Draft Technical Assessment Report:

Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025

Appendix

Office of Transportation and Air Quality
U.S. Environmental Protection Agency

National Highway Traffic Safety Administration
U.S. Department of Transportation

And

California Air Resources Board

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Appendix A CARB Analysis of Vehicle Load Reduction Potential for Advanced Clean Cars

In 2013, CARB staff contracted with Control-Tec (now Novation Analytics) to identify “best-in-class” vehicle road load reduction technologies that were already in production and explore the hypothetical impact on greenhouse gas (GHG) reductions if such technologies were applied to the entire California vehicle fleet (CARB contract #13-313).[1] The goal of the contract was to provide ARB with some perspective on the current status of road load reduction technologies such as improvements in aerodynamics, tire rolling resistance, and vehicle mass reduction. That said, it was not to determine the feasibility of future road load reductions or to project a likely scenario for future model year vehicles. By the structure of the contract, the projection excludes any new technology or improvements to technology that will undoubtedly occur beyond what was already implemented in model year (MY) 2014 (with the exception of full-size van aerodynamics, where MY 2015 was used since the MY 2014 models were at the end of their design cycle). By design, the contract also did not evaluate powertrain technology such as engine and transmission related items that are the primary mechanism by which manufacturers are expected to comply with future GHG standards.

A model-based approach was utilized by Control-Tec to analyze the entire MY 2014 light-duty vehicle fleet. Attributes for each vehicle (mostly based on manufacturer reported data such as road-load ABC coefficients, curb weights, etc.) were entered into Control-Tec’s ENERGY system. By breaking down the road load coefficients combined with adjustments made by the ENERGY model, the physics-based software model was able to estimate aerodynamic drag, tire rolling resistance, and vehicle mass for each vehicle in the database (~1350 unique vehicle combinations). Once a baseline was established, vehicles were broken into appropriate categories for each of the road load contributors (aero, tire, mass). Aerodynamics categories were narrowed down to: coupe, convertible, sedan, hatch/wagon, SUV, minivan, full-size van, and pickup. Tire categories were narrowed down to: fuel economy oriented, balanced, and performance oriented. Mass categories were narrowed down to: coupe, convertible, sedan, hatch/wagon, SUV, van, and pickup.

Once the baseline was established, distributions of aero, tire, and mass were made for each category. By looking at the distributions and using engineering judgement, a best-in-class approximation for each category was established. To minimize the impact of data anomalies, errors, and imprecision related to the model, best-in-class was never chosen to be the actual best (i.e., the 100th percentile) and was chosen at different levels for each of the three technology categories based on the robustness of the data and model estimation. For aero, the 90th percentile was chosen as best-in-class, yielding a range of about 8 to 12 percent improvement in Cd over the median vehicles depending on the vehicle category. For tire rolling resistance, the 75th percentile was chosen as best-in-class, yielding a range of about 11 to 14 percent improvement in rolling resistance from the median vehicles depending on the tire category. For mass, the 98th percentile was chosen for all non-luxury vehicles and the 90th percentile was chosen for luxury vehicles as the best-in-class, yielding a range of about 6 to 10 percent mass reduction from the median, depending on vehicle category.

Once these best-in-class attributes were determined for each category, the road load reduced fleet simulation could begin. This was done by moving all vehicles that were less than the best-in-class up to the best-in-class level within their category. Vehicles that were already better than the median resulted in a smaller incremental improvement being applied than for vehicles that were worse than the median. Vehicles that were already at or above the best-in-class level remained unchanged from the baseline.

The baseline fleet that was modeled was based on all vehicles certified for sale in California for MY 2014 and weighted with California sales. The fleet simulation then stepped through several discrete steps to add in best-in-class performance. Using ENERGY, the first step was to apply best-in-class aerodynamics, followed by applying best-in class tire rolling resistance, and then applying best-in-class mass. Since the load-reduced fleet would have improved acceleration performance, Control-Tec chose to reduce engine displacement to maintain the baseline performance of each load-reduced vehicle. Next the fuel tank capacity of each vehicle was reduced to maintain the baseline range. Finally, the powertrain efficiency of each vehicle was re-optimized to regain the baseline energy conversion efficiency.

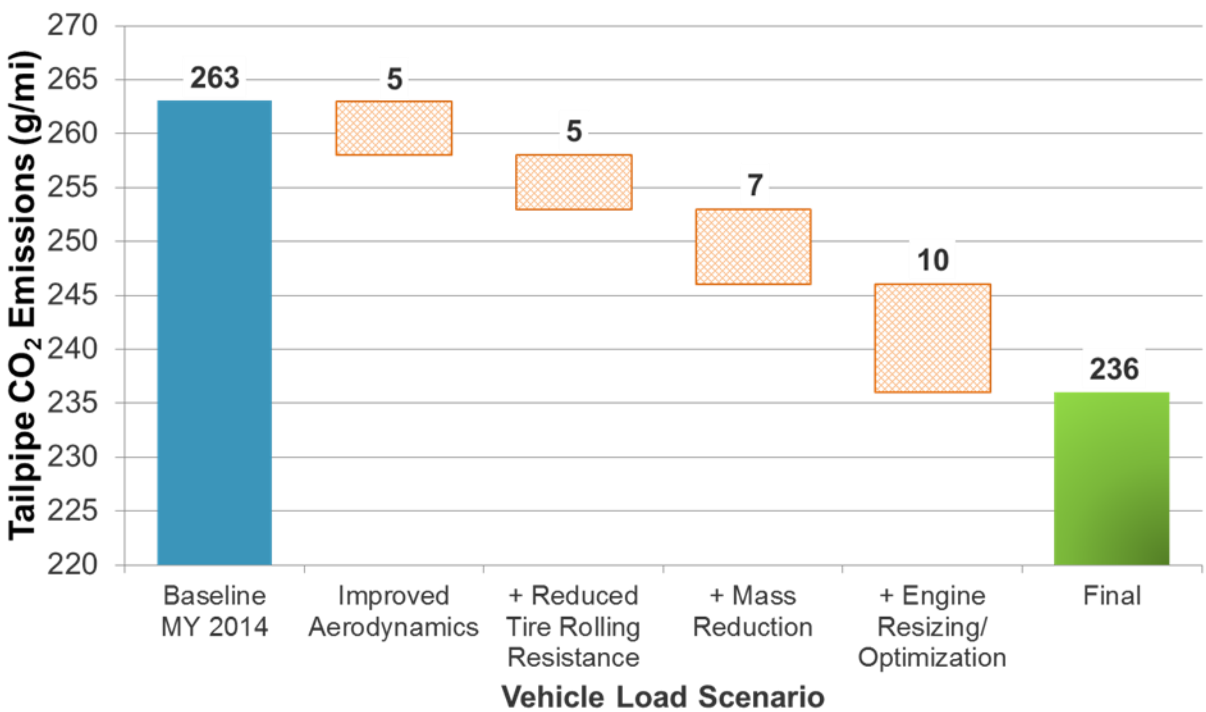


Figure A.1 Potential Reduction in CO_2 Emissions by Adoption of Best-In-Class MY2014 Technologies

As shown in Figure A.1, the results of the fleet simulation found a potential 10.4 percent reduction in CO_2emissions from applying road load reduction technology already deployed in some MY 2014 vehicles across the entire vehicle fleet. For the baseline MY 2014 CA fleet, this represents a hypothetical 27 g/mi CO_2reduction from the sales-weighted fleet.

Control-Tec uses the term "Vehicle Energy Intensity" (units of MJ/km) to describe how much energy is required to move a vehicle. This allows comparisons to be made between vehicles. It also allows us to compare the results of the contract to the projections done by EPA and NHTSA as part of the original rulemaking. As part of the work that Novation Analytics (formerly Control-Tec) has done for the Auto Alliance and Global Automakers, they have modeled the

EPA and NHTSA baselines and projections from 2008 and 2010[2]. When the results of the ARB contract #13-313 were scaled for US sales volumes, it shows that best-in-class MY 2014 road load is similar to what the agencies projected for MY 2021 passenger car road load and MY 2025 light truck road load. One difference is that the agencies assumed more aerodynamic and tire rolling resistance advances and less mass reduction than what was found in the contract #13-313 results. That said, there is room for improvement with respect to all three of these aspects. For example, some of the tire rolling resistance reductions assumed by the agencies in the FRM were projected to not be available until the 2020 timeframe and could reflect additional reductions beyond what is available in the MY 2014 fleet. Additionally, it is reasonable to assume that by the 2022 to 2025 time frame there will be further improvement from what was determined to be best-in-class in MY2014.

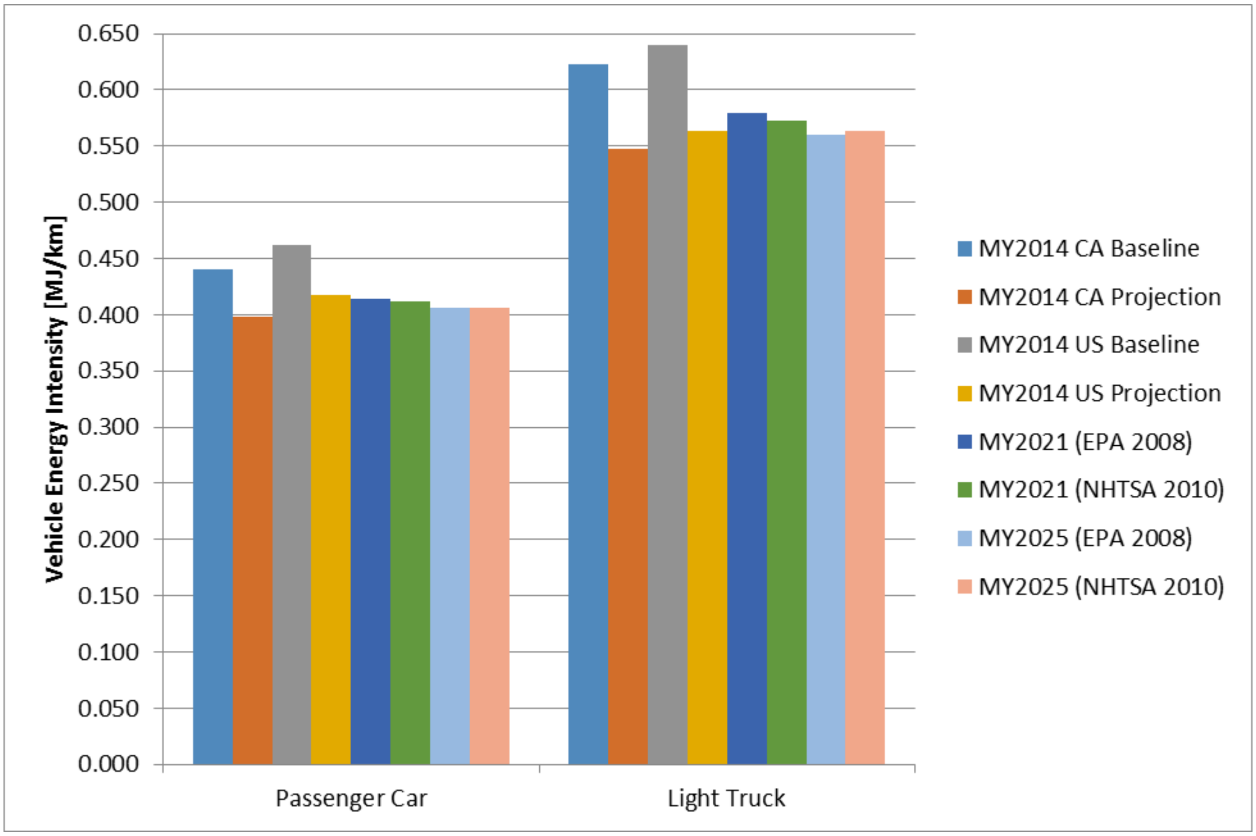


Figure A.2 Sales-Weighted Vehicle Energy Intensity

As noted earlier, however, it is important to note that this project was based completely on technologies (and their associated implementation of them) already deployed in MY 2014 vehicles and was limited in scope to focus solely on road load reduction. As such, the analysis includes no consideration of additional road load reduction that may be achieved over the next ten years either with new or additional technologies applied or with further refinement in implementation of existing technologies. And, as can be expected, vehicle manufacturers have already introduced MY 2015 and MY 2016 vehicles that have further road load reductions than the MY 2014 fleet and would result in a new characterization of best-in-class performance. Further, no improvements to the powertrain or efficiency were analyzed other than a constrained downsizing of the engine displacement to match the original vehicle performance characteristics.

Appendix B Mass Reduction Technologies

The development and adoption of lightweight materials and design optimization tools in the automotive sector has accelerated over the past 5 years and will continue as OEM's adopt lightweight materials and/or design strategies into their plans for meeting the 2017-2025 GHG/CAFE standards. Information on material technologies is also available in the several light weighting holistic vehicle studies completed in 2010-2016 through projects funded by EPA, NHTSA, ARB, ICCT, Transport Canada, Environment Canada, Natural Resources Canada and others, as mentioned and referenced in Chapter 5 of this report. Holistic vehicle studies were taken to the next level through the MMLV project funded by DOE/Ford/Magna in which several new technologies developed and at least six vehicles were built for vehicle level analyses including durability, crash and corrosion. This Appendix contains only a small snapshot of more recent activities and findings in the world of materials for automotive use with most from the past few years.

The information in this Appendix was collected based on information from trade associations, technical conferences, academia, and other sources. Associations referenced here include the Aluminum Association and its members, American Iron and Steel Institute and its members, the American Chemistry Council and its members. Technical presentations provided a wealth of knowledge and were presented at a number of conferences including the SAE World Congress and SAE Government/Industry, DOE Annual Merit Review, Great Designs in Steel, Global Automotive Lightweight Materials. Other resources including Ducker Worldwide, A2Mac1, and academia resources including WPI, MSU, UofM and a number of other institutions. More information is planned to be added as the agencies further review the information received over the past few years and gather additional material information through meetings, conferences, etc. in the upcoming year as we work towards the Proposed Determination/NPRM.

Lightweight materials are being reviewed and adopted by OEM's as part of their vehicle compliance plans. The rates of adoption vary between OEMs and within OEM product lines. Some OEMs have delved into redesign of a number of vehicle components with AHSS, such as hot formed steels in the a-pillar and roof rail, or adoption of aluminum intensive structure as with the Land Rover vehicles or Ford's F150. Others have adopted only one or more lightweight material closure panels. Material development is still ongoing for use in the automotive industry, such as higher strength aluminum, generation 3 steels and composite fiber.

Development for new lightweight materials and processes are ongoing at national and international laboratories, academia and industry.[3] LightMAT (Lightweight Materials Consortium)[A] has been formed and includes a number of the US National Laboratories who are there to work towards "Accelerating development and deployment of lightweight materials by connecting manufacturers to national laboratories." One of the focuses here and in other laboratories include looking at the development of higher strength aluminum casting materials. The new developments in engine design result in higher compression forces on engine blocks, heads and valves. Advanced propulsion materials are being researched at ORNL such that the same size engine block and head can be used to deal with these higher combustion forces and more power can be obtained within the same engine block size. ORNL and industry are creating

[A] National labs include Los Almos, NETL, NREL, ORNL, PNNL, Fermilab, Lawrence Livermore National Laboratory, Brookhaven, Ames Laboratory, ANL, INL, Sandia National Laboratories; https://lightmat.org/.

affordable materials with improved properties through integrated computational materials engineering (ICME) and through alloy development research efforts.[4]

Efforts between industry, university and government are also a part of efforts in Canada as well. NSERC Automotive Partnership Canada (APC, National Research Council's (NRC's) Automotive and Surface Transportation (AST) program, and National Resource Canada's Program on Energy R&D (PERD). Other efforts bring the technologies through to commercial application through Industry Canada's Automotive Innovation Fund (AIF) and the Automotive Supplier Innovation Program (ASIP). At least one effort, MagNET,[5] was an international collaboration with five Canadian Universities, 2 Canadian National Labs (CANMET and NRC-CNBC) and 8 companies with international collaborations in the USA, Germany, Japan, Australia, etc. which focused on developing magnesium materials for the transportation sector.

Other research focuses are currently underway in the materials industry and academia to make metal materials less expensive. The continuous cast production method for aluminum and magnesium is a promising technology and as of 2015 some aluminum parts for the MYF150 are being made with this process. Research is also progressing in the composite area including CAE modeling of composites for structural applications, [6] reduced cost fibers (such as from biomass) and mass production timing (such as stamp able thermoplastic CFRP). Higher temperature plastics are also coming into the marketplace which create new opportunities for lightweighting in areas such as the engine throttle body and cooling lines.

To begin the process of lightweight material adoption, engineers select materials to use for a component based on the design criteria of the component and the specific properties of the material. In designing lightweight components, a key consideration is strength of a material relative to its density. The Ashby plot in Figure 1 below, compares these properties for the major classes of materials used in vehicles. Each class of material has advantages when used to design certain components.

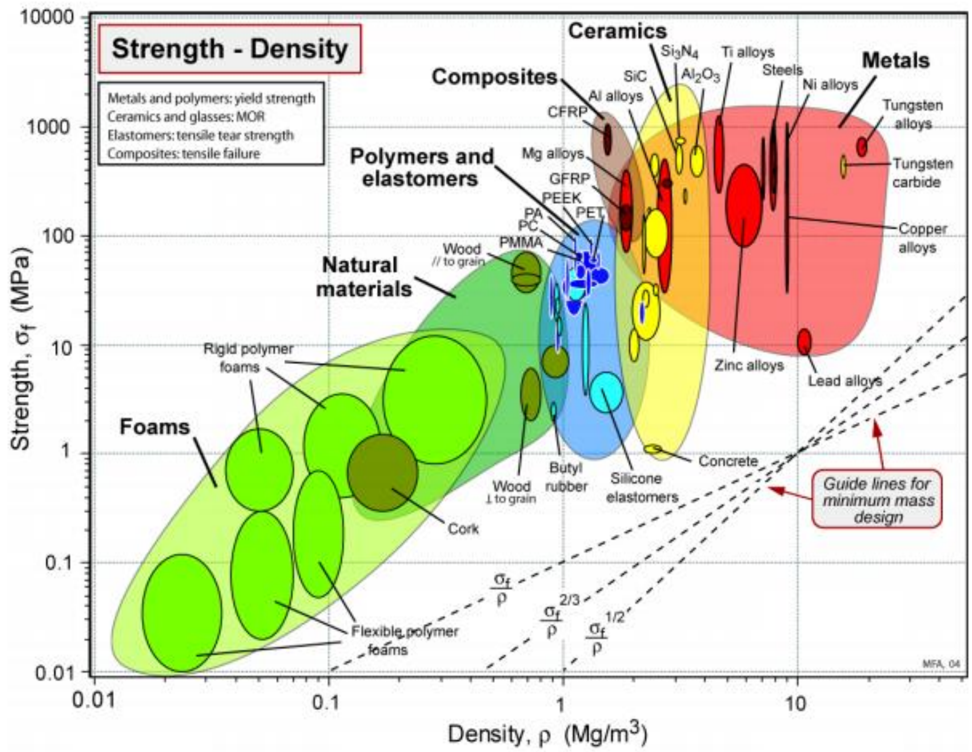


Figure B.1 Ashby Plot for Material Strength-Density[7]

Taking material from concept to production involves commitment on the part of the OEM and a holistic viewpoint such that secondary mass possibilities are achieved and the optimization of engine downsizing assures the best effectiveness in reducing GHG/CAFE for mass reduction activities.[8] In the automotive marketplace today we have seen adoption of steel in the creative cost effective solutions for the vehicle structure (MY2017 Cadillac XT5) and suspension components (F150 Control Arm). Aluminum is gaining popularity in a number of components including closures (Chevy Malibu) and castings in BIW structures (F150). Magnesium is finding its way into IP and tailgate designs (Pacifica). Carbon fiber/composites are challenging the metals in areas of oil pans, seat structures, bumpers, etc. Research continues to create new facets of this story through reduced costs from product design, new material manufacturing processes, to incorporating recycled material. A short description of lightweight materials (steel, aluminum, magnesium, composites and plastics) addressing Feasibility, Mass Reduction, Cost, Safety, Research and Recycling are contained herein.

To begin the discussion of mass reduction technology, we acknowledge the powerful activity of design optimization which is enhanced by the ever improving CAE design tools available today. Recent events with the MY2017 Cadillac XT5 vehicle redesign and consideration of joint design along with the lightweighting of the Honda Civic 1.5L turbo engine show the strength of redesign to saving mass.

B.1 Design Optimization

The typical design process within an OEM includes a complex web of existing supplier relationships and comfort with the existing BIW/chassis design and resultant warranty experience (either through years of development and/or on-road experience). Those OEM's and design teams able to work with the latest design and analysis tools in CAE, along with improved materials and processes, can achieve notable lightweighting and durable results. While there are many examples to choose from in the marketplace today, the following discussion focuses on the MY2017 Cadillac XT5 (component design and system design) and the 2016 Honda Civic 1.5L turbo engine design (component designs, material changes, process changes). Additional mass reduction ideas utilizing the aspect of design include the act of combining several stamped steel pieces into one cast piece. This can be seen in airbag housings, seat frames and aluminum castings incorporated in the BIW components as shown in the Ford F150 and the MMLV Mach I BIW.

The MY2017 Cadillac XT5 light weighting story is described in SAE Automotive Engineering article "Cadillac XT5's new platform cuts weight-at less cost"[9]. The midsize crossover was made 292lb (132kg) lighter than the SRX it replaces by "driving out waste." The majority of this was from the platform with 86kg mass reduction, while a new 5 link rear suspension accounts for 70lb (32kg) and dissipative materials used for acoustic attenuation 30lb (14kg). The steel-structured vehicle was able to achieve mass reduction through careful optimization using the latest design tools: "the C1 structure employs a range of high-strength steels and that by intricately modeling how each contributes to the overall chassis assembly, then paying particular attention to optimizing the joints not only between those steels but throughout the structure." The article ends with the statement that design optimization was, in effect, more important than the materials themselves. "It all goes back to analytical tools," Mihalko claimed. "They just keep getting better."

An example of mass reduction which incorporates design, material change and process changes is the 2016 Honda Civic turbocharged 1.5-Liter In-Line 4 Cylinder, see Figure B.2. The trend in design is to achieve higher horsepower out of a smaller overall engine package. While unknown to be utilized in this engine, high strength aluminum alloys are being developed and are beginning to be utilized in diesel engines in Europe. "The Civic's available new DOHC 1.5-liter engine is the first turbocharged engine ever to be offered in a Honda-brand automobile in America. With direct injection, low-inertia Mono scroll turbo system with electrical waste-gate and dual Variable Valve Timing Control (VTC), the turbocharged Civic power plant develops the horsepower and torque of a much larger engine, and is anticipated to help the Civic receive excellent EPA estimated fuel economy ratings." [10] SAE paper describing this technology[11] states that "The author's investigation of how to reduce engine weight resulted in a reduction of about 30kg compared to a conventional NA engine with the same output."

Figure B.2 Mass Savings from Honda Civic 1.5L Engine Redesign Technologies[10]

Mass Reduction was achieved through design steps, material changes and process changes as described in Table B.1.

Table B.1 Honda Civic 1.5L Mass Reduction Technologies (Design, Process and Material Changes), - 30kg Mass

Component(s)	Technology	% Part Mass Reduction noted in SAE paper[11]
Cylinder Block and Crankshaft	lightweight die-cast aluminum block with individual reinforced main bearing caps to minimize weight.	
	Cast-in iron cylinder liners	
	Micropolished lightweight forged-steel crankshaft	
Pistons and Connecting Rods	lightweight pistons have a carefully optimized skirt design to minimize reciprocating weight, which minimizes vibration and increases operating efficiency	
	Lightweight, high-strength steel connecting rods are heat-forged in one piece and then "crack separated" to create a lighter and stronger rod with an optimally fitted bearing cap. 30% reduction in cross section area.	15%
Cylinder Head and Valvetrain	lightweight DOHC cylinder head that is made of pressure-cast aluminum alloy.	
	exhaust port cast directly into the cylinder head, the need for a traditional separate exhaust manifold is eliminated.	
	Sodium filled exhaust valves with more durable valve material	18%
Camshafts	new thin-wall hollow	
Cylinder Head	Smaller M12 sparkplugs (from M14)	
Intercooler Pipes	Replace aluminum pipes before and after the intercooler with PP-GF15 resin formed by blow molding. Overall length shortened through bellows shape design which also absorbs pipe shaking.	20%

B.2 Material Advancements - Steel

FEASIBILITY: The Light Duty Greenhouse Gas emission and CAFE standards provide opportunities for the steel industry to present OEMs with steel alternatives to the other lightweight materials. In order to lightweight the steel, the strength of the steel needs to increase in order for the steel product, such as sheet metal, to be made thinner. Manufacturing parameters, such as elongation limitations, have to be taken into account when determining the application of a steel in order to avoid material splitting and spring-back in component forming.

In a presentation on crash worthiness[12], WorldAutoSteel lists the steel grades available to vehicle manufacturers and how research and development have resulted in the development of numerous steel grades, summarized below in Figure B.3. The grades available at the time of the Ultralight Steel Auto Body (ULSAB) project are shown in orange (2002), grades at the time of the Future Steel Vehicle project (2011) are listed in grey, and the newest grades (2014) are in white. Each steel grade listed below is given an alphanumeric classification based on the type of steel (referring to the treatment process used to establish its microstructure) the yield strength of the steel, and the ultimate tensile strength (sometimes referred to as tensile strength) of the steel. Other sources refer to steel grades with a single numerical material strength description, which corresponds to the tensile strength of the steel.

Lightweighting with AHSS: Steel Continues to REINVENT

Materials Portfolio

DP 210/440	HSLA 490/600	DP 700/1000	CP 1050/1470
IF 260/410	DP 500/800	CP 750/900	HF 1050/1500
BH 280/400	CP 500/800	TPN 750/900	DP 1150/1270
IF 300/420	TWIP 500/980	DP 750/980	MS 1150/1400
DP 300/500	HSLA 550/650	TRIP 750/980	HF 1200/1900
FB 330/450	CP 600/900	TWIP 750/1000	MS 1250/1500
DP 350/600	TWIP 600/900	CP 800/1000	
TRIP 350/600	DP 600/980	DP 800/1180	
TRIP 400/700	TRIP 600/980	CP 850/1180	ULSAB AVC Grades (2002)
HSLA 420/500	Q&P 650/980	MS 950/1200	FutureSteelVehicle (2011)
FB 450/600	CP 680/780	TWIP 950/1200	AHSS Guidelines V5.0 (2014)
TRIP 450/800	TPN 680/780	CP 1000/1200	
TWIP 480/900	HSLA 700/780	MS 1050/1470	

WorldAutoSteel

Figure B.3 Lightweighting with AHSS: Materials Profile (www.autosteel.org)[12]

Today research and development is ongoing to develop a high strength, cold rolled 3rd generation (>1 GPa) steel that can be formed and will be an option to the higher cost hot forming requirements of current steels with greater than 1 GPa tensile strength. Guidance on use of the steel is provided by worldautosteel.org which announced the availability of its AHSS guidelines[13] in October 2015. The site states that "Version 5.0 also reflects new content highlighting the broader materials portfolio, advanced fabrication technologies, and optimized joining processes."

Substituting mild steel with high-strength steel grades into vehicle structures has significant potential for reducing vehicle weight. The S-in-Motion project conducted by ArcelorMittal, for example, estimates that, using only commercially available grades of high-strength steel, this kind of substitution could reduce vehicle weight (mainly from a vehicle's body-in-white (BIW) and door structure) by as much as 23 percent for sedans and 20 percent for SUVs. If soon-to-be commercially available steel grades were to be incorporated as well, those numbers could increase to 26 percent and 21 percent respectively[14]. This study also presents cost information of the materials in comparison to mild steel. The substitution of commercially available high-strength steel resulted in a 7 percent increase in sedan material costs, or about $1/kg saved[14].

STRUCTURE: The potential of using a hot formed, multi-steel alloy was identified as a replacement for manufacturing certain automotive body parts. Vehicle bumpers made with this metal blend could be made thinner and more modular without excessive costs or the need for additional reinforcement compared to the original Mg-B-Steel. A-Pillars could be reduced in size and mass and yield improved visibility, which is helped by the ease of integration of those pillars. B-pillars were better able to absorb energy and minimize displacement, allowing for reduced material usage at the expense of slight cost increases.

CASTINGS: Current trends by the National Research Council forecast a continued decrease in typical iron castings by at least 50 percent. Aluminum castings are increasingly being incorporated into newly designed vehicles. Lightweighting of iron castings through thin-wall iron castings is being explored by the federal government’s LIFT (Lightweight Innovations for Tomorrow) as a way provide similar performance to ductile iron at a lower mass. Partners in this project include Grede and Eaton, Michigan Technological University, American Foundry Society, Comau, PDA and Massachusetts Institute of Technology. The group expects to have some results by 2016.

SHEET: Steel sheet has gauge limitations in vehicle closure applications due to oil canning and so limits the ability of steel sheet to compete with aluminum sheet in vehicle closures on the basis of mass reduction. However, supports can be applied to support thinner gauge in critical areas. A study by Arcelor Mittal on a steel door design was presented at Great Designs in Steel in 2014 in which 3G optimization methodology was utilized as well as Arcelor Mittal's Usibor 1.5GPa hot formed steel and other high strength steels.[15] Overall, as shown in Figure B.4, the results were a 4.1kg (28 percent) mass reduction using higher strength steels and an optimized design. The cost difference for a 200,000 vehicle volume production for materials, forming and assembly was an increase of $13.00, with a slightly lower cost of materials but more than doubling the cost for forming. The aluminum door design in the EPA lightweighting study for the light duty truck was a 10kg (35 percent) reduction at $59.15 increase in OEM direct cost for a 450,000 production volume vehicle.[15] A number of evaluations in oil canning, torsion, etc. were included in both analyses. Overall, higher strength steels can provide an option for mass reduction for vehicle closures with lower costs than aluminum, but with less potential amounts of mass reduction.

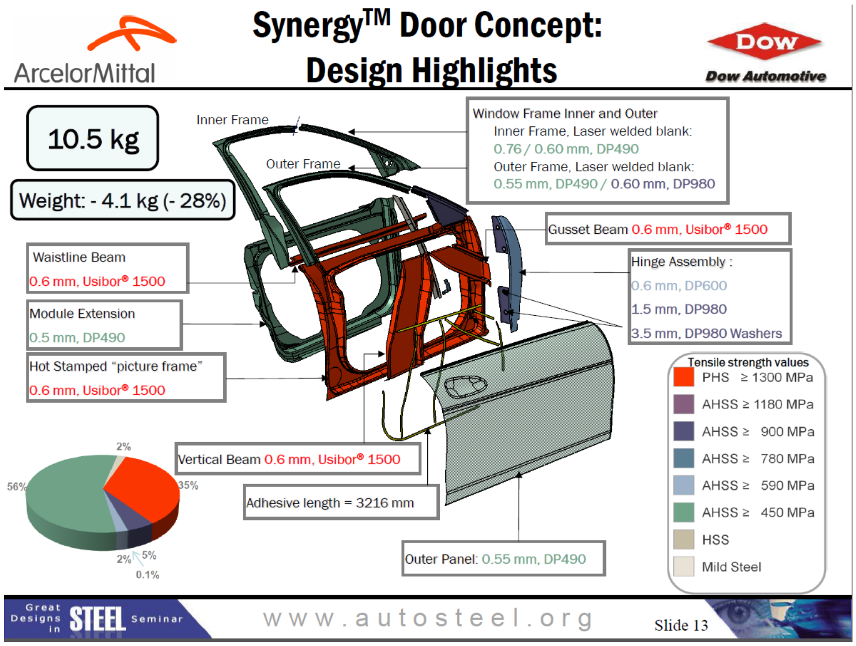


Figure B.4 Arcelor Mittal's Synergy Door Concept Design Highlights [15]

NEW STEELS: Announcements for new materials are still ongoing and as of October 9, 2015, ThyssenKrupp revealed that they had developed for hot forming, the hybrid material TriBond. The site states that "The new three-layer material consists of ultrahigh-strength steel in the middle and ductile steel on the outside. This delivers properties that cannot be realized with homogeneous materials: high ductility and maximum strength in one product. TriBond is particularly suitable for structural parts in cars that need to display both very high strength and ductility, such as longitudinal members and B-pillars. TriBond improves vehicle safety while at the same time allowing cost-efficient weight reduction."[16]

FACILITY UPGRADES: A number of steel manufacturers have made multimillion dollar upgrades in their production facilities in order to accommodate production of the higher strength steels.

Nucor announced in January 2012 that they planned to increase steel capacity for plants in Tennessee, Nebraska, and South Carolina by over 1 million tons; most of which was expected to be used for automotive purposes. The total cost of the upgrades was estimated around $290 million17. This, along with other projects, led Nucor's sales to automotive companies to increase by 20 percent between 2014 and 2016.[18] The company has recently stated that they are aiming to increase the portion of its total shares to automotive companies from 40 percent to 50 percent in the next two years.[18]

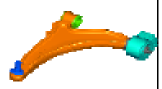
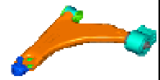
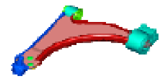
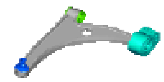
In June 2015, AK Steel announced[19] a $29 million investment to a project involving modifying the Hot Dip Galvanizing Production Line at the Dearborn Works facility (acquired by AK Steel in September of 2014) for the specific purpose of producing next-generation advanced high-strength steels. This project, scheduled to be completed by Fall 2016 and beginning commercial production in 2017, will allow coated and cold-rolled steel to be produced on the same production line. In addition, they have also invested $36 million in establishing a Research and Innovation Center in Middleton, Ohio to be finished by the end of 2016. AK Steel hopes that the technical expertise provided by this facility will allow even more new steel grades to enter the market.

ThyssenKrupp in Germany has invested several hundred million dollars to renovate their facility in which a variety of steel grades are made and they have a U.S. distribution system to supply material as needed. An online article by POSCO, dated September 2015, states that "POSCO is expanding its production of specialized premium automotive steel sheets. Construction of the 7CGL (Continuous Galvanizing Line) started on September 3 at Gwangyang Steelworks, strengthening its position as the second largest auto sheet manufacturer in the world. With an annual production capacity of 500,000 tons, and a total investment of 255.4 billion KRW, the 7CGL is a specialized production line exclusively for AHSS (Advanced High Strength Steel) and is expected to be completed in June 2017. AHSS produced by Gwangyang Steelworks' 7CGL will be supplied to finished carmakers around the world, such as Volkswagen, GM, Renault Nissan and Toyota."[20]

MASS REDUCTION: High strength steels allow the use of smaller gauge metal and hence result in lightweighting. Use of load path optimization tools along with high strength steel result in further mass reduction. Mass reduction using these tools and materials can be seen with individual component studies and in some cases steel can regain some of the components that had gone over to aluminum or plastic. The amount of mass reduction seen on redesigned BIW will vary based on the amount of design optimization and the amount of higher strength steels utilized in the design.

