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16. Abstract

This research project is to inform NHTSA and EPA's development of Phase 2 Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles (Class 2b – 8). A preceding report (Report #1) evaluated individual potential engine and vehicle fuel savings technologies over a wide range of duty cycles. This report evaluates the effectiveness of packages of those individual technologies as well as other related topics. After an introduction, Section 2 includes fuel consumption simulation results for both engine and vehicle technology packages in Class 2b through Class 8 trucks. Section 3 describes the results of parameter sweep studies, covering aerodynamic drag, tire rolling resistance, vehicle empty weight, and axle ratios. Section 4 covers a brief review of vocational truck specification issues, and Section 5 is a survey of natural gas vehicle costs, along with some implementation issues for natural gas powered vehicles. Section 6 provides an overview of overall performance simulation project conclusions.

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EXECUTIVE SUMMARY

In 2011, the National Highway Traffic Safety Administration and Environmental Protection Agency (EPA) jointly issued a first phase of fuel efficiency and greenhouse gas (GHG) standards that apply to medium- and heavy-duty on-highway engines and vehicles for model years (MY) 2014 to 2018 and beyond. These regulations are commonly referred to as "Phase 1" of the Heavy-Duty National Program. The standards cover all vehicles in weight classes 2b through 8, which encompasses most vehicles with gross vehicle weight ratings (GVWR) over 8,500 pounds except for a limited number of passenger vehicles covered under the light duty corporate average fuel economy (CAFE) standards, and recreational vehicles, which were included in EPA's GHG standards but not NHTSA's fuel efficiency standards. Phase 1 has two implementation stages. EPA's greenhouse gas emission standards are mandatory beginning with MY 2014. NHTSA's fuel consumption standards are voluntary in model years 2014 and 2015, becoming mandatory with model year 2016 for most regulatory categories. Commercial trailers were not regulated in Phase 1. The Phase 1 GHG and fuel consumption standards were developed using input from a number of studies that evaluated the fuel saving technologies that are available, such as the NESCCAF 2009 report [1] and the NHTSA and NAS 2010 reports [2], [3].

The research project described in this report has been completed for NHTSA to help to inform the next phase ("Phase 2") of the regulations, which would set standards in coordination with EPA for model years beyond Phase 1. In order to prepare for Phase 2, NHTSA directed SwRI to update prior research on fuel saving technologies to reflect the effects of the Phase 1 regulations, as well as to include technical progress that has been made over the last few years. In particular, SwRI was tasked with assessing the current commercial fleet technology baseline at the time of contract award (MY 2011/2012) and assessing the effectiveness and cost of potential fuel efficiency/GHG improving technologies for the Phase 2 timeframe (post MY 2018 for vehicles and engines).

When considering potential fuel efficiency/GHG-reducing technologies, NHTSA directed SwRI to include a range of factors: design, functionality, duty cycle, use (type of work done by the vehicle), and factors that can influence the effectiveness, feasibility, and cost. Vehicle safety, utility, and performance are also to be considered.

Final Report #1 of this project [4] covered a literature review, creation of a list of engine and vehicle technologies to be evaluated in the program, and the list of engines and vehicles to be evaluated. Report #1 also provides the results of simulation studies for the individual engine and vehicle technologies over a range of drive cycles and payloads. Section 3.4 of Report #1 addresses the trade-offs between engine-out NO_x and fuel consumption. Section 4 addresses testing and simulation approaches, including appropriate efficiency metrics. Certain certification issues are also addressed. Section 4.3 of Report #1 covers worldwide regulatory approaches for truck fuel consumption and GHG emissions.

In this second technical report, the results from the following tasks are provided:

Results from simulation of both engine and vehicle technology packages.
The results of parameter sweep studies, covering aerodynamic drag, tire rolling resistance, vehicle empty weight, and axle ratios.
A brief review of vocational truck specification issues.
A survey of natural gas vehicle costs, along with some implementation issues for natural gas powered vehicles.

Except for the natural gas vehicle cost survey, this project involves simulation results that were supported by experimental data wherever possible. See Section 2.2 regarding the accuracy and limitations of the simulation techniques used in this project.

