and Solar) Control Technologies

EPA is proposing a credit for technologies which reduce the amount of solar energy which enters a vehicle's cabin area, reduce the amount of heat energy build-up within the cabin when the vehicle is parked, and/or reduce the amount of cooling/heating energy required through measures which improve passenger comfort. The State of California Air Resources Board (CARB) has studied the effectiveness of many of these technologies, and had proposed including them in their Cool Cars and Environmental Performance Label programs.[41] The National Renewable Energy Laboratory (NREL) conducted an extensive research project as part of the SAE's Improved Mobile Air Conditioning Cooperative Research Program (I-MAC). The purpose of this program was to study the effectiveness of a variety of technologies which can reduce the amount of fuel used for the purpose of climate control in light-duty vehicles. In this study, known as the Vehicle Ancillary Loads Reduction Project, NREL estimated the effectiveness of window glazing/shades, paint, insulation, and seat and cabin ventilation technologies in reducing A/C-related fuel consumption and emissions.[42] EPA has evaluated these technologies and assigned a credit amount for each, based on their ability to reduce cabin air temperatures during soak periods and improve passenger comfort.

Based on the NREL's studies, which estimated that when these technologies are combined, a 12 °C reduction in cabin air temperature during soak will result in a 26% reduction in A/C-related fuel consumption, or a 2.2% reduction in fuel consumption (and by extension, CO2 emissions) for each 1 °C reduction in cabin air temperature..[43] If the A/C-related CO2 emissions impact is 13.8 g/mi for cars and 17.2 g/mi for trucks, this 2.2% reduction in CO2 emissions results in a credit of 0.3 g/mi for cars (13.8 g/mi x 0.022) and a credit of 0.4 g/mi for trucks (17.2 g/mi x 0.022) for each degree centigrade reduction in cabin air temperature.

5.2.3.5.1 Glazing

When a vehicle is parked in the sun, more than half of the thermal energy that enters the passenger compartment is solar energy transmitted through, and absorbed by, the vehicle's glazing (or glass).[42] The solar energy is both transmitted through the glazing and directly absorbed by interior components, which are then heated, and absorbed by the glass, which then heats the air in the passenger compartment through convection and interior components through re-radiation. By reducing the amount of solar energy that is transmitted through the glazing, interior cabin temperatures can be reduced, which results in a reduction in the amount of energy needed to cool the cabin and maintain passenger comfort. Glazing technologies exist today which can reduce the amount of solar heat gain in cabin by reflecting or absorbing the infrared solar energy. NREL's study determined that cabin air temperature could be reduced by up to 9.7 °C with use of glazing technologies on all window locations. Technologies such as window films and coatings and absorptive or solar-reflective material within the glass itself are currently used in automotive glazings, both for privacy (e.g. tinting) and improved passenger comfort. One measure of the solar load-reducing potential for glazing is Total Solar Transmittance, or Tts, which is expressed in terms of the percentage of solar energy which passes through the glazing. Lower Tts values for glazing result in lower cabin temperatures during solar soak periods. EPA considers the April 15, 2008 version of the International Organization for Standardization's (ISO) 13837 - standard to be the appropriate method for measuring the solar transmittance of glazing used in automotive applications.