FRONT LOWER CONTROL ARM: The Executive Summary of a 2010 study by USCAR/USAMP, AISI and DOE on a Lightweight Suspension (ASP-340) prepared by Multimatic Engineering's Hannes Fuchs, PhD contained the results of a study which examined the maximum mass savings and related costs for steel based designs of a front lower control arm compared to a baseline aluminum forging front lower control arm[21]. Stiffness-based topology optimization methods were used to identify promising concepts using the Optistruct solver. Of the stamped clamshell, I-beam with tubular flange and forged steel, the clamshell design had the same equivalent mass to the aluminum forging, as shown in Figure B.5, and it utilized a combination of DP780 stampings and SAE 1020 steel bushings using hot dipped galvanized sheet steel[21]. An April 2013 article by Automotive Design and Production contained a statement by Ron Kripitzer of SDMI at the time which said "Two years ago," says Krupitzer, "We did a project with GM and Multimatic [multimatic.com] to match the weight of the forged aluminum lower control arm on the Malibu." The result was a thin steel clamshell that matched the weight of the aluminum part, but was 30 percent cheaper. GM switched the part to steel."[22]

FUEL TANK: A study to redesign a fuel tank for the 2013 Cadillac ATS out of commercial grade steel and compared it to the baseline plastic fuel tank by Spectra Premium Industries was completed in 2014 and presented at Great Designs in Steel in 2013.[23] It was found that, in addition to meeting all of the manufacturability and cyclic pressure requirements, they could increase the volume of the tank while decreasing its mass, either by 14.0 percent and 9.6 percent respectively or a 17.6 percent mass reduction with equivalent volume.[23]

Design	Baseline AL Forging	Stamped Clamshell	I-Beam w/ tubular flange	Forged Steel
Image - Assembly				
Trial	Base	Tr344	Tr485	Tr108
Material type	A6082-T6	DP780	SAE 550X, DP 980, DP 780 tube	AISI 15V24
Mass Detail	(kg)			
Control arm only	1.48	1.69	1.71	1.91
Washer	0.10	0.00	0.00	0.00
Ride bush bolt	0.07	0.00	0.00	0.00
Rivets	0.00	0.06	0.06	0.00
Weld	0.00	*0.04*	*0.06*	0.00
FLCA w/ BJ housing & bolt	1.65	1.79	1.83	1.91
Ball joint internals*	0.36	0.24	0.24	0.24
FLCA w/ integrated BJ	2.01	2.03	2.06	2.14
Handling bush (A)	0.22	0.22	0.22	0.22
Ride bush (B)	0.84	0.84	0.84	0.84
Complete FLCA Assy	3.07	3.08	3.12	3.20

*Note: Steel designs incorporate a weight optimized ball joint (-0.12kg); re-design of the baseline FLCA ball joint out of the scope of this project

Figure B.5 Front Lower Control Arm Stamped Clamshell Design Comparison[21]

BODY IN WHITE: A range of mass reduction amounts have been realized through a number of BIW redesigns. Evaluating the study results show that the amount of mass reduction appears to be related to the amount of mild steel remaining in the vehicle design. The BIW studies include the redesign of the 2012 Cadillac ATS/CTS (74kg - 17 percent mild)[24], Acura TLX (25kg - 41 percent mild)[25], 2015 Nissan Murano (15.9kg - 49 percent mild), 2016 Chevy Cruze (24kg), Civic (31kg, 42 percent mild), and MY2014 Silverado 1500. A short description of each follows:

2015 CADILLAC ATS/CTS: The first runner up to the 2015 Altair Enlighten Award was awarded to General Motors. "[GM] developed and used innovative computer-aided engineering (CAE) methods to achieve a 163 pounds (74 kg) weight reduction on the Alpha architecture of the 2012 Cadillac ATS/CTS. Immersive lattice topology optimization, strategic structural bulkhead placement, and multi-disciplinary load case optimization, were used, along with expert interpretation of the results, to lead the design of the architecture structure. The Alpha architecture's delivers mass efficiency, stiffness, safety, structural feel, and has improved fuel economy without degrading on-road performance characteristics."[24] The materials used for this vehicles are shown in Figure B.6 below.

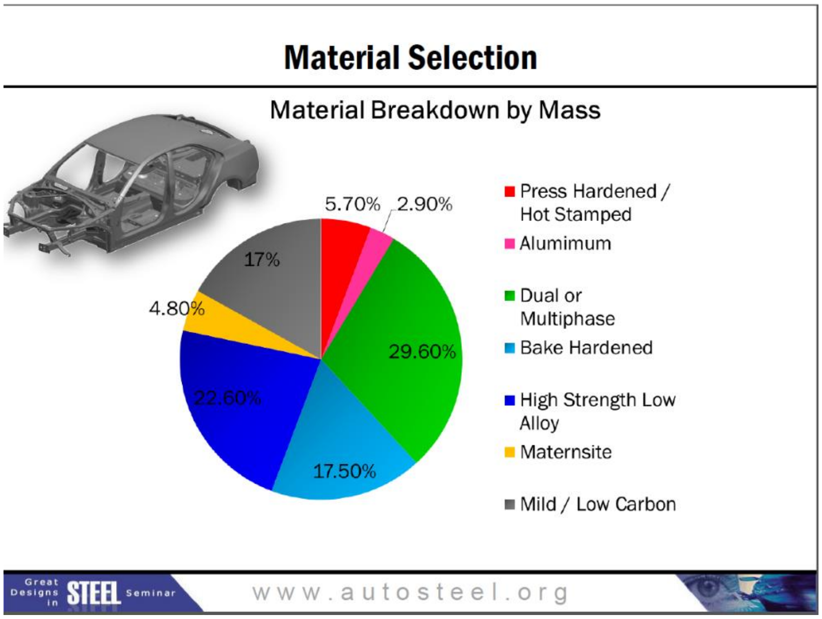


Figure B.6 Redesign of the Cadillac ATS/CTS to Achieve 74kg of Mass Reduction[24]

2015 ACURA TLX: The Acura TLX achieved 25kg of mass reduction in the BIW and a comparison of the TLX to the Cadillac ATS/CTS above reveals that this lower amount was partly due to the amount of mild steel remaining in the Acura TLX (41 percent), in Figure B.7, compared to the 17 percent remaining in the Cadillac ATS/CTS in Figure B.6. Both Figures show the choices of high strength steel from mild to press hardened hot stamped Usibor and their related percentages. A smaller amount of aluminum and magnesium (Acura TLX cast IP beam) are included.

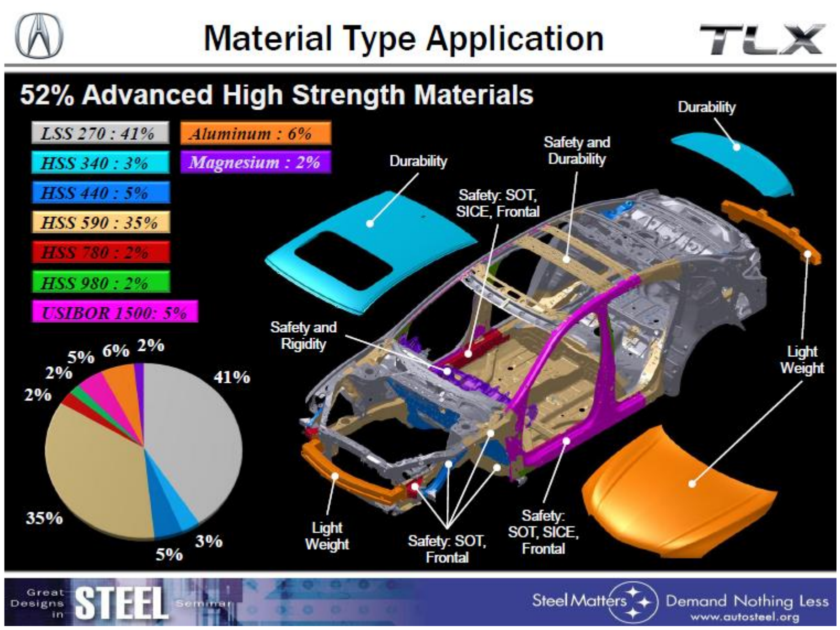


Figure B.7 Material Type Application for the Acura TLX Presented at 2015 Great Designs in Steel[25]

2015 NISSAN MURANO: Presentation of the 2015 Murano at the 2015 Great Designs in Steel[26] included information that 6 percent mass reduction (15.9kg) was achieved in the BIW through application of high strength steels up to 1.2GPa. Amounts of the grades of steel included 49 percent mild, 3 percent complex phase (1180), 6 percent dual phase (980), 7 percent dual phase (780), 15 percent dual phase (590), 3 percent Quasi High Strength (440), 11 percent Quasi high Strength (390). In addition to a change in material with a stronger steel and thinner gauge, components were redesigned to remove unneeded material. The Murano received good ratings on all of the FMVSS tests and received a good rating on the IIHS small overlap.

2016 CHEVY CRUZE: The MY2016 Chevy Cruze was described in a June 2015 Takes on Tech article stating that "(The) Cruze will weigh about 250 pounds less than the 2015 model it replaces. This is accomplished through an aluminum engine block and increased use of press-hardened steel, a process of heating steel blanks until they are malleable. Then they are formed and rapidly cooled in specially designed dies. The result is a lighter weight, but stronger piece that is equally or more crashworthy than thicker heavier pieces that would be welded together."[27] An article by GM Corporate Newsroom states "It is constructed of about 8-percent hot-stamped/high-strength steels, which contributes to an approximately 27-percent stiffer body structure that is also 53 pounds (24 kg) lighter than the current Cruze. The lighter structure is also larger than the current model, with the new Cruze's 106.3-inch (2,700 mm) wheelbase stretching nearly an inch longer, while supporting front and rear suspensions with wide tracks (60.8-inch front/61.3-inch rear)[28]."

2016 HONDA CIVIC: The 2016 Honda Civic design has more high-strength steel being used than in previous years. Compared to the 2013 equivalent, the 2016 Honda Civic has increased the proportion of high-strength steel used in body structure from 55 percent to 58 percent, see Figure B.8. [29] The BIW also has an increased use of hot stamped steel from 1 percent to 14 percent. The vehicle BIW weight decreased by about 31kg, with around 4kg coming just from redesigning B-pillars and the front floor panel with high-strength steel. The effects of this substitution is expected to be seen in IIHS crash testing later this year.

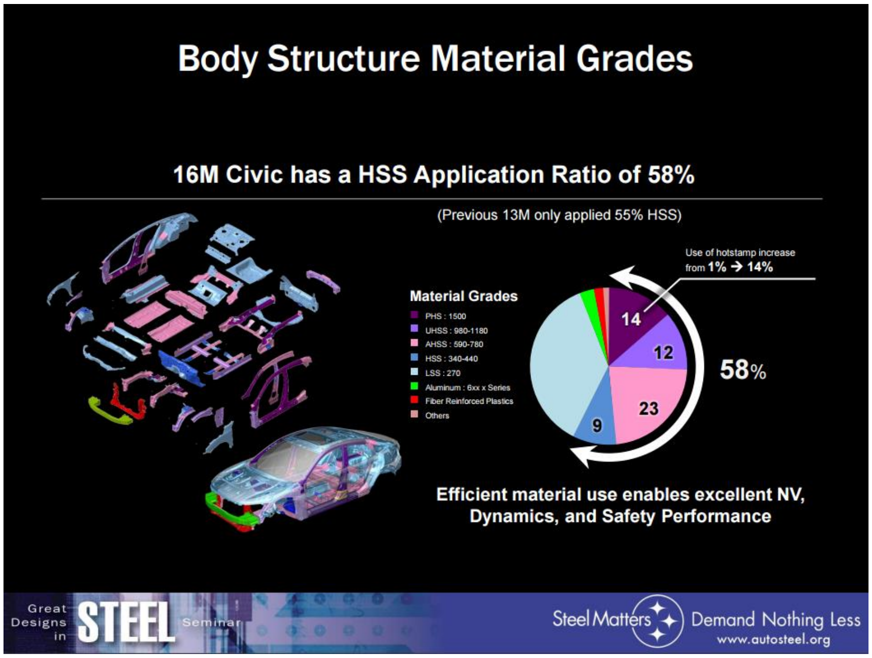


Figure B.8 Body Structure Material Grades for 2016 Honda Civic[29]

2014 SILVERADO 1500: Changes to the 2011 MY Silverado 1500 for the 2014 MY Silverado 1500 are shown in Figure B.9. The article from which this Figure was taken states the main rails and key cross members of Silverado and Sierra's updated frames are high-strength steel with major elements hydro-formed for reduced mass and improved strength. Their pickup boxes are made from roll-formed steel for increased strength and reduced mass, compared with the stamped beds used by major competitors."[30] This vehicle was also designed to improve its performance on the IIHS small overlap and to meet improved FMVSS safety tests which came into existence. Several aluminum components were also added to the vehicle. Overall the MY2014 Silverado 1500 was 22kg lighter than the MY2011 Silverado according to data from the EPA and NHTSA light duty vehicle studies described in this Draft TAR.

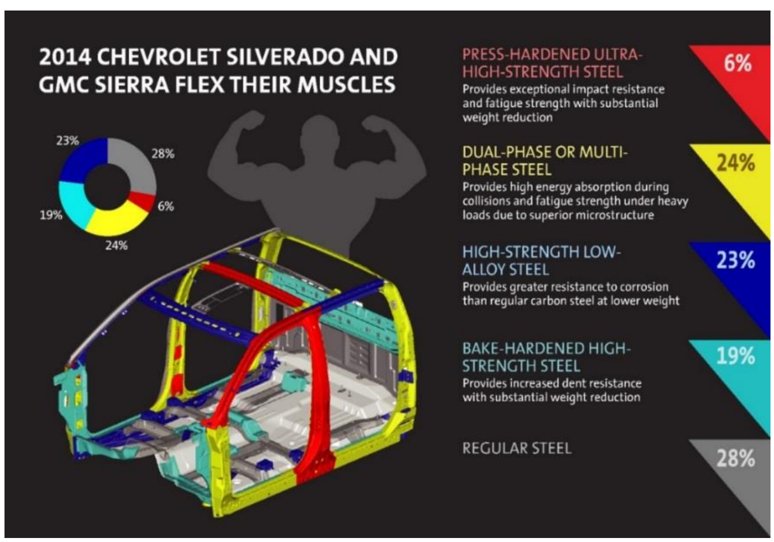


Figure B.9 High Strength and Ultra High Strength Steel changes in the 2014 Silverado 1500[30]

FUTURE STEEL VEHICLE: Beyond the advances being made by OEMs, representatives of the steel industry have undertaken the Future Steel Vehicle project in order to demonstrate the potential BIW mass reduction of high-strength steel. In their GDIS presentation from 2011[31], representatives of World Auto Steel discussed how they were able to achieve a 35 percent reduction in vehicle mass compared to a 1994 benchmark without significant additions to the cost of the vehicle. In that example, the reductions in material costs were translated into using smaller amounts of stronger steels that were more expensive than traditional mild steel, which yielded an overall mass reduction while maintaining both safety (due to the higher material strength) and cost.

AGENCY MASS REDUCTION STUDIES: The EPA Midsize CUV[32] and the NHTSA Passenger Car[33] lightweighting studies both used the high strength steel BIW as the main solution for mass reduction. EPA light duty pickup truck lightweighting utilized an AHSS frame.[34]

COST: The use of high-strength steel in place of other lightweight materials provides vehicle manufacturers with a cost-effective method of mass reduction compared to other materials. According to Quandl, the price of steel as of April 2016 was around $50 USD /tonne, down significantly from a peak of $470USD/tonne at the beginning of 2015[35]. By contrast, the price of aluminum as of April 2016 was close to $1560 USD /tonne with a January 2015 peak close to $2060 USD/tonne[36]. The fluctuation of these prices between January 2013 and May 2016 are shown below in Figure B.10 and Figure B.11. The cost of more advanced steel, according to Steel Market Development Institute Automotive Vice President Jody Hall, in comparison to mild steels are generally 10-20 percent higher, discounting the need for more expensive additives such as manganese. A more complete list of the costs of various high-strength steel grade can be found in Figure B.3 in which one can observe how specific treatment processes and relative material strengths impact steel costs. Efforts are underway to develop cold rolled 3rd gen steels by using an annealing process rather than alloy process. This will decrease the cost to produce cold rolled 3rd generation steel.

Figure B.10 London Metals Exchange Steel Billet Prices (in $USD/tonne)[35]

Figure B.11 London Metals Exchange Aluminum Prices (in $USD/tonne)[36]

Table B.2 Pricing of Steels Used in EPA Lightweighting Studies by EDAG[34]

Item #	Steel Grade	Ref Material Price ($/kg)	Grade	HDG	Exposed	Tailor Rolled Coil	Tubes (straight, as shipped)	Multiwall Tube Blank	Tool Investment Factor	Line Rate Factor	Reject Rate Factor
			Premium ($/kg)	Premium ($/kg)	Premium ($/kg)	Premium ($/kg)	Premium ($/kg)	Premium ($/kg)			
1	Reference US Spot Midwest Market Price Trend 2009										
	Cold Rolled Reference -Mild 140/270	0.93	0.00	0.06	0.05	0.55	0.25	0.65	1.0	1.0	1.0
2	BH 210/340	0.98	0.05	0.06	0.10	0.55	0.25	0.65	1.05	0.95	1.05
3	BH 260/370	0.98	0.05	0.06	0.10	0.55	0.25	0.65	1.05	0.95	1.05
4	BH 280/400	1.00	0.07	0.06	0.10	0.55	0.30	1.10	1.05	0.95	1.05
5	IF 260/410	1.00	0.07	0.00	0.10	0.55	0.30	0.70	1.05	0.95	1.05
6	IF 300/420	1.03	0.10	0.00	0.10	0.55	0.30	1.10	1.05	0.95	1.05
7	HSLA 350/450	1.05	0.12	0.10	NA	0.55	0.30	1.50	1.05	0.95	1.05
8	HSLA 420/500	1.07	0.14	0.10	NA	0.55	0.45	1.25	1.10	0.90	1.10
9	HSLA 490/600	1.09	0.16	0.10	NA	0.55	0.45	1.65	1.10	0.90	1.10
10	HSLA 550/650	1.28	0.35	0.10	NA	0.55	0.45	1.65	1.10	0.90	1.10
12	SF 570/640	1.28	0.35	0.10	NA	NA	0.45	2.05	1.10	0.90	1.10
13	SF 600/780	1.28	0.35	0.10	NA	NA	0.45	2.05	1.10	0.90	1.10
14	TRIP 350/600	1.33	0.40	0.10	NA	NA	0.45	1.25	1.10	0.90	1.10
15	TRIP 400/700	1.38	0.45	0.10	NA	NA	0.45	1.65	1.10	0.90	1.10
16	TRIP 450/800	1.43	0.50	0.10	NA	NA	0.50	1.30	1.15	0.85	1.15
17	TRIP 600/980	1.48	0.55	0.10	NA	NA	0.55	1.35	1.15	0.85	1.15
18	FB 330/450	1.13	0.20	0.10	NA	0.55	0.30	1.10	1.05	0.95	1.05
19	FB 450/600	1.18	0.25	0.10	NA	0.55	0.45	1.65	1.10	0.90	1.10
20	DP 300/500	1.13	0.20	0.10	0.10	0.55	0.45	0.85	1.10	0.90	1.10
21	DP 350/600	1.19	0.26	0.10	0.10	0.55	0.45	1.25	1.10	0.90	1.10
22	DP 500/800	1.24	0.31	0.10	NA	0.55	0.50	0.90	1.15	0.85	1.15
23	DP 700/1000	1.31	0.38	0.10	NA	NA	0.55	0.95	1.15	0.85	1.15
25	DP 1150/1270	1.31	0.38	0.10	NA	NA	0.55	0.95	1.15	0.85	1.15
26	CP 500/800	1.24	0.31	0.10	NA	NA	0.50	1.30	1.15	0.85	1.15
27	CP 600/900	1.28	0.35	0.10	NA	NA	0.52	1.32	1.15	0.85	1.15
28	CP 750/900	1.33	0.40	0.10	NA	NA	0.52	1.32	1.15	0.85	1.15
29	CP 800/1000	1.38	0.45	0.10	NA	NA	0.55	1.35	1.15	0.85	1.15
30	CP 1000/1200	1.40	0.47	0.10	NA	NA	0.60	1.40	1.20	0.80	1.20
31	CP 1050/1470	1.40	0.47	0.10	NA	NA	0.60	1.80	1.20	0.80	1.20
32	MS 950/1200	1.40	0.47	NA	NA	NA	0.60	1.00	1.20	0.80	1.20
33	MS 1150/1400	1.41	0.48	NA	NA	NA	0.60	1.40	1.20	0.80	1.20
34	TWIP 500/980	2.13	1.20	0.10	NA	NA	0.60	1.80	1.20	0.80	1.20
35	MS 1250/1500	1.44	0.51	0.10	NA	NA	0.65	1.05	1.20	0.80	1.20
36	HF 1050/1500 (22MnB5)	1.68	0.75	NA	NA	0.55	0.65	1.05	1.20	0.80	1.20
	Base Aluminum	2.20	0.00						1.00	1.00	1.00
	Al 6111 Exposed	4.29	2.09						1.00	1.00	1.00
	Al 6111	4.29	2.09						1.00	1.00	1.00
	Al 6061	4.29	2.09						1.00	1.00	1.00
	Al 5454	3.85	1.65						1.00	1.00	1.00
	Al 5182	3.85	1.65						1.00	1.00	1.00
	Al 5754	3.85	1.65						1.00	1.00	1.00
	Al 6022	4.29	2.09						1.00	1.00	1.00
	Al 6082	4.29	2.09						1.00	1.00	1.00
	Al 7000	4.68	2.48						1.00	1.00	1.00
	Al Sandcast (Generic)	12.10	9.90						1.00	1.00	1.00

Additional costs are imposed onto steel products in order to ensure they meet certain performance standards that are not as concerning to other materials, such as aluminum. As demonstrated by Multimatic Engineering's Hannes Fuchs, PhD,[21] a redesigned front lower controller arm (FCLA), in order to meet OEM corrosion standards, required coatings that increased the final material costs of the part by 11-18 percent. Despite the costs associate with the base material itself, steel has been shown to yield significant overall cost savings with finished products. The redesigning of the front lever control arm from an aluminum-based design to a steel-based design resulted in cost savings up to 34 percent without suffering performance loss or significant mass increases. The maximum savings were obtained from a clamshell design that utilized a combination of DP780 stampings and SAE 1020 steel bushings.

The Future Steel Vehicle presentation stated that 35 percent mass reduction in the body structure (102kg), over a mild steel design 1994 reference vehicle, was achieved through use of 97 percent HSS and AHSS and nearly 50 percent Gigapascal steels. Great consideration was made to evaluate all aspects of the lightweight BIW design including for global crash requirement, body structure stiffness, ride and handling and durability, noise, vibration and harshness, manufacturing, affordability, and platform variants. This was achieved at no cost penalty. Details can be found in the "Future Steel Vehicle" presentation in the EPA Docket.[37]

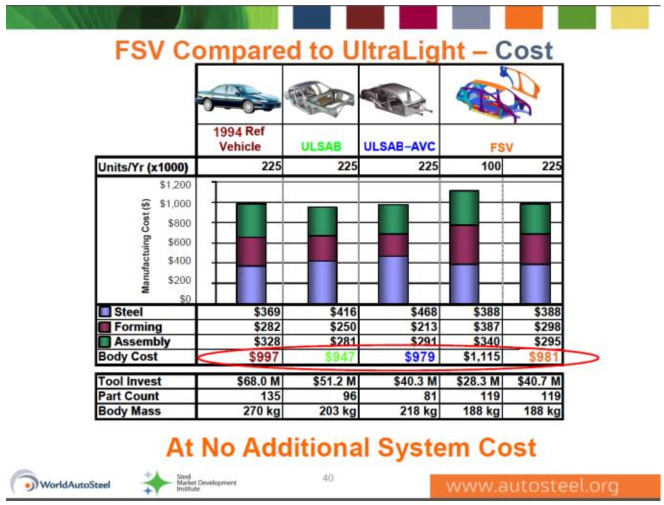


Figure B.12 FSV Comparison to 1994 Reference Vehicle[37]

A description of the InCar®plus program at ThyssenKrupp noted that "With more than 40 innovations focused on increasing the efficiency of cars in the future, ThyssenKrupp's engineers have developed new products in the areas of powertrain, chassis and steering, as well as automotive body. ThyssenKrupp's InCar®plus presents solutions and components for automotive manufacturers with weight savings of up to 60 percent and cost reductions of up to 10 percent. InCar®plus technologies can also make a significant contribution to climate protection, allowing manufacturers to reduce carbon dioxide emissions up to eight grams per 0.6 mile."[38]

SAFETY: High strength steels improve the safety of the passenger compartment in the safety compliance tests. Creative design with steel in the BIW is also used to achieve lighter weight and increased safety. The latest safety tests include higher standards for several FMVSS tests, including roof crush and side crash, as well as the IIHS small overlap test. The strategy typically used to meet these requirement includes strengthening the material of the passenger compartment through a reinforced door ring and vehicle design load path optimization using high strength steels. The BIW designs for the 2015 Nissan Murano and 2016 Honda Civic are highlighted below.

SAFERCAR.GOV RATINGS: The work by OEM's to incorporate lightweighting into vehicles and related safety ratings can be found on the website safercar.gov. A comparison of MY2011 to MY2016 is used due to the fact that NHTSA adopted newer ratings in 2011 and the vehicles are to be compared on the same basis, see Table B.3. Several vehicles are noted in the press as being 6-9 percent lighter than their predecessors and include the 2016 Chevrolet Malibu (300 lbs lighter) and the 2015 Cadillac CTS (200-300 lbs lighter). The 2016 Honda Civic has a number of mass reduction and design changes in the BIW and even though the overall mass did not decrease notably (due to larger size, etc.), its safety ratings are of interest. The Nissan Murano is an SUV, compared to the other sedans in the table. The star ratings for all of these vehicles are the same or higher in safety than their predecessor designs. The star ratings are based on Frontal Crash, Side Crash and Rollover.

Table B.3 Vehicle NHTSA Star Ratings (from Safercar.gov)

Vehicle	2011 (2008 era)	2015-2016
Chevrolet Malibu	4	5
Cadillac CTS	NYR, 4 for Rollover	5
Nissan Murano	4	4
Honda Civic	3	5

REAR CRASH: Other redesign upgrades improved safety performance while also decreasing mass. This can be seen in detail in the Honda Civic 2016 GDIS presentation in Figure B.13. For both rear and side impact cases, softzones were incorporated which created a designed crush zone. Other changes included a high load front bumper system, a high load capacity sub frame with link bracket, a tailor tempered hotstamp center pillar and a tailor tempered hotstamp one piece rear frame.

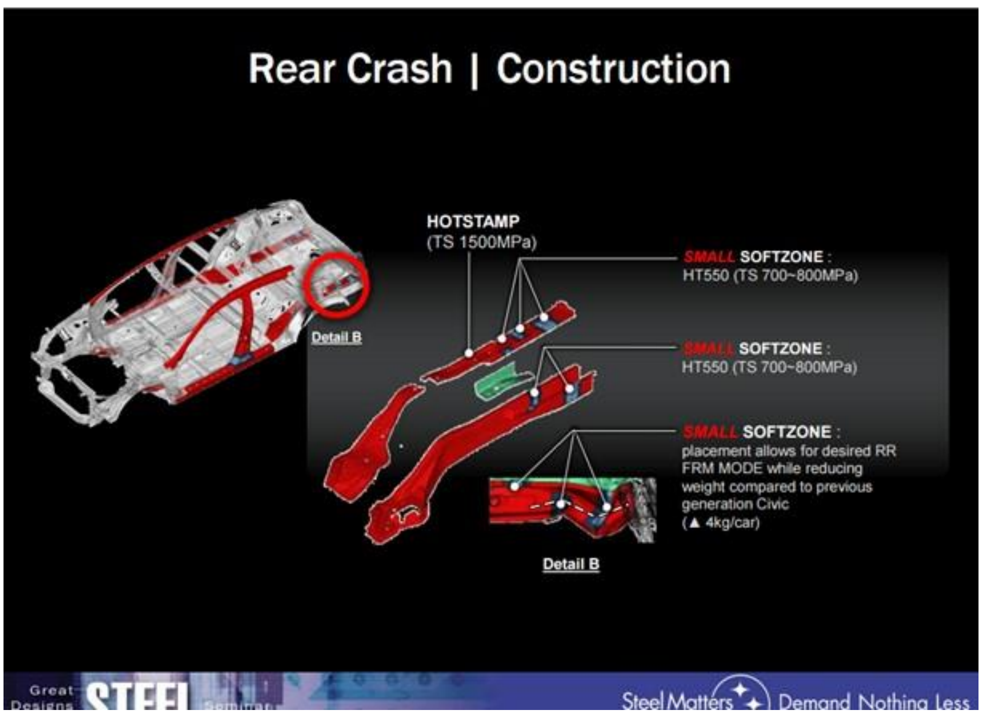


Figure B.13 Honda Civic Rear Crash Construction Including Softzones While Reducing Mass[29]

IIHS SMALL OVERLAP: The 2015 Nissan Murano received the top safety pick from IIHS. The safety of a vehicle is most closely linked to the design of the vehicle; in particular, the design of the car's Body-in-White (BIW). An assessment of IIHS crash testing at the Great Designs in Steel 2014 conference cited the potential for improving poor performing vehicles by introducing either new structural reinforcements or providing reinforcement to existing parts even without changing the material used in the structure. [39] As such, load path optimization is a commonly used strategy to assure compliance with a number of other FMVSS safety crash tests. Figure B.14 and Figure B.15 illustrate the design changes in the Nissan Murano.[40]

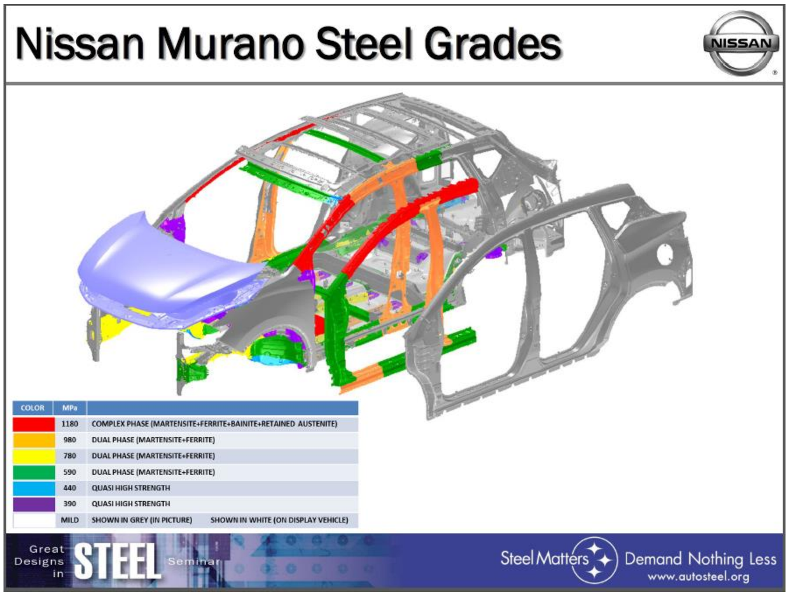


Figure B.14 Nissan Murano Steel Grades used in IIHS Compliance - 3D View[40]

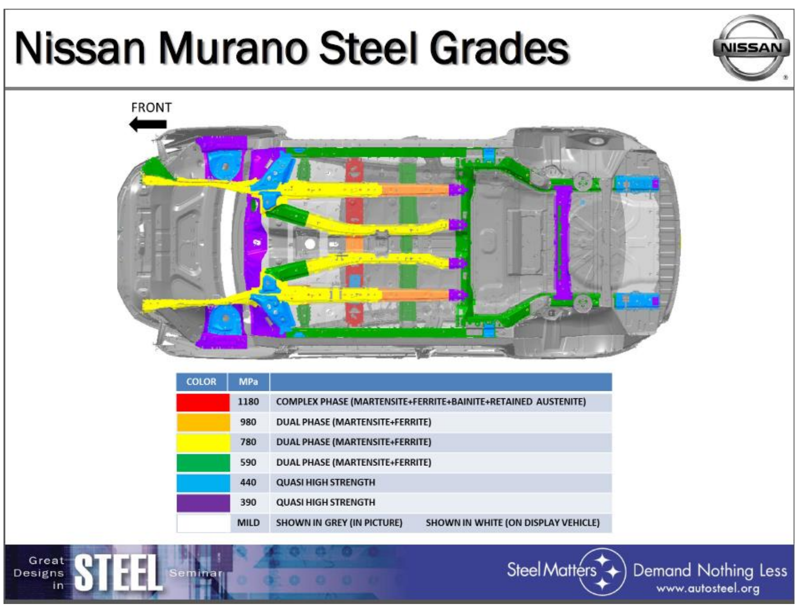


Figure B.15 Nissan Murano Steel Grades for IIHS Compliance - Bottom View[40]

Another example of design modifications for increased safety was presented on the Honda Civic at the 2016 Great Designs in Steel, see Figure B.16.[29] The vehicle received the “Good” rating on the IIHS Small Overlap and results showed an improvement over the “Good” rating received on the previous Civic.

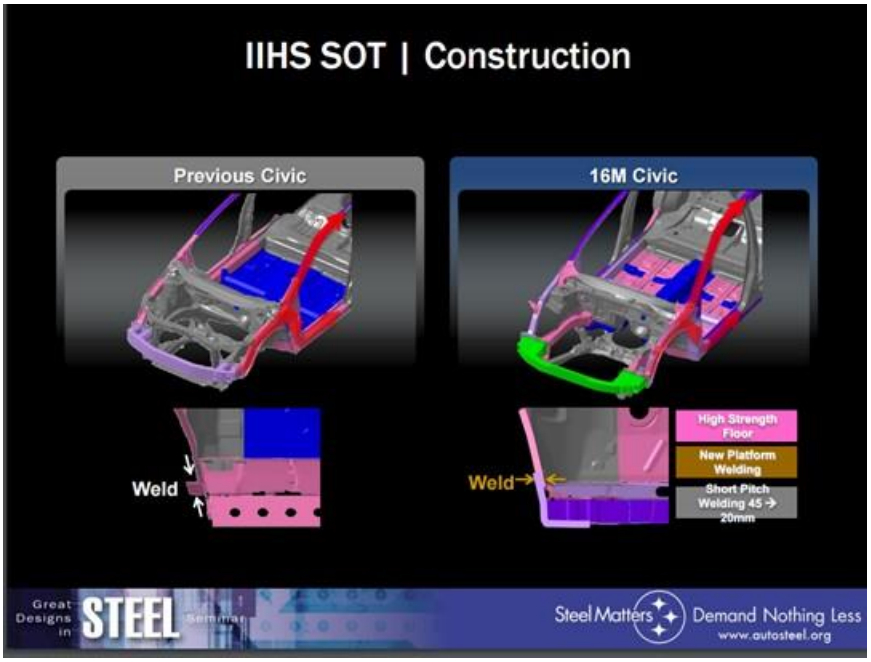


Figure B.16 Honda Civic IIHS Small Overlap Test Construction Upgrades[29]

RESCUE: One unintended consequence of the increase to stronger grades of steel is that they can potentially pose to be a challenge to rescue workers in certain situations. In his presentation at Great Designs in Steel in 2015, Roy Moore detailed how the use of high-strength steels was requiring the development of new tools and new strategies of rescue for fire and rescue teams' ability to intervene in serious accidents and that these professionals need to be made aware of changes in vehicle steel such that tools can be developed. Roy acknowledged that people were walking away from accidents from vehicles made with newer grade steels compared to years past.[41]

AGENCY MASS REDUCTION STUDIES: The EPA Midsize CUV[32] and the NHTSA Passenger Car[33] lightweighting studies both used the high strength steel BIW as the main solution for mass reduction. EPA light duty pickup truck lightweighting utilized an AHSS frame.[34] Detailed CAE analyses was performed and presented in the studies for both the base and light-weighted CAE models.

RESEARCH: The targets for 3rd generation advanced steel grades, outlined by the DOE, involved steel grades with a combined yield strength/elongation of 1200MPa and 30 percent, as well as 1500 MPa and 20 percent respectively[42]. As a result, third generation steels are the focus of research for a number of steel companies. The general thought is that cold forming a high strength steel is less expensive than the current hot forming methods utilized to achieve strengths over 1100MPa. In terms of saving money the current thinking is that it depends on the learning curve and cost to produce which is changing as research continues. Third generation AHSS steels will cost more for the steel, but cost less for the forming. Steel companies are looking at various strategies to create this steel including annealing and alloying of steel which is more expensive. Whether generation 3 steels will be less expensive overall compared to hot forming steels is yet to be determined. The location for use of third generation steels includes the areas of energy absorption, such as the rails and crush tubes, to the intrusion resistance areas of the B pillar, A pillar, rockers, and cross members.

One potential area of steel research that seems to be able to meet these qualification is NanoSteel developed by the NanoSteel Company. Speaking at the 2016 Great Designs in Steel conference, AK Steel's Vice President of Sales and Customer Service Eric Peterson talked about how the properties of these grades of steel could allow for more variable part geometry and material optimization, yielding reductions in both mass and cost. One particular grade, the third-generation NXG1200 nanosteel (with 1200 MPa ultimate tensile stress and 55 percent max elongation) had a maximum draw depth that was more than double that of conventional steel.[43] Figure B.17 below shows the potential range of material properties for NanoSteel in comparison to other established grades.

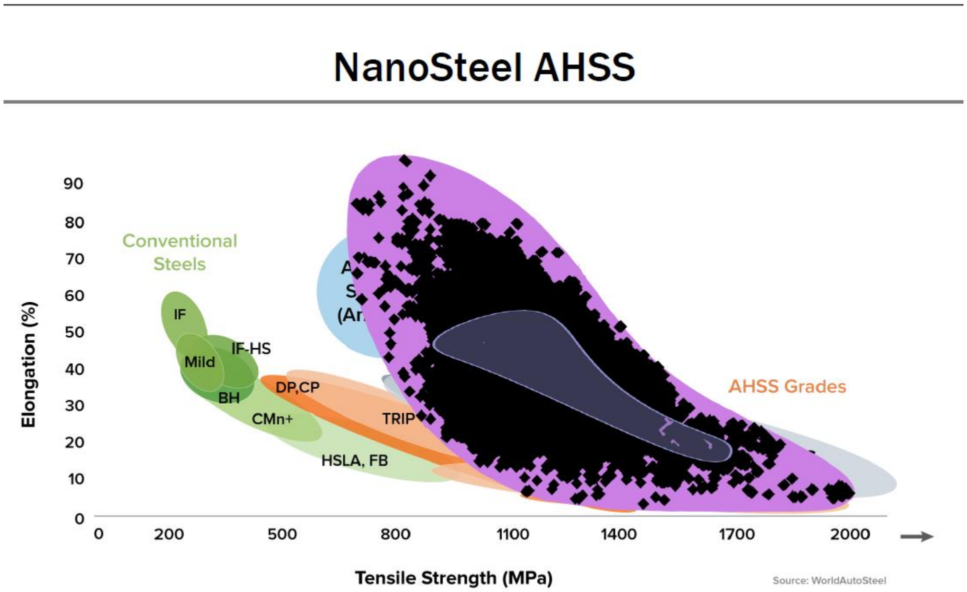


Figure B.17 Comparisons of Established Steel Grades and Potential Nanosteel Grades (in purple)[44]

This steel is formed by processing a steel alloy as bulk metallic glass, and heating it to allow crystalline grains to nucleate. The process yields a steel composed of nano-scale grains (less than 100nm). This extremely small grain size means that grain reorganization dominates as the deformation mechanism, resulting in a high ductility at low temperatures while retaining a high strength.