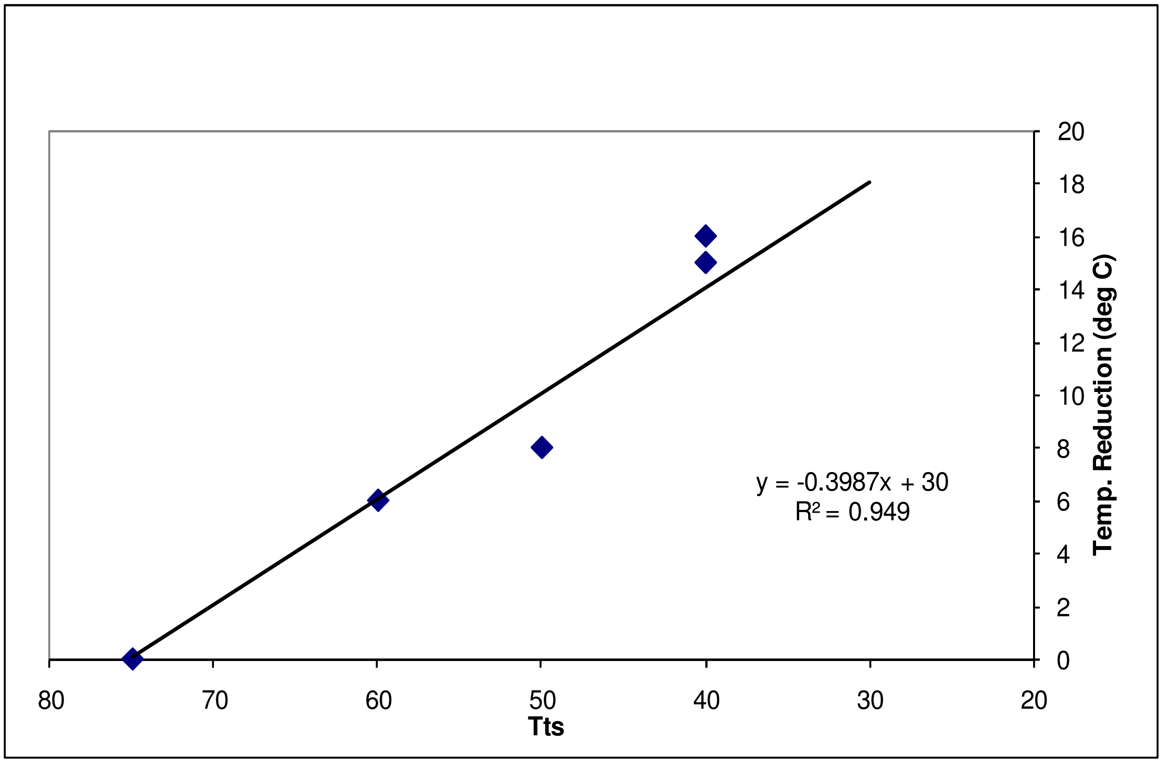
A method for estimating the effect of the solar performance of glazing technologies was developed by EPA and CARB, with input from NREL and the Enhanced Performance Glass Automotive Association (EPGAA). This method utilizes the measured Tts of the glazing used in a vehicle to estimate its effect on cabin temperature during soak conditions. The contribution that each glass/glazing location on the vehicle has on the overall interior temperature reduction is determined by its Tts (relative to a baseline level) and its area. For purposes of this proposal, EPA considers the basline Tts to be 62% for all glazing locations, except for rooflites, which have a baseline Tts of 40%. The relationship between the Tts value for glass/glazing and a corresponding reduction in interior temperature is has been established using the data from NREL testing, as shown in Table 5-24.

Table 5-24 Effect of Tts on Interior Temperature Reduction

Glass/Glazing Position	Baseline Tts for Glazing Type (%)	Solar Control Tts	Measured Breath Air Temperature Reduction (°C)	Estimated Temperature Reduction from 23.8 °C Baseline (°C)
All	62 (solar absorbing)	40	9	15
All	62 (solar absorbing)	40	10	16
All	75 (light green)	50	8	8
All	75 (light green)	60	6	6

Using the NREL data and estimated temperature reductions, the linear correlation between Tts and breath air (interior) temperature reduction was developed, and is shown in Figure 5-11.

Figure 5-12 Correlation Between Tts and Estimated Interior Temperature Reduction



From the slope of this correlation between the Tts value and reduction in cabin air (also referred to as "breath air") temperature, a method for estimating the amount of interior temperature reduction (in degrees Celcius) for a specific glass location and its Tts specification was developed, and is shown in Equation 5-4 .

Equation 5-4 – Estimated Breath Air Temperature Reduction for Glazing with Improved Solar Control

$$Estimated\ Temperature\ Reduction = 0.3987\ x\ (Tts_{\ baseline} - Tts_{\ new})$$

where $Tts_{baseline}$ *= 62 for windshield, side-front, side-rear, rear-quarter, and backlite locations, and 40 for the rooflite location*

To determine the total amount of glass/glazing credit generated for a given vehicle, the contribution (in terms of estimated temperature reduction) for each glazing location is calculated using the glass manufacturer's Tts specification. The contribution of each glass location is then normalized to determine the effect each glazing location on the overall vehicle temperature reduction. The method for normalizing the contributions is to to multiply the estimated temperature reduction of Equation 5-4 by the ratio of the glass area of each location divided by the total glass area of the vehicle. The total vehicle temperature reduction is the sum of the normalized contributions for each location. To calculate the glazing credit generated (in grams of CO2 per mile), the sum of the total vehicle temperature reduction (in degrees Celsius) multiplied by 0.3 for cars, or 0.4 for trucks.

5.2.3.5.2 Active Seat Ventilation

The NREL study investigated the effect that ventilating the seating surface has on the cooling demand for a vehicle. By utilizing a fan to actively remove heated, humid air that is typically trapped between the passenger and the seating surface, passenger comfort can be improved, and NREL's Thermal Comfort Model predicted that A/C system cooling load could be reduced, and a 7.5% reduction in A/C-related emissions can be realized.[43] While seat ventilation technology does not lower the cabin air temperature, it indirectly affects the load placed on the A/C system through the occupants selecting a reduced cooling demand due to their perception of improved comfort. Using the EPA estimate for the A/C-related CO2 emissions impact of 13.8 g/mi for cars and 17.2 g/mi for trucks, a 7.5% reduction in CO2 emissions with active seat ventilation results in a credit of 1.0 g/mi for cars (13.8 g/mi x 0.075) and a credit of 1.3 g/mi for trucks (17.2 g/mi x 0.075).

5.2.3.5.3 Solar Reflective Paint

As the vehicle's body surface is heated by solar energy when parked, heat is transferred to the cabin through conduction and convection. Paint or coatings which increase the amount of infrared solar energy that is reflected from the vehicle surface can reduce cabin temperature during these solar soak periods. While the amount of heat entering the cabin through the body surface is less than that which enters through the glazing, its effect on cabin air heat gain is measureable. NREL testing estimated that solar-reflective paint and coatings can reduce cabin air temperature by approximately 1 °C, whereas glazing technologies can reduce cabin air temperature by up 10 °C. Using the EPA estimate for credits due to cabin air temperature reductions of 0.3 g/mi for cars 0.4 g/mi for trucks for each degree centigrade of temperature reduction, a 1.2 °C reduction due to solar reflective paint results in a credit of 0.4 g/mi for cars and 0.5 g/mi for trucks.

5.2.3.5.4 Passive and Active Cabin Ventilation

Given that today's vehicle are fairly well sealed (from an air leakage standpoint), the solar energy that enters the cabin area through conductive and convective heat transfer is effectively trapped within the cabin. During soak periods, this heat gain builds, increasing the temperature of the cabin air as well as that of all components inside the cabin (i.e. the thermal mass). By venting this heated cabin air to the outside of the vehicle and allowing fresh air to enter, the heat gain inside the vehicle during soak periods can be reduced. The NREL study demonstrated that active cabin ventilation technology, where electric fans are used to pull heated air from the cabin, a temperature reduction of 6.9 °C can be realized. For passive ventilation technologies, such as opening of windows and/or sunroofs are and use of floor vents to supply fresh air to the cabin (which enhances convective airflow), a cabin air temperature reduction of 5.7 °C can be realized.[43] Using the EPA estimate for credits due to cabin air temperature reductions of 0.3 g/mi for cars 0.4 g/mi for trucks for each degree centigrade of temperature reduction, a 6.9 °C reduction due to active cabin ventilation results in a credit of 2.1 g/mi for cars and 2.8 g/mi for trucks. For passive cabin ventilation, a 5.7 °C temperature reduction results in a credit of 1.7 g/mi for cars and 2.3 g/mi for trucks.

5.2.3.6 Summary of Thermal (and Solar) Control Credits

The amount of credit that a manufacturer can generate for thermal and solar control technologies is shown in Table 5-25.

Table 5-25 Off-Cycle Credits for Thermal Control Technologies

Thermal Control Technology	Estimated Breath Air Temp. Reduction	Credit (g CO2/mi)	
		Car	Truck
Glass or glazing	up to 9.7 °C	up to 2.9	up to 3.9
Active Seat Ventilation	N/A*	1.0	1.3
Solar reflective paint	1.2 °C	0.4	0.5
Passive cabin ventilation	5.7 °C	1.7	2.3
Active cabin ventilation	6.9 °C	2.1	2.8

* Active seat ventilation is not a temperature reduction technology, but rather a comfort control technology, capable of reducing A/C-related emissions by 7.5%

To earn off-cycle thermal control credits – up to a maximum of 3.0 g/mi for cars, and 4.3 g/mi for trucks - a vehicle must be equipped with the thermal control technology, in accordance with the specifications and definitions in this proposed rulemaking. If a technology meets the specifications, its use in a vehicle will generate credits, in accordance with the value set forth in the thermal control technology list. The one exception to a single credit value for a technology is glazing technologies, where the method for determining the credit is described in section 5.2.3.5.1.

5.2.3.6.1 Definition and Solar Control Credit Technologies

Credit for solar control technologies can be generated for MY 2017-2025 vehicles which utilize them. In the absence of a performance test to measure the affect of these technologies, For all solar control technologies except glazing, EPA will rely on manufacturers complying with a specification for, or description of, each technology to assure that the emissions reducing benefits are be realized in real-world applications. Below are the descriptions and specifications that EPA is proposing for the solar control technologies listed in Table 5-25. EPA will use these definitions and specifications to determine whether the credits are applicable to a vehicle.

- *Active Seat Ventilation* – device which draws air from the seating surface which is in contact with the occupant and exhausts it to a location away from the seat
- *Solar Reflective Paint* – vehicle paint or surface coating which reflects at least 65 percent of the impinging infrared solar energy, as determined using ASTM standards E903, E1918-06, or C1549-09
- *Passive Cabin Ventilation* – ducts or devices which utilize convective airflow to move heated air from the cabin interior to the exterior of the vehicle
- *Active Cabin Ventilation* - devices which mechanically move heated air from the cabin interior to the exterior of the vehicle

EPA is seeking comment on whether these definitions and specifications are adequate to ensure that the technologies used to generate credits will result in lower cabin temperatures during soak conditions and/or lower A/C-related CO2 emissions.