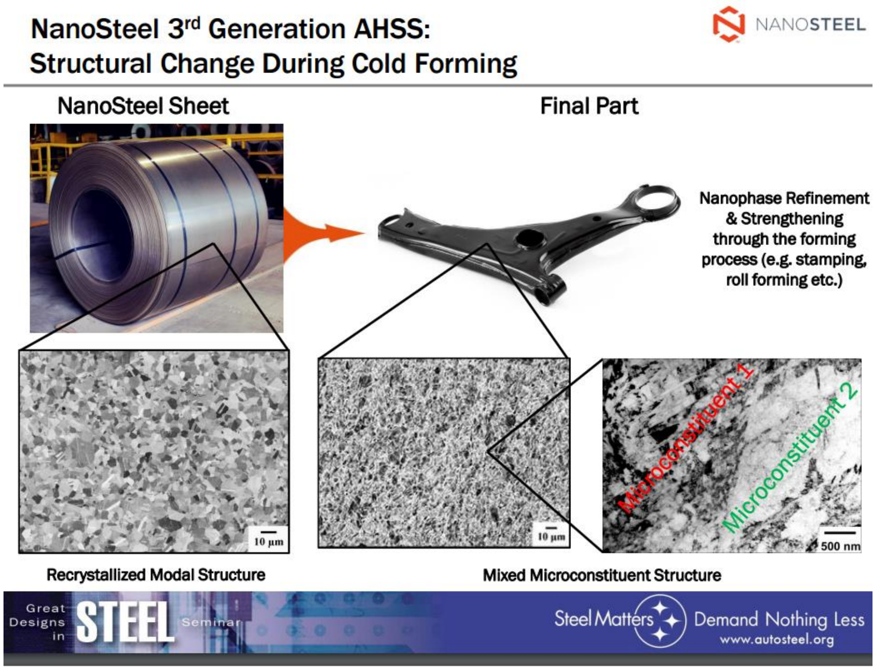


Figure B.18 NanoSteel 3rd Generation AHSS: Structural Change During Cold Forming[44]

NanoSteel has partnered with AK Steel Corporation to manufacture NanoSteel sheet at a commercial scale. As of April 2016 they have delivered some of this material to General Motors for testing and evaluation.[45] Evaluation by OEMS will help determine how well NanoSteel can be incorporated with their existing manufacturing processes such as stamping and welding. It is designed for production in conventional steel mills using existing technology and its latest chemistry contains no boron which is a concern during steel recycling.[44] Additional work is also needed to evaluate long-term properties of these materials, such as fatigue life, creep, and corrosion.

Carpenter Steel, an aerospace focused steel company, has several third generation steels that can be used for automotive use and they are called Temper Tough and PremoMet. "Temper Tough™ is an air-melted, cobalt-free quench and tempered alloy that has a unique combination of high strength and high toughness attributes."[46] Temper Tough is an arc melted, cobalt free, high strength, high toughness quenched and tempered alloy which attains typical 1999MPa UTS with 60-65 kvisin. (66-71 MPavm) fracture toughness.[47] PremoMet Alloy is a premium melted, cobalt-free alloy which attains 1999MPa UTS with 60-65 ksi sqrt(in) (66-71 MPa swrt(m)) fracture toughness.[48] Carpenter steel is not a steel company and would need to license the technology.

Another effort to achieve these goals, conducted by Sun[49], revealed that the potential improvements to these parameters are limited by the alloying elements added to the steel. An ongoing research effort overseen by Hector and Krupitzer[42] is attempting to create and calibrate models of material behavior in order to more quickly develop new steel alloys capable of meeting these goals.

A microlattice material has been developed by HRL Laboratories through a joint venture between Boeing and General Motors (GM), in collaboration with Cal Tech and UC Irvine, see

Figure B.19. Weighing only about one tenth as much as carbon fiber. "The microlattice looks like a sponge or a mesh, and is simultaneously flexible and very strong, according to Boeing. Should it become widely used, Boeing (BA) said the material could help airlines save huge amounts of money."[50] The new microlattice is likely to be used in structural components, such as sidewall or floor panels of commercial jets. The use of this material in vehicles will likely be a number of years away as it has been stated that the first likely place is on space rockets in about five years and into commercial planes about five years after that. The cost of manufacturing will have to come down a little more before it is economically feasible to use on cars.

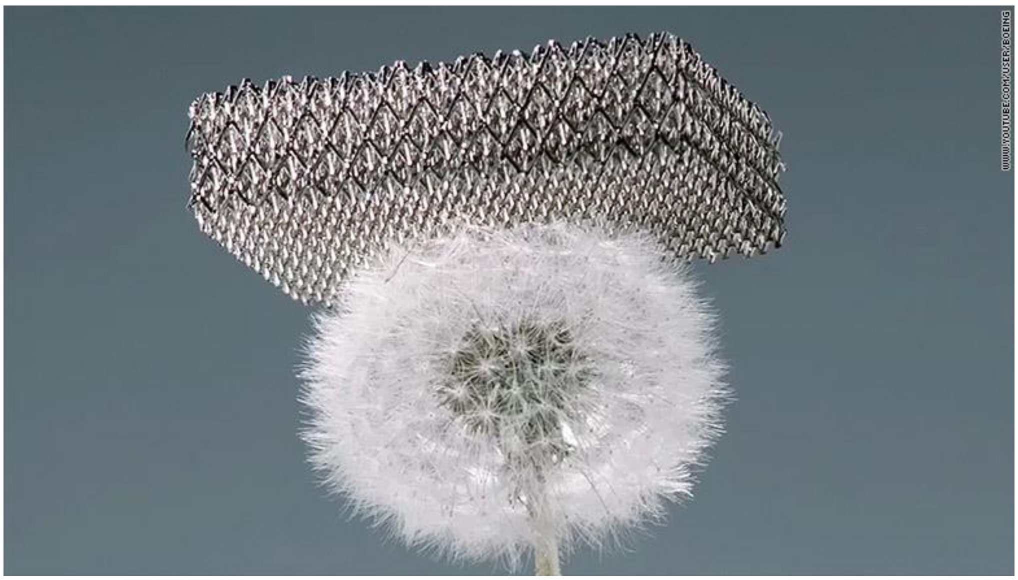


Figure B.19 Microlattice Material by HRL Laboratories

Beyond the development of new steel grades, there are other issues with the deployment of mass-produced high-strength steels in automobiles. U.S. Steel stated that the main sources of focus and innovation for these steels to be viable needs to be production and manufacturing.

In the production phase, part geometry optimization needs to continue to improve in order to retain performance and durability while continuing to reduce the amount of material and costs. The necessary coatings for these steels, as highlighted in the FLCA case study, will be necessary to resist corrosion (galvanic corrosion in particular), but they also will need to be reconciled with demands for improved reparability.

The high material performance of these steels requires adapting the production and forming methods used currently for lower strength steels. For example, material springback, which is the tendency of a particular material to return to its original state after plastic deformation and subsequent unloading, becomes more prevalent with greater yield strength as demonstrated by Shi and Konieczny.[51] As a result, the prediction of springback in certain parts has become an active area of research for steel companies. One of the most accurate methods for empirical springback prediction has been the Yoshida method, as described by Shi and Konieczny, which the uses the results of tensile and compressive testing, as well as optimization algorithms to determine the stress-strain relations of the material. Another option posed by Bhuyan et al.[52] involves DFSS as a tool for optimizing springback prediction by modifying a set of simulation parameters that represent aspects of part stamping.

In the manufacturing phase, U.S. Steel highlights the need to focus on improving the joining process, which is necessary for both improving reparability and avoiding localized areas of corrosion. The majority of joining in the vehicle's body structure is related to welding the different grades of metal together. As such, a number of advancements have been made by the steel industry to improve both the number of welding options available, but also the quality of each method. The increased use of laser welding, as described by Patwa and Bratt, not only provides a more easily automated welding process, but it also allows for more flexibility in the welding process, providing for both stronger welds and less material necessary to sustain a part's strength.[53] The inclusion of pulsation and metal core wiring in the more familiar field of gas-metal arc welding (GMAW) allowed Rajan and Liao to more easily maintain the strength of corrosion-resistant steel after welding.[54]

Research on joining also includes the use of other methods, such as adhesive bonding. The different methods of welding available have varying effects on the joints they produce depending on which method is used and which metals are involved. Bohr[55] studied the joint efficiency (defined as the ratio of weld strength to parent material strength of welded steels (mild, dual-phase [AHSS], and TRIP [UHSS]) using various joining methods. Based on these findings, the maximum joint efficiency can be obtained using structural adhesives, which are administered with methods like resistance spot welding (RSW). According to Mirdamadi et al.[56], these adhesives allow the loads on the welds to dissipate over a wider area and avoid stress concentrations at weld points. The mass of adhesives is approximately 2-3kg per vehicle.

To reduce the mass associated with the typical addition of dampening materials, one possible approach for steel is to use a composite materials such as QuietSteel, a product developed by the Material Sciences Corporation consisting of a viscoelastic layer sandwiched between layers of coated steel.[57] The result was significant reductions in structural and airborne noise compared to solid steel, as well as cost and mass savings compared to NVH-treated steel[57].

<u>Lightweighting Cast Iron components: </u>Cast stainless steel has been developed which can replace cast iron components.

RECYCLING: Advanced high strength steel is finding a home in automobile BIW design. AHSS consists mostly of iron but includes alloying material in smaller quantities depending on design properties. If high alloy scrap is able to be separated from normal scrap steel for recycling, it is possible to reduce alloy costs for new steel by utilizing the alloying elements that are not oxidized during the BOF process.[58]

B.3 Material Advancements - Aluminum

FEASIBILITY: Automobiles with a number of aluminum components, including body-in-white (BIW) and closures, have been produced for more than a decade through products produced by OEM's such as Jaguar and Lotus.

The aluminum industry is undergoing unprecedented growth as OEM's work to adopt more aluminum in their vehicles. The Ducker Worldwide 2015 North American Light Vehicle Aluminum Content Study Executive Summary[59] reports that the amount of aluminum in vehicles has been increasing over the last decade, and Figure B.20 illustrates anticipated future increasing adoption rates for closures and completed bodies. The report also shows that the use of aluminum for rolled, extruded and vacuum die cast products is expected to increase through

2025. Figure B.21 illustrates Ducker's estimate for the potential demand increase of Rolled, Extruded and Vacuum Die Cast Aluminum Product.

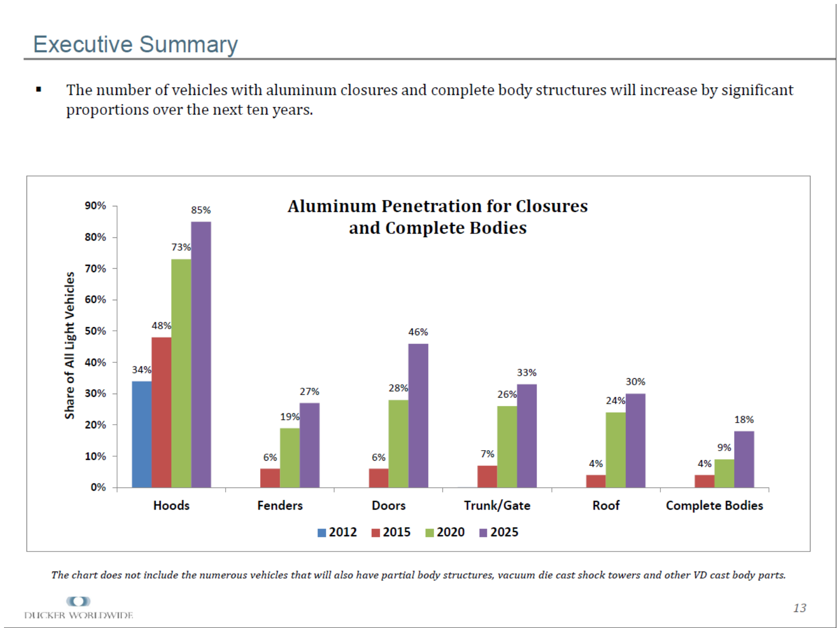


Figure B.20 Ducker Worldwide on Aluminum Penetration for Closures and Complete Bodies

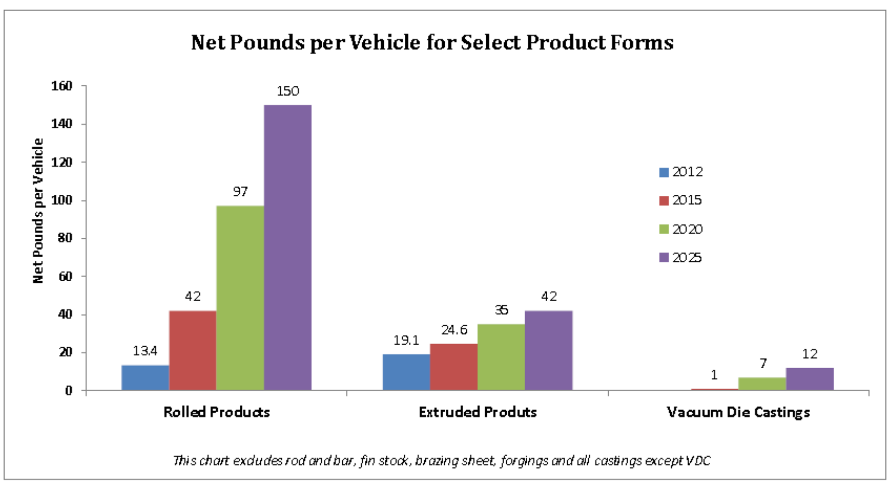


Figure B.21 Ducker Worldwide Estimates of Rolled, Extruded and Vacuum Die Cast Aluminum Product Demand Increase

Global availability of aluminum is also an important consideration. Today, OEM's can produce the same vehicle in multiple places throughout the world. Figure B.22 highlights facilities run by Novelis, a global supplier of rolled aluminum.

Figure B.22 Novelis Automotive Global Supply

OEM's looking to adopt aluminum in their closures typically begin with the hood in order to understand modifications needed in the production phase. Aluminum intensive vehicles include higher end cars such as Jaguar, and more recently, the MY2015 Ford F150 light duty pickup truck. Ford uses 700 lbs. of aluminum in the F150 beginning in MY2015 and some of it is used in extrusions while the majority of it is composed of other forms including aluminum sheet.

SHEET ALUMINUM: As with the steel industry, the aluminum industry is working to advance material strength and formability to allow additional gauge reductions in the future for automotive use. Aluminum gauges have decreased over the past few years due to improved strength of sheet alloys, improved formability of sheet alloys, and OEM confidence in aluminum field performance – flutter, dent resistance, manufacturing confidence and OEM design optimization skills. The MicroMill sheet forming process by Alcoa yields material with 30percent greater strength and 40percent greater formability may be another avenue for enabling technology to achieve further mass and cost reduction. Alcoa recently released an announcement of several offerings. Higher strength aluminum grades currently exist and the 7000 series aluminum has been found to be used in bumper systems. Seven thousand series aluminum is typically used for the aerospace industry and is more expensive so is not often the choice of aluminum in automotive designs.

With the rapid adoption of sheet aluminum, one concern is whether there is enough finishing equipment to supply the amount of aluminum sheet needed by the OEM's for production. Aluminum companies have been adding finishing equipment as they sign production agreements with OEM's. For example, ALCOA invested approximately $500M in two plants to produce enough material for the newly designed F150.[60] Likewise, the Canadian company Rio Tinto has recently added additional smelter capacity in Canada which run on hydroelectric power.[61] Aluminum is also found to be made in smelters using energy that run off gas from the petroleum industry in the Middle East, or coal based smelters in the US and China.

CAST ALUMINUM: An announcement in April 2016 by Alcoa on higher strength aluminums for casting offers new opportunities for aluminum.[62] The article states that

"SupraCast, EZCast, VersaCast and EverCast - have undergone extensive trials with automakers and their suppliers, beating customers' expectations on strength, thermal performance and corrosion resistance. Compared to incumbent material, they are stronger, lighter weight, and offer at least 20 percent better fatigue resistance." Eck Industries is testing SupraCast in engine cylinder heads. The article states that VersaCast is 40-50 percent the weight of cast iron, with 50 percent better resistance to fatigue…all of the new specialty alloys offer good to excellent castability, weldability, and corrosion resistance."

SupraCast – Superior strength at elevated temperatures for high performance power train applications, SupraCast offers thermal conductivity combined with high structural integrity ideal for cylinder heads, connecting rods, turbo chargers, brake calipers, and engine blocks.

EZCast – Appreciable yield strength and elongation gains compared to traditional alloys in this space, EZCast is named for the high fluidity, thermal stability and low shrinkage that make it easy to cast and ideal for a variety of different, crash-resistant structural components, including, engine cradles, cross-members, side doors, radiator mounting, engine mounts, sub-frames and shock towers.

VersaCast – Outperforming cast iron up to 94percent and typical aluminum alloy alternatives by at least 40 percent, VersaCast is designed to help OEMs achieve optimal performance in the most demanding structural applications while continuing to make vehicles lighter. VersaCast is suitable for automotive, aerospace or military components where high strength is required; its excellent castability allows for complicated shapes.

EverCast – A high strength and high fatigue resistant alloy, EverCast is optimized for safety critical components in braking, steering and suspension brackets.

EXTRUSIONS: A number of extruded components are utilized on vehicles. A summary of aluminum grade, alloy/temper, ultimate (MPa) and Yield (MPa) and respective automotive applications are listed in Figure B.23. A visual of the vehicle components are shown in Figure B.24 and Figure B.25Figure .

Kaiser Aluminum Automotive Alloys / Tempers

Aluminum Grade	Alloy/ Temper	Ultimate (Mpa)	Yield (Mpa)	Automotive Applications
High Strength, Safety Critical	6082-T6	350	310	A-Pillars, Axles, Belt Reinforcements, B-Pillars, Door Hinge Supports, Door Rear Support Pillars, Front Bumper Beams, Headers, Middle Floor Supports, Rear Bumper Beams, Rear Frame Rails, Rockers, Roof Bows
High Strength, Safety Critical	7046-T5 KL26	420	390	
High Strength, Structural	6061-T6	310	280	Anti Sub Bars, Axles, Bed Bottom Cross Members, Door Beltline Reinforcements, Floor X-Member Supports, Frame Rail Cross Members, Front Headers, IP Beams, Middle Floor Supports, Radiator Supports, Radiator X-Members, Roof X-Members, Side Panel X-Members, Sub frames, Tailgate Inner Supports, Upper Rad Supports
High Strength, Structural	7003-T5	340	300	
High Strength, Crush Quality	6063-T6	225	200	A-Pillars, Engine Cradles, Front Frame Rails, Front Rails, IP Beams, Roof Rails, Shotguns, Shotgun Under Support, Upper Rails, Upper Rails (Shotgun)
High Strength, Crush Quality	7003 CQ	300	240	

Click here for Typical Aluminum Extrusion Alloys for Auto/Truck Applications chart
Click here for Structural Alloys – Relative Properties chart

10 KAISER ALUMINUM

Figure B.23 Kaiser Aluminum Automotive Alloys/Tempers[63]

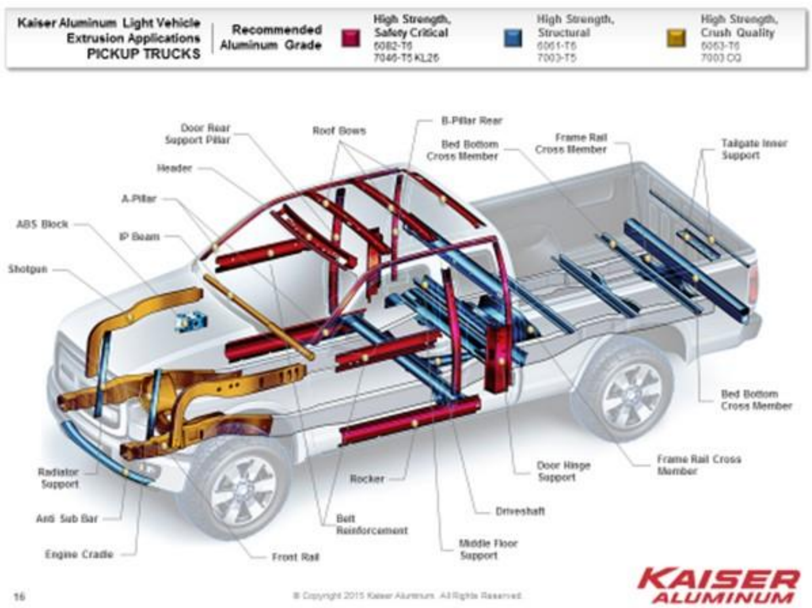


Figure B.24 Kaiser Aluminum Light Vehicle Extrusion Applications in Pickup Trucks[63]

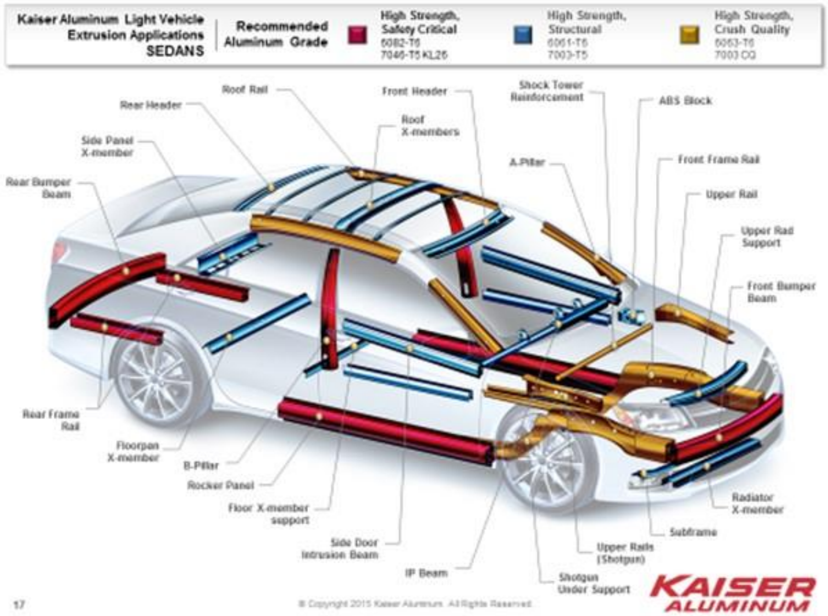


Figure B.25 Kaiser Aluminum Light Vehicle Extrusion Applications in Sedans[63]

While previously used on the lower sales volume Corvette, fast pace manufacture hydroformed aluminum extrusions became well known with the entrance of the MY2015 F150 into the marketplace. Slight modifications to the tooling and to the design of the part were all that were required to make a hydroformed aluminum part compared to a steel part for the front rail and roof rail as shown in Figure B.26.

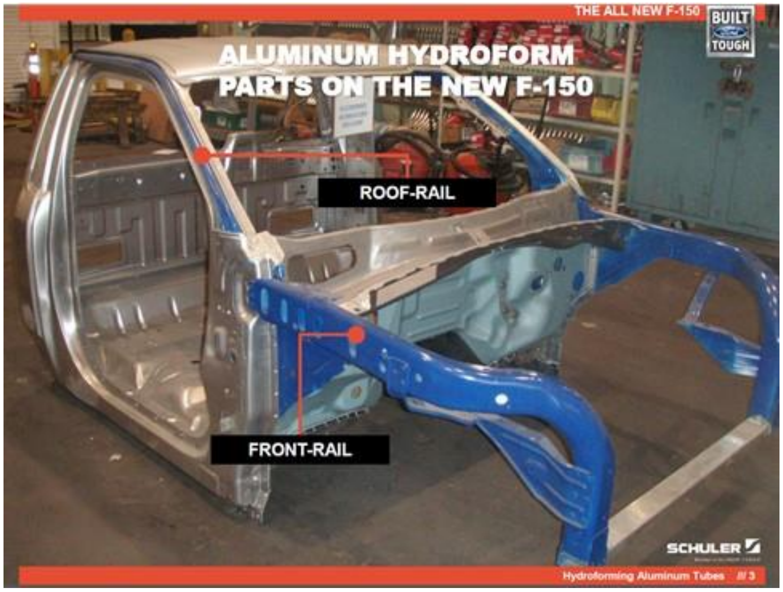


Figure B.26 Aluminum Hydroform Parts on the F-150[64]

JOINING: Joining of aluminum is also an area that has had a lot of attention and the Aluminum Association has assembled a Joining Manual to provide information on working with aluminum. The details can be found by accessing the DriveAluminum website[65] and summary information on joining can also be found in a report by CanmetMATERIALS.[66]

MASS REDUCTION: Aluminum is one third the density of steel and is favored as a lightweighting option in vehicle closures. Aluminum is also used for a variety of other applications, however the mass saved when replacing steel with aluminum is typically less than one third due to the lower strength of aluminum, requiring additional material or larger components. One example is a driveshaft of a light duty pickup truck. The aluminum driveshaft has a larger diameter compared to the steel driveshaft in order to handle the loads. Stronger aluminum grades require less material, and therefore enable more weight savings.

F150: The MY2015 F150's 700 kg mass reduction is 12-13 percent reduced from the MY2014 F150. Ford included a number of mass reduction technologies in the F150 as well as some increased performance features for which some of the mass reduction achievements were offset. For example, the performance improvements include increased hauling and towing, hence thicker steel frame and related components. In addition, the overall vehicle dimensions have been increased. A visual comparison of the two trucks can be seen in Figure B.27. A comparison of the results from a F150 4x4 Supercrew with 6.5 foot bed are shown in Table B.4 . Results show an increased footprint of 0.79 sq ft and an increased height of 0.8 inches. The increased height also affects aerodynamics. Specific aluminum use in the LDT BIW and closures is shown in Figure B.28. Forty percent of the aluminum sheet used in manufacturing is recycled in a close loop recycling system with aluminum sheet manufacturers. An article by the Green Car Reports states that the Ford F150 plants recycle enough aluminum for 30,000 trucks a month.[67] This provides a notable return to the OEM on the material.

Figure B.27 2014 Ford F-150 versus 2015 Ford F-150 Weight in Pounds[68]

Table B.4 Comparison of Dimensions on F150 4x4 Supercrew 6.5ft Bed F150 4x4 Supercrew 6.5ft Bed Dimension Comparison

Dimension	2014 (in)	2015 (in)	Difference (in)
wheelbase	156.5	156.8	0.3
trackwidth	67	67.6	0.6
footprint (sq ft)	72.82	73.61	.79 sq ft
length	243.9	243.7	-0.2
width (excl mirrors)	79.2	79.9	0.7
height	76.5	77.3	0.8

Figure B.28 Aluminum Makeup of the F150[69]

There are several mass adds in the F150. An article states "The new F-150 also has more than 350 feet of structural adhesive beads to supplement the joint strength provided by fasteners. The adhesive also blocks noise and moisture and enhances collision performance. Like the use of aluminum and special fasteners, these adhesives are well proven after years of reliable service. In the past decade, the amount of structural adhesives in car and truck bodies in general has increased by 50 percent."[69]

LAND ROVER RANGE ROVER, ETC.: The new Range Rover model is 420 kg (~16 percent) lighter than the previous model due to its all-aluminum body structure. In addition, JLR is targeting to make a Range Rover from 75 percent recycled content aluminum. A closed-loop agreement was made through which Novelis will recover all of the scrap from the automaker. This lessens the overall price for aluminum sheet by providing a refund for the scrap to the OEM.

Figure B.29 Aluminum Intensive Vehicles Include Land Rover, Ford F150 and Tesla S

AGENCY HOLISTIC VEHICLE STUDIES: A number of aluminum components were utilized in the 2012 holistic vehicle studies by EPA, NHTSA, CARB, and DOE/Ford/Magna as described in Section 5.2 and in the original reports. The BIW and closure changes to aluminum were typically the highest mass save changes in the vehicle designs.

The Aluminum Association's analysis of the EPA Midsize CUV with material replacement also based its work on aluminum BIW. As of June 2016, the Aluminum Association funded a project with EDAG, Inc. to re-analyze the inputs for aluminum sheet and extrusions given the information from recent (2015/2016) production aluminum programs (F-150, Land Rover, Audi, Jaguar, Cadillac, …). The inputs are based on improved aluminum sheet materials which were used to reduce mass. Typical gauge comparisons from recent production include those seen in Table B.5. The body and structure will be redesigned for grade and gauge to match collision and NVH performance of the original vehicle. Study will explore expanded use of extruded hollow sections to achieve lower mass and cost. It is expected that the report will be completed by fall of 2016.

Table B.5 Recent Production Aluminum Program Specifications

Production Models:	Pre 2015	Post 2015
Typical closure gauge	1.4 mm	0.9 mm
Typical structure gauges	3.0 – 4.0 mm	2.0 – 3.0 mm

COST: The demand for aluminum for automotive use has increased dramatically over the past few years. The cost for aluminum as of November 2015 is approximately $0.70/lb for the raw material and $1.70/lb. - $2.00/lb. for sheet given market fluctuations. The price for primary aluminum is influenced by the availability of bauxite, the cost of energy to smelt aluminum from bauxite, labor costs, and exchange rates. The cost of aluminum sheet is governed by the ratio of primary/secondary and the process with which aluminum sheet is made.

Today the vast majority of primary aluminum for the North American automotive market comes from Canada which uses hydropower to smelt the bauxite into aluminum. (Import Sources to the U.S. (2010–13): Canada, 63 percent; Russia, 5 percent; United Arab Emirates, 5 percent; China, 4 percent; and other, 23 percent). Secondary aluminum is typically utilized in cast and extrusions and has a lower cost energy requirement than steel to create secondary aluminum. In 2014, the Geological survey stated that aluminum recovered from purchased scrap in the United States was about 3.63 million tons, of which about 53 percent came from new (manufacturing) scrap and 47 percent from old scrap (discarded aluminum products). Aluminum recovered from old scrap was equivalent to about 33 percent of apparent consumption.

Some of the players in the aluminum sheet market make primary aluminum and sheet while others use secondary aluminum, with a minimal amount of primary, to make sheet. Novelis is one company that does not own any smelters and hence uses secondary aluminum for its sheet metal in addition to some primary to make up the needed supply. Novelis has a goal to utilize 80 percent secondary aluminum by 2020 in their sheet product. OEM's including Jaguar Land Rover and Mercedes purchase their aluminum sheet from Novelis and therefore uses secondary aluminum in their vehicles. Extrusions can also be made with 100 percent secondary aluminum and any aluminum scrap can be mixed together in extrusions. OEM's have the opportunity to receive a larger payback for prompt scrap if the scrap is separated into 5000 series and 6000 series grades.

Advancements have been made over the past few years on producing aluminum extrusions with very tight tolerances. In addition continuous casting processes have been developed to produce Class A surface quality material**.** The new process comes from Alcoa who developed the Micromill™ technology announced in September 2015. The Micromill™ saves manufacturing cost for it takes 20 minutes to create aluminum sheet vs 20 days in the traditional mill. Alcoa has a number of patents on this technology. Alcoa has announced plans to license its Micromill™ technology for continuous casting of aluminum sheet through the manufacturing equipment company Danieli Group[70]. An article states "Ford will begin using Micromill material in 2016 F-150 production in the fourth quarter of 2015, and plans to increase its use over the next several years on a range of vehicle components and future platforms."[60] Peter Friedman, Ford global manager of structures and stamping, Research & Advanced Engineering stated "The door inner is one of the most difficult parts in automotive stamping,"… "The ability to produce an alloy using Alcoa's Micromill technology to make that part is a real statement for how this process can benefit the automotive industry and Ford in particular."[60] If used for only non-Class A surfaces, Micromill™ products can support up to 30 percent of the aluminum used on an aluminum intensive. Alcoa has qualification agreements in place with a number of OEM's on several continents.

Figure B.30 Micromill - Continuous Cast Aluminum Sheet

Stronger aluminum grades, such as 7000 series used in aerospace, will allow for thinner aluminum, and however is often at a higher cost premium.

Costs for aluminum product used in the 2012 U.S. EPA Light Duty Pickup Truck lightweighting study, based on traditional rolling and finishing mill lines, are listed in Figure B.2. Costs have decreased since the time of this study.

SAFETY: Research shows that two vehicles with an Aluminum BIW have been thoroughly evaluated in the recent NHTSA and/or IIHS safety protocol.

- The MY2015 F150 is an aluminum intensive light duty pickup truck which was lightweighted by approximately 700 lbs. with its redesign and aluminum intensive material body. The vehicle achieved 5 start rating from NHTSA on overall rating along with a 5 star frontal crash, 5 star side crash and 4 star rollover crash. While not a federal regulatory test, the Insurance Institute for Highway Safety and Highway Loss Data Institute performed a safety test of the IIHS small overlap on the 2015 Ford F-150. IIHS tested the Crew Cab, as seen in Figure B.31. The Crew Cab earned 2015 Top Safety Pick, ‘Good’ performance in 4 of 5 assessments, occupant compartment stayed intact, low risk of injury to dummy’s head, chest, legs and feet, and withstood 6 times its weight in roof crush.

Figure B.31 Aluminum F150 Crew Cab Performances in IIHS Small Overlap Crash Test[71]

- The Tesla Model S has an aluminum BIW and has achieved a five start rating by NHTSA[72]. The design has crumple zones in front and back and the battery pack is an integral part to the vehicle safety load path.

- The DOE/Ford/Magna funded MMLV project built several lightweight vehicles for crash testing. The BIW for the vehicle contained a high percentage of aluminum. The crash, durability and performance testing results met or exceeded expectations.[140] More information on the MMLV project can be found in B.8.

RESEARCH: A number of additional research efforts are ongoing in the field of aluminum for the automotive industry, due to time limitations only a few are listed here.

UPDATED ALUMINUM INPUTS TO HOLISTIC VEHICLE STUDY: The holistic vehicle studies used in Chapter 5.2 were based on material inputs developed in 2010 timeframe. The Aluminum Association is funding EDAG, Inc. to with the NHTSA MY2014 light duty pickup truck CAE models to redesign the body and structure for grade and gauge to match collision and NVH performance of the original vehicle and to reevaluate aluminum cost. Study will also explore expanded use of extruded hollow sections to achieve lower mass and cost. This work is expected to be completed in the fall of 2016.

The reduction in aluminum gauges seen in production vehicles (MY2015 F-150, Land Rover, Audi, Jaguar, Cadillac, etc.). Recent production aluminum programs utilize improved aluminum sheet materials to reduce mass. The revised material gauges are due to at least four factors including: 1) Improved minimum strength of sheet alloys, 2) Improved formability of sheet alloys, 3) OEM confidence in aluminum field performance – flutter, dent resistance, manufacturing confidence, 4) OEM design optimization skills.

Typical gauge comparisons:

Production Models:	Pre 2015	Post 2015
Typical closure gauge	1.4 mm	0.9 mm
Typical structure gauges	3.0 – 4.0 mm	2.0 – 3.0 mm

The Aluminum Association is also working to advance material strength and formability to allow additional gauge reductions in the future. One such example is the Alcoa MicroMill which yields material with 30percent greater strength and 40percent greater formability which may likely be the enabling technology allowing further mass and cost reduction.[73]

ALCOA/CanmetMATERIALS: Higher strength grades of aluminum in many processing venues is one area of development for aluminum. Warm and hot forming will likely increase to develop the potential for lower energy/higher strength processing. Alcoa recently announced new alloys that include high temperature, stable precipitates that could increase engine operating temperatures and therefore combustion efficiency. CanmetMATERIALS provided resources to investigate these materials by Alcoa.

LightMAT: The Pacific Northwest National laboratory is part of LightMAT[74] (Lightweight Materials Consortium) which is a consortium of a number of government laboratories. This organization is a resource for industry to evaluate new materials. Offerings include Characterization, Computational Tools and Processing/Manufacturing. The site states that "Projects will focus on reducing the cost and improving the performance of a mix of near-and-long-term vehicle technologies…..Activities will contribute to achieving the goals of the EV Everywhere Grand Challenge, with a focus on accelerating the development of advanced batteries, power electronics, and lightweight materials technologies, while also supporting technology development to reduce petroleum consumption through advancements in combustion engines, alternative fuels, and other enabling technologies."

PNNL: PNNL has also developed a new friction stir welding technique (FSW) that joins together aluminum sheets of varying thicknesses. PNNL says that the updated joining technique is ten times faster than current FSW techniques, representing for the first time manufacturers high volume assembly requirements. A group of PNNL, General Motors, Alcoa and TWB Company LLC created an aluminum door inner consisting of a thicker gauge aluminum near the door's hinge (where additional strength is needed), to a thinner gauge used throughout the rest of the door panel. As a result the piece was reduced in weight by 62 percent.

Figure B.32 Aluminum Door Inner Made with Friction Stir Welding Technique[75]

BETTER QUALITY CAST ALUMINUM: Additional research is ongoing to allow the aluminum industry to obtain a better overview of itself to develop better methods to identify aluminum quality in the casting process. Shaymus Hudson, PhD Candidate and Lab Manager at the Advanced Casting Research Center in the Department of Mechanical Engineering at Worcester Polytechnic Institute is focused on pushing the capabilities of LIBS for monitoring impurities in real time. This is an extension of the work done at the Energy Research Company (ERCo, Plainfield, NJ) who develops LIBS for liquid metal applications. A lot of the work has been done in measuring bulk chemistry in real time.

In order for light metals to meet the demands for critical applications in the automotive and aerospace industries, tight control over the composition and cleanliness of the metal must be achieved before casting. Cleanliness typically refers to the level of solid particle inclusions (typically oxides) and dissolved hydrogen. Cleaner metal results in greater metal fluidity and feeding capability during casting, higher casting properties, improved machinability, better surface finish and overall reduction in reject castings. Although various technologies have been developed to measure and remove impurities, dissolved elements and suspended particle impurities persist. Quick analysis of melt composition and quality, carried out in-situ, is of great value in casting operations. There are no quantitative measurement techniques that can quickly determine chemistry, concentration, and size distribution of unwanted inclusions.

The ability to analyze liquid metals has direct applications for real-time process control. In the case of liquid metal processing, it is critical that operating parameters be adjusted accordingly so that the chemistry and quality of the melt be within predetermined limits. Current analytical approaches for determining chemical composition of the melt include spark optical emission spectroscopy, atomic absorption spectroscopy (AAS), X-ray florescence (XRF), and inductively coupled plasma spectroscopy (ICP). These methods are limited because they are off-line in nature, based on analysis of solid metal at ambient temperature, and require laborious manual sampling. Because of the potential in saving time, energy, and materials, as well as improved quality assurance, the use of laser-induced breakdown spectroscopy (LIBS) in liquid metal for real time analysis has generated significant interest in metals processing. The benefits of LIBS over other spectroscopic techniques include: 1) LIBS can be used on conductive and non-conductive materials; 2) sample preparation is unnecessary; 3) only an optical line of sight is required for measurement; 4) measurements are performed in seconds; 5) it can be carried out in-situ. Figure B.33 is a schematic of the LIBS apparatus.

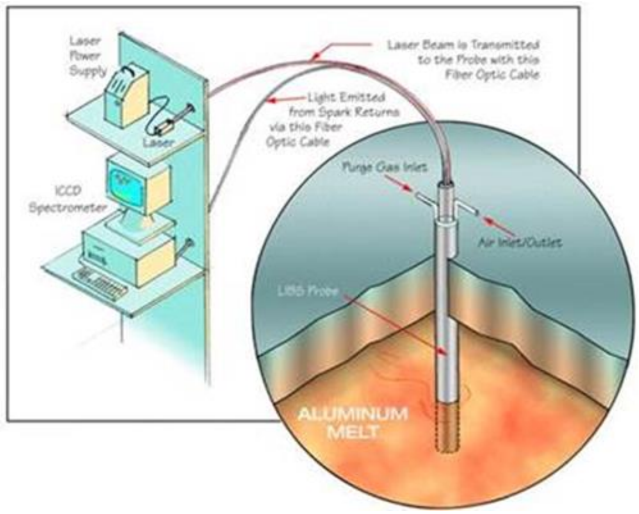


Figure B.33 Schematic of the LIBS ApparatusB

The U.S. EPA lightweighting study on a light duty pickup truck contains the following in regards to aluminum casting: "Utilizing high-strength ceramic particles uniformly distributed throughout an aluminum alloy matrix creates a material with one-third the density of cast iron but with comparable strength and wear resistance. Components requiring stiff, lightweight alloys that need to accelerate and change direction at high frequency such as pistons and wrist pins leverage the most benefit from aluminum MMC. Increased tool wear makes machining this material difficult. Selective reinforcement or the use of aluminum MMC only in high-stress areas of a part can minimize cost. Continued development of this option would provide additional benefits for lightweighting."

RECYCLING: The recycling of aluminum is well established, and provides a lower energy intensive manufacturing process for creating sheet aluminum. Novelis is one company known for recycling aluminum and re-melting aluminum for use in cans, automotive sheet and other products. Figure B.34 shows the steps Novelis follows in the recycling process (green steps).

[B] http://www.er-co.com/libs-melt.html.

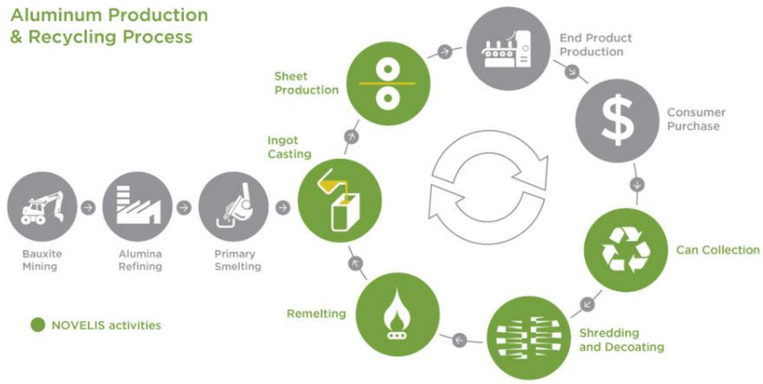


Figure B.34 Novelis Aluminum Production and Recycling Process[76]

IMPROVEMENTS IN ALUMINUM RECYCLING IDENTIFIED: More vehicles are being designed and manufactured with aluminum closures or aluminum BIW structural components. Within the next 10 years, many aluminum intensive vehicles will enter the recycling stream. Sean Kelly and Professor Diran Apelian, of Worcester Polytechnic Institute's Center for Resource Recover and Recycling, conducted a study: "Automotive aluminum recycling at end of life: a grave-to-gate analysis." They examined the end of life recycling process for automobiles to determine what percentage aluminum is currently being recovered and how much is lost as waste. Limitations within the aluminum recovery process including intelligent sorting and cleaning operations prevent 100 percent recovery. Their study found that more than 99 percent of recyclable material from end-of-life vehicles makes it through the dismantling and material separation process. The majority of waste is lost during the aluminum recovery process. When scrap aluminum is melted down for recovery, aluminum oxide forms at the interface between the air and the molten aluminum. This aluminum oxide, and any impurities captured with it are the primary waste products of the recovery process. These losses bring the total rate of aluminum recovery to 91 percent. Design improvements for smelting recovered aluminum can reduce aluminum oxide formation. Improvements such as side well furnaces and feeders ensure that the thin aluminum scrap is introduced deep into the molten aluminum rather than on top. This method reduces the surface area of melting aluminum that is exposed to the air and reduces the amount of aluminum oxide formed thus increasing the percentage aluminum recovered. Some aluminum companies like to note that they use high amount of secondary aluminum (ex: Novelis), while some have focused on producing primary aluminum (Alcoa). The net cost for a sheet aluminum manufacturer when working with primary aluminum or secondary aluminum is the same due to the cost of balancing the blend of aluminum in the secondary smelter.[77]

FORD'S ALUMINUM RECYCLING for the F150: Ford began producing the first high volume aluminum intensive light duty pickup truck for the 2015 model year, and incorporate manufacturing scrap (tolling) into the material supply**.** An overview of the recycling process for the F150 was presented by Ford at the Automotive World's Tokyo Big **S**ight Conference in 2016[78]. Keeping the two streams of 5xxx and 6xxx series scrap separated results in a larger payback to the OEM than if the materials were combined**.** According to information in the presentation at the 2016 Tokyo Big Insight Conference, with use of approximately 275 million kilograms of aluminum for the F150, it is calculated that 91 million kg of this is from recycled aluminum from the production process (5 percent of the scrap goes onto secondary market such as castings). Several slides describing the process are presented in Figure B.35, Figure B.36 and Figure B.37. Additional information is noted in a 2014 article, "Ford made a big investment in closed-loop recycling for the 2015 F-150, partnering with aluminum suppliers Novelis and Alcoa to recycle aluminum scraps from Ford's manufacturing process directly into aluminum for more F-150s. These scraps, most of which come from stamping windows into body panels….."[79] More can be found on the process in several websites: http://novelis.com/behind-the-scenes-automotive-closed-loop-recycling/ and http://www.forbes.com/sites/joannmuller/2014/11/05/novelis-is-lightening-fords-load-on-new-f-150/#6e93f028d0e0.

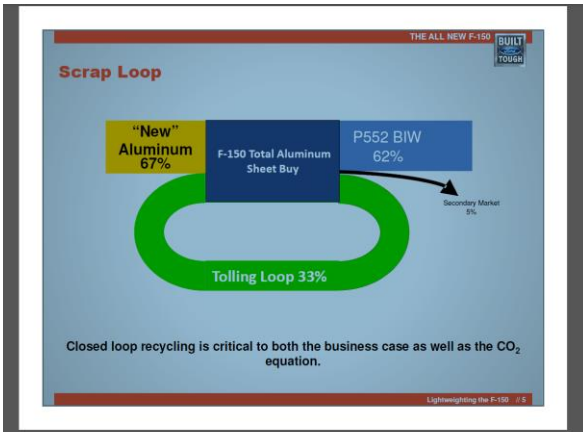


Figure B.35 Scrap Loop - 33% Manufacturing Scrap is Recycled into New Sheet Product and 5% Castings

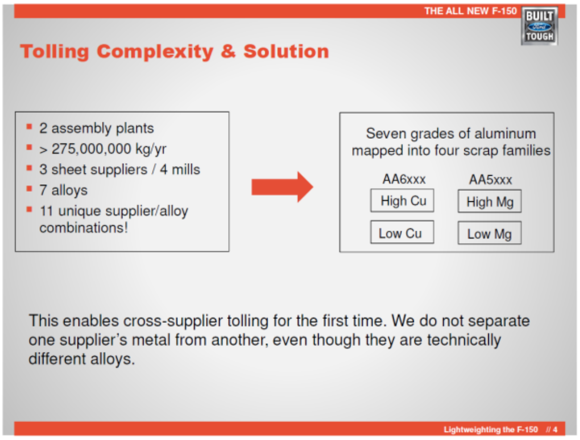


Figure B.36 Coordinating Aluminum Material Recycling 5xxx and 6xxx Grades

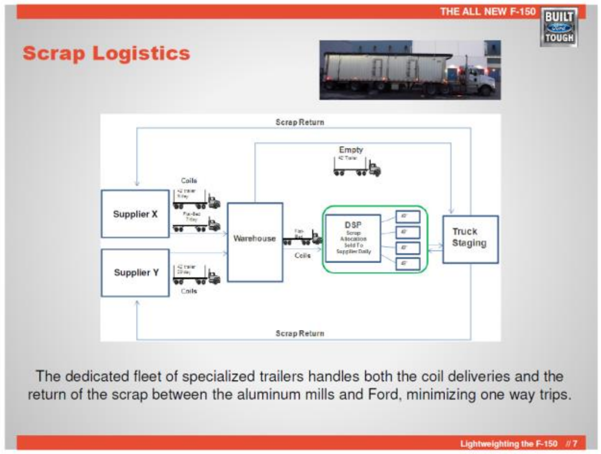


Figure B.37 Maximizing Tractor Trailer Use for Recycled and New Al Product to F150 Production Facilities

In February 22, 2016, Jaguar announced[80] "Jaguar Land Rover and Novelis developed an automotive product called RC5754 aluminum alloy that contains up to 75 percent recycled content. Both companies recently announced that RC5754 has been integrated into the production of passenger vehicles. The two companies developed it as part of Jaguar's REALCAR (Recycled Aluminum Car) project. It was introduced initially in the new Jaguar XE but will soon be used in all new and legacy Jaguar models." The article continues to say that "Closed-loop manufacturing is part of creating a circular economy, as Jaguar mentions in its sustainability report. A case study on the REALCAR project by the University of Cambridge Institute for Sustainability Leadership describes a closed-loop value chain as taking "a fundamentally non-linear approach." Implementation of it is "predicated on the notion of a circular economy, combining both forward and reverse supply chains, and where product waste is incorporated in the production of new versions of the products," researchers said. In other words, it is a different way of manufacturing, one in which the entire lifecycle of a product and the components to manufacture it are considered. In this case, the lifecycle of a vehicle and its components are considered."

B.4 Material Advancements - Magnesium

FEASIBILITY: OEM's have utilized magnesium on and off over the past century to save mass in vehicle design, see Figure B.38. Most magnesium parts are integrated into the vehicle interior and powertrain as opposed to the BIW or chassis, though some applications do exist.[86] According to Ducker Worldwide, the average car currently contains about 10 lbs of magnesium in its design, a number that is expected to triple by 2025.[81] However, while magnesium substitution has been shown to successfully reduce part mass more than most materials, the higher material costs can make similar products made of aluminum and steel more attractive.[86] Reliable availability and consistency cost can be a concern.

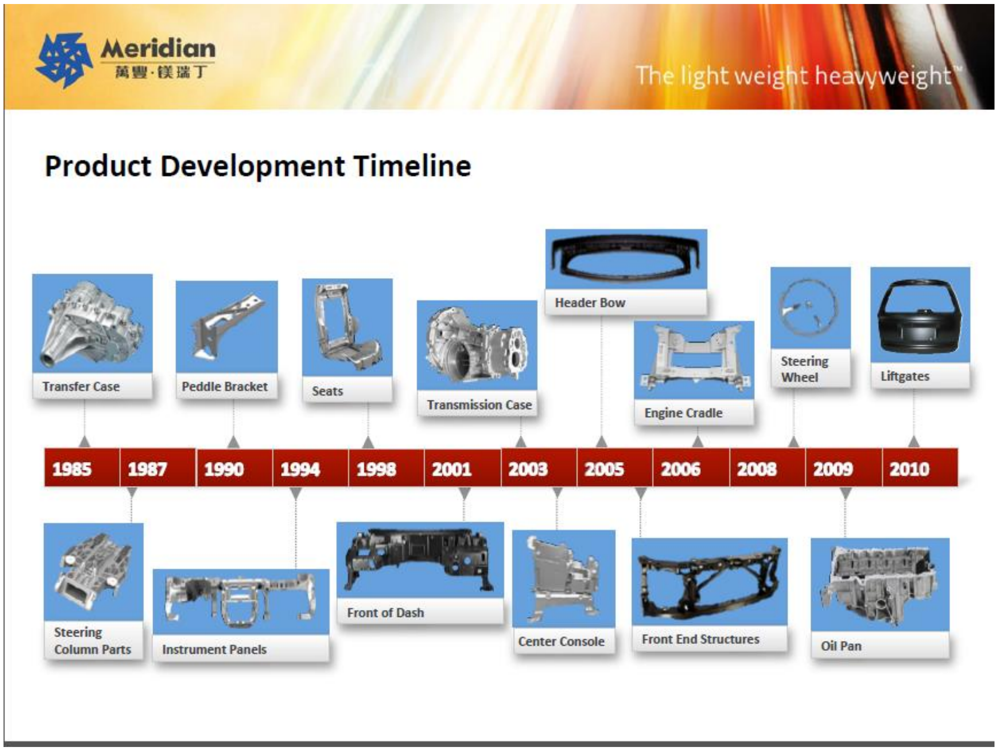


Figure B.38 Product Development Timeline for Magnesium Automotive Components, Meridian[82]

A number of OEMs have made efforts to incorporate magnesium into their projects and to advance research into future applications. Ford, GM and Chrysler are all active members in magnesium powertrain research, with GM having been the first company to actively incorporate magnesium into instrument panels, a practice that is much more widespread today.[86] Other OEMs like Volkswagen, Audi, and BMW have also started substituting magnesium parts, although the adoption rate varies between automotive markets in the United States and Europe.[86]

In terms of production, one company, Shiloh Industries Inc., has announced a move to double the size of magnesium production plants in both the United States (Tennessee) and in Poland in order to satisfy future demand.[81,81]

An October 2012 article states that "General Motors has announced that it is testing a new process for forming magnesium sheet metal panels that will allow for thinner, stronger, and lighter pieces than produced by the competition.[83] Currently, most magnesium parts are die-cast (like the fixed-roof structure for the Corvette Z06), meaning only parts with a significant section thickness can be rendered from the metal. GM's new thermal-forming process for magnesium enables the company to shape thin structural panels from the lightweight material." The process was demonstrated in limited production by GM for an inner trunk lid panel as shown in Figure B.39.

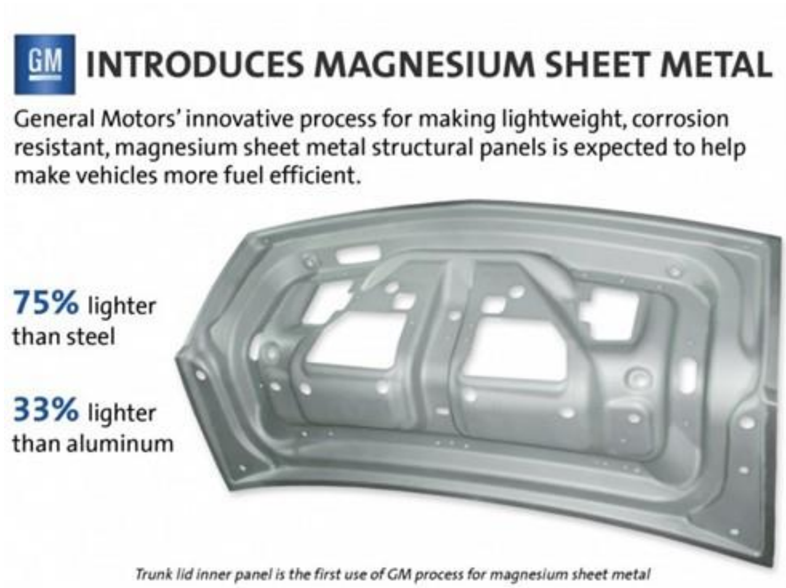


Figure B.39 GM Capability to Make Structural Panels out of Magnesium[83]

Ford is also using a magnesium inner on the MKT liftgate. According to Ford Product Development Design and Release Engineer of Liftgates, "because the magnesium liftgate inner is cast instead of stamped, we were able to develop variable thickness. We did extensive CAE analysis to see how the magnesium would functionally perform in a high impact event and made structural improvements such as ribbing for added strength."[84] The use of magnesium in liftgates allows for secondary mass savings in the tailgate powerlift opening systems. "The MKT engineers stress that although magnesium raw material cost is more than steel, an all-steel liftgate would be much more complicated and expensive to manufacture than the magnesium/aluminum liftgate, and too heavy for power lift systems to open." More information on magnesium can be found on the International Magnesium Association website. [85]

Additional information will be researched for the Proposed Determination on how OEM's addressed the corrosion issues with magnesium in their latest uses of magnesium in tailgate inners**.**

MASS REDUCTION: According to the International Magnesium Association, the substitution of magnesium has the potential to achieve 75 percent mass savings over steel and 33 percent over aluminum without sacrificing the strength or integrity of a given part. One reason given for this is the formability of magnesium, the ease of which allows for part geometry that eliminates the amount of wasted material through integration of both thin and thick areas.[81] Not only that, but when choosing to make thinner sections of a part, magnesium can achieve a minimum wall thickness about 40 percent less than that of aluminum.[86]

The material shortcomings of magnesium come from the fact that it has a very low yield strength compared to steel and aluminum. The yield strength of magnesium parts can range from 80-140 MPa depending on the casting method used.[86] As a result, to meet yielding requirements, magnesium-based components require either additional material to create reinforcements or rely heaving on optimized part geometry.[86] Design optimization also plays a role in maximizing mass reduction from existing magnesium product designs.

Some examples of magnesium incorporation into vehicles are given below in Table B.6. One more substantial initiative currently being undertaken by Fiat-Chrysler is to incorporate magnesium into the design of the 2017 Pacifica minivan, specifically, the lift gate.[81] The analysis being conducted for this project, according to the company, could indicate whether or not magnesium substitution could become part of the design process for some of its other models. Other components being designed in magnesium include the IP and transfer case housings.

Table B.6 Applications of Magnesium in Automotive Production by OEMs

OEM	Model	Component	Mass Save	Reference
Chrysler	Pacifica	Tailgate (mag & al)	2.2kg	http://www.wsj.com/articles/casting-the-future-of-lighter-vehicles-1455892867#[81]
Jaguar	XF	Cross Car Beam	2.0kg	2.0kg saved from existing magnesium cross car beam - used optimization tools for design https://www.lbcg.com/media/downloads/events/545/herbert-fackler-meridian.10039.pdf[82]
Renault Samsung Motors	SM7 Nova	Rear power seat and trunk contact	2.2kg 61%	First use of Magnesium plate https://worldindustrialreporter.com/renault-posco-develop-magnesium-sheet-metal-autos/[87]
Porsche	911 GT3 RS	Roof - magnesium sheet		http://press.porsche.com/news/release.php?id=911[88]
Ford	Ford Explorer	3rd row seat back frame		http://www.intlmag.org/showcase/MgShowcase15_Feb2011.pdf[89]
Ford	2010 Lincoln MKT*	Tailgate (mag & al) die cast mag	22 lbs.	http://www.intlmag.org/showcase/mgshowcase12_mar10.pdf[85]
Chevrolet	ZO6 Corvette	Engine Cradle	10.85kg 33%	Industry's first magnesium high pressure die cast. http://www.intlmag.org/showcase/MgShowcase15_Feb2011.pdf[89]

COST: As of early 2016, a kilogram of magnesium costs auto makers roughly \$3.75 (1.70/lb), while the same amount of aluminum costs \$1.54.[81] Steel costs between 40 cents and 98 cents per kilogram, depending on the grade, according to industry data. About 15-20 years ago, the price for magnesium was \$4.00 per pound (with inflation) based on 40,000 to 60,000-ton chemical plants. While the price has come down since then, it remains more costly than aluminum, which minimizes its overall use and production. Figure B.40 shows the changes in the price of magnesium during the past 25 years.

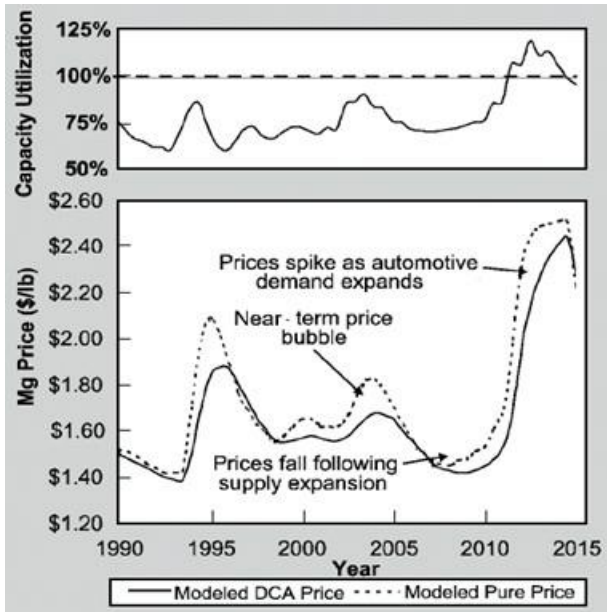


Figure B.40 Price of Magnesium over 25 Years (not adjusted for inflation)

The cost for magnesium needs to consider the fact that one acquires more material when considering 'cost per kg' due to the fact that magnesium is approximately 25 percent the density of steel. Assuming the component does not need significant additional material for strength or stiffness, then more components could be made for the same kg.

SAFETY: Currently magnesium is utilized in seat frames, IP's and specifically in the 2017 Chrysler Pacifica liftgate, Sheet magnesium has also been shown to be viable through a door closure made by Altair. Magnesium is inherently known to be brittle, however alloys of magnesium can change the properties. The Phase 2 High Development lightweighting project by ARB/Lotus Engineering, as described and referenced in Chapter 5, utilized magnesium front end in its CAE modeling and final lightweight BIW design.

RESEARCH: A number of research projects are ongoing in the field of magnesium.

DOE: In 2015, DOE has continued making progress on various magnesium-based research projects introduced over the past few years.

1. Infinium Inc., has been working on increasing its magnesium production through zirconia electrolysis that forms clean and cost-effective magnesium. Recently, the company announced their new project goal of producing 500 pounds of primary magnesium metal and producing a magnesium-neodymium master alloy in exchange for a WE43 castable magnesium alloy in die casting.

2. Arizona State University's Ira A. Fulton School of Engineering. Main objective of the project is to have a better understand of corrosive and protective behavior in magnesium alloys. By doing this, they can, hopefully, create magnesium-aluminum alloy scheme used for corrosion protection and use the alloy to create a Kinetic Monte Carlo (KMC) simulation that incorporates pH changes to understand and predict corrosion behaviors of magnesium-aluminum alloys. As of now, the pH goal was a success, but the Mg-Al alloy scheme still must be improved upon.

3. Researchers at ASU, Mark Horstemeyer of Mississippi State University and Santanu Chaudhuri of the University of Illinois at Urbana-Champaign have partnered to research corrosion, but at grain boundaries in magnesium alloys. This was done through corrosion scale modeling and experimental research, and this also helps bring light to the fact that magnesium alloys are easily corroded in the presence of salt water.

PNNL: The Pacific Northwest National Laboratory is currently working on new methods that add a greater ductility to magnesium alloys. The PNNL hopes to develop an "empirical casting process simulation tool" that can examine fluctuations in the ductility of magnesium alloy detected. The goal is to create a modelling framework for future use of magnesium alloy designs and the casting process.

This isn't the PNNL's only research project, however, as they are also looking into the self-pierce riveting (SPR) process. This process strongly allows for the joining of similar and non-similar metals with magnesium. The biggest barrier to the SPR process is its rate and efficiency. Because of this, one of their biggest goals for this project is to enhance the SPR technology that currently exists and make it more widely used for joining magnesium intensive components with other metals. Along with this project, they are also working on investigating in-situ kinetics, which will help develop modeling tools for "accurate microstructure prediction" for magnesium alloy castings. This process will also help understand the concept of phase evolutions during heat-treatment. Understanding high cooling-rates is the biggest barrier, since the experimental technique to study in situ cooling rates does not exist, yet.

ORNL: At the Oak Ridge National Laboratory, principal investigators M.P. Brady and Donovan Leonard are heading in the direction of creating a scientific foundation of magnesium alloys with reduced corrosiveness and understanding of film formation on magnesium alloys. Their main objective is to portray how the addition of metals to magnesium to create alloys affect overall film formation. Along with this project, Guang-Ling Song worked on a similar perspective as to Brady and Leonard, but decided to research further into the passivity of magnesium alloys in order to create a stainless magnesium alloy. She determined that the magnesium alloy, even though anodic polarization, could not be passivized in any way.

US AMP: James F. Quinn of General Motors partnered with the U.S. Automotive Materials Partnership for developments in improved crashworthiness of the front end magnesium sub-structure of a vehicle, hoping for the front end to be more easily formed, durable, and sufficiently well-characterized. These factors require low-cost materials in order to achieve these performance objectives, which is currently one of three barriers in doing this project, with the other two barriers being acquiring adequate predictive tools and manufacturability.

The DOE report out for the USAMP project summarized their work under the title heading "Technology Transfer Path." The documentation stated the following:

-"Increased use of Mg as a lightweighting material alternative in automotive structural design is fraught with both economic and technical challenges including material cost, perceived durability concerns, a receding supplier base in North America, and manufacturing concerns such as joining and surface treatment.

-Although massive incorporation of Mg components into articulated subassemblies such as the originally-envisioned 'front end' appears unlikely in the near term, Mg will continue to have a role in vehicle lightweighting, predicated on its attractive features of low density, high specific stiffness and amenability to thin-wall die casting and component integration.

- In this case, efforts devoted to improve strength and durability (fatigue) of castings, joining to dissimilar metals and finishing alternatives will remain quite relevant.

- Comments regarding the constituent stakeholders are as follows:

…..OEMs. Improved material properties models for specific grades of Mg (e.g. AM60B, ZE20) will be of value in various design simulations including crashworthiness. Developments in the physical metallurgy of advanced grades of Mg (e.g. ZE20, ZEK100) may eventually permit utilization of lightweight components in load-sensitive applications where more isotropic behavior of the metal is desirable. Knowledge gained with regard to corrosion protection systems and scope of applicability – particularly for novel, multi-material pretreatments – is expected to be of value. Additionally, novel joining methods and parameters such as rivet coatings are of interest. Durability modeling of joining technologies is of general value, as are novel approaches for joining dissimilar metals.

…...Suppliers. USAMP has enlisted over 30 distinct suppliers of materials, technologies and services relating to the design, production and incorporation of Mg components in automotive structures over the course of the several MFERD projects. Through technical committees and web-based tools suppliers are both engaged in discussion of Mg technologies as well as in providing often unique adaptations of existing technologies for deployment with Mg. Suppliers are thus engaged in understanding the particular technical challenges and building their capabilities to meet expanded use of Mg alloys in vehicle lightweighting.

……Universities. A long-range goal of the MFERD initiative, originally set forth by its architects, has been the fostering of greater Mg technology education and innovation through the university system. To this end, 11 universities have been engaged in the overall project with nine in the current embodiment, focusing on physical metallurgy, ICME, durability, metal deformation and corrosion. Such sponsored university research was intended to instill a greater interest in Mg science and technology among students, as well as providing a means for linking knowledgeable graduating students with possible opportunities in supplier or OEM organizations. At the end of its second full fiscal year, the project team has received all component parts and begun construction of "demonstration" structures using the joining and finishing technologies evaluated and developed – including FSW, AIW and SPR. Subsidiary studies of joining durability and corrosion have been completed or are underway for the materials and technologies being employed. A concerted effort to produce, characterize and simulate extrusion processing of the advanced Mg alloy ZE20 was undertaken this year.

University of Michigan Principal Investigator John E. Allison made it clear that there was a great lack of quantitative knowledge of high-pressure die casting (HPDC) magnesium process, which is used in 90 percent of commercial magnesium products due to fast and greatly economical production. The lack of the understanding of this process limits the ability to reduce overall costs and to optimize magnesium components. This also limits the knowledge of micro segregation and phase transformation during the HPDC process, which is one of the bigger obstacles to overcome along with developing "physics-based transformation micro models."

B.5 Material Advancements - Plastics

FEASIBILITY: In March of 2014, the American Chemistry Council's Plastics Division led the work to assemble the "Plastics and Polymer Composites Technology Roadmap for Automotive Markets"[90] which sets a path forward for the plastics and polymer composites and automotive industries through 2030 and beyond. The document states that "This work is focused on the North American market but also addresses globally significant issues." The roadmap provides the following definitions for Plastics and Polymer Composites:

"The term "plastics" refers to two-dimensional chains or three-dimensional networks of repeating chemical units formed into a material. Polymers occur in nature and can be manufactured to serve specific needs. The majority of manufactured plastics are thermoplastics, two dimensional chains that, once formed, can be heated and reformed over and over again. The other group of plastics, called thermosets, is formed by creating three-dimensional networks that do not melt once formed. Both types of plastics are used in automotive applications today."[90]

""Polymer composites" refers to material systems that combine a plastic resin (the raw material used in plastics and polymer composites) with a filler material to produce improved properties. Filler materials can be talc, short glass or carbon fibers, long glass or carbon fibers, or long continuous glass or carbon supports. Resins in such composites can be thermosets or thermoplastics. The term "composites" can also refer to plastic-metal hybrid structures, cored sandwich structures, and other arrangements that combine polymeric materials with other material classes."[90]

This section focuses on plastics and the following section on polymer composites.

Plastics are a versatile class of material that are heavily utilized throughout the automotive industry. Plastics can be quickly processed into a variety of shapes and structures through a wide array of forming methods. Furthermore most plastics have a significantly lower density than most metals which provides the opportunity to realize significant weight savings through materials substitution. Because most plastics have specifically engineered chemical structures, their properties can be tuned to meet the design needs of a specific part or parts. The major drawback to this design flexibility is that designers must take into account the specific formulation and processing of a given plastic when selecting a material to work with. Many plastics have the added advantage that they can be colored in mold, which can eliminate the need to paint components. Furthermore the ease of forming plastics makes it possible to consolidate components into a single part and minimize the number of steps required to manufacture that part[26].

NON-POWERTRAIN TECHNOLOGIES

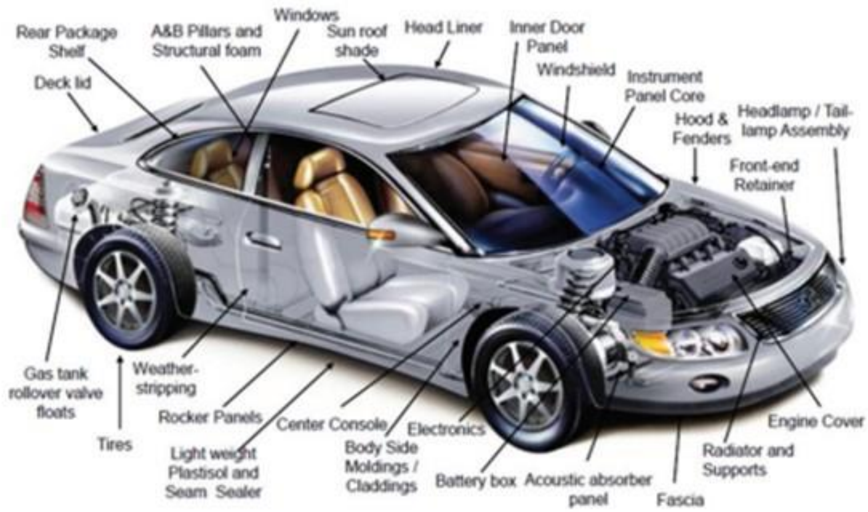


FIGURE 6.2 Auto part targets for lightweight plastics and rubber. Illustration provided by 3M Company.

Figure B.41 Auto Part Targets for Lightweight Plastics and Rubber (3M Company) [99]

Plastic lightweighting using Polyone and Mucell as outlined in the agency lightweighting studies which are described and referenced in Section 5.2.

MASS REDUCTION and COST: Development of high performance thermoplastics with high chemical, thermal, and dimensional stability has allowed manufacturers to start replacing some metal powertrain components that with plastics ones. These high performance polymers include polyimid (Sabic ULTEM™, Solvay Torlon®), polyamid (Sabic NORYL GTX™, Solvay Amodel®), and polyphenelyne sulfide (Solvay Ryton®, Toray Torelina™) compounds. The high thermal and dimensional stability of these polymers to around 200 °C allows them to be used in air management applications like hot air inlets, turbocharger components, and EGR components. Additionally, these polymers' chemical stability allows them to replace metal components in chemically harsh environments such as fuel systems, coolant handling, and EGR systems. These high performance thermoplastics can be formed using combinations of advanced manufacturing techniques, such as extrusion, blow molding, and over molding. This allows them to be quickly formed into complex hollow structures such as air ducts and rigid coolant lines. Table B.7 highlights some components made from these high performance polymers to replace metal parts.

Table B.7 Metal to Plastic Conversions High Performance Polymers[91]

Component	Material	Replaced material	Part Weight	Mass Save
Steering Knuckle	Polythalamide (PPA)	Al Alloy	1.043 kg	-60%
CAC Hot Air Duct	Polyphenylene Sulfide (PPS)	Coated steel	0.787 kg	-
Throttle Body	Polyphenylene Sulfide (PPS)	Al Alloy	0.362 kg	-60%
10 Port Water Outlet	Polythalamide (PPA)	Metal	0.275 kg	-62%
Gearbox Cooling Inlet and Outlet	Polyphenylene Sulfide (PPS)	Metal	0.195 kg	-59%

By-pass Water Pipe	Polyphenylene Sulfide (PPS)	Metal	0.023 kg	-86%

The American Chemistry Council's Plastics Division and the Society of Plastics Engineers Automotive Division published a book entitled "199 Ways Automotive Plastics Save OEM Costs" published in August 2013.[92] Table B.8 below lists a few weight saving examples from the book.