5.2.4 Summary of Proposed Credits

Table 5-26 summarizes the preapproved technologies and off-cycle credits available to manufacturers. If manufacturers wish to receive off-cycle credits for other technologies, they must follow the procedures laid out in section III of the Preamble (and in the regulations). Any vehicle or family of vehicles receiving credits from this list can receive a maximum of 10 grams/mile in credits.

Table 5-26: Initial off-cycle credit estimates (Maximum Available Credits)

Technology	Adjustments for Cars		Adjustments for Trucks	
	g/mi	gallons/mi	g/mi	gallons/mi
High Efficiency Exterior Lights	1.1	0.000124	1.1	0.000124
Engine Heat Recovery	0.7	0.000079	0.7	0.000079
Solar Roof Panels	3.0	0.000338	3.0	0.000338
Active Aerodynamic Improvements	0.6	0.000068	1.0	0.000113
Engine Start-Stop	2.9	0.000326	4.5	0.000506
Electric Heater Circulation Pump	1.0	0.000113	1.5	0.000169
Active Transmission Warm-Up	1.8	0.000203	1.8	0.000203
Active Engine Warm-Up	1.8	0.000203	1.8	0.000203
Solar Control	3.0	0.000338	4.3	0.000484

5.3 Pick-up Truck Credits

The agencies recognize that the standards under consideration for MY 2017-2025 will be most challenging to large trucks, including full size pickup trucks. The agencies goal is to incentivize the penetration into the marketplace of "game changing" technologies for these pickups, including their hybridization. EPA proposes a credit for manufacturers that employ significant quantities of hybridization on full size pickup trucks, by including a per-vehicle credit available for mild and strong hybrid electric vehicles (HEVs). This provides the opportunity to begin to transform the most challenged category of vehicles in terms of the penetration of advanced technologies, allowing additional opportunities to successfully achieve the higher levels of truck stringencies in MY 2022-2025.

Access to this credit is conditioned on a minimum penetration of the technology in a manufacturer's full size pickup truck fleet with defined criteria for a full size pickup truck (minimum bed size and minimum towing capability). EPA proposes that mild HEV pickup trucks are eligible for a 10 g/mi credit during 2017-2021 if the technology is used on a minimum percentage of a company's full size pickups, beginning with at least 30% of a company's full size pickup production per year in 2017 and ramping up to at least 80% per year in 2021. Strong HEV pickup trucks would be eligible for a 20g/mi credit during 2017-2025 if the technology is used on at least 10% per year of the company's full size pickups. See Table 5-27, below.

Table 5-27: Penetration Thresholds for Pickup Truck Credits

Model Year	Mild HEV	Strong HEV	10 g/mi performance	20 g/mi performance
2017	30%	10%	15%	10%
2018	40%	10%	20%	10%
2019	55%	10%	28%	10%
2020	70%	10%	35%	10%
2021	80%	10%	40%	10%
2022	N/A	10%	N/A	10%
2023	N/A	10%	N/A	10%
2024	N/A	10%	N/A	10%
2025	N/A	10%	N/A	10%

EPA is also proposing a performance-based incentive credit for full size pickup trucks which achieve a significant reduction below the applicable target. EPA proposes this credit to be either 10 g/mi or 20 g/mi for pickups achieving 15% or 20% better CO_2 than their target, respectively. Further description of these values is presented in Section 5.3.4 below.

The performance-based credit will be available for model years 2017 to 2021 for the 10 g/mi credit and a vehicle meeting the requirements would receive the credit until 2021, or until its CO_2 level increases. The 20 g/mi performance-based credit would be available for a maximum of 5 consecutive years within the model years of 2017 to 2025, provided its CO_2 level does not increase. Minimum per year penetration rates are defined in Table 5-27, above.

Unlike the hybrid credit, this performance-based credit has no technology or design requirements. Automakers can use any technology as long as the vehicle's CO_2 performance is at least 15% or 20% below its footprint-based target. A vehicle cannot receive both the HEV and performance-based credit.

5.3.1 Pick-up Truck Definition

For the purposes of the full size pickup truck hybrid technology incentive credit or the full size pickup truck performance-based incentive credit, to be considered as eligible for the credit, a vehicle is a full size pickup truck if it meets the requirements specified in item 1 and 2 below, as well as either item 3 or 4.