Table B.8 Composite Technologies from the 2013 book "199 Ways Automotive Plastics Save OEM Costs"[92]

Component	Material	Mass Save	Cost Change	Page
Integrated Camera Retention Hardware	TYC852X PA66 (Polyamid)	-15%	-45% (replaces 4 separate parts)	12
Bi LED Achromatic Plastic Lens	Makrolon LED2245 PC (Polycarbonate)	-45%	$14.3/vehicle	16
Diesel Exhaust Fluid System	Multiple polymers and molding processes	-85%	-40%	59
Advanced Passenger Airbag Chute	Thermorun TT860B TPO (Thermoplastic Polyolefin)	-.612kg	-4.36/vehicle	68
Integrated Bumper Energy Management Device	Hifax Tyc773 TPO (Thermoplastic Polyolefin)	-50%	-20% plus $1/vehicle	69
LED Headlamp Reflectors	Ultem AUT200 PEI (Polyetherimid)	-50%	-30%	85
Multi-Functinoal Exchange Blow molding Airduct	Marlex AMN-010 PP (Polypropylene) Santoprene 101-73 TPV (Thermoplastic Vulcanizate))	-30-40%	-25-35%	96

The Plastics and Polymer Composites Technology Roadmap for Automotive Markets addresses a number of topics regarding plastics and polymer composites. The resource contains information regarding the 2014 Chevrolet Corvette Stingray. The article states "innovative door-trim technology that eliminates the need for adhesive and secondary process steps to help reduce direct costs by 7% and weight by 5%".[93]

The EPA lightweighting studies, one on the Midsize CUV and another on the Light Duty Truck, contain detailed information on the use of Mucell/Polyone to lightweight plastic components.

LyondellBasell is a supplier of PE, PP, and compounded PP (talc filled, glass filled, TPO) products and has a number of products for 'low density', see Table B.9

Table B.9 LyondellBasell Weight Reduction Activities

	Low density TPO products for fascia applications	Low density TPO products for Instrument panels / consoles	Low density TPO products for higher stiffness mold in color applications	Low density TPO products for higher stiffness painted applications
Overview	Supplier of PE, PP, and compounded PP (talc filled, glass filled, TPO) products			
Feasibility (all questions apply to each technology)	Applications include fascia and other exterior trim parts (body side moldings, wheel flares, sill moldings, etc.) - components in production at various OEMs. Newer building blocks have allowed us to formulate a lower density product with similar property characteristics to incumbent material	Applications include Instrument panels / trim, center consoles. Material approved at various OEMs - not yet in production. Newer building blocks have allowed us to formulate a lower density product with similar property characteristics to incumbent material	Applications include front end grilles, cowl grilles, misc. trim. Material approved at various OEMs - in production at Ford in grille applications replacing ASA material. Newer building blocks have allowed us to formulate a lower density product with similar property characteristics to incumbent material	Applications include painted grilles, spoilers, body panels, liftgate outers, etc. Material in production in a hood extractor applicatiaon at FCA. Newer building blocks have allowed us to formulate a lower density product with similar property characteristics to incumbent material
Mass Reduction	Current latest low density material in production has a 0.97 g/cm3 density - replacing products with a 1.00 - 1.03 g/cm3 density (3-6% mass reduction)	New product offers 0.99 g/cm3 density - could drop in and replace current product with 1.035 g/cm3 density (~4% mass reduction)	New product offers ~6-7% density advantage (1.08 g/cm3 vs. 1.16 g/cm3) over incumbent TPO products. Although similar in density to ASA, has been proven to produce lower weight products as molded	New product offers ~6% density advantage (1.14 g/cm3 vs. 1.07 g/cm3) over PC/ASA or PC/ABS engineering resins. Similar density savings achieved vs. incumbent TPOs.
Cost	Cost/lb of material is slightly higher, but is offset by the weight reduction	Cost/lb of material is slightly higher, but is offset by the weight reduction	Cost/lb of material is slightly higher vs traditional TPO, but is offset by the weight reduction. (Accurate cost comparison vs. ASA is unknown	Accurate cost savings vs. engineering resins (PC/ASA or PC/ABS) is unknown, but believed to be a savings.
Safety	No	No. (product does need to perform well with laser scoring - has been tested)	No	No

Research	Currently developing a "next gen" product with at 0.95 g/cm3 density target	Currently developing a "next gen" product with at 0.97 g/cm3 density target		
Recycling	Product can be recycled - would need to establish proper reclamation channels for post-consumer goods (and paint removal in some cases)	Product can be recycled - would need to establish proper reclamation channels for post-consumer goods (and paint removal in some cases)	Product can be recycled - would need to establish proper reclamation channels for post-consumer goods	Product can be recycled - would need to establish proper reclamation channels for post-consumer goods (and paint removal in some cases)

RESEARCH: Polimotor 2 is a technology development project lead by Matti Holztberg and sponsored by Solvay Specialty Polymers. The project's goal is to develop a polymer intensive internal combustion engine and demonstrate its viability in motorsport. The project follows on the developments of the Polimotor project which developed a polymer intensive engine and raced it in the 1985 International Motor Sports Association Camel GT Championship in the group C2 category. Polimotor 2's goals are to build a 4 cylinder, turbo charged, double overhead cam engine with an output of between 375 and 400 HP, and realize a total mass reduction of 40 percent over a conventional metal engine. The Polimotor 2 design calls for metal cylinder walls, combustion chambers, cam shaft and crank shaft. The engine block, oil pan and cam box will be made of glass fiber reinforced thermoset polymers. Other components including the air intake plenum, cam cover, throttle body, and cam sprockets will be made of a variety of high performance thermoplastics.[94]

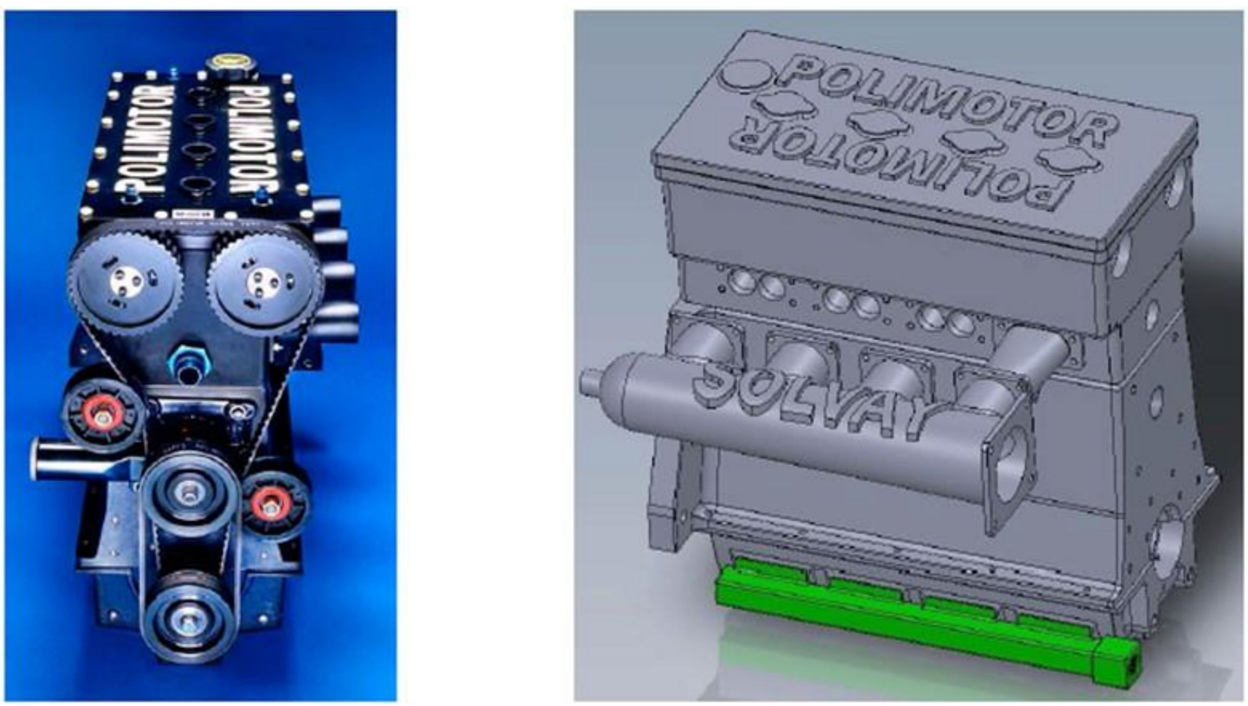


Figure B.42 Photo of Polimotor 1 (left) and a Computer Rendering of Polimotor 2 (right)[94]

B.6 Material Advancements - Composites

FEASIBILITY: Fiber reinforced polymer composites are a class of material that are composed of two or more components. First is the polymer matrix which provides rigidity to the composite. The second component are the fibers which are embedded in the matrix. The fibers are generally made of a stronger material than the matrix, and improve the overall strength of the material. Finally, additional additives and fillers may be incorporated to improve specific material properties such as toughness, thermal resistance or formability. It is possible to tailor the material properties of a fiber reinforced composite by properly selecting the composition and arrangement of its component materials. The information contained in this section is a snapshot of some of the technologies and practical applications of composites. EPA requests additional information on technologies and related mass reduction, costs, current/expected application, etc. available to OEM's.

Carbon fiber reinforced polymer composites are of particular interest for automotive applications because they can be designed to have mechanical properties that are comparable to steel, but have a significantly lower density.[90] Furthermore, they can have good energy absorbing characteristics in a crash which can improve vehicle safety. There are several challenges to utilizing carbon fiber composites in vehicle design. Currently the cost per pound for carbon composite parts is higher than for equivalent metal parts.[95] This is due in part to the high material costs of carbon fibers as well as for the polymer resins used. Furthermore, manufacturing a carbon fiber composite parts is generally more labor intensive and difficult to automate than manufacturing a solid metal component. In many cases the fibers are laid-up by hand, slowing production time and manufacturing labor costs. Additionally because they are complexly structured materials, using CAE to design and predict the performance of a composite part is more challenging than for traditional metals. Despite these challenges, Carbon fiber composites have been used in many boutique, low production volume sports cars where their unique properties allow for significant performance improvements. In order to overcome the technical challenges posed by carbon fiber composites, there is continued widespread research in the field. This includes academic research conducted at universities, government lead projects such as the DOE Institute for Advanced Composites Manufacturing Innovation (IACMI) and industry partnerships such as the U.S. Automotive Materials Partnership (USAMP). Carbon fiber product forms are illustrated in Figure B.43Figure .

Figure B.43 Carbon Fiber Product Forms[96]

Glass Fiber (Fiberglass) is included in numerous forms within the transportation and automotive industries as a way to provide mechanical strength, light-weighting and corrosion resistance (no galvanic corrosion) as the industry moves towards improved fuel economy and load capacities. Current methods often will use hybrid constructs to use traditional materials and composite materials to optimize solutions which can also streamline assembly through part consolidation.

Glass Fibers: Some of the key product forms and applications of fiberglass as well as mechanical and physical properties of fiberglass composite Sheet Molding Compound (SMC) compared to traditional construction materials are included in the following Table B.10.

Table B.10 Use of Fiberglass in Light-Weighting in the Transportation Industry[97]

Fiber Technology	Characteristics	Features	Application
Long Fiber Reinforced Thermoplastics (LFTP)	Continuous glass fiber and processes that generates long fiber lengths	Enables significant strengthening and stiffening of thermoplastics without sacrificing moldability, shape forming, or aesthetics	Light-weight bumper systems, wind deflectors for improved aerodynamics, and other non-structural parts
Dry Used Chopped Strand Fiberglass Thermoplastics	Short glass filaments	Corrosion resistant, non-conductive. Some glass and polymer systems can also be heat and hydrolysis resistant for additional robust and long-lasting solutions.	Commonly used for injection molded parts. Within the automobile cabin and under the hood, covers, fasteners, interior profiles and more
Bulk Molding Compound (BMC) and Sheet Molding Compound (SMC)	A fiber rich compound of thermoset paste and fiberglass can be heat pressed to different conformation	Advances in the technology have enabled the manufacturability of "Class A" surface finish parts in addition to the faster moldability and part throughput. Mechanical strength and ability for part consolidation	For large area panels, structural components and aesthetic features
Filament Wound Fiberglass	Filament winding of continuous glass		Very common in the production of natural gas cylinders used for fuel tanks in vehicles and is also employed in more non-conventional ways like the production of leaf springs for sports vehicles.
Fiberglass Muffler Insulation	Silentex provides solution to "glass packs" which were a short-life muffling solution due to the thermal degradation of glass	Sound isolation and thermal resistance	Longer lasting muffler systems.

Table B.11 Glass-Fiber Sheet Molding Compound Mechanical and Physical Property Comparison[96]

Material	Tensile Strength, Mpa	Tensile Modulus, Gpa	Specific Gravity	Plastic Deformation	Damage Tolerance
Steel	360	210	7.8	High	Low
Aluminum	240	69	2.7	Moderate	Low
Class A SMC	75	10	1.91	Low	High
Structural SMC	175	16	1.88	Low	High

"The primary advantage of glass-fiber SMC is that it has a low density while retaining damage tolerance due to the low plastic deformation. Existing knowledge of glass-fiber composite material properties and modeling capabilities for Finite Element Analysis make the assessment of part-level performance readily accessible. This enables evaluation of the appropriateness of traditional, glass-fiber composite or hybrid (traditional material with composite) part performance without costly prototype testing. The capability to create hybrid part designs for optimal strength, light-weighting, crash-worthiness, acoustics and cost enable manufacturers to optimize full systems to meet Safety, Environmental and Performance requirements economically."[96]

DOE/Ford/Magna MMLV Mach I: For the chassis components, glass-fiber-reinforced polymer (GFRP) springs were designed by Ford and NHK Sprint group using glass fiber and epoxy resin. These springs were put into MMLV prototypes and performed very well. The springs were first put into Ford Engineering specifications for load/rate test, fatigue test and other tests. The GFRP springs from the MMLV project were used in the 2015 Audi A6 Ultra Avant, and the Renault Megane Trophy RS where they saved 40 percent mass as compared to the original steel springs. "Audi states that typically a steel spring weighs some 2.7 kg (6.0 lb.) compared to the 1.6 kg (3.5 lb.) of the composite alternative. Of the total 4.4 kg (9.7 lb.) saved for the A6 ultra, about half concerns unsprung weight, so there is the double bonus of weight saved and ride improved, as the suspension reacts more quickly to road surface variations." In addition to the benefit of mass reduction, composite spring is not subject to corrosion, and reduces suspension noise. The manufacturing process is also reported to consume less energy than needed to produce steel springs. Cost information shared at the presentation of paper SAE 2015-01-1237 in the 2015 SAE World Congress included insights that the CFRP springs may have been equal to or slightly less expensive than the traditional steel spring. Finally, the GFRP spring is designed to be installed in place of existing standard steel coil springs without requiring any changes to the suspension packaging. Replacement of steel coil springs on both front and rear axles are shown in the below figure.[98]

Figure B.44 Glass Fiber Reinforced Polymer Springs (Right) Are A Drop In Replacement For Steel Suspension Springs (Left)[98]

Lexus: At the 2016 North American International Auto Show in Detroit Michigan, Lexus announced its new flagship coupe, the 2018 LC 500. As described in the following paragraphs on carbon fiber composites, the multi-material design incorporated, reinforced fiber composites in combination with extensive use of high-strength steels and aluminum. The composite components included a Glass-SMC deck lid.

<u>Carbon fiber composites:</u> These components are typically found on specialty vehicles such as the Chevrolet Corvette and the BMW i3. In these cases the cost of carbon fiber was offset by the gains in vehicle performance that it introduced. However, for most mainstream applications, the

high cost of the technology has not outweighed the mass savings of carbon fiber when compared to other lightweight materials. Nevertheless, a 2014 IHS Quarterly Q3 report on automotive plastics predicts automotive demand for carbon fiber to nearly triple from 3,400 metric tons in 2013 to 9,800 in 2030.[99] The same report notes that the current the supply of carbon fibers is limited. There are relatively a small number manufacturers of the raw materials for carbon composites, and the startup costs for a new supplier to enter the market are relatively high. The report warns that a disruption at a single material supplier could potentially significantly disrupt carbon composite production. The material precursors for the fibers are expensive and processing the precursors into carbon fibers is a slow and energy intensive process. Significant increases in carbon fiber production would be required to support widespread adoption of carbon composites in automobiles. At the 2009 SPE Automotive Composites Conference, keynote speaker Kalyan Sehanobish from Dow Chemical noted that, at the time, if every new car used 5 lbs of carbon fiber, the demand would exceed global carbon fiber capacity by 4 times.[100]

As noted earlier, carbon fiber composite parts have been incorporated into a number of commercially available vehicles. The following examples note some of the applications in which these composites are currently being used, and their benefits.

PLASAN: Plasan (http://plasancarbon.com/) currently manufactures components for the Chevrolet Corvette, the Dodge Viper, and Ford Shelby GT500KR. In 2015 Plasan installed manufacturing improvements that allowed them to manufacture carbon fiber components more quickly. The components made for the Corvette include the roof, lift gate assembly, hood, roof bow cover, splitter, and fender. The Corvette is the first vehicle with some Class A carbon fiber closures. The majority of the bodywork for the 5th generation Dodge Viper is made from carbon fiber including the lift gate, roof and hood. The November 2015 issue of SAE Automotive Engineering reports that between 100 and 120 lb. of weight reduction in the current Viper as compared to its first model can be attributed to the use of carbon fiber. The same article notes that the cost of carbon fiber for the Dodge Viper has down to about $8 per pound. This is a significant improvement over past costs, but still higher than the general industry target of $5 or lower. Plasan also manufactured the hood on the Ford Shelby GT500KR. Total production per year at their Michigan plant is 30,000 to 50,000 vehicles.

BMW: The BMW i3 is a carbon fiber intensive vehicle which also incorporates aluminum (in bumpers, etc.) as well as body panels made of SMC. Data from the A2Mac1 database shows that the BMW i3 Extended Version BIW weighs 142.5kg while the Toyota Prius BIW weighs 282.5kg. The footprints of the two vehicles are nearly the same; 43.48 sq. ft for the BMWi3 and 44.29 sq. ft. for the Prius.

Figure B.45 BIW Comparison of BMWi3 (left) and Prius (right)

Lexus: At the 2016 North American International Auto Show in Detroit Michigan, Lexus announced its new flagship coupe, the 2018 LC 500. Lexus used a multi-material approach when designing the car to reduce weight and position the vehicle's center of mass for optimal handling characteristics. The multi-material design incorporated, reinforced fiber composites in combination with extensive use of high-strength steels and aluminum. The composite components include: a carbon fiber roof, carbon fiber door inner structures trunk floor, and a Glass-SMC deck lid. Overall the multi-material design approach resulted in resulted in a total vehicle mass reduction of 100kg.[101,102]

MMLV: The Multi Material Lightweight Vehicle project (MMLV) co-sponsored with DOE/Ford/Magna includes several composite fiber components: engine oil pan, front cover, cam carrier, wheels, seats and IP. No cost information was provided.[C]

Table B.12 MMLV Composite Fiber Component Summary

Component	Technology	Mass Savings
Front Cover (engine)	Long Carbon Fiber Thermoset Composite	24% (1.0kg)
Oil Pan	Long Carbon Fiber Thermoset Composite	33% (1.02kg)
Engine Cam Carrier	PF30/5% CF	15% - future to add more carbon fiber for add'l strength
Wheels	5Jx19 Carbon Fiber	42% (1.56kg per) (over Al)
Seats	Design Optimization and carbon fiber	6% seat back structure and 26% for cushion structure=17% (1.6kg/veh)
IP/CCB	Reduce part count from 71 to 21 parts, carbon fiber	30% (5.2kg)

For the engine components, SAE paper 2015-01-1239[103] reports that “Ford Motor Company worked with material supplier, BASF Corporation, plus Montaplast GmbH, Hexion Inc., and WGS Global Services LC to design and develop the Front Cover, Oil Pan, and Cam Carrier based off the production Ford 1.0L I3 EcoBoost engine.” The paper continues to state that “The injection molded carbon fiber material has demonstrated good machinability and dimensional stability.”

For the chassis components, SAE paper 2015-01-1237 (MMLV: Chassis Design and Component Testing)[104] contains a description of the carbon fiber composite wheels. The carbon fiber composite wheels from the MMLV project were designed for weight and durability performance and resulted in improved vehicle dynamic attributes such as acceleration, steering, and handling due to reductions in rotational inertia and unsprung mass. The SAE paper reports that “The carbon fiber wheels for the prototype MMLV vehicles have a mass of only 6.15 kg/wheel. This is a 4.59kg mass reduction, a 43 percent weight save over the Fusion cast

[C] Some information for some of the MMLV Mach 1 components became available on June 7, 2016 with the IBIS Associates, Inc. presentation at 2016 DOE AMR titled "Vehicle Lightweighting: Mass Reduction Spectrum Analysis and Process Cost Modeling". This was received too late for consideration for the TAR.[141]

aluminum wheels. The wheels went under several in-use durability tests and passed all with the exception of peeling of the outer clear coat layer. This issue has been overcome and is planned for a 2016 Mustang Shelby GT350R…. Ford says that the pieces weigh a mere 18 pounds each, compared to around 33 pounds for a comparable aluminum wheel. This, Ford claims, adds up to a 60-pound total reduction in unsprung weight, and a 40-percent drop in rotational inertia."[104]

For the interior systems, SAE paper 2015-01-1236 (MMLV: Lightweight Interior Systems Design)[105] contains a description of the carbon fiber composite seats and IP. The paper describes the design and potential weight savings after prototypes were built and physical tests were performed. The design intent for both components was 40 percent chopped carbon fiber filled nylon (CFRP) and the prototype intent was woven carbon fiber fabrics and epoxy composite prototypes using hand lay-up and vacuum bagging. At the time of the paper the differences between the CAE results and the physical tests for the seat were being further investigated and the physical test results for the IP/CCB were pending.

Research is ongoing to address the current shortcomings of composite technology which include cost, cycle time and damage detection/repair. Carbon fiber/glass fiber reinforced composite technologies (lower cost than carbon fiber alone) still require significant development in order to meet production demands for a 250-450k assembly line. It is possible to use carbon fiber for components requiring Class A surface finish, although some preparation by handwork is required which makes cycle time longer. Damage detection and repair of composite fiber structural components is still being worked on because internal damage to a composite as a result of a crash is not easily detected by visual inspection.

<u>Sheet molding compounds (SMC):</u> SMC's are fiber-reinforced thermoset composites that are produced in moldable sheets and can be formed into large composite parts by compression molding, injection molding or roll forming.[106] SMCs are typically relatively short chopped fibers and powdered fillers mixed with a thermoset resin. Traditionally SMCs have used glass fibers as reinforcement, however carbon fibers have also been used to reduce mass and improve mechanical properties. SMCs are heavier when compared to long continuous fiber composites, but their advantage is that they are more easily formable which reduced production costs. Typically a mineral filler like calcium carbonate is used in SMCs which contributes to their increased mass.[107] Lighter fillers have been used such as glass beads, and ground up scrap carbon fiber composites[108]. Because SMC uses chopped fibers, it is also a potential application for reclaimed carbon fibers from recycled composite components[109].

Currently SMC is used in the body panels of the BMW i3 and the Alfa Romeo 4C. The use of SMC on the Alfa Romeo enabled a 20 percent weight reduction in comparison with sheet steel body panels.[110]

Owens Corning commissioned a study to understand light-weighting opportunities in the area of automobile structures and the results are described as follows. "A current production, front wheel drive CUV/minivan was selected with the area of study being the rear tub. The current vehicle uses a 0.034" thickness steel material, with a net weight of 30.9 pounds. It is estimated that moving to aluminum would require 0.050" thickness aluminum, with an estimated weight of 15.8 pounds. Various SMC composite alternatives were examined, looking at multiple compound formulations. The most favorable, from a mass reduction perspective, would yield a composite thickness of 0.108" and a corresponding weight of 18.9 pounds. Additionally, the current steel production part has an add-on heat shield due to the proximity of the tub to the exhaust system. Moving to a composite construction could eliminate the heat shields, yielding an additional 1.0 pound reduction. This would result in a total reduction of 13.8 pounds or 44 percent."[98]

SMC has been used in the automotive industry since the 1970s and advancements continue to be made in the weight reduction capabilities of the composite materials as manufacturability improves. A total of 20 lbs of mass reduction were achieved for the C7 Corvette through improvements in the formulation of SMC used. Figure B.46 shows the weight reductions for the C7 Corvette. The mass reductions highlight improvements beyond the current SMC formulation.

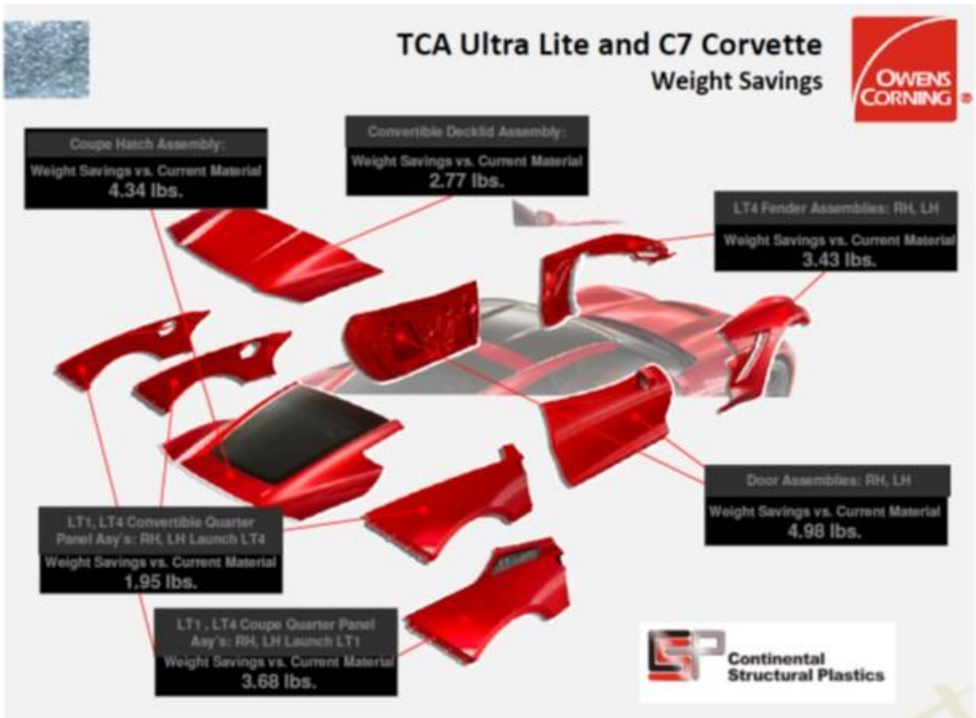


Figure B.46 Part -By Part Weight Savings Realized By Improving the SMC Formulation Used In the C7 Corvette

Research continues and SABIC has a timeline for when potential plastic/composite materials may be available for the marketplace as shown Figure B.47

Figure B.47 SABIC Potential Lightweight Crash Energy Management Solutions[111]

Plastics are also seeing an increased role in automotive light weighting solutions. IHS provided the following information.

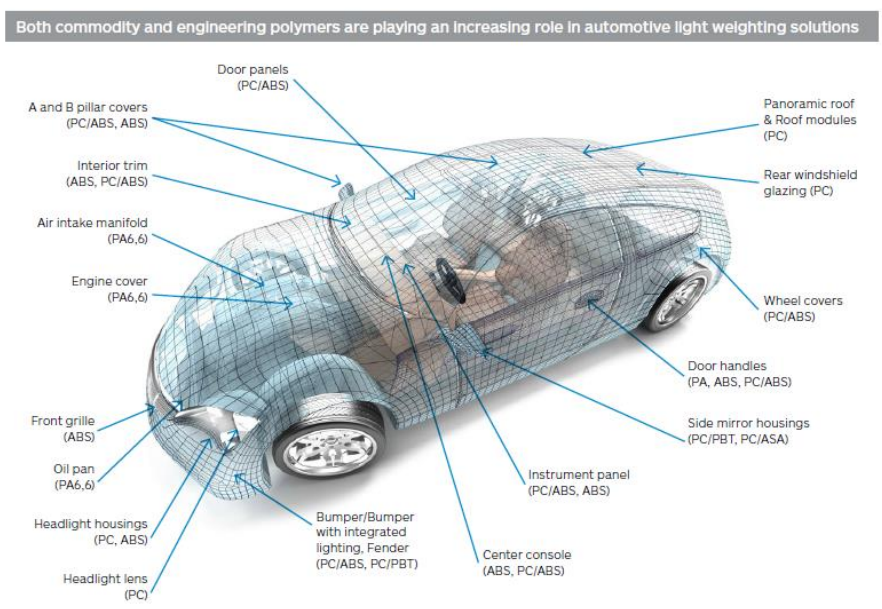


Figure B.48 Commodity and Engineering Polymers are Playing an Increasing Role in Automotive Light Weighting Solutions[99]

Sandwich composites which get their structure from a low density and low cost core sandwiched between carbon fiber layers for strength, may allow engineers to design components that use as little carbon fiber as necessary, potentially reducing cost as well as mass. IHS highlights this approach stating that " the chemical industry has come up with an answer to the cost issue: foam, polymer, fiber composites. Using standard polymer materials extruded with glass fibers and sandwiched with structural foams, the industry can now reproduce these Class A surfaces at a greatly reduced weight of metals and cost of carbon, while still maintaining structural integrity." Ford used this approach in developing the carbon fiber deck lid for its Focus Fuel Cell Vehicles (FCV) for the 2004 model year. For this project, the Class A outer panels sandwiched an aramid honeycomb core that improved the deck lid's stiffness and strength. By using this sandwich composite the Focus FCV realized a mass reduction of 60 percent as compared to the production Focus steel deck lid.[112] The November 2015 issue of SAE Automotive Engineering reports that Covestro markets a honeycomb sandwich composite under the name Baypreg. They suggest using it for interior trim applications such as sun shades and cargo load floors. Covestro claims that Baypreg can save 30-50 percent on weight as compared to conventional materials. BASF has developed solutions to impregnate fibers with resins and then over mold with plastics to produce lightweight structural components.[113]

The American Chemistry Council's Plastics Division and the Society of Plastics Engineers Automotive Division published a book entitled "199 Ways Automotive Plastics Save OEM Costs" published in August 2013.[92] Table B.13 below lists a few technologies from the book.

Table B.13 Composite Technologies from the 2013 Book "199 Ways Automotive Plastics Save OEM Costs"[92]

Technology	Material	Mass Save	Cost Change	Page
Front Bolster Assembly	Ultramid A3WG7 35% Glass Filled PA6 GF PA	0.8kg	-$2.50 variable -50% labor	9
Bio Recycled Structural Guard	Enduraprene 2395C BioTPE (Recycled TPE from tires and reinforced with coconut shell powder)	-3%	-2%	13

The 2015 Altair Enlightenment award was awarded to NAFILean for their biomass source for fibers and the introduction of such into an automobile (Peugeot 308). The article stated "Second runner-up was awarded to Faurecia together with Automotive Performance Materials (APM). The NAFILean (Natural Fibers for Lean Injection Design) solution brought sustainable design to instrument panels, center consoles and door panels of the 2013 Peugeot 308 by integrating a natural, hemp-based fiber with polypropylene, which allows for complex shapes and architectures along with a weight savings of 20-25 percent."

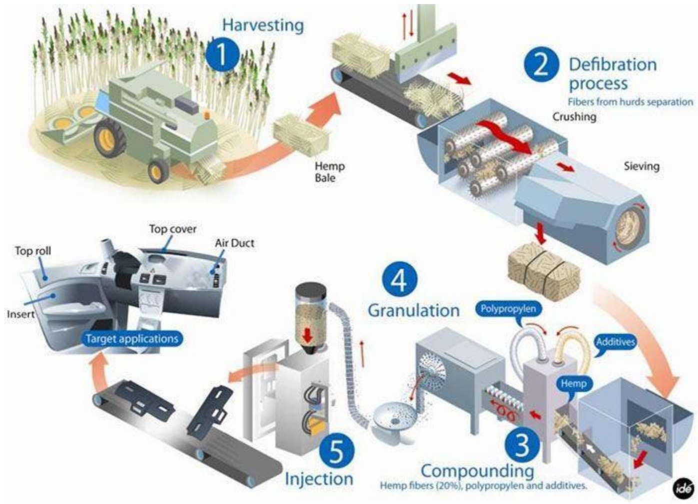


Figure B.49 NAFILean Biomass Source for Fibers and Introduction into the Automobile[114]

Finding solutions to light weighting is a universal effort. This is clearly noted by the Society of Plastics Engineers Automotive Division's finalists for its 2015 Automotive Innovation Awards Competition. Nominated parts must be on vehicles that are in production during the 2016 calendar year. The categories considered for awards were: Materials, Chassis/Hardware, Aftermarket, Body Exterior, Body Interior, Environment, Powertrain, Process/Assembly/Enabling Technologies, and Safety**.**

Materials: Ultralight Class A Body Panels on the 2016 GM Chevrolet Corvette sports car. Tier Supplier is Continental Structural Plastics and the material is TCA Ultra Lite SMC/compression molding. The description is "A new 1.2 SG SMC eliminated 9 kg of body-panel weight after a running change from a mid-density grade, where no tooling changes were required. Suitable for Class A or structural components, the new composite offers 28 percent mass reduction vs. mid-density (1.6 SG) grades and 43 percent vs. conventional (1.9 SG) SMC. It provides greater benefits vs. metal, including reduced weight and tooling costs, enhanced design flexibility, corrosion and dent resistance, and superior surface finish. Key to achieving the ultralow density was replacement of CACO3 with hollow-glass microspheres and use of a proprietary surface treatment to improve the resin/reinforcement interface."

Chassis/Hardware: Fiberglass/Epoxy Composite Coil Spring on the 2015 Audi AG Audi A6 Avant wagon with Tier Supplier S. Ara Composites S.A.S. Material supplier is Hexion. Inc. The Material/Process is epikote epoxy+fiberglass/modified filament winding. The description is "This weight-saving epoxy/fiberglass composite coil spring is the first of its kind to be used in the suspension system of a series-production vehicle. Using a patented, modified filament winding process, the application replaced traditional steel coil springs, reducing weight 40 percent and enabling the suspension system to react more quickly to changing road surface conditions, thereby improving vehicle handling and NVH. Significant work was done on resin chemistry and resin/fiber interface to ensure efficient load transfer and long-term mechanical performance, as well as finding an efficient, cost-effective production method capable of meeting build volumes."

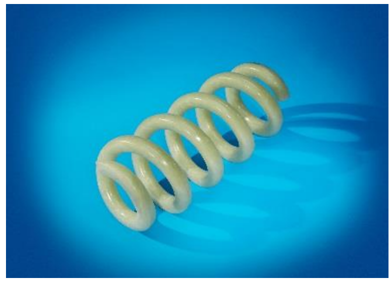


Figure B.50 Epoxy Composite Coil Spring

Aftermarket: Transparent Lightweight Wind Deflector on a 2016 General Motors Co. corvette Stingray convertible sports car. The Supplier/Toolmaker is Polytec FOHA Inc. /SABIC. The Material/Process is Lexan 9043 PC with Exatec 900 coating/CNC trimmed sheet. The description is "This is the first use of a self-mounted, transparent and frameless wind deflector for convertible cars that meets AS2 ANSI and ECE requirements. The steeply raked design minimizes air turbulence and noise when the top is down. Replacing glass with PC lowered mass 33 percent and allowed a contoured shape to be achieved that would have been difficult and costly in glass. A laser-etched monogram under the surface is unobtrusive to vision during driving, yet visible during inspection and meets regulatory requirements for glass marking. A plasma coating enhances scratch, chemical, and UV resistance for long use life."

Body Exterior: Push to release exterior serviceability fastener on the 2015 Ford Motor Co Ford Mustang sports car by ITW Deltar Fasteners and PA 6/6 Injection molding

Body Interior: Rear-Seat Folding Head Restraint for the 2015 Ford motor Co. Ford F-150 pickup by the Windsor Machine Group/Hawk Plastics Ltd and includes PP copolymer/injection molding.

Environment: Seat Fabric from Recycled Materials on the 2015 Ford Motor Co. Ford F-150 pickup by Johnson Controls Inc./Sage Automotive Interiors using Repreve PET/Multiple. Description is "The fiber used in this innovative seat fabric is made from a hybrid blend of 100 percent recycled materials, including post-industrial fiber and post-consumer water bottles. The fabric meets Ford design and comfort requirements without any compromise in quality, durability, or performance. The switch from virgin fiber was achieved at cost parity, while providing significant environmental benefits, including diverting over 5-million water bottles from landfills just this year. To help close the loop further, there are now PET bottle collection bins installed at the Ford Research & Engineering campus. The bottles are recycled to help form this fiber."

Powertrain: Heated Tip Fuel Injector on the 2015 Honda Motor Co Honda Fit subcompact and City sedan by Delphi Powertrain with material Zytel HTN54G35EF BKB336 PPA/Injection molding

Process/Assembly/Enabling Technologies: IMX Instrument Panel on the 2014 Hyundai Motor Group Hyundai i20 supermini by Hyundai-Mobis/HaneEhwa using Multiflex 3202 TPO/compression-injection molding. Description is "To eliminate scratches and a hard "plastic" feel, a 2-shot compression-injection soft IP was developed. The back-foamed TPO foil is compression-injected with the PP substrate, which in turn is integrally injection molded with the TPO passenger-side airbag door. All the work is done in a single tool. To increase foam softness and stability of the integral injection molding, the TRIZ method and design of experiments tools were used. The resulting part saves $10 USD/vehicle and reduces mass 300g."