1. The vehicle must have an open cargo box with a minimum width between the wheelhouses of 48 inches measured as the minimum lateral distance between the limiting interferences (pass-through) of the wheelhouses. The measurement would exclude the transitional arc, local protrusions, and depressions or pockets, if present.[q] An open cargo box means a vehicle where the cargo bed does not have a permanent roof. Vehicles sold with detachable covers are considered "open" for the purposes of these criteria.

2. Minimum open cargo box length of 60 inches defined by the lesser of the pickup bed length at the top of the body (defined as the longitudinal distance from the inside front of the pickup bed to the inside of the closed endgate; this would be measured at the height of the top of the open pickup bed along vehicle centerline and the pickup bed length at the floor) and the pickup bed length at the floor (defined as the longitudinal distance from the inside front of the pickup bed to the inside of the closed endgate; this would be measured at the cargo floor surface along vehicle centerline).[r]

3. Minimum Towing Capability – the vehicle must have a GCWR (gross combined weight rating) minus GVWR (gross vehicle weight rating) value of at least 5,000 pounds.[s]

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[q] This dimension is also known as dimension W202 as defined in Society of Automotive Engineers Procedure J1100.

[r] The pickup body length at the top of the body is also known as dimension L506 in Society of Automotive Engineers Procedure J1100. The pickup body length at the floor is also known as dimension L505 in Society of Automotive Engineers Procedure J1100.

[s] Gross combined weight rating means the value specified by the vehicle manufacturer as the maximum weight of a loaded vehicle and trailer, consistent with good engineering judgment. Gross vehicle weight rating means the value specified by the vehicle manufacturer as the maximum design loaded weight of a single vehicle, consistent with good engineering judgment. Curb weight is defined in 40 CFR 86.1803, consistent with the provisions of 40 CFR 1037.140.

4. Minimum Payload Capability – the vehicle must have a GVWR (gross vehicle weight rating) minus curb weight value of at least 1,700 pounds.

EPA is seeking comment on expanding the definition of a full-size truck by reducing the minimum wheelhouse width requirement from 48 inches to a value around 42 inches, provided the vehicle is able to tow at least 6,000 lbs. Note that this is 1,000 lbs higher than requirement 3, above.

5.3.2 Hybrid Pickup Technology

5.3.2.1 Mild Hybrid Pickup Technology

Mild hybrid pickup trucks are those trucks that meet the definition of a full-size pickup, in Section 5.3.1 above and have a powertrain with lower-power hybrid technology. Often, a mild hybrid is characterized by the addition of a belt-driven starter-alternator of higher power capacity than a standard alternator. The drive belt system also typically has a feature that enables the belt tension to be maintained at proper levels during generator operation as well as when the starter-alternator is used to start the engine. Alternatively, an axial motor can be mounted on the crankshaft, usually in the bell housing before the transmission. This motor can be directly attached to the engine, or can be clutched to decouple it from the engine. The vehicle uses a conventional transmission such as an automatic, manual, CVT, or DCT with an appropriate conventional coupling such as a torque converter or clutch.

The battery can be between 36V to over 150V nominal (or more), but generally the higher the voltage, the higher the performance of the system. Most mild hybrid pickups are expected to offer at least 100V of battery voltage due to the higher power requirement of these heavy vehicles. Mild hybrids are capable of start-stop operation, and regenerative braking, but unlike strong hybrids they are not capable of any significant electric-only operation.

Mild hybrids are less capable than strong hybrids because of lower power capability, but mild hybrids are lower cost and may be easier to adapt to some vehicles without making major powertrain, chassis or body changes. EPA and NHTSA did not model mild hybrid pickups for the NPRM, but intends to include them in the modeling for the final rule.

5.3.2.2 Strong Hybrid Pickup Technology

Strong hybrid pickups are vehicles that meet the definition of a full-size pickup in Section 5.3.1 above and have hybrid systems that are more capable than mild hybrid systems. Strong hybrids generally have an integrated transmission-drive motor system with a large, powerful electric drive motor-generator (often two motors). The transmission usually is specifically designed to integrate the motor-generator(s) and often the coupling between the engine and transmission such as a torque converter is removed with its functions handled by the electric drive motor system. The transmission can also be replaced by a power split device that uses a planetary gearset and two motor-generators. Strong hybrids typically have high voltage battery packs over 300 V to provide the high power necessary for their increased capability.

Strong hybrids are capable of start-stop operation, have significant braking regeneration capability and are often capable of driving exclusively on battery power up to 35-45 mph. They are also capable of launching the vehicle on electric drive alone, although they typically cannot accelerate above 15-20 mph while operating on electric drive exclusively.

5.3.3 Mild and Strong HEV Pickup Truck Definitions

A vehicle that meets the definition of a full-size truck above, must meet additional design and performance requirements to be eligible for the hybrid full-size truck incentive. Mild and strong hybrids are both characterized by stop-start capability and regenerative braking and eligible vehicles for this incentive must have both features. Additionally, the level of hybridization (mild or strong) is characterized by the amount of energy recovered during regenerative braking. The methodology for determining the amount of recovered braking energy is discussed below.

Table 5-28: Requirements for Full-Size Pickup Hybridization Incentive

Hybrid Type	Mild Hybrid	Strong Hybrid
Stop-Start	Yes	Yes
Regenerative Braking	Yes	Yes
Amount of Recovered Energy	15% -75%	75%

5.3.3.1 Measurement of Recovered Braking Energy

EPA proposes to incorporate a metric – the total percentage of available vehicle braking energy recovered over the test cycle – as a way to define levels of hybrid vehicles. For a given vehicle and road load profile (characterized by ETW and A, B and C dyno test "coastdown" coefficients), a theoretical amount of required braking energy can be calculated over the city and highway test cycles. This maximum braking energy is the sum of the extra braking force needed to slow the vehicle enough to follow the test cycle trace upon decelerations. Hybrids recapture a portion of this energy by driving the electric motor (in reverse) as a generator, which ultimately provides electrical power to the battery pack. Depending on the level of hybridization, this amount of recaptured energy can range between a few percent of total available braking energy up to theoretically almost 100% of all braking energy.

This metric is a way to simplify the characterization of a hybrid as a “mild” or “strong” hybrid. Batteries and motors must increase in scale to recover braking energy at a greater rate. As the power rating of the motor and battery increases, a greater percentage of braking energy can be recovered on rapid decelerations. So, all components of a hybrid system – the battery pack size and power rating, the motor rating, etc. – are implicitly reflected in the percentage of braking energy recovered.

The procedure involves calculating the available braking energy on the FTP city cycle using the equation derived below. This value is compared to the actual energy recovered by the vehicle during FTP city cycle testing. Since energy into and out of the hybrid drive system battery is a standard part of emissions testing of hybrid vehicles, this procedure introduces no additional test burden. However, energy flow into the battery must be separated from the sum of energy into and out of the battery which is typically less than 1% of total fuel energy used during the test.

The measured energy into the battery is divided into the total calculated braking energy to determine if the vehicle is a mild or strong hybrid. For a mild hybrid, the recovered energy must be greater than 15% and less than 75% of the calculated available braking energy. For a strong hybrid, the recovered braking energy must be greater than 75% of the calculated available braking energy.

5.3.3.2 Spreadsheet documentation and calculation methodology details

Equation 5-5 defines the brake energy recovery efficiency (expressed as a percentage), or η_{recovery}:

Equation 5-5:

$$\eta_{recovery} = \frac{E_{recovered}}{E_{brake\_\max}}$$

$E_{\text{recovered}}$, the total brake energy recovered over the 4-bag FTP test (in kWh) is calculated in Equation 5-6.

Equation 5-6:

$$E_{recovered} = \frac{V \int i(t)dt}{3600 * 1000}$$

With i(t) defined as measured current into the battery (in amps) and V defined as the nominal battery pack voltage. **Current flowing out of the battery (discharge) is not included.**

Equations to calculate the maximum theoretical braking energy:

E_{brake_max} (kWh) is calculated by integrating required braking power (P_{brake}) at each point in the test cycle[t] over the entire test, shown in Equation 5-7.

Equation 5-7

$$E_{brake\_\max} = \frac{\int P_{brake}(t)dt}{3600}$$

P_{brake} (kW) – the vehicle braking power required to follow the drive trace during decelerations – represents the amount of braking force (expressed as power) in addition to the existing road load forces which combine to slow the vehicle. It is expressed in Equation 5-8. By convention, only negative values are calculated for braking[u] .

Equation 5-8

$$P_{brake} = P_{accel\_reqd} - P_{roadload}$$

P_{accel_reqd} (kW), in represents the total applied deceleration power necessary to slow the vehicle. It is calculated as the vehicle speed, v (in m/s) multiplied by the deceleration force (vehicle mass * required deceleration rate), as shown in Equation 5-9.

Equation 5-9

$$P_{accel\_reqd} = v * m_{ETW} * \frac{dv}{dt}$$

Where:

m_{ETW} (kg) is the mass of the vehicle based on equivalent test weight (ETW)

dv/dt (m/s2) is the required acceleration/deceleration for the vehicle to match the next point on the vehicle trace

$P_{roadload}$ (kW) is the sum of the road load forces (N) as calculated from the experimental vehicle coastdown coefficients, A, B and C. It is calculated in Equation 5-10.

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[t] These calculations assume a “4-bag” FTP schedule, or 2 consecutive UDDS cycles, as is common for testing HEVs for charge balancing purposes.

[u] All power terms are negative when power is applied to the vehicle (as in braking). Power provided by the vehicle (such as tractive power – in the case of acceleration) would be positive.