Safety: Floor Rocker Reinforcement on the 2015 FCA U.S. LLC Jeep Renegade SUV from Tier Supplier/Processor Proma Group/Redstamp and SABIC for materials and Redstamp Toolmaker. The material is Noryl GTX 910 MPPE/PA using injection molding. The description is "An optimized MPPE/PA 6 honeycomb geometry in a plastic/metal hybrid proved to be a very efficient energy-absorbing crash-box structure in this floor rocker reinforcement. Not only is the component E-coat capable, but it is very easy to assemble into the vehicle's BIW. Since the plastic honeycomb is integrally attached to two steel flanges during injection molding, no structural adhesives are needed. The mixed-material solution took 1 kg of weight out of the BIW, saved approximately 10 percent, and contributed tooling savings vs. previous steel solutions."

MASS REDUCTION: It has been estimated that the use of carbon fiber can reduce the mass of the vehicle/component by 25 to 70 percent compared to steel. This is only a rough estimate that accounts for the relative densities of steel, and the components of carbon fiber composites. This type of estimate also assumes that a part's geometry will remain the same when changing materials. In reality manufacturing and design constraints significantly affect the final mass of a composite part. A component should be designed from the ground up with the specific material properties of the composite in mind in order to achieve the maximum mass reduction possible. Table B.5 lists the mass savings of various components.

Table B.14 Mass Savings from Use of Fiber Composites and Plastics

Vehicle	Component	Component Mass Save	% Reduction	Notes
MMLV	Seat	1.6 kg	42%	Original seat 3.8 kg
MMLV	IP/CCB	5.2 kg	43%	Originally 12.1 kg - Reduced 71 parts to 21 parts
MMLV	Front Cover	1.0 kg	24%	
MMLV	Oil Pan	1.02 kg	33%	Original 3 kg cast aluminum
MMLV	Wheel	4.59 kg/wheel	43%	Carbon fiber replacing Fusion cast aluminum wheels
Ford Mustang Shelby	Wheel	6.8 kg/wheel	45%	Original wheel was 15 kg. total 27.2 kg. mass reduction in unsprung weight and 40% drop in rotational inertia
Audi A6 Ultra Avant, Renault Megane Trophy RS	Springs	1.6 kg	59%	Glass fiber composite compared to steel at 2.7 kg/spring for a total 4.4 kg mass save Lack of corrosion
Audi A6	Infotainment carrier		50%	
Peugeot 308	Instrument panels, center consoles, door panels		25%	Hemp fibers with polypropylene
BMW i3	BIW	140 kg*	50%*	*Compared to Toyota Prius: i3 footprint = 43.48 ft^2 Prius footprint = 44.29 ft^2 , excludes front end and B pillar for BMWi3 BIW
Alfa Romeo 4C	Body panels		20%	SMC replacing steel
2013 SRT Viper	Lift Gate Assembly, Roof Assembly, Hood Assembly	68 kg		68 kg save over previous model
Ford Focus FCV	Deck Lid	6.3 kg	58%	Carbon fiber composite replacing steel from 2004 Focus
Chevrolet C7 Corvette	Body panels	9 kg		SMC improvements over previous SMC formulation
Agency Lightweighting Studies	Components to which Polyone/Mucell Is applied		10%	Trim, etc.

In December of 2012, NHTSA published a study titled "Investigation of Opportunities for Lightweight Vehicles Using Advanced Plastics and Composites."[115] The National Crash Analysis Center at the time was located at The George Washington University and they worked in conjunction with WTH Consulting LLC and Structural Integrity Division, University of Dayton Research Institute. The project was part of implementing the Plastics and Composite Intensive Vehicle (PCIV) safety roadmap. The project was performed on a MY2007 Silverado

1500 and the primary goal was to identify and evaluate the safety benefits of structural plastics and composites for applications to make vehicles lighter. The document contains details of the work and the overall result was a 19 percent decrease of the 2307kg LDT. No costing was performed for this work.

COST: Carbon Fiber composites produce high performance components, yet they are expensive when compared to metals. The price of carbon composites can range from $5/lb-$16/lb. The major cost drivers are the raw materials, tooling, labor, and equipment. The cost and yield of the composite is from which it is collected and the cost of the conversion. A whitepaper written by The American Chemistry Council's Plastics Division suggests that the current natural gas supply boom could lead to reduced prices for polymer resins. They argue that abundant shale gas could be used as a polymer feed stock and reduce costs as compared to current feed stock sources. The article Carbon Composites Are Becoming Competitive and Cost Effective, by Infosys[116], states: “The global composites materials market is about $28Bn in 2014 and is growing at 15-20 percent per year… However, for correct assessment entire life cycle cost need to be considered including maintenance and operation” [3]. It is generally suggested that for carbon fiber composite use to be widespread, the cost should be no higher than $5/lb.[117]

The $5.00/lb price point for carbon fiber is supported by the cost study performed for the mass reduction evaluation based on the MMLV project Mach 2 design, see Figure B.55. This project was supported by sponsored by DOE/Ford/Magna. The conclusion of the cost study was that the cost of carbon fiber needed to be $4.20/lb to $6.00/lb in order to reach the project's cost target.

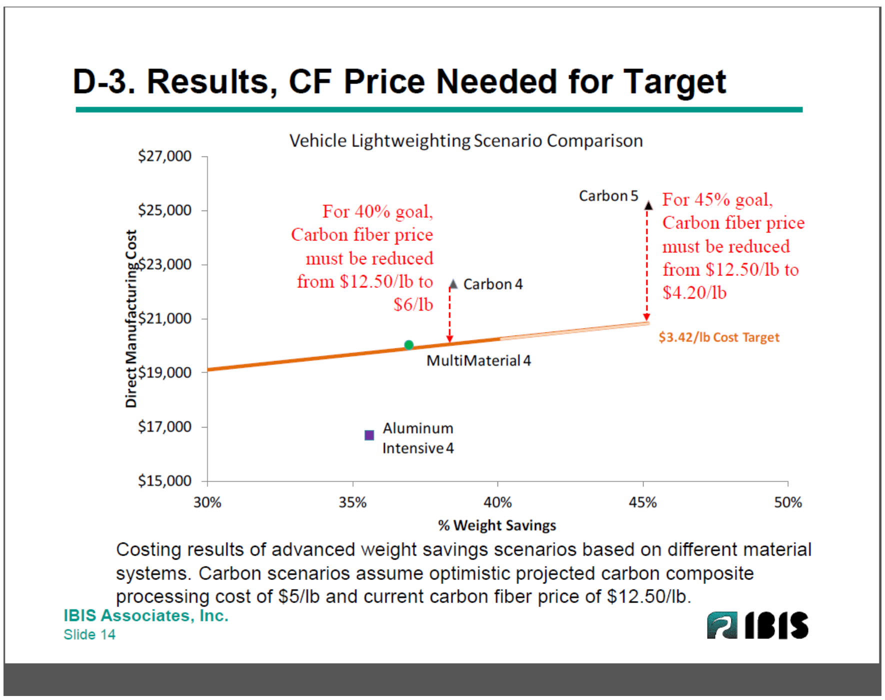


Figure B.51 Technical Cost Modeling for Vehicle Lightweighting 40% and 45% Weight Reduction[117]

There are many approaches to reducing the cost of fiber composite parts. As mentioned previously, ORNL is pursuing research into reducing both the material and energy costs of producing carbon fibers.[D] Additionally the design of the composite material itself can potentially be adjusted to realize reduced material and manufacturing costs.

Another engineering approach that could potentially reduce the cost of composite parts is parts consolidation and integration. Because plastics and composites can be molded into complex shapes, it may be possible to design a component as a single complex part as opposed to several smaller parts that require assembly. This type of design reduce manufacturing costs by reducing manufacturing time and cutting down on the amount of assembly tooling required. The 2013 Ford Escape demonstrated this sort of parts consolidation with a two-shot molding window lift carrier plate. The part was produced using 10 components with 10 assembly steps as compared to its predecessor's 21 components and 16+ processing and assembly steps.[118]

The ability to perform computer analyses with automotive materials is very important in today's design world with CAE optimization tools being used to shave millions of dollars off the cost of bringing a vehicle design to market. Advancements have been made to predict carbon fiber performance, however certain carbon fiber production methods have not lend themselves to predictability. Changes in the production methods have allowed better predictively of performance. The MMLV project by DOE/Ford/Magna incorporated CAE modeling of the carbon fiber components in the seat and the SAE paper on the seat durability evaluations state that the CAE results were still under review at the time of the writing of the paper (Jan/Feb 2015). Pacific Northwest National Laboratory (PNNL) is leading a DOE project in conjunction with, Purdue University, Autodesk, PlastiComp, Toyota, and Magna to develop an accurate CAE tool for modeling injection-molded long-carbon-fiber thermoplastic composites. A parallel project with the same goals is being led by ORNL and supported by Ford, BASF, PlastiComp, ASPN/Minco, the University of Illinois, Virginia Polytechnic Institute, and Moldex3D North America. The goals of both projects are to accurately predict the spatial, orientation, and length distributions of the fibers as a result of injection molding process, and to use these distributions to predict a molded part's mechanical performance characteristics.[119]

Table B.15 Summary of Key Parameters which will Influence the Cost of Composites in the Future for Automobiles

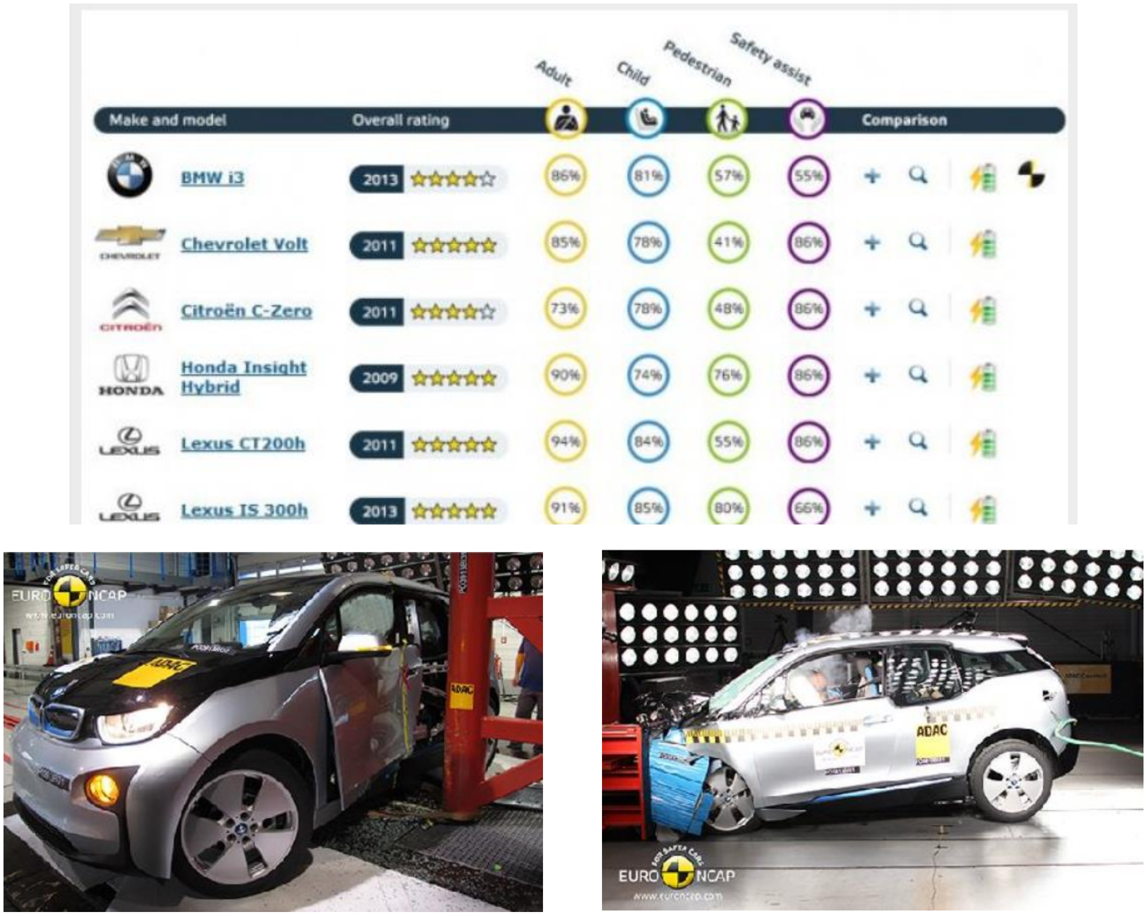
Material	Product Forms	Processing Techniques	Design Methods
Low cost carbon fibers	High volume production	Combination of chopped/continuous multi material systems	Advancements in CAE
Fast curing resins	Compression molding of prepregs		Better integration methods with metals
Carbon/Epoxy-SMC's	Out of autoclave processes - high speed RTM, Reactive RTM		
Strong/durable adhesives	Automation in adhesive bonding		

SAFETY: In order to reduce development costs, OEM's rely on CAE methods to predict component performance in a crash test. Even though the general mechanical properties of

[D] Another strategy to reduce material costs may be to combine carbon fibers with glass fibers because the performance requirements of carbon fiber in automobiles are not as great as for aerospace.

composites are reasonably well understood, predicting their behavior in a crash has been a challenge. The defining characteristics of a fiber composite, its complex structure and composition of dissimilar materials, introduce significant complexity in the prediction of possible failure modes. Despite these modeling challenges, fiber composites can be designed to have specific energy absorption values that significantly outperform metals like aluminum and mild steel.[120] Vehicles with significant composite structural components such as the BMW i3 and i8 and the Alfa Romeo 4C are in production and in the marketplace**,** demonstrating that carbon fiber can be safely designed and manufactured for structural applications.

Safety rating of BMWi3 was noted by the Euro NCAP safety testing and it achieved 4 out of 5 stars.[121]



Make and model	Overall rating	Adult	Child	Pedestrian	Safety assist	Comparison
BMW i3	2013	86%	81%	57%	55%	
Chevrolet Volt	2011	85%	78%	41%	86%	
Citroën C-Zero	2011	73%	78%	48%	86%	
Honda Insight Hybrid	2009	90%	74%	76%	86%	
Lexus CT200h	2011	94%	84%	55%	86%	
Lexus IS 300h	2013	91%	85%	80%	66%	

Figure B.52 Safety of the BMWi3 from Euro NCAP[121]

RESEARCH: Glass fiber (fiberglass) is a common material and has been used for decades in automobile components and typically in vehicle closures and more recently in suspension leaf springs and coil springs. Leaf spring components have shown safety and durability in their incorporation in Class 8 tractors, an option on Medium Duty vocational vehicles, such as the Mercedes Sprinter. More recently glass fiber coil springs have been incorporated in the Audi A6.

Significant research and development has occurred and continues to occur to address issues related to carbon fiber. Topics include reducing the cost of manufacturing (specifically through lower cost fibers), CAE modeling of the reaction of carbon fiber components during a crash, reducing the manufacturing times of carbon fiber composite parts, and recycling. This section contains only a small fraction of the world of research for carbon fiber being sponsored at a number of universities and government labs.

LOWER COST FIBER: The Department of Energy's Vehicles Technology Office is supporting research through ORNL to develop lower cost carbon fibers. Their research addresses both the high material cost of the polyacrylonitrile (PAN) precursor used to make carbon fibers as well as the high energy costs required to process the fibers.[119] One of their approaches is to mix the lower cost polymer, lignin, with the PAN precursors to reduce the raw material costs without significantly impacting material performance. Commercial scale manufacturing tests of this precursor are being conducted by Zoltek Companies, Inc. ORNL is working to develop an atmospheric plasma processing technique for oxidizing PAN fibers to address the high energy cost and large time requirements for processing PAN. The target of this project is make processing speed about three times faster while realizing significant energy savings as compared to current processing methods. ORNL is also evaluating the use of textile acrylic fibers instead of PAN as a carbon fiber precursor. ORNL has established their Carbon Fiber Technology Facility (CFTF) as a user facility intended to support scaling up new technologies to commercial production levels. The facility has a customizable 390 ft processing line capable of producing up to 25 tons of carbon fiber per year.[122] The CFTF has developed a method for making high quality carbon fibers from low-cost textile grade acrylic fibers. The method could reduce fiber production costs by up to 50 percent. The CFTF's next step in developing this technology is to develop licensing partnerships with fiber manufacturers to implement the new production process at commercial scale.[123,124]

Other academic institutions are working on various carbon fiber related projects and some of these are funded through the Department of Energy as well. Professor Randy Lewis at Utah State University is leading one such project. His goal is to evaluate whether synthetic spider silk developed in his group's lab can be used as a suitable precursor for making high quality carbon fibers.[125] Other projects involving carbon fiber include the University of Delaware on developing a carbon fiber reinforced, thermoplastic structural B pillar (2016) and the Michigan State University Composite Materials and Structure Center on a way to identify weak spots in the carbon fiber after an incident (ongoing).

PRESENTED AT DOE AMR 2016 DOOR DESIGN: (as of Oct 1, 2015) DOE is sponsoring a project at Clemson University, see Figure B.53, led by Srikanth Pilla at CU's International Center for Automotive Research, mechanical and automotive engineering departments, to develop a 42.5 percent lighter door with a price of $5.00 per lb weight saved. "Researchers said the door would meet or exceed standards governing fit, function, safety, stiffness, crash performance, noise, vibration and harshness. The assembly would be recyclable when the vehicle hits the end of its life on the road, they said." “Going forward, this is an important criterion since we are running short of landfill space,” Pilla said. “In fact, European environmental legislation already mandates that 95 percent of vehicle materials be recycled,….” [126]

Applicant	Location	Project Title/ Description	Federal Cost Share[1]
Wide Bandgap (WBG) Power Module R&D – Integrated Power Modules (Area of Interest 1)			
General Motors LLC	Pontiac, MI	This project will research, develop, and demonstrate a highly integrated wide bandgap power module for next generation plug-in vehicles.	$3,993,697
Delphi Automotive Systems, LLC	Troy, MI	This project will develop a low cost, ultra-compact power module using innovative integrated-cooling to increase power density, improve performance, and reduce cost.	$1,788,303
Ultra-Light Door Design, Manufacturing and Demonstration (Area of Interest 2)			
Vehma International of America, Incorporated	Troy, MI	This project will develop and demonstrate an advanced drivers-side front door architecture comprised of lightweight materials, functionally integrated component parts, innovative mechanisms and door seal systems.	$4,222,292
TPI Composites, Incorporated	Warren, RI	This project will design, develop, and demonstrate an ultra-light hybrid composite door and utilize predictive engineering (PE) to identify robust material and process design cycles.	$2,987,269
Clemson University	Clemson, SC	This project will utilize a systems approach to design and demonstrate an ultra-lightweight carbon fiber reinforced thermoplastic composites door assembly through the integration of unique designs, novel materials, and manufacturing technologies and joining/assembly of sub-systems.	$2,249,994
Body-In-White Joining of Carbon Fiber Composites to Lightweight Metals (Aluminum, Advanced High Strength Steel, or Magnesium) at Prototype Scale for High-Volume Manufacturing (Area of Interest 3)			
General Motors LLC	Warren, MI	This project will develop and demonstrate the joining of carbon fiber reinforced thermoplastic composites to lightweight aluminum using friction stir scribe (FSS) technology enabling multi-material (CFRP / aluminum) body-in-white structures for vehicles.	$1,608,687

Figure B.53 2015 DOE Vehicle Technologies Program Awards[127]

MICHIGAN STATE UNIVERSITY: DIS-ASSEMBLY and REPAIR: Researchers at Michigan State University's Composite Vehicle Research Center (CVRC) are leading efforts on novel joining techniques that allow rapid assembly, dis-assembly and repair of similar and dissimilar material substrates (metals to composites), increase light-weighting possibilities, while meeting the automotive assembly-line requirements through projects funded in part by the U.S. Department of Energy and the American Chemistry Council. Working with a unique thermally activated thermoplastic-based adhesive the goal is to rapidly assemble, disassemble and re-assemble. This is important in repair-ability of composites as well as load transfer and part consolidation. Modeling of the adhesives and substrates and resulting components in detail is also a part of this work, and will be used to increase joining efficiency and experimentally validate the numerical models and to develop design tools and databases. Additionally, integration of non-destructive evaluation (NDE) tools allow for validation of numerical models and allow for health monitoring of the joints, substrates and resulting components during and after manufacturing. MSU is collaborating with OEM's to assess feasibility of this work into the automotive process.

Professor Haq and his team are working on advanced adhesives with special properties that allow them to be taken apart, repaired or healed and this is obtained by adding electrically conductive nanoparticles to the adhesives. "Millions of these nanoparticles are embedded in the adhesive… By using what we call targeted heating we can bond them and reverse the bond and take them apart. When activated with the right kind of electromagnetic radiation, the nanoparticles begin to vibrate and heat the adhesive. Just the adhesive heats up without having to heat up the entire structure." Michigan State University leads the light-and-heavy-duty vehicle technology component of the Institute for Advanced Composites Manufacturing Innovation, or IACMI, a 122-member consortium funded by a more than $70 million commitment over five years from the U.S. Department of Energy.[123]

The increased use of fiber-reinforced polymer (FRP) composite materials calls for new non-destructive evaluation (NDE) methodologies for rapid and reliable assessment of fatigue, disbonds (interfaces) and delaminations (inter-layers) in the resulting materials and structures. Prof. Lalita, Prof. Haq and their team at MSU have applied a variety of NDE techniques with reasonable success for the inspection of composites, multi-material joints and other structural components. The NDE method of choice depends strongly on the electrical and mechanical properties of the test material. At MSU, we have worked on glass fiber reinforced plastic (GFRP) and carbon fiber reinforced plastic (CFRP) materials as well as metal-to-composite joints for rapid inspection and reliable detection of defects and disbonds using model-based studies for probe development and physics-based signal processing.

In the case of CFRP samples we have worked extensively on development of low cost eddy current sensors. Carbon based composites, are electrically conducting with different values of conductivity along different directions. Eddy current (EC) techniques, based on electromagnetic induction, are fast, noncontact and allow real-time imaging of defects that typically cause local variations in electrical conductivity. The method can image at fiber-level resolution enabling us to gain structural information including fiber distribution and texture, fiber misalignment, missing fiber bundle, gaps, wrinkles, cracks, delamination and impact damages.

GFRP composite materials are non-conductive and hence low frequency electromagnetic methods are not effective. However, at high (microwave) frequency the dielectric properties of the material can be exploited for detecting discontinuities/defects in GFRP structures. MSU is developing microwave methods using Time Reversal techniques for detecting, locating and imaging defects in GFRP. MSU is also working on optical methods for detecting and characterizing damage in GFRP samples. In contrast to OCT, ballistic scanners rely on detecting ballistic photons transmitted through the material. Since glass fibers and many epoxy resins have good transmission properties in the visible range, optical transmission scanning method has been used at MSU for NDE of GFRP composites.

Further, MSU has worked extensively on using ultrasonic techniques using guided waves for structural health monitoring of large composite structures.

US AMP: One important safety related component that is rarely made of carbon fiber is the bumper beam. This is due to the previously noted challenges in accurately predicting the failure modes of a composite part. This issue is the topic of a project by U.S. AMP to publicly develop techniques for CAE modeling of carbon fiber structural components. The U.S. AMP presented at the DOE AMR in 2015 on "Validation of Material Models for Crash Simulation of Automotive Carbon Fiber Composite Structures (VMM)" with 50 percent of the project complete and end date of 11/30/2016. It is a joint project between U.S. AMP and seven other universities and companies. The project is focused on fabricating a representative CFC Front

Bumper and Crush Can System (FBCC), conducting crash tests and performing predictive crash simulations for critical high and low speed impact cases. Through this project two promising representative unit cell models have been developed to characterize the nonlinear crash responses of composite structures. One is the meso-scale material model developed at the University of Michigan, and the other is the Micro-plane mode model developed at North Western University. Current work on this project includes conducting baseline testing on a steel FBCC design, and fabricating and testing a FBCC composed of a carbon composite. The results of these tests will be used to evaluate the CAE models.[128] Fiat in collaboration with the Polytechnic University of Turin, has also worked on developing a glass fiber, thermoplastic composite bumper beam assembly.[129]

B PILLAR: BMW sponsored a project with the University of Delaware to develop a carbon fiber B pillar. NHTSA supported this work under Grant #201439-124015. Results were shown at the SAE G/I meeting in 2016.[130] Dirk Heider, the Assistant Director for the University of Delaware – Center for Composite Materials, presented a summary of the project "High Performance Computing Study for Composite Intensive Vehicle Design." "Integrating Carbon Fiber Composites (CFC) into primary vehicle structures results in weight reduction that meets future fuel economy and emission standards, while fulfilling safety requirements. Funded by NHTSA and overseen by NCMS, the University of Delaware-Center for Composite Materials (UD-CCM) and BMW are leading the technical development of the “High Performance Computing Study for Composite Intensive Vehicle Design” study to design, manufacture and test CFRP structural vehicle components. The team is currently investigating thermoplastic (TP) carbon fiber reinforced materials for vehicle side frame structures (B-Pillar). The B-pillar design developed at UD-CCM meets structural and crash safety requirements (e.g. FMVSS No. 214) using TP composites and offers advantages (e.g. recycling, joining) compared to thermoset with the potential for improved crash performance. State-of-the-art CAE tools simulating full vehicle to component & test setup behavior is used to optimize manufacturability and structural/crash performance. The design of the B-pillar is followed by the manufacturing and testing of a prototype at UD-CCM and validation of the predictive engineering tools. The program goal is to attain equal or better occupant safety performance at reduced weight as equivalent vehicle components in the market today."

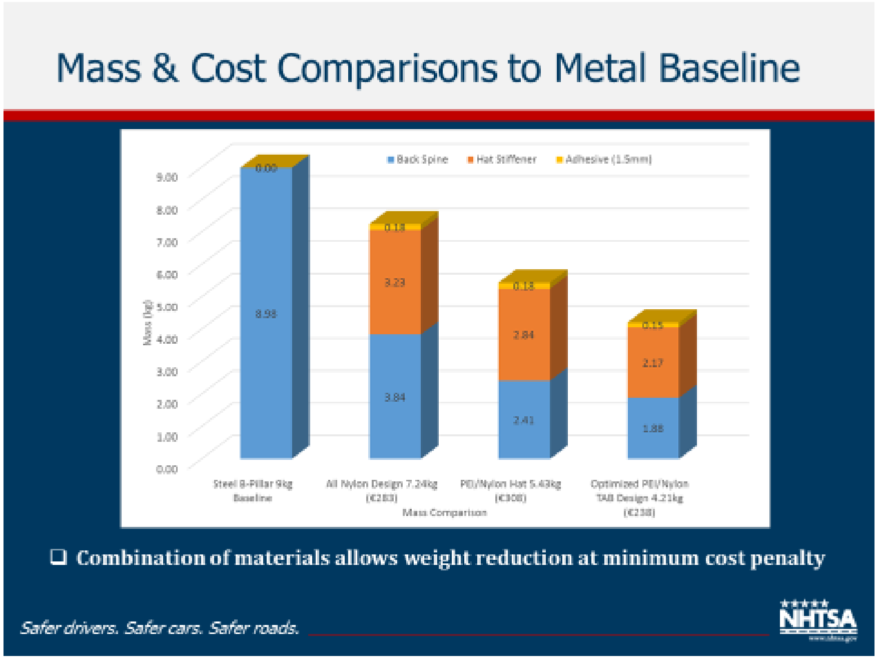


Figure B.54 Mass and Cost Comparisons of Composite Fiber B Pillar to Metal Baseline

RECYCLING: Recycling of thermoplastics is an ongoing area of research for many companies and academia institutions. One of the major roadblocks to recycling fiber composites with thermosets, is that the thermoset resins that are widely used as matrix material cannot be melted down, and are very chemically resistant. These properties are desirable for an in service component, but make recycling difficult.

Efforts ongoing include:

- ELG Carbon Fiber (GALM UK 2016) presentation
- Recycling BMWi3
- Directive on End-of Life Vehicle 2000/53/EC = the first EU waste directive with which the EU Commission has introduced the concept of Extended Producer Responsibility
- Efforts at the Composite Recycling Technology Center, identified on the Port of Port Angeles in Washington State.
- Aerospace industry focus on recycling

ELG Carbon Fiber (GALM UK 2016): At the GALM UK 2016 presentation by ELG,[131] a patented process for recovery of carbon fiber from manufacturing waste and end of life products using a modified pyrolysis process was presented. ELG also has an extensive R&D program with leading universities and research organizations to understand how recycled carbon fiber can be used. ELG has reclaimed more than 1,000 tonnes of carbon fiber from manufacturing waste in 2015 (20,000 tons of carbon fiber head to the landfill each year).

Current fiber reclaiming processes include milled, chopped and pelletized fibers for compounding. These are then used in Nonwoven carbon fiber/thermoplastic hybrid mats for composites manufacture and Nonwoven carbon fiber/thermoplastic hybrid mats for composites manufacturing.

BMWi3: Manufacture scrap recycling: Some companies for composite fiber recycling are expanding however it is not known if the product base for composite fiber recycled content will expand. BMW uses some manufacturing scrap recycled product in its BMWi3.

EU COMMISSION: "The Directive on End-of Life Vehicle 2000/53/EC is the first EU waste directive with which the EU Commission has introduced the concept of Extended Producer Responsibility." This requires that recycling be taken into account when a product is produced. The BMWi3 began to be sold in the marketplace in 2013/2014 so there are not many, if any, vehicles at their end of life to analyze this trend. BMW manufactured about 30,000 vehicles worldwide from May 2013 to mid-2014. The regulation requires that an opportunity for recycling needs to be identified and not that the vehicles have to be followed through to being recycled.

The targets are twofold:

	As of 1 January 2006	As of 1 January 2015
Reuse & Recycling	80%	85%
Reuse & Recovery	85%	95%

PORT OF WASHINGTON: The Composite Recycling Technology Center, identified on the Port of Port Angeles in Washington State, has a vision to create a new world leading industry for reclaiming, recycling and reprocessing carbon fiber composites that grows Washington State's advanced manufacturing industry and talented workforce. The goal is to address the 2 million pounds of carbon fiber (CF) composite material that enters landfills in WA State annually. The Q&A attachment to the site states that it is estimated that Washington state waste streams will double over the next five to eight years with expansion of regional manufacturing with requests from waste producers in other parts of the country asking them to take their manufacturing trim. The current markets for recycled carbon fiber materials are the sporting goods and agricultural product areas as well as several industrial markets.

AEROSPACE: Boeing has been working to find re-uses of its carbon fiber from its airplanes for a number of years. Currently carbon fiber components are being deposited in landfills or have found homes in sports equipment such as protective athletic gear. Research for the recycling of carbon fiber components is still underway at academic institutions. In the fall of 2015, the University of Alabama at Birmingham and Rassini, a Mexican industrial company engaged in the design and manufacturing of suspension and brake components for the automotive industry, announced a research project to engineer a fully recyclable thermoplastic suspension system.

A December 2014 article titled "From scrap to hatch: Recycled carbon fiber flies on ecoDemonstrator" reveals that the majority of carbon fiber scrap is ending up in landfills. The one location that Boeing has developed to use recycled carbon fiber is in small access doors on the underside of the airplane’s wings. The article states "By using reclaimed carbon fiber, the company would reduce energy use and carbon dioxide emissions associated with creating the product from scratch. Researchers estimate that using reclaimed carbon fiber to make composite components would reduce carbon dioxide emissions associated with manufacturing that part by about a third. It also would divert hundreds of thousands of pounds of composite material from landfills in the coming decades, and it would enable lighter designs and reduce material use compared to current processes to make new parts." The industry is still looking for a high volume use for recycled carbon fiber that will keep the waste out of landfills.

The topic of carbon fiber composite recycling has been researched for many years. The aerospace industry has been working on processes for recycling of carbon fiber. According to the Journal of Composite Materials article on "Recyclability and reutilization of carbon fiber fabric/epoxy composites," 2011 (DOI: 10.1177/0021998311420604) the industry has been investigating ways to recycle CFRP products since the 1990's. "Boeing and other industrial organizations have come together in 2006 to establish a common industry working group, Aircraft Fleet Recycling Association (AFRA), with a mutually shared commitment to improving older fleet asset management and fostering the recovery and reuse of aerospace materials." The article describes the recycling of (aerospace grade) carbon fiber as is seen in several different ways and include broad descriptions of mechanical, thermal and chemical processing. One way to recycle CFRP parts is through a mechanical process in which the CFRP parts are crushed and reduced to powders. These powders are reutilized as fillers in new composites (SMC/BMC), not as structural reinforcement. The engineering benefit of using the recycled powders is that they are lighter than the filler material that they replace. The journal article also describes a method for removing the polymer matrix by immersing the composite in boiling sulfuric acid. This method recovers the carbon fibers and maintains their mechanical properties. One company's business model is to connect people with carbon fiber scrap to those looking to use carbon fiber scrap. Carbon Conversions, previously known as MIT-RCF, states that about 20-25 percent of annual total consumption in 2015 (30 million pounds) of carbon fiber is scrap. The site states that 5 percent is currently recycled and some landfills require a premium for dumping carbon fiber reinforced materials. The company "manufacturers roll goods for composite reinforcement, and chopped, seeded recycled carbon fiber for thermoplastic compounding. The non-woven materials are made with recycled carbon fiber, either (1) alone or in combination with other structural fibers for infusion with thermoset polymers or (2) in combination with thermoplastic polymer fibers to be compression molded. Our chopped, seeded fiber is specially sized for making injection molding compounds."[132]

CONNORA TECHNOLOGIES AND THERMOSET RESINS: Recently, California based startup Connora Technologies (www.connoratech.com), has begun to commercialize a new epoxy hardener that allows the epoxies cured with it to be chemically broken down into reprocess able thermoplastics. Their product, Recycleamine®, is composed of amine groups linked by a central cleavage group. The cleavage group can be broken when immersed in a heated dilute acetic acid bath. In a composite this process causes the thermoset matrix to break down and be dissolved, leaving behind the composite's fiber reinforcement. The dissolved polymer solution can then be dried out and reprocessed as a thermoplastic polymer. Because this product relies on normal epoxy chemistry, it is compatible with commonly used epoxy resins such as Epon™ Resins 862, and 828. The resulting mechanical properties of the thermoset resins are comparable to those made using traditional hardeners.[133] This approach to recycling composites differs from previous methods because it allows for reclamation of the reinforcing fibers, as well as reclamation of a useable polymer from the matrix material. In recognition of this development Chemical & Engineering News highlighted Connora technologies as one of their ten startups to watch in their November 2015 cover story.[134]

Information on this topic can also be found at the composites world website http://www.compositesworld.com/articles/recycled-carbon-fiber-update-closing-the-cfrp-lifecycle-loop.

B.7 Material Advancements - Glass

FEASIBILITY: Pittsburgh Glass Works has two products that has been incorporated into OEM lines. The first is a cooperative effort with Corning to develop a lightweight hybrid glass and the second is reflective technologies in its solar glazing.

Lightweight Glass: Aluminosilicate and Soda-Lime laminated hybrid: On December 17, 2015 USA Today reported that a lightweight glass will be debut on the 2017 Ford GT. According to the article, "Ford worked with Corning to develop a special type of Gorilla Glass, a thin hybrid glass laminate used on smartphones and other consumer electronic devices, for the car's windshield, rear engine cover and bulkhead. The material is 30 percent lighter-glass on the GT weighs only 45 pounds, with 12 pounds shaved off - and is stronger, clearer and more durable."[135] The lightweight glass will also allow a lower center of gravity for better vehicle handling. "The glass is 3-4mm thick while a conventional windshield is 4-6mm thick." Ford worked with Pittsburgh Glass Works, LLC (PGW) on the lightweight glazing technologies. The windshield in the Ford GT Supercar is the first of its kind in OEM production to include the installation of unique capabilities to fabricate Aluminiosilicate and Soda-Lime laminated hybrid construction.

Figure B.55 Lightweight Glass on 2017 Ford GT Yields 30% Mass Savings[136]

PGW InfraRed (IR) reflective technologies in solar glazing: PGW presented "Glazing Technology Contribution to Meeting Regulatory Targets" during the Glass Applications technical session of the 2016 SAE World Congress.[137] As PGW states in a press release on April 12, 2016 "In addition, PGW utilizes Infra Red (IR) reflective technologies in its solar glazing to help reduce the thermal load through the glass, which reduces the use of air conditioning."

The technology would also allow significant secondary mass benefits.

1. Currently vehicle air conditioning systems can be just as powerful as those used to air condition a small house (about 2-3 ton). The needs for such a system in a vehicle is to cool down the inside of the vehicle at a faster rate and from a higher temperature. If the vehicle did not heat up then a smaller air conditioner could likely be used and this then reduces the need for mass in other components or liquids.
2. A smaller air conditioning system likely means less refrigerant.
3. Smaller air conditioning system related hoses, fans, compressor, etc. would be needed.
4. Less loads on EV and hybrids for better battery range.