Equation 5-10

$$P_{roadload} = v * \left(A + Bv + Cv^2\right)$$

5.3.4 Performance Based Pickup Truck Incentive Credit Thresholds

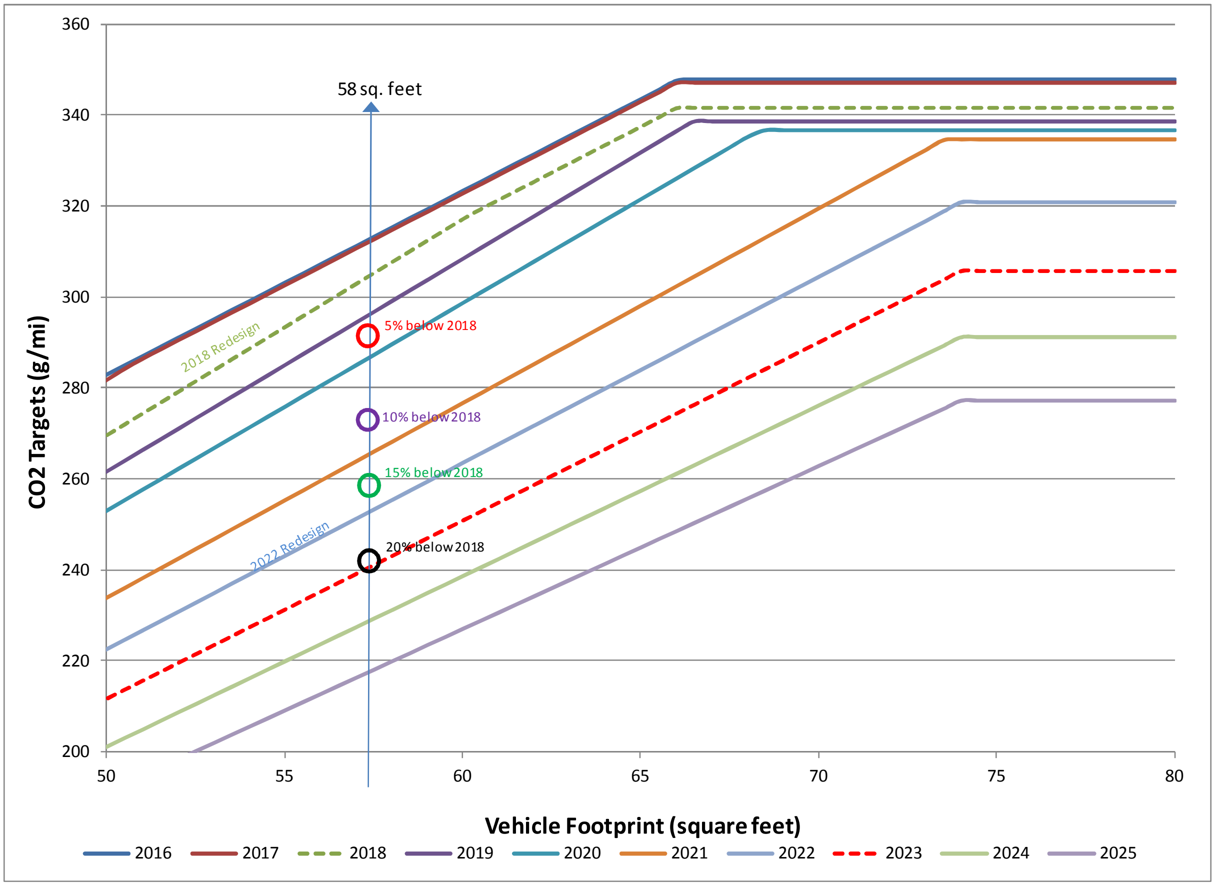
This section describes how the agencies arrived at the proposed threshold values of 15% and 20% better than the footprint target for the qualification of performance based pickup truck incentive credits. The basis for the credit is to provide an incentive for conventional (non-hybrid) pickup trucks to significantly outperform their footprint based standard (or target) much as the HEV technologies are expected to do.

Based on the lumped parameter model (described in Chapter 3 of this joint TSD) HEVs on pickup trucks are approximately 15% more effective than non-hybrids. However this is dependent on a great many factors so there is a range of improvement that an HEV can exhibit, dependent on the weight, electrification level, HEV architecture, engine/transmission, utility ratings, control strategy, etc. Rather than comparing directly to a given HEV technology, we have instead determined the thresholds based on the year-on-year stringency of the standards (targets). We use the GHG standards for illustrative purposes, though the exercise could have also been conducted using the fuel economy targets.