B.8 Multi-Material Technology Examples

This section summarizes technologies that include multi-material designs.

MMLV: DOE/Ford/Magna Mach 1: The DOE National Energy Technology Laboratory Award Number No. DE-EE0005574 is a research project to investigate and validate a selected multi material lightweight vehicle design, identify technology gaps associated with the manufacture of a multi-material vehicle, and evaluate prototype vehicle performance on selected tests. The project and its results are outlined in a number of SAE papers which are assembled in an softbound book by SAE and is available online.[138] Related cost information is found in Section B.9

The project had a number of subsystem projects which are shown in Figure B.56.

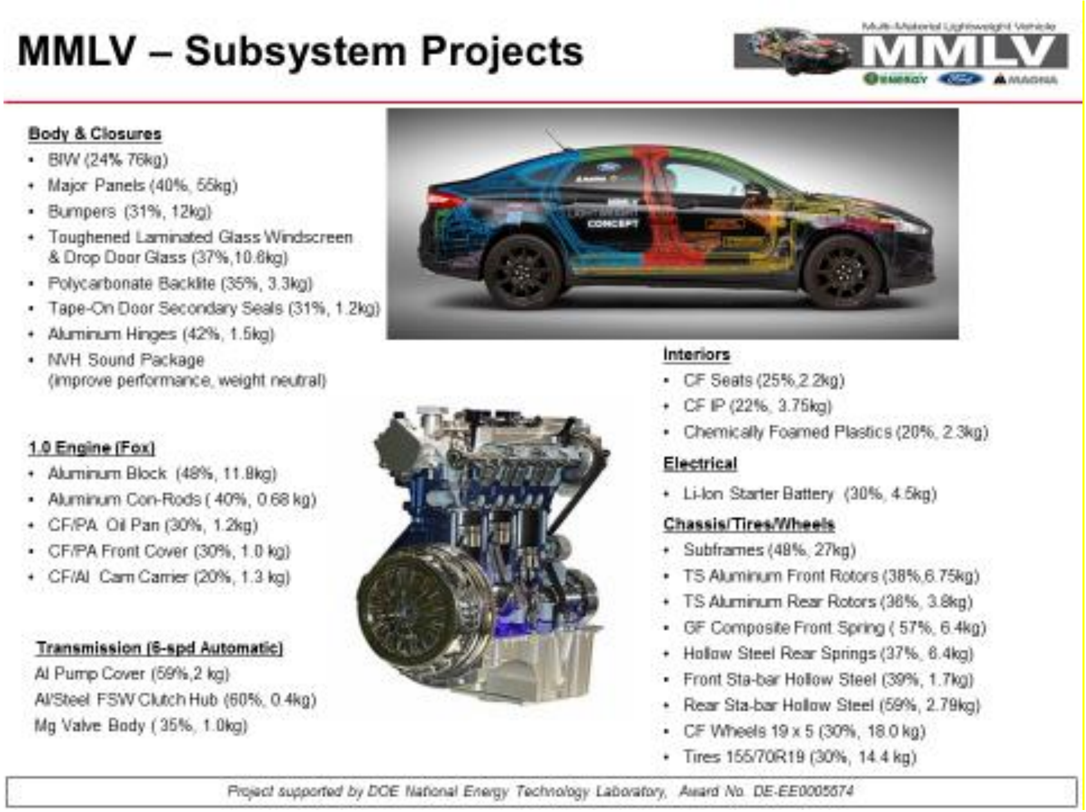


Figure B.56 MMLV - Subsystem Projects[139]

The BIW was light-weighted from 96 percent steel and 4 percent hot stamped steel to a design of 64 percent aluminum, 29 percent steel and 7 percent hot stamped steel, see Figure B.57.[140] Overall, the vehicle project achieved 23.3 percent mass reduction. Eight vehicles were designed and built and underwent durability (crash, corrosion, mileage, etc.). The crash plan is outlined in Figure B.57. All crash, durability and performance testing results met or exceeded expectations.[140]

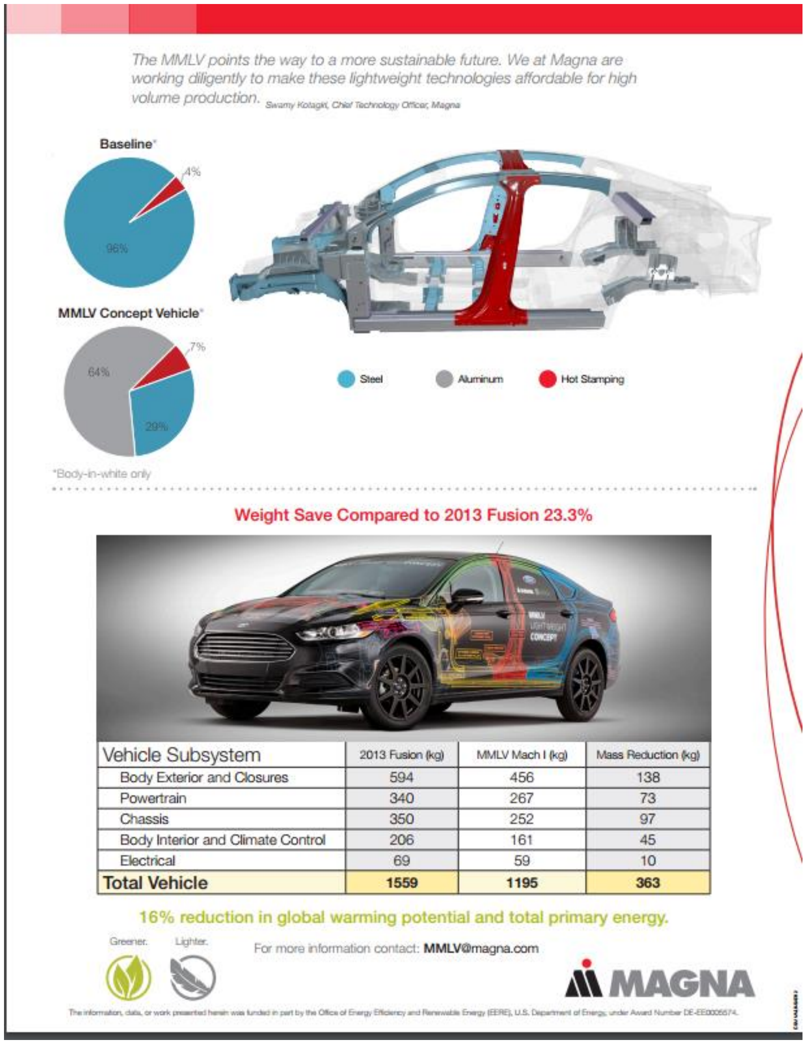


Figure B.57 MMLV Mach 1 BIW Design and Overall Mass Reduction Summary[140]

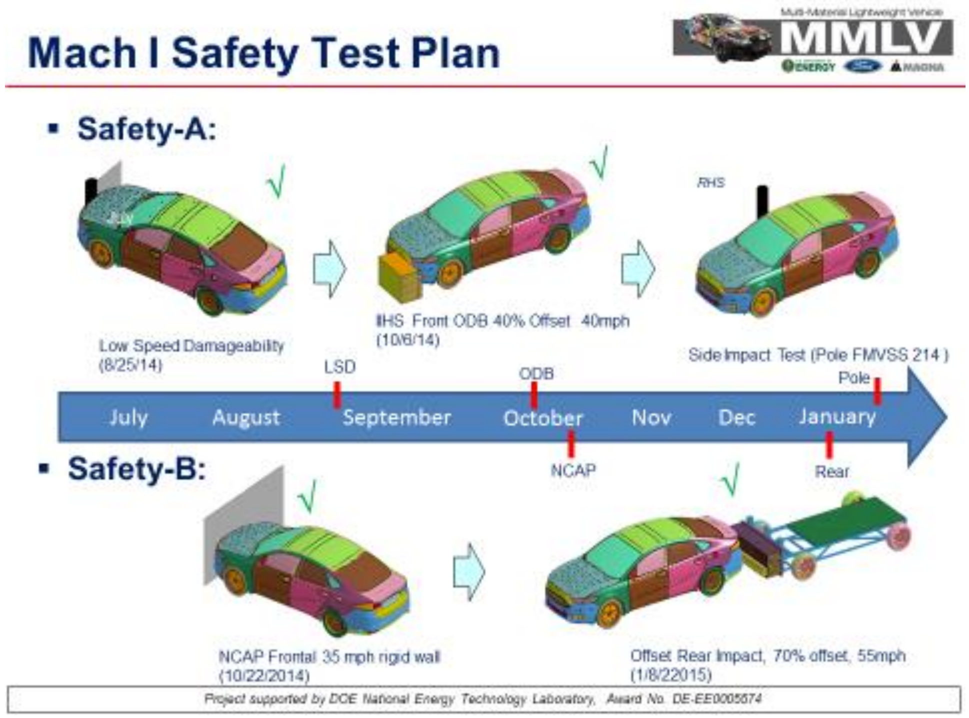


Figure B.58 Mach I Crash Safety Test Plan[139]

LACKS WHEEL TRIM SYSTEM (http://www.evolvehybrid.com/)

Lacks Wheel Trim system is located in Novi, MI and was founded in 1961. Its Global Partners include BMW, Daimler AG, Fiat Chrysler Automobiles, Ford, Freightliner, General Motors, Honda, Nissan, Tesla Motors, Toyota Group and Volkswagen Group. LWTS has developed the eVOLVE™ Wheel. This wheel design balances a lightweight structure with optimal aerodynamics. The wheel has at its core an optimized lighweight aluminum structure which is then covered by an optimal aero composite design cover. One design was made for the Ford Focus. The production wheel weighed 23.7 lbs. and eVOLVE™ wheel resulted in a mass of 19.20 lbs. The study revealed a fuel economy effect of City: +0.4 mpg, Highway + 1.1 mpg (http://www.evolvehybrid.com/fuelefficiency1.html). In addition to lightweight, turbulence management is achieved by the composite cover and this cover can be changed per OEM specs without changing the base wheel underlay design which saves R&D time. The composite cover also adds visual aesthetics for appearance purposes.

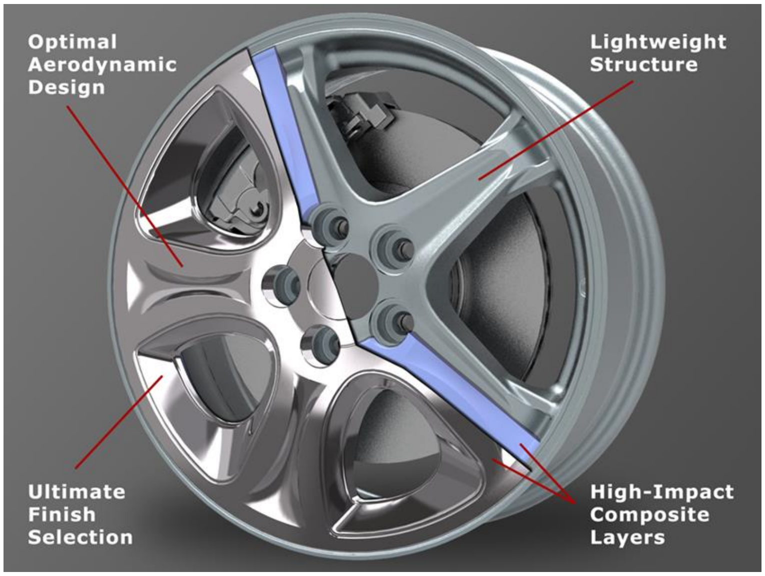


Figure B.59 Lacks Wheel Trim System eVOLVE™ Wheel

http://www.evolvehybrid.com/Resources/eVOLVE_Cutaway(lg).jpg

2017 Chrysler Pacifica Magnesium/Aluminum Liftgate

http://blog.fcanorthamerica.com/2016/01/11/chryslers-pacifica-minivan-is-new-from-the-ground-up/. Combining Magnesium with Aluminum easier than Magnesium with Steel due to the added mass of sealant needed with Steel for corrosion inhibition.

B.9 Additional Vehicle Level Cost Analysis

A presentation was given by IBIS Associates, Inc., Energetics Inc., and Idaho National Laboratory, at the 2016 DOE AMR in June of 2016, on "Vehicle Lightweighting: Mass Reduction Spectrum Analysis and Process Cost Modeling."[141] This information was not able to be considered in the cost curve modeling or methodology for cost curve application due to the time of availability of the work. The work examined Low, Moderate and Higher risk mass reduction technologies including their mass save and their cumulative $/lb. Multiple lightweighting strategies from various vehicle mass reduction programs were reviewed for each scenario (Low, Moderate, and High). Results are shown in the following figures: Figure B.60, Figure B.61, Figure B.62, and Figure B.63. Overall, the work listed the following for a midsize vehicle:

- Low Risk on a midsize vehicle would be 17 percent mass save with cost of weight save being $0-$2.00/lb. This would be achieved with increased aluminum, moderate price premium and low technical risk.

- Medium Risk would be 27 percent mass savings with a best case cost of $2.00/lb. This would be achieved with increased magnesium, component redesign, system downsizing, lightweight interior materials and glazing.

- High Risk would be for levels to achieved 45 percent mass reduction with cost of \$7.00/lb and requires carbon fiber at significantly reduced cost per pound, extensive use of Magnesium, advanced electrical and interior systems, consumer acceptance of some de-contenting.

The report also listed 7 percent improvement in fuel efficiency for 10 percent mass reduction.[E]

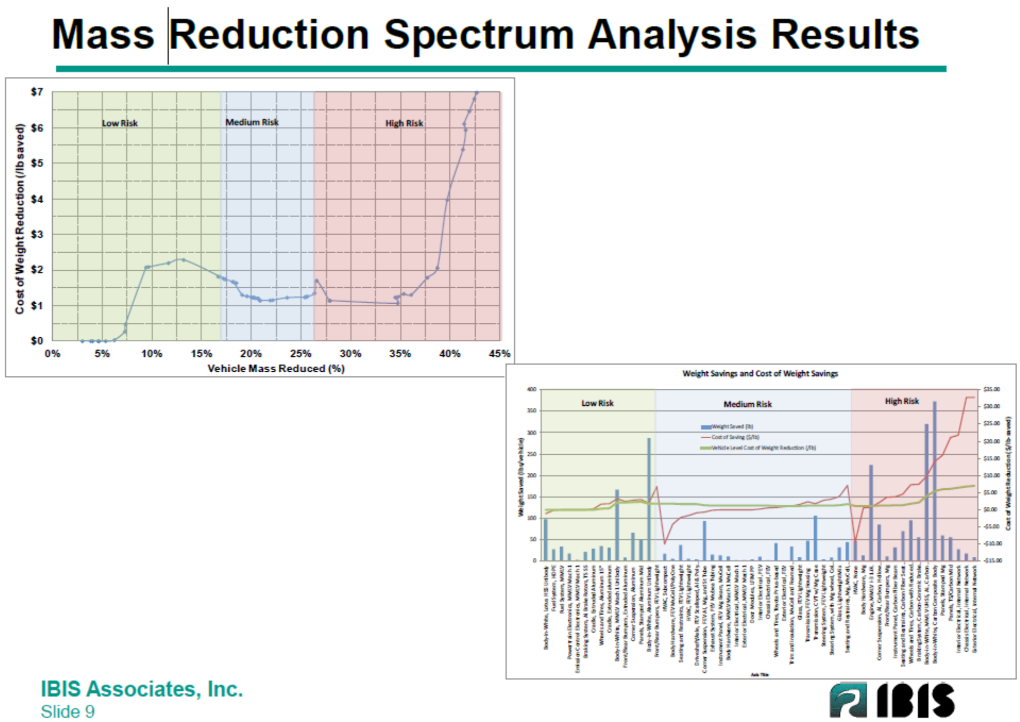


Figure B.60 Mass Reduction Spectrum Analysis Results, IBIS Associates, Inc. [141]

[E] To relate this to reduction in CO_2, the fuel economy (base and new) would each be put into reciprocal expression (1/x) and then percentage determined. This is typically less than the fuel economy change in percentage.

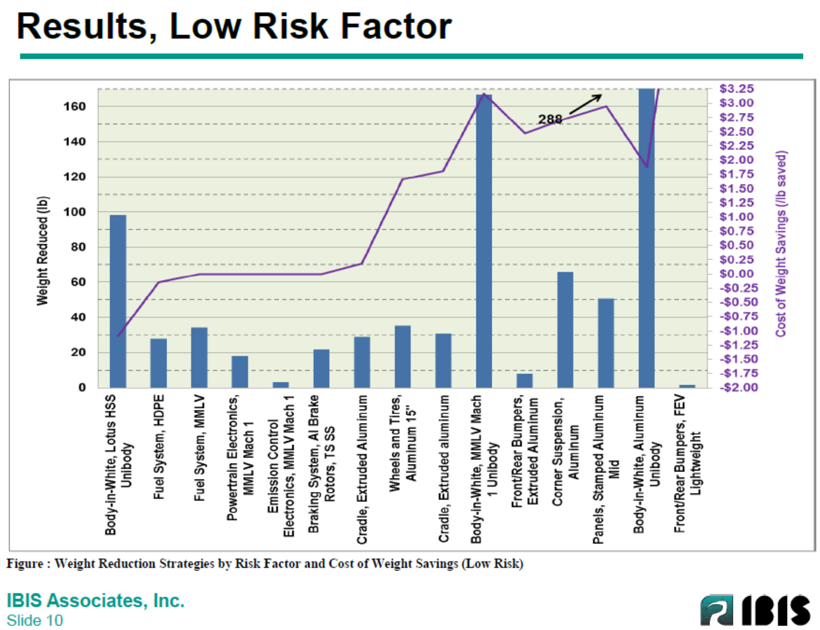


Figure B.61 Results, Low Risk Factor (lb, \$/lb) by IBIS Associates, Inc.[141]

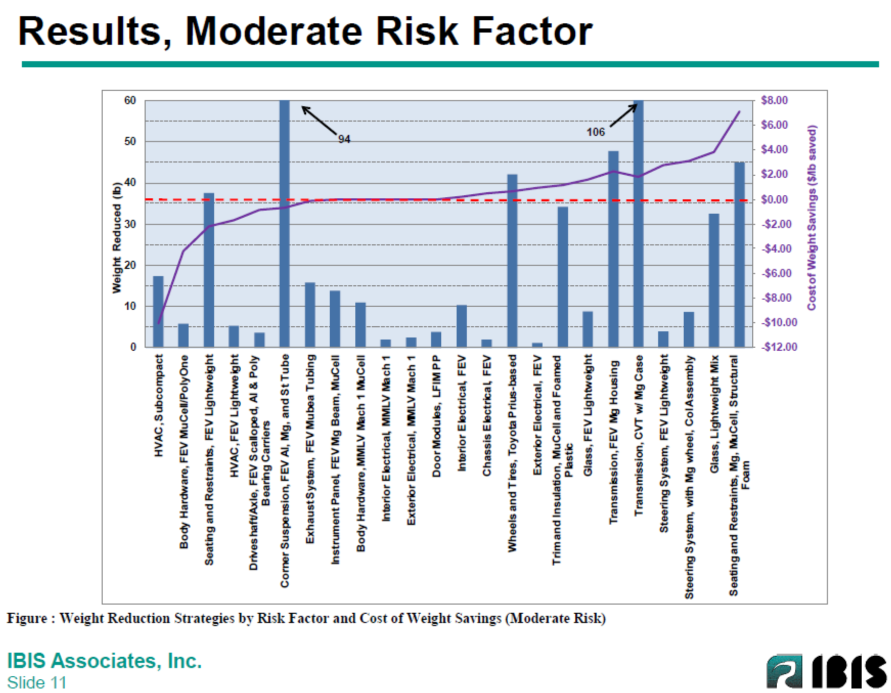


Figure B.62 Results, Moderate Risk Factor (lb, \$/lb) by IBIS Associates, Inc.[141]

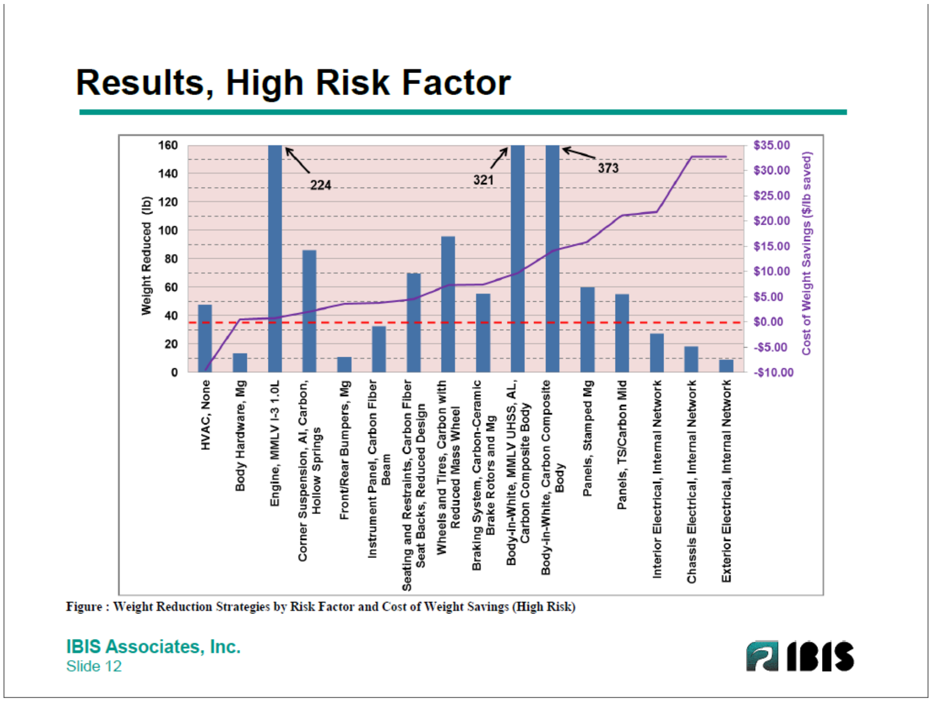


Figure B.63 Results, High Risk Factor (lb, $/lb) by IBIS Associates, Inc[141]

B.10 Mass Reduction Technology Adoption Trends in the Marketplace

Mass reduction is one technology which can involve a number of aspects of a vehicle and as such can require consideration of a number of factors including addressing new material adoption issues, addressing crash safety (CAE material modeling and vehicle crash correlation), vehicle cost optimization, etc. which take time to adopt and analyze. We also do not expect the adoption of mass reduction technologies to be the same across all OEMs since the strategy to meet the GHG/CAFÉ standards are OEM specific. Several vehicles are illustrated in the figures below which show the trends for these popular vehicles since the 2008 era. A number of lightweight technologies have been adopted in the 2016 Honda Civic (Figure B.64) and the 2016 Chevy Malibu (Figure B.65). The trend in lightweighting shows the release following the MY2008 model (ex: MY2014) was typically similar in footprint and mass than the MY2008 model and the next release (ex: MY2016) is larger and slightly notably lighter than the previous model. Some of the mass reduction savings is offset with increased vehicle dimensions and mass for additional safety requirements. Some OEM's also incorporate improved NVH and aerodynamics as a part of the latest OEM offerings.

Attribute	2008 (2005-2011)	2014 (2012-2015)	2016
Wheelbase	106.3	105.1	106.3
Track width	59, 60.2	59-59.2, 59.9	60.9-61.5
Footprint	43.6	43.4	45.2
Curb Weight	2628-2945	2749-3002	2742-2923
Length	176.7-177.8	177.3-179.4	182.3
Height	53.5-56.5	55-56.5	54.9-55.7
Width	68.9-69	69	70.8
mpg	26 city/34 hwy	31 city/41 hwy	31 city/42 hwy

Figure B.64 Images and Specifics of Honda Civic Sedan (2008, 2014, 2016)[142]

Attribute	2008 (2008-2012)	2014 (2013-2015)	2016
Wheelbase	112.3	107.8	111.4
Track width	59.6,60	62.2,62	62.6,62.5
Footprint	46.6	46.5	48.4
Curb Weight	3415-3649	3393-3660	3086-3388
Length	191.8	191.5	193.8
Height	57.7	57.6	57.6
Width	70.3	73	73
mpg	22 city/32 hwy	25 city/36 hwy	27 city/37 hwy

Figure B.65 Images and Specifics of Chevy Malibu (2008, 2014, 2016)[143]

Adoption of lightweight technology for light duty pickup trucks through 2016 includes slight lightweighting of the MY2014 Silverado 1500 with AHSS and a few aluminum technologies as well as the vehicle redesign and adoption of aluminum intensive technologies in the MY2015 F150. Both of these vehicles are also slightly larger in vehicles dimensions and greater performance.

Appendix C EPA's OMEGA Model

Applying technologies efficiently to the wide range of vehicles produced by various manufacturers is a challenging task. In order to assist in this task, EPA is again using a computerized program called the Optimization Model for reducing Emissions of Greenhouse gases from Automobiles (OMEGA). Broadly, OMEGA starts with a description of the future vehicle fleet, including manufacturer, sales, base CO_2 emissions, footprint and the extent to which emission control technologies are already employed. For the purpose of this analysis, EPA uses OMEGA to analyze over 200 vehicle platforms which encompass approximately 1300 vehicle models in order to capture the important differences in vehicle and engine design and utility of future vehicle sales of roughly 15-17 million units annually in the 2021-2025 timeframe.[F] The model is then provided with a list of technologies which are applicable to various types of vehicles, along with the technologies' cost and effectiveness and the percentage of vehicle sales which can receive each technology during the redesign cycle of interest. The model combines this information with economic parameters, such as fuel prices and a discount rate, to project how various manufacturers would apply the available technology in order to meet increasing levels of emission control. The result is a description of which technologies are added to each vehicle platform, along with the resulting cost. The model can also be set to account for various types of compliance flexibilities.[G]

EPA has described OMEGA's specific methodologies and algorithms previously in the model documentation,[144] the Draft TAR version of the model is publically available on the EPA website at https://www3.epa.gov/otaq/climate/models.htm, and it has been peer reviewed.[145]

C.1 OMEGA Pre-Processors, Vehicle Types & Packages

Individual technologies can be used by manufacturers to achieve incremental CO_2reductions. However, EPA believes that manufacturers are more likely to bundle technologies into "packages" to capture synergistic aspects and reflect progressively larger CO_2reductions with additions or changes to any given package. In addition, manufacturers typically apply new technologies in packages during model redesigns that occur approximately once every five years. This way, manufacturers can more efficiently make use of their redesign resources and more effectively plan for changes necessary to meet future standards.

Therefore, the approach taken by EPA is to group technologies into packages of increasing cost and effectiveness. Costs for the packages are a sum total of the costs for the technologies included. Importantly, the package costs and effectiveness represent those respective values relative to a "null" package of technologies. That "null" package consists of a fixed valve, port fuel injected engine mated to a 4 speed automatic transmission and having a declared 0 percent level of mass reduction. This "null" package is not meant to reflect an actual vehicle, but rather a technology "zero cost floor" or "zero effectiveness floor" from which costs and effectiveness of packages can be measured. This way, the technology package cost and effectiveness for the set

[F] EPA's analysis fleet actually contains roughly 2200 vehicle models, but many of those are the result of very minor differences in footprint and not truly different models.

[G] While OMEGA can apply technologies which reduce CO_2 efficiency related emissions and refrigerant leakage emissions associated with air conditioner use, this task is currently handled outside of the OMEGA core model. A/C improvements are highly cost-effective, and would always be added to vehicles by the model, thus they are simply added into the results at the projected penetration levels.

of technologies on any actual vehicle can be determined relative to the null, an OMEGA package cost and effectiveness can then be calculated relative to the null, and the delta between the actual vehicle package and the OMEGA package can then be easily calculated. Effectiveness is somewhat more complex, as the effectiveness of individual technologies cannot simply be summed. To quantify the CO_2 (or fuel consumption) effectiveness, EPA relies on ALPHA and the Lumped Parameter Model, which are described in greater detail in Section 5 of this Draft TAR.

C.1.1 Vehicle Types

As was done in the 2012 FRM, EPA uses 19 different vehicle types to represent the entire fleet in OMEGA. This was the result of analyzing the existing light-duty fleet with respect to vehicle size and powertrain configurations. All vehicles, including cars and trucks, were first distributed based on their relative size (i.e., vehicle class), starting from compact cars and working upward to large trucks. Next, each vehicle was evaluated for powertrain, specifically the engine size, I4, V6, and V8, then by valvetrain configuration (DOHC, SOHC, OHV), and finally by the number of valves per cylinder. We further designate some vehicle types as towing vehicle types and some as non-towing vehicle types. This towing/non-towing determination impacts the types of packages made available to specific vehicle within each vehicle type since only non-towing vehicle types are considered to be appropriate for electrification beyond strong HEV (i.e., to plug-in HEV or full BEV).

For this Draft TAR, EPA has used the same 19 vehicle types as were used in the 2012 FRM with the exception that vehicle type 18, a large pickup truck vehicle type in the 2012 FRM, is now designated as a large MPV vehicle type. The implication to that change is slightly different effectiveness and cost values for vehicles mapped into that vehicle type since large MPV (or large SUV) values differ from the large truck values. EPA believes (at this time) that these 19 vehicle types broadly encompass the diversity in the fleet as the analysis is appropriate for "average" vehicles Each of these 19 vehicle types is mapped into one of six vehicle classes: Small car, Standard car, Large car, Small MPV, Large MPV, and Truck.

As such, the six OMEGA vehicle classes serve primarily to determine the effectiveness levels of new technologies by determining which vehicle class is chosen within the lumped parameter model (see sections 1.4 and 1.5 below). So, any vehicle models mapped into a Large MPV vehicle type will get technology-specific effectiveness results for that vehicle class. The same is true for vehicles mapped into the other vehicle classes. Similarly, any vehicle models mapped into a Large MPV vehicle type will get technology-specific cost results for that vehicle class. The same is true for vehicles mapped into the other vehicle classes. This is true only for applicable technologies, i.e., those costs developed on a vehicle class basis such as advanced diesel, hybrid and other electrified powertrains. Note that most technology costs are not developed according to vehicle classes but are instead developed according to engine size, valvetrain configuration, etc. A detailed table showing the 19 vehicle types, their baseline engines, their descriptions and some example models for each is contained in the table below.

Table C.1 List of 19 Vehicle Types used to Model the Light-duty Fleet

Vehicle Type #	Base Engine	Base Trans	Vehicle Class	Description	Example Models	Towing?
1	I4 DOHC 4v	4sp AT	Small car	Subcompact car I4	Ford Fiesta, Chevy Sonic, Toyota Yaris	No
2	I4 DOHC 4v	4sp AT	Standard car	Compact car I4	Ford Focus, Chevy Cruze, Toyota Corolla	No
3	V6 DOHC 4v	4sp AT	Standard car	Midsize car V6	Ford Fusion, Chevy Malibu, Toyota Camry	No
4	V6 SOHC 2v	4sp AT	Standard car	Midsize car V6	Honda Accord, Acura TL	No
5	V8 DOHC 4v	4sp AT	Large car	Large car V8	Ford Mustang, Cadillac CTS, Lexus LS460	No
6	V8 OHV 2v	4sp AT	Large car	Large car V8	Chevy Corvette, Chevy Camaro	No
7	I4 DOHC 4v	4sp AT	Small MPV	Small MPV I4	Ford Escape, Chevy Equinox, Toyota RAV4	No
8	V6 DOHC 4v	4sp AT	Large MPV	Midsize MPV V6	Ford Edge, Chevy Equinox, Toyota FJ Cruiser	Yes
9	V6 SOHC 2v	4sp AT	Large MPV	Midsize MPV V6	Acura MDX, Honda Pilot	Yes
10	V6 OHV 2v	4sp AT	Large MPV	Midsize MPV V6	Chevy 1500 Express Van	Yes
11	V8 DOHC 4v	4sp AT	Truck	Large MPV V8	Ford E350 Van, Toyota Land Cruiser, Jeep Grand Cherokee	Yes
12	V8 OHV 2v	4sp AT	Truck	Large MPV V8	Dodge Durango, Chevy Tahoe	Yes
13	I4 DOHC 4v	4sp AT	Small MPV	Small truck I4	Nissan Frontier, Toyota Tacoma	No
14	V6 DOHC 4v	4sp AT	Large MPV	Full-sized Pickup truck V6	Ram 1500, Ford F150, Toyota Tacoma	Yes
15	V6 OHV 2v	4sp AT	Large MPV	Full-sized Pickup truck V6	Chevy Silverado, Honda Ridgeline	Yes
16	V8 DOHC 4v	4sp AT	Truck	Full-sized Pickup truck V8	Ram 1500, Ford F150, Nissan Titan, Toyota Tundra	Yes
17	V8 SOHC 2v	4sp AT	Truck	Full-sized Pickup truck V8	Ford F150 SuperCab, Ford Raptor Pickup	Yes
18	V8 SOHC 3v	4sp AT	Large MPV	Large MPV V8	Ford Expedition, Lincoln Navigator	Yes
19	V8 OHV 2v	4sp AT	Truck	Full-sized Pickup truck V8	Ram 1500, Chevy Silverado, GMC Sierra	Yes

Note: I4=inline 4 cylinder; V6/8=V-configuration 6/8 cylinder; DOHC=dual overhead cam; SOHC=single overhead cam; OHV=overhead valve; 4v/3v/2v=4/3/2 valves per cylinder; sp=speed; AT=automatic transmission; MPV=multi-purpose vehicle.

C.1.2 Technology Packages, Package Building & Master-sets

Importantly, the effort in creating the packages attempts to maintain a constant utility and acceleration performance for each package as compared to the baseline package. As such, each package is meant to provide equivalent driver-perceived performance to the baseline package. There are two possible exceptions. The first is the towing capability of vehicle types which we have designated "non-towing." This requires a brief definition of what we consider to be a towing vehicle versus a non-towing vehicle. Nearly all vehicles sold today, with the exception of the smaller subcompact and compact cars, are able to tow up to 1,500 pounds provided the vehicle is equipped with a towing hitch. These vehicles require no special OEM "towing package" of add-ons which typically include a set of more robust brakes and some additional transmission cooling. We do not consider such vehicles to be towing vehicles. We reserve that term for those vehicles capable of towing significantly more than 1,500 lbs. For example, a base model Ford Escape can tow 1,500 pounds while the V6 equipped towing version can tow up to 3,500 pounds. The former would not be considered a true towing vehicle while the latter would. Note that all large trucks and large MPV vehicle classes are considered towing vehicles in our analysis.

We do not address towing at the vehicle level. Instead, we deal with towing at the vehicle type level. The importance of this distinction can be found in the types of hybrid and plug-in hybrid technologies we apply to towing versus non-towing vehicle types.[H] For the towing vehicle types, we apply a P2 hybrid technology with a turbocharged and downsized gasoline direct injected engine. These packages are expected to maintain equivalent towing capacity to the baseline engine they replace. For the non-towing vehicle types, we apply a P2 hybrid technology with an Atkinson engine (not an Atkinson-2 engine) that has not been downsized relative to the baseline engine. The Atkinson engine, more correctly called the "Atkinson-cycle" engine, is used in the current Toyota Prius and Ford Escape hybrid. We have maintained the original engine size (i.e., no downsizing) to maintain utility as best as possible, but EPA acknowledges that due to its lower power output, an Atkinson cycle engine cannot tow loads as well as a standard Otto-cycle engine of the same size. However, the presence of the hybrid powertrain would be expected to maintain towing utility for these vehicle types in all but the most severe operating extremes. Such extremes would include towing in the Rocky Mountains (i.e., up very long duration grades) or towing up Pike's Peak (i.e., up a shorter but very steep grade). Under these extreme towing conditions, the battery on a hybrid powertrain would eventually cease to provide sufficient supplemental power and the vehicle would be left with the Atkinson engine doing all the work. A loss in utility would result (note that the loss in utility should not result in breakdown or safety concerns, but rather loss in top speed and/or acceleration capability). Importantly, those towing situations involving driving outside mountainous regions would not be affected.

The second possible exception to our attempt at maintaining utility is the electric vehicle range. We have built electric vehicle packages with ranges of 75, 100 and 200 miles. Clearly these vehicles would not provide the same utility as a gasoline vehicle which typically has a range of over 300 miles. However, from an acceleration performance standpoint, the utility would be equal to if not perhaps better than the gasoline vehicle. We believe that buyers of electric vehicles in the MYs 2021-2025 timeframe will be purchasing the vehicles with a full understanding of the range limitations and will not attempt to use their EVs for long duration

[H] This towing/non towing distinction is not an issue for non-HEVs, EPA maintains whatever towing capability existed in the baseline when adding/substituting technology.

trips, at least not without first determining their refueling strategy. As such, we believe that the buyers of EVs will experience no loss of expected utility.