The targets (curve standards at a given footprint) become more stringent each year. However the typical vehicle is redesigned every 5 (or 6 years for some larger trucks). When a vehicle is redesigned, it is assumed that the emissions will not just meet the footprint target, rather it should exceed it so that in general it is generating credits for the first two or three years of the product life, and generating credit deficits for the latter two or three years, until the next redesign. While it is true that any given vehicle is not required to meet its footprint target, any given manufacturer must meet its fleet obligation which is based on the footprint and sales volumes of the vehicles it produces. Therefore, under normal (business-as-usual) circumstances, each manufacturer will be designing and redesigning some of their vehicle models each year and some vehicles will exceed their targets (for about 2-3 years each) and others will fall short (for about 2-3 years each), thus allowing the manufacturer to average their fleet in order to come into compliance on any given year. This product development “cadence” is an important element of understanding lead time, technology phase-in caps, manufacturer capital investments, and the performance based thresholds.

In the following hypothetical example, illustrated in Figure 5-13, a recently redesigned 58 square foot pickup truck is certified in MY 2018. Its target is 308 g/mi. This truck will not receive another redesign until 2022. Under normal circumstances, a typical vehicle would likely be 10% better than the standard, which would make it a credit generator for three years and a deficit generator for two years (consistent with the usual regulatory strategy outlined in the previous paragraph). At 15% below target (262 g/mi) this truck will generate credits for four years and deficits only in its last year. At 20% below target (246 g/mi) the truck will generate credits for the full five year product development cycle.

Figure 5-13. 2017-2025 Truck GHG Standard Curves, with Example Redesign of a 58 sq. foot truck



The analysis depends somewhat on the footprint selected. Table 5-29 shows the truck footprint targets for each model year for three sample trucks with footprints: 58, 67 and 74 sq ft, and three scenarios: 10%, 15% and 20% better than the standard. The table also shows (on the right) the number of years for each of the sample trucks before they start generating deficits. In the 10% scenario, the trucks create deficits in 3.4 years on average. In the 15%, it takes 4.7 years and for 20% it takes 5.7 years on average. Based on this analysis, the agencies have chosen to propose the 15% and 20% threshold as these are significantly better than the business-as-usual (~10%) scenario. The performance thresholds of 15% and 20% therefore represent CO_2 reductions greater than what EPA expects companies would typically plan for during a redesign of these products, given the level of the proposed standards and the CO_2 targets for typical full size pickup trucks. These levels are also technically within reach of the companies if they pull ahead technologies which they may not otherwise need until the later years of the program, or in the case of the later years of the program, a pull-ahead of technologies beyond what is needed for MY2025.

Table 5-29: Truck CO2 Footprint Targets for 10%, 15% and 20% Thresholds

Footprint	**10%** better than std	# of yrs before creating deficits

	58.0	67.0	74.0	
2017	315	347	347	**2017**
2018	308	342	342	**2018**
2019	299	339	339	**2019**
2020	290	331	337	**2020**
2021	268	307	335	**2021**
2022	255	292	321	**2022**
2023	243	278	306	**2023**
2024	231	265	291	**2024**
2025	220	252	277	**2025**

58.0	67.0	74.0	
283	312	312	
277	308	308	
269	305	305	
261	298	303	
241	276	301	
230	263	289	
219	250	275	
208	238	262	
198	227	249	

58.0	67.0	74.0
4	4	6
3	3	5
2	3	5
2	2	4
3	3	3
3	3	3

avg **3.4**

	Footprint			
Footprint	58.0	67.0	74.0	
2017	315	347	347	**2017**
2018	308	342	342	**2018**
2019	299	339	339	**2019**
2020	290	331	337	**2020**
2021	268	307	335	**2021**
2022	255	292	321	**2022**
2023	243	278	306	**2023**
2024	231	265	291	**2024**
2025	220	252	277	**2025**

15% better than std

58.0	67.0	74.0	
268	295	295	
262	290	290	
254	288	288	
246	281	286	
228	261	285	
217	248	273	
207	236	260	
197	225	247	
187	214	236	

# of yrs before creating deficits

58.0	67.0	74.0
5	5	7
4	5	7
4	4	6
3	3	5
4	4	4

avg **4.7**

	Footprint			
Footprint	58.0	67.0	74.0	
2017	315	347	347	**2017**
2018	308	342	342	**2018**
2019	299	339	339	**2019**
2020	290	331	337	**2020**
2021	268	307	335	**2021**
2022	255	292	321	**2022**
2023	243	278	306	**2023**
2024	231	265	291	**2024**
2025	220	252	277	**2025**

20% better than std

58.0	67.0	74.0	
252	278	278	
246	273	273	
239	271	271	
232	265	269	
215	245	268	
204	234	257	
194	223	244	
185	212	233	
176	202	222	

# of yrs before creating deficits

58.0	67.0	74.0
6	7	8
5	6	
5	5	
4	5	

avg **5.7**

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