To prepare inputs for the OMEGA model, EPA builds "master-sets" of technology packages.[I] The master-set of packages for each vehicle type are meant to reflect both appropriate groupings of technologies (e.g., we do not apply turbochargers unless an engine has dual overhead cams, some degree of downsizing, direct injection and dual cam phasing) and limitations associated with penetration caps (see joint TSD 3.5 and the brief discussion in Section C.1.3). We then filter that list by determining which packages provide the most cost effective groups of technologies within each vehicle type—those that provide the best trade-off of costs versus CO_2 reduction improvements. This is done by ranking those groupings based on the Technology Application Ranking Factor (TARF). The TARF is the factor used by the OMEGA model to rank packages and determine which are the most cost effective to apply. The TARF is calculated as the net incremental cost (or savings) of a package per kilogram of CO_2 reduced by the package relative to the previous package. The net incremental cost is calculated as the incremental cost of the technology package less the incremental discounted fuel savings of the package over 5 years. The incremental CO_2 reduction is calculated as the incremental CO_2 /mile emission level of the package relative to the prior package multiplied by the lifetime miles travelled. More detail on the TARF can be found in the OMEGA model supporting documentation (see EPA-420-B-10-042). We also describe the TARF ranking process in more detail below. Grouping "reasonable technologies" simply means grouping those technologies that are complementary (e.g., turbocharging plus downsizing) and not grouping technologies that are not complementary (e.g., dual cam phasing and coupled cam phasing).

To generate the master-set of packages for each of the vehicle types, EPA has built packages in a step-wise fashion looking first at "simpler" conventional gasoline and vehicle technologies, then more advanced gasoline technologies such as turbocharged (with varying levels of boost) and downsized engines with gasoline direct injection and then hybrid and other electrified vehicle technologies. This was done by assuming that auto makers would first concentrate efforts on conventional gasoline engine and transmission technologies paired with some level of mass reduction to improve CO_2 emission performance. Mass reduction varied from no mass reduction up to 20 percent as the maximum considered in this analysis.[J]

Once the conventional gasoline engine and transmission technologies have been fully implemented, we expect that auto makers would apply more complex (and costly) technologies such as turbocharged and downsized gasoline engines and/or converting conventional gasoline engines to advanced diesel engines in the next redesign cycle.

[I] We build a master-set of packages for each model year for which we run OMEGA because penetration caps result in different technologies being available and costs change over time resulting in different costs every year.

[J] Importantly, the mass reduction associated for each of the 19 vehicle types was based on the vehicle-type sales weighted average curb weight. Although considerations of vehicle safety are an important part of EPA's consideration in establishing the standards, note that allowable weight reductions giving consideration to safety is not part of the package building process so we have built packages for the full range of 0-20% weight reduction considered in this analysis. Weight consideration for safety is handled within OMEGA as described in Chapter 8 of this Draft TAR.

From there, auto makers needing further technology penetration to meet their individual standards would most likely move to hybridization, both mild and strong hybrids. For this analysis, we have built all of our mild hybrid packages using the newly emerging 48 Volt technology. We have built two types of strong hybrid packages for this Draft TAR analysis, consistent with the 2012 FRM. The first type is for non-towing vehicle types and uses an Atkinson-cycle engine with no downsizing relative to the baseline engine. The second P2 hybrid type is for towing vehicle types and uses a turbocharged and downsized engine (rather than an Atkinson-cycle engine) to ensure no loss of towing capacity.[K]

Lastly, for some vehicle types (i.e., the non-towing vehicle types), we anticipate that auto makers would move to more advanced electrification in the form of both plug-in hybrid (PHEV, sometimes referred to as range extended electric vehicles (REEV)) and full battery electric vehicles (EV).

Importantly, the HEV, PHEV and EV (called collectively P/H/EV) packages here take into consideration the impact of the weight of the electrified components, primarily the battery packs. Because these battery packs can be quite heavy, if one removes 20 percent of the mass from a gasoline vehicle but then converts it to an electric vehicle, the resultant net weight reduction will be less than 20 percent. We discuss this in more below where we provide additional discussion regarding the P/H/EV packages.

The result of this package building process is a set of "Package List" files, one for MY2021 and one for MY2025. These package list files provide a description of each package, a unique package number for that package which follows that package throughout the OMEGA process within a given model year, and details of each technology and associated codes within each package. The distinction being made here is that the package description may include dual cam phasing (DCP), but the package details might indicate DCP on a V6 engine for one package, and DCP on an I4 engine for another package in the same vehicle type since this second package includes turbocharging and downsizing. The package list files used as part of EPA's Draft TAR analysis are contained in the docket and on our website at [link] and the step-by-step process is detailed below.

In building MY2021 packages, we proceed according to the following sequence of steps for non-towing vehicle types (note that underlined technologies are simply meant to guide the reader to differences between technologies included in packages):

1) With no mass reduction:
   a) With TRX11 & again with TRX12 (2 packages):
      i) Low friction lubes, engine friction reduction level 1, improved accessories level 1, electric power steering, lower rolling resistance tires level 1, passive aero, low drag brakes, variable valve timing
   b) With TRX11 & again with TRX12 (2 packages):

[K] Note that the Atkinson-cycle engine used in strong HEVs is not the same high compression ratio Atkinson-cycle engine EPA refers to as Atkinson-2 in Chapters 5 and 12 of this Draft TAR.

   i) Low friction lubes, engine friction reduction level 1, improved accessories level 1, electric power steering, lower rolling resistance tires level 1, passive plus active aero, low drag brakes, variable valve timing

c) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 1, improved accessories level 2, electric power steering, lower rolling resistance tires level 1, passive plus active aero, low drag brakes, variable valve timing

d) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 1, improved accessories level 1, electric power steering, lower rolling resistance tires level 2, passive aero, low drag brakes, variable valve timing

e) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 1, improved accessories level 1, electric power steering, lower rolling resistance tires level 2, passive plus active aero, low drag brakes, variable valve timing

f) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 1, improved accessories level 2, electric power steering, lower rolling resistance tires level 2, passive plus active aero, low drag brakes, variable valve timing

g) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 2, improved accessories level 1, electric power steering, lower rolling resistance tires level 2, passive aero, low drag brakes, variable valve timing

h) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 2, improved accessories level 1, electric power steering, lower rolling resistance tires level 2, passive plus active aero, low drag brakes, variable valve timing

i) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 2, improved accessories level 2, electric power steering, lower rolling resistance tires level 2, passive plus active aero, low drag brakes, variable valve timing

j) Steps 1.a through 1.i with cylinder deactivation (18 packages)

k) Steps 1.a through 1.i with gasoline direct injection (18 packages)

l) Steps 1a. through 1.i with cylinder deactivation and gasoline direct injection (18 packages)

m) Steps 1.a through 1.l with stop-start (72 packages)

- n) Steps 1.a through 1.m with secondary axle disconnect (144 packages)
- o) Any package in Steps 1.a through 1.m that includes gasoline direct injection, add Atkinson-2 (144 packages)
- p) Step 1.o, add cooled EGR (144 packages)
- q) Any package in Steps 1.a through 1.m that includes gasoline direct injection, replace cylinder deactivation with discrete variable valve lift and add turbo-downsize 18-bar (144 packages)
- r) Any package in Steps 1.a through 1.m that includes gasoline direct injection, replace cylinder deactivation with discrete variable valve lift and add turbo-downsize 24-bar plus cooled EGR (144 packages)
- s) Any package in Steps 1.a through 1.m that includes gasoline direct injection, add Miller-cycle plus cooled EGR (144 packages)
- t) Step 1.a through 1.s with TRX21 & again with TRX22 (1008 packages)

2) With 5percent mass reduction
   - a) Repeat Step 1 (2016 packages)
   - b) Step 2.a packages with improved accessories level 2, add mild HEV 48V (336 packages)
   - c) Step 2.a packages with gasoline direct injection, engine friction reduction level 2 and lower rolling resistance tires level 2, add advanced diesel (24 packages)
3) With 10percent mass reduction
   - a) Repeat Step 2 (2376 packages)
   - b) Step 3.a packages with improved accessories level 1 and no advanced diesel, add strong HEV (48 packages)
4) With 15percent mass reduction
   - a) Repeat Step 3 (2424 packages)
5) With 20percent mass reduction
   - a) Build PHEV20 & PHEV40 (REEV20 & REEV40) (2 packages)
   - b) Build EV75, EV100, EV200 (3 packages)

In building MY2021 packages, we proceed according to the following sequence of steps for towing vehicle types:

6) Repeat Steps 1 & 2 from the non-towing sequence (4392 packages)
7) With 10percent mass reduction
   - a) Repeat Step 2 (2376 packages)

   b) Step 7 packages with improved accessories level 1, turbocharging and downsizing, but without mild HEV 48V and without advanced diesel, add strong HEV (96 packages)

8) With 15percent mass reduction

   a) Repeat Step 7 (2472 packages)

In building MY2025 packages, we proceed according to the following sequence of steps for non-towing vehicles types (note that underlined technologies are simply meant to guide the reader to differences between technologies included in packages; note also that the presence of fewer penetration caps in MY2025 means less iteration on first level technologies resulting in fewer sub-steps within Step 1):

1) With no mass reduction

   a) With TRX11 & again with TRX12 (2 packages):

      i) Low friction lubes, engine friction reduction level 1, improved accessories level 1, electric power steering, lower rolling resistance tires level 1, passive aero, low drag brakes, variable valve timing

   b) With TRX11 & again with TRX12 (2 packages):

      i) Low friction lubes, engine friction reduction level 1, <u>improved accessories level 2</u>, electric power steering, lower rolling resistance tires level 1, passive plus <u>active aero</u>, low drag brakes, variable valve timing

   c) With TRX11 & again with TRX12 (2 packages):

      i) Low friction lubes, <u>engine friction reduction level 2</u>, improved accessories level 1, electric power steering, <u>lower rolling resistance tires level 2</u>, passive aero, low drag brakes, variable valve timing

   d) With TRX11 & again with TRX12 (2 packages):

      i) Low friction lubes, <u>engine friction reduction level 2</u>, <u>improved accessories level 2</u>, electric power steering, <u>lower rolling resistance tires level 2</u>, passive plus <u>active aero</u>, low drag brakes, variable valve timing

   e) Steps 1.a through 1.d, with cylinder deactivation (8 packages)

   f) Steps 1.a through 1.d, with gasoline direct injection (8 packages)

   g) Steps 1.a through 1.d, with cylinder deactivation and gasoline direct injection (8 packages)

   h) Steps 1.a through 1.g with stop-start (32 packages)

   i) Steps 1.a through 1.h with secondary axle disconnect (64 packages)

   j) Any package in Steps 1.a through 1.i that includes gasoline direct injection, add Atkinson-2 (64 packages)

   k) Step 1.j, add cooled EGR (64 packages)

l) Any package in Steps 1.a through 1.i that includes gasoline direct injection, replace cylinder deactivation with discrete variable valve lift and add turbo-downsize 18-bar (64 packages)

m) Any package in Steps 1.a through 1.m that includes gasoline direct injection, replace cylinder deactivation with discrete variable valve lift and add turbo-downsize 24-bar plus cooled EGR (64 packages)

n) Any package in Steps 1.a through 1.m that includes gasoline direct injection, add Miller-cycle plus cooled EGR (64 packages)

o) Step 1.a through 1.n with TRX21 & again with TRX22 (448 packages)

2) With 5percent mass reduction

   a) Repeat Step 1 (896 packages)

   b) Step 2.a packages with improved accessories level 2, add mild HEV 48V (224 packages)

   c) Step 2.a packages with gasoline direct injection, engine friction reduction level 2 and lower rolling resistance tires level 2, add advanced diesel (16 packages)

3) With 10percent mass reduction

   a) Repeat Step 2 (1136 packages)

   b) Step 3.a packages with improved accessories level 1 and no advanced diesel, add strong HEV (16 packages)

4) With 15percent mass reduction

   a) Repeat Step 3 (1152 packages)

5) With 20percent mass reduction

   a) Repeat Step 4 (1152 packages)

   b) Build PHEV20 & PHEV40 (REEV20 & REEV40) (2 packages)

   c) Build EV75, EV100, EV200 (3 packages)

In building MY2025 packages, we proceed according to the following sequence of steps for towing vehicles types:

6) Repeat Steps 1 & 2 from the non-towing sequence (2032 packages)

7) With 10percent mass reduction

   a) Repeat Step 2 (1136 packages)

   b) Step 7 packages with improved accessories level 1, turbocharging and downsizing, but without mild HEV 48V and without advanced diesel, add strong HEV (32 packages)

8) With 15percent mass reduction

   a) Repeat Step 7 (1168 packages)

9) With 20percent mass reduction

   a) Repeat Step 8 (1168 packages)

The package lists are then sent through EPA's TEB-CEB "Machine" which is the tool in the OMEGA process that brings together technology costs and technology effectiveness (via the Lumped Parameter Model) to determine package level costs and effectiveness. The TEB-CEB Machine calculates the Technology Effectiveness Basis and the Cost Effectiveness Basis of each package. With package level costs and effectiveness, we can then use the OMEGA Master-set generator tool to generate a Master-set of packages. The Master-set of packages adds to the package cost and effectiveness values the 5-year discounted fuel savings and lifetime CO_2 reductions for each package.[L] These additional metrics allow for calculation of a TARF for each unique package contained in the applicable package list. Importantly, in building packages and the Master-sets of packages, we have not yet considered the baseline fleet beyond the sales-weighted metrics of each of the 19 vehicle types. Instead, we have considered only appropriate groupings of technologies into packages and built packages and Master-sets based on the 19 vehicle types and the sales-weighted attributes of those vehicle types (e.g., CO_2 and curb weight).

C.1.3 Master-set Ranking & the Technology Input File

This master-set of packages is then ranked by TARF within vehicle type for each Master-set of packages necessary to represent the reference case and the control case. In this Draft TAR, this requires 4 Master-sets: Reference case in MY2021, Reference case in MY2025, Control case in MY2021 and Control case in MY2025. However, we can use the same Master-set for both the Reference case in MY2021 and the Control case in MY2021 since the same set of costs apply. The end result being a necessary set of 3 Master-sets for a given OMEGA run. Should any effectiveness or cost value, synergy factor, fuel price, etc., be changed, a different Master-set or group of Master-sets would be required.

The ranking process is handled by the OMEGA pre-processing Ranking Algorithm (contained in the docket) which calculates the TARF of each package relative to the sales-weighted representative package within a given vehicle type. The package with the best TARF is selected as OMEGA package #1 for that vehicle type. The remaining packages for the given vehicle type are then ranked again by TARF, this time relative to OMEGA package #1. The best package is selected as OMEGA package #2, etc.

An important consideration in the ranking process is the penetration caps which cannot be exceeded to ensure that the packages chosen by the ranking do not result in exceedance of the caps. As such, if package #2 contains a technology, for example TRX21, but the penetration cap for TRX21 is, say 60 percent, then only 60 percent of the population of vehicles in the given vehicle type would be allowed to migrate to package #2 with the remaining 40 percent left in package #1. We had a detailed discussion of penetration caps in Section 3.5 of the final joint TSD in support of the 2012 FRM.[146] For this Draft TAR, we have used the same penetration caps as presented there with the exception of adding a new penetration cap for the Atkinson-2 technology which was not considered in the 2012 FRM. For the new mild HEV 48V technology,

[L] These metrics are calculated using the sales weighted CO_2 level of all vehicles mapped into each specific vehicle type.

we have used the same penetration cap as used for the mild HEV technology described in the 2012 FRM. For the new Miller cycle technology we have used the 24-bar turbocharging penetration caps used in the 2012 FRM. The penetration caps used in this Draft TAR analysis are shown in the table below.

Table C.2 Penetration Caps used in OMEGA Central Analysis Runs

Tech code	Tech	2021	2025
Aero 1	Aero – passive	100%	100%
Aero 2	Aero – passive with active	80%	100%
ATK2	Atkinson-2	80%	100%
CCC	Camshaft configuration changes without downsizing	100%	100%
CCP	Coupled cam phasing	100%	100%
CVVL	Continuous variable valve lift	100%	100%
DCP	Dual cam phasing	100%	100%
Deac	Cylinder deactivation	100%	100%
DSL-Adv	Advanced diesel	30%	42%
DVVL	Discrete variable valve lift	100%	100%
EFR1	Engine friction reduction level 1	100%	100%
EFR2	Engine friction reduction level 2	60%	100%
EGR	Cooled exhaust gas recirculation	30%	75%
EPS	Electric power steering	100%	100%
EV75	Full battery electric vehicle 75 mile range	5%	8%
EV100	Full battery electric vehicle 100 mile range	5%	8%
EV200	Full battery electric vehicle 200 mile range	5%	8%
DI	Gasoline direct injection	100%	100%
IACC1	Improved accessories level 1	100%	100%
IACC2	Improved accessories level 2	80%	100%
LDB	Low drag brakes	100%	100%
LRRT1	Lower rolling resistance tires level 1	100%	100%
LRRT2	Lower rolling resistance tires level 2	75%	100%
LUB	Engine changes to accommodate low friction lubes	100%	100%
MHEV48V	Mild hybrid 48V	50%	80%
P2 or HEV	Strong hybrid	30%	50%
REEV20	Range extended or plug-in electric vehicle 20 mile range	8%	11%
REEV40	Range extended or plug-in electric vehicle 40 mile range	8%	11%
SAX	Secondary axle disconnect	100%	100%
Stop-start	Stop-start without electrification	100%	100%
TDS18	Turbocharging with downsizing 18-bar	100%	100%
TDS24	Turbocharging with downsizing 24-bar	30%	75%
TRX11	Transmission – step 1 or current generation	100%	100%
TRX12	TRX11 with improved efficiency	30%	100%
TRX21	Transmission – step 2 or TRX11 but with additional gear-ratio spread	80%	100%
TRX22	TRX21 with improved efficiency	30%	100%
TURBM	Miller cycle or ATK2 with turbocharging	30%	75%
WR10	Weight reduction of 10% from EPA's "null"	100%	100%
WR15	Weight reduction of 15% from EPA's "null"	100%	100%
WR20	Weight reduction of 20% from EPA's "null"	0%	100%

Also tracked are the credits available to the package which are also included in this ranking process.[M] The table below presents 2014 baseline data used in the TARF ranking process.

Table C.3 Lifetime VMT & Baseline CO_2 used for the TARF Ranking Process

Vehicle Type	Description	Base engine	Car/ Truck	2021MY Lifetime VMT	2025MY Lifetime VMT	Base CO_2 (g/mi)
1	Subcompact car I4	I4 DOHC 4v	C	181,389	185,782	201.5
2	Compact car I4	I4 DOHC 4v	C			219.9
3	Midsize car V6	V6 DOHC 4v	C			277.3
4	Midsize car V6	V6 SOHC 2v	C			266.3
5	Large car V8	V8 DOHC 4v	C			321.7
6	Large car V8	V8 OHV 2v	C			374.2
7	Small MPV I4	I4 DOHC 4v	C			269.6
8	Midsize MPV V6	V6 DOHC 4v	T	212,601	217,750	335.2
9	Midsize MPV V6	V6 SOHC 2v	T			316.0
10	Midsize MPV V6	V6 OHV 2v	T			445.9
11	Large MPV V8	V8 DOHC 4v	T			387.7
12	Large MPV V8	V8 OHV 2v	T			426.7
13	Small truck I4	I4 DOHC 4v	T			326.8
14	Full-sized Pickup truck V6	V6 DOHC 4v	T			377.3
15	Full-sized Pickup truck V6	V6 OHV 2v	T			357.2
16	Full-sized Pickup truck V8	V8 DOHC 4v	T			424.1
17	Full-sized Pickup truck V8	V8 SOHC 2v	T			535.6
18	Full-sized Pickup truck V8	V8 SOHC 3v	T			467.1
19	Full-sized Pickup truck V8	V8 OHV 2v	T			393.5

Note: C/T designation here only impacts lifetime VMT determination in calculating lifetime CO_2 reductions for packages.

Once a Master-set is ranked, the result is a Ranked-set of packages with a maximum of 50 packages for each vehicle type. This Ranked-set of packages is used to generate the Technology input file for the OMEGA core model and to generate the "Scenario packages" to be applied to vehicles within each vehicle type. In the Technology input file, the package progression, or "flow" of packages is included. The package progression is key because OMEGA evaluates each package in a one-by-one, or linear progression. The packages must be ordered correctly so that no single package will prevent the evaluation of the other packages. For example, if we simply listed packages according to increasing effectiveness, there could well be a situation where an HEV with higher effectiveness and a better TARF than a turbocharged and downsized package with a poor TARF could never be chosen because the turbocharged and downsized package, having a poor TARF, would never get chosen and would effectively block the HEV from consideration. For that reason, it is important to first rank by TARF so that the proper package progression can be determined. In other words, packages do not necessarily flow from a given package to the next package listed. Because of the penetration caps, a package listed as, for example, step 8 might actually come from step 5 rather than from step 7. As such, within OMEGA, the incremental cost for step 8 would be the cost for step 8 less the cost for step 5 and similar for the effectiveness values. All of the Ranked-sets of packages and the Technology

[M] We have included credits for aerodynamic treatments level 2, 12V stop-start, mild HEV and strong HEV.

input files are contained in the docket and at our website at https://www3.epa.gov/otaq/climate/models.htm.

C.1.4 Applying Ranked-sets of Packages to the Projected Fleet

As noted above, when we apply a package of technologies to an individual vehicle model in the baseline fleet, we must first determine which package of technologies are already present on the individual vehicle model. From this information, we can determine the effectiveness and cost of the individual vehicle model in the baseline fleet relative to the “null” package that defines the vehicle type. Once we have that, we can determine the incremental increase in effectiveness and cost for each individual vehicle model in the baseline fleet once it has added the package of interest. This process is known as the TEB-CEB process, which is short for Technology Effectiveness Basis - Cost Effectiveness Basis. This process allows us to accurately reflect the level of technology already in the 2014 baseline fleet as well as the level of technology expected in the MYs 2021-2025 reference case (i.e., the fleet as it is expected to exist as a result of the MY 2021 standards).

The TEB-CEB Machine is again used, along with a set of Scenario packages, to generate the actual TEB and CEB values for each package as it is applied to each individual model within the analysis fleet. These TEB and CEB values, along with the off-cycle effectiveness (OEB) values are then used in the Market input file and serve as one of the primary inputs to the OMEGA core algorithms.

The TEB-CEB Machine's process when applying Ranked-set packages to actual vehicles can be broken down into four steps. The first step in the process is to break down the available GHG control technologies into five groups: 1) engine-related, 2) transmission-related, 3) hybridization, 4) weight reduction and 5) other. Within each group we gave each individual technology a ranking which generally followed the degree of complexity, cost and effectiveness of the technologies within each group. More specifically, the ranking is based on the premise that a technology on a baseline vehicle with a lower ranking would be replaced by one with a higher ranking which was contained in one of the technology packages which we included in our OMEGA modeling. The corollary of this premise is that a technology on a baseline vehicle with a higher ranking would be not be replaced by one with an equal or lower ranking which was contained in one of the technology packages which we chose to include in our OMEGA modeling. This ranking scheme can be seen in Visual Basic Macro contained within the TEB-CEB Machine which is in available in the docket and on our website at https://www3.epa.gov/otaq/climate/models.htm.

In the second step of the TEB-CEB process, these technology group rankings are used to estimate the complete list of technologies which would be present on each vehicle after the application of a technology package. In other words, this step indicates the specific technology on each vehicle after a package has been applied to it. The Machine then uses EPA's lumped parameter model to estimate the total percentage CO_2 emission reduction associated with the technology present on the baseline vehicle (termed package 0), as well as the total percentage reduction after application of each package. The Machine uses this approach to determine the total cost of all of the technology present on the baseline vehicle and after the application of each applicable technology package.

The third step in this process is to account for the degree to which each technology package's incremental effectiveness and incremental cost is affected by the technology already present on the baseline vehicle. For this analysis, we also account for the credit values using a factor termed "Other effectiveness basis (OEB).

As described above, technology packages are applied to groups of vehicles which generally represent a single vehicle platform and which are equipped with a single engine size (e.g., compact cars with four cylinder engine produced by Ford). Thus, the fourth step is to combine the fractions of the CEB and TEB of each technology package already present on the individual baseline vehicle models for each vehicle grouping. For cost, percentages of each package already present are combined using a simple sales-weighting procedure, since the cost of each package is the same for each vehicle in a grouping. For effectiveness, the individual percentages are combined by weighting them by both sales and base CO_2 emission level. This appropriately weights vehicle models with either higher sales or CO_2 emissions within a grouping. Once again, this process prevents the model from adding technology which is already present on vehicles, and thus ensures that the model does not double count technology effectiveness and cost associated with complying with the modeled standards.

The other effectiveness basis (OEB) was designed to appropriately account for credit differences between technologies actually on the vehicle and technology packages applied through the technology input file. As an example, if a baseline vehicle includes start stop technology, and the applied package does not, the model needs to account for this different in off-cycle credit. The OEB is an absolute credit value and is used directly in the model's compliance calculations.

C.1.5 New to OMEGA since the 2012 FRM

The TEB-CEB Machine also calculates the off-cycle effectiveness basis (OEB) and tracks the individual technologies in each vehicle model at each step in the TARF process. This latter element is new since the 2012 FRM and allows OMEGA to more efficiently track and provide via output files the technology penetration rates for each OMEGA run. Also new since the 2012 FRM are the nature of the TEB and CEB values. Those values are now stated in terms of actual CO_2 level and actual $/package costs. In past versions of OMEGA, the TEB and CEB values were expressed as percentages (percentage CO_2 change, percentage cost change) of the given package relative to the package from which it came. This made use of TEB and CEB results very difficult to work with and not particularly useful outside the OMEGA core algorithms. Now, the TEB and CEB information is straight CO_2/mile and $/package, making them much easier to understand and more useful.

C.2 OMEGA Overview

The OMEGA model evaluates the relative cost and effectiveness of available technologies and applies them to a defined vehicle fleet in order to meet a specified GHG emission target. Once the regulatory target (whether the target adopted in the rule, or an alternative target) has been met, OMEGA reports out the cost and societal benefits of doing so. The model is written in the C# programming language, however both inputs to and outputs from the model are provided using spreadsheet and text files. The output files facilitate additional manipulation of the results, as discussed in the next section.

OMEGA is primarily an accounting model. It is not a vehicle simulation model, where basic information about a vehicle, such as its mass, aerodynamic drag, an engine map, etc. are used to predict fuel consumption or CO_2 emissions over a defined driving cycle.[N] Although OMEGA incorporates functions which generally minimize the cost of meeting a specified CO_2 target, it is not an economic simulation model which adjusts vehicle sales in response to the cost of the technology added to each vehicle.[O]

OMEGA can be used to model either a single vehicle model or any number of vehicle models. Vehicles can be those of specific manufacturers as in this analysis or generic fleet-average vehicles as in the 2010 Joint Technical Assessment Report supporting the MY 2017-2025 NOI. Because OMEGA is an accounting model, the vehicles can be described using a relatively few number of terms. The most important of these terms are the vehicle's baseline CO_2 emission level, the level of CO_2 reducing technology already present, and the vehicle's "type," which indicates the technology available for addition to that vehicle to reduce CO_2 emissions. Information determining the applicable CO_2 emission target for the vehicle must also be provided. This may simply be vehicle class (car or truck) or it may also include other vehicle attributes, such as footprint.[P] In the case of this Draft TAR, footprint and vehicle class are the relevant attributes.

Emission control technology can be applied individually or in groups, often called technology "packages," as discusses above. The OMEGA user specifies the cost and effectiveness of each technology or package for a specific "vehicle type," such as midsize cars with V6 engines or minivans. The user can limit the application of a specific technology to a specified percentage of each vehicle's sales (i.e., a "maximum penetration cap"), which for this analysis, are specified a priori by EPA. The effectiveness, cost, application limits of each technology package can also vary over time.[Q] A list of technologies or packages is provided to OMEGA for each vehicle type, providing the connection to the specific vehicles being modeled.

OMEGA is designed to apply technology in a manner similar to the way that a vehicle manufacturer might make such decisions. In general, the model considers three factors which EPA believes are important to the manufacturer: 1) the cost of the technology, 2) the value which the consumer is likely to place on improved fuel economy and 3) the degree to which the technology moves the manufacturer towards achieving its fleetwide CO_2 emission target.

Technology can be added to individual vehicles using one of three distinct ranking approaches. Within a vehicle type, the order of technology packages is set by the OMEGA user. The model then applies technology to the vehicle with the lowest Technology Application Ranking Factor (hereafter referred to as the TARF). OMEGA offers several different options for calculating TARF values. One TARF equation considers only the cost of the technology and the

[N] Vehicle simulation models may be used in creating the inputs to OMEGA as discussed in Joint TSD Chapter 3 as well as Chapter 1 and 2 of the RIA.

[O] While OMEGA does not model changes in vehicle sales, RIA Chapter 8 discusses this topic.

[P] A vehicle's footprint is the product of its track width and wheelbase, usually specified in terms of square feet.

[Q] "Learning" is the process whereby the cost of manufacturing a certain item tends to decrease with increased production volumes or over time due to experience. While OMEGA does not explicitly incorporate "learning" into the technology cost estimation procedure, the user can currently simulate learning by inputting lower technology costs in each subsequent redesign cycle based on anticipated production volumes or on the elapsed time.

value of any reduced fuel consumption considered by the vehicle purchaser. The other two TARF equations consider these two factors in addition to the mass of GHG emissions reduced over the life of the vehicle. Fuel prices by calendar year, vehicle survival rates and annual vehicle miles travelled with age are provided by the user to facilitate these calculations.

For each manufacturer, OMEGA applies technology (subject to penetration cap constraints) to vehicles until the sales and VMT-weighted emission average complies with the specified standard or until all the available technologies have been applied. The standard can be a flat standard applicable to all vehicles within a vehicle class (e.g., cars, trucks or both cars and trucks). Alternatively the GHG standard can be in the form of a linear or constrained logistic function, which sets each vehicle's target as a function of vehicle footprint (vehicle track width times wheelbase). When the linear form of footprint-based standard is used, the "line" can be converted to a flat standard for footprints either above or below specified levels. This is referred to as a piece-wise linear standard, and was used in modeling the standards in this analysis.

The emission target can vary over time, but not on an individual model year basis. One of the fundamental features of the OMEGA model is that it applies technology to a manufacturer's fleet over a specified vehicle redesign cycle. OMEGA assumes that a manufacturer has the capability to redesign any or all of its vehicles within this redesign cycle. OMEGA does not attempt to determine exactly which vehicles will be redesigned by each manufacturer in any given model year. Instead, it focuses on a GHG emission goal several model years in the future, reflecting the manufacturers' capability to plan several model years in advance when determining the technical designs of their vehicles. Any need to further restrict the application of technology can be effected through the caps on the application of technology to each vehicle type mentioned above.

Once technology has been added so that every manufacturer meets the specified targets (or exhausts all of the available technologies), the model produces a variety of output files. These files include information about the specific technology added to each vehicle and the resulting costs and emissions. Average costs and emissions per vehicle by manufacturer and industry-wide are also determined for each vehicle class.

C.3 OMEGA Model Structure

OMEGA includes several components, including a number of pre-processors discussed above and a baseline vehicle forecast (see Chapter 4). The OMEGA core model collates this information and produces estimates of changes in vehicle cost and CO_2 emission level. Based on the OMEGA core model output, which now includes the technology penetration of the new vehicle mix, the scenario impacts (fuel savings, emission impacts, and other monetized benefits) are calculated via a post-processor called the OMEGA Inventory, Cost and Benefits Tool (ICBT) discussed in Chapter 12 of this Draft TAR. These pre- and post-processors and the OMEGA core model are available in the docket and on our website at https://www3.epa.gov/otaq/climate/models.htm.

OMEGA is designed to be flexible in a number of ways. Very few numerical values are hard-coded in the model, and consequently, the model relies heavily on its input files. The model utilizes five input files: Market, Technology, Fuels, Scenario, and Reference. Figure C.1 shows the (simplified) information flow through OMEGA, and how these files interact.

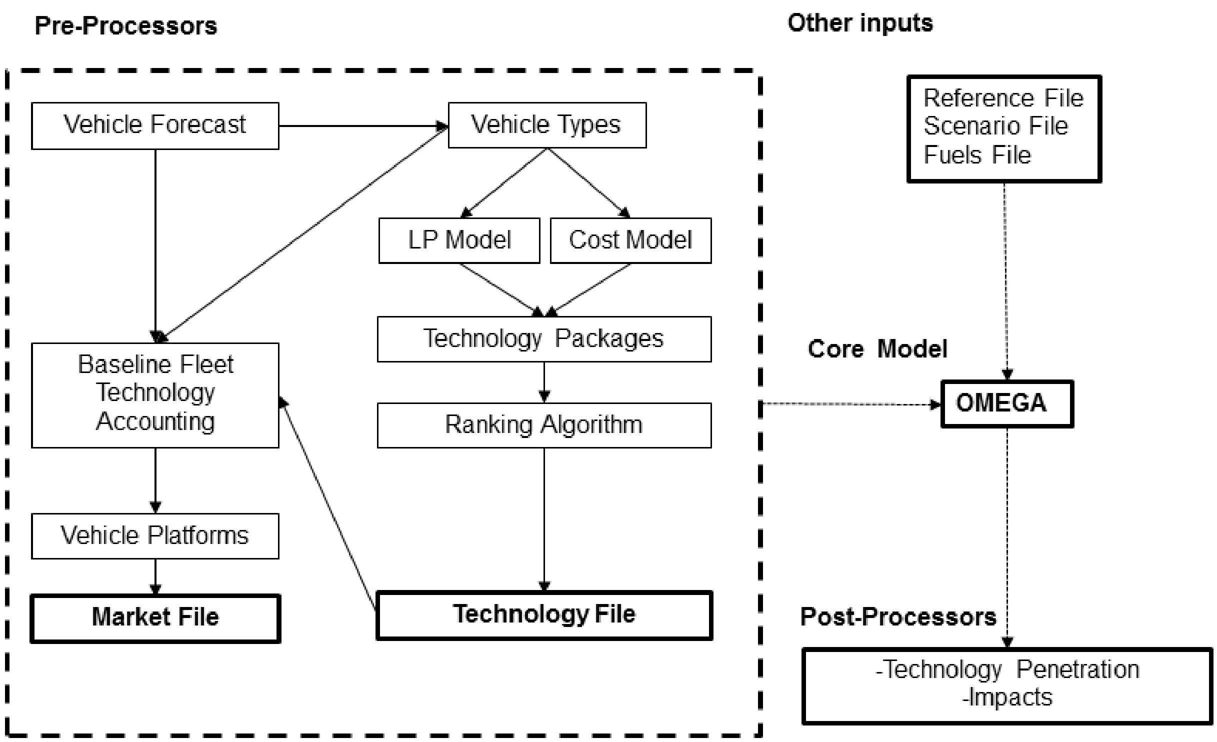


Figure C.1 Information Flow in the OMEGA Model

OMEGA uses four basic sets of input data. The first, the market file, is a description of the vehicle fleet. The key pieces of data required for each vehicle are its manufacturer, CO_2 emission level, fuel type, projected sales and footprint. The model also requires that each vehicle be assigned to a particular vehicle type (currently, we use 19 vehicle types for reasons described in Chapter 4 and below) which tells the model which set of technologies can be applied to that vehicle. Chapter 4 contains a description of how the market forecasts were created for modeling purposes, and includes a discussion on how EPA defined the 19 vehicle types. In addition, the degree to which each vehicle already reflects the effectiveness and cost of each available technology in the baseline fleet must be input. This prevents the model from adding technologies to vehicles already having these technologies in the baseline. It also avoids the situation, for example, where the model might try to add a basic engine improvement to a current hybrid vehicle.

The second type of input data, the technology file, is a description of the technologies available to manufacturers which consists primarily of their cost, effectiveness, compliance credit value, and electricity consumption. This file is generated by the Ranking algorithm and a post-processor tool which puts the Ranking algorithm output files into the proper format for OMEGA In all cases, the order of the technologies or technology packages for a particular vehicle type is designated by the model user in the input files prior to running the model.

The third type of input data describes vehicle operational data, such as annual scrap rates and mileage accumulation rates, and economic data, such as fuel prices and discount rates. These estimates are described in Chapter 10 and are contained in the Reference, Fuels and Scenario input files.

The fourth type of data describes the CO_2 emission standards being modeled. These include the MY2021 standards and the MYs 2022-2025 standards. As described in more detail in Chapter 5 of the joint TSD supporting the 2012 FRM, the application of A/C technology is evaluated in a separate analysis from those technologies which impact CO_2 emissions over the 2-cycle test procedure.[147] For modeling purposes, EPA applies this A/C credit by adjusting manufacturers' car and truck CO_2 targets by an amount associated with EPA's projected use of improved AC systems. The targets are specified in the Scenario input file along with details such as each scenario's name and the appropriate Market, Technology, Reference and Fuel file to use for each specific scenario.

The input files used in this analysis, as well as the current version of the OMEGA model, are available in the docket and on EPA's website at https://www3.epa.gov/otaq/climate/models.htm.

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