LONG HAUL TRUCKS AND ENGINES

Based on the technologies studied in this project, it appears that there is the potential to improve long haul truck engine fuel consumption by 2-5% without a waste heat recovery system, and by 6% to 9% with a waste heat recovery system. These improvements are achieved compared to the 2019 baseline on cruise speed cycles. Achieving this level of benefit requires the use of complex and expensive technologies that are not yet fully developed, such as a waste heat recovery system (see [5] for cost information). The potential fuel savings achievable using an aggressive friction reduction package and downspeeding are in the 2% to 5% range.

It should be pointed out that 6-9% fuel consumption reduction with waste heat recovery system is obtained on the cruise speed cycles. Because waste heat recovery systems have a slow transient response, the benefit will be much lower on transient cycles. When evaluating technology benefits over the agencies' regulatory cycles, the benefits will be less than these numbers quoted here. This is because composite weighting is used over three certification cycles – 55 and 65mph cruise and the CARB transient cycle. For a long haul tractor with high roof sleeper, CARB, 55mph and 65mph use weightings of 5%, 9% and 86%, respectively. Therefore, even though up to 9% benefits can be obtained on the 65mph cruise cycle, the total composite certification cycle benefits with the weighting factors will be about 0.5-1% less than 6-9% presented in this report.

It should be also pointed out that all technology improvements under consideration here are based on a long haul truck engine used in a tractor with a high roof sleeper. Some of key technologies, such as waste heat recovery, would not be effective for a day cab engine, and therefore the overall benefits over the agencies' certification categories would be further reduced. Another point is that this study assumes that all technologies under consideration will be realized in a long haul tractor engine. However, in reality, not all technologies can be applied to all engines on market in the Phase 2 time frame. For example, it is unrealistic to assume that the waste heat recovery system would be 100% used for all engines in Phase 2, because of its high cost and uncertainties of reliability and warranty.

An aggressive reduction in Cd (25%) and Crr (30%) provides a 20% fuel consumption reduction on the long haul NESCCAF cycle. Savings are slightly higher under steady-state cruise conditions (55 and 65 MPH). Other vehicle improvements such as a reduction in accessory power demand (such as the air conditioner), reduced chassis friction, and 6X2 axles can add another few percent in fuel savings. T700 vehicle package 4 combined all of the previously mentioned features with an engine featuring waste heat recovery and other technologies, and it achieved a fuel consumption reduction of 29% on the NESCCAF cycle, with slightly higher savings on the steady-state cruise cycles. This amounts to almost a 50% MPG improvement, which is the goal of the SuperTruck program.

Since long haul vehicles tend to have high annual VMT and fuel costs, the segment can support a higher investment in fuel saving technology, while still offering an acceptable payback. Note that this report does not include any cost/benefit analysis. However, note that a significant amount of R&D will be required to make improvements on this scale production feasible and cost-effective.

Bringing trailers into the regulatory scheme has significant potential benefits. Trailer aerodynamics and tire rolling resistance make a substantial contribution to overall vehicle power demand. In many cases, ownership of the tractor and trailer is different, so trailer owners may not directly benefit from any fuel savings the trailer provides. Also, many in the industry have pointed out that greater aerodynamic benefits can be realized if a trailer is optimized for a particular tractor design, rather than making generic improvements to the trailer without consideration of the tractor configuration.

VOCATIONAL AND MEDIUM DUTY TRUCKS

Because vocational and medium duty trucks tend to have a much lower annual VMT, they burn much less fuel per year. This makes the hurdle for achieving cost-effective fuel saving technologies much higher. Vocational/MD trucks also tend to operate on lower speed, more transient drive cycles. This reduces the potential benefits of both Cd and Crr improvements. Many vocational/MD trucks have custom bodies fitted, which are designed to accomplish a specific work task (dump trucks, cement mixers, waste haulers, utility service trucks, oil field service trucks, tanks, flatbeds, box delivery trucks, etc.) The variety and often low technical capability of the body manufacturers makes aerodynamic improvements a particular challenge. Nevertheless, there are still some fuel savings that can be achieved.

Many vocational and medium duty trucks have opportunities for fuel savings that were outside of the scope of this project. Examples include reduced cooling fan power demand and improved efficiency of engine driven accessories such as hydraulic and power-take off systems.

Based on the technologies evaluated in this project, it appears that medium duty diesel engines have the potential for fuel savings of 2% to 4% beyond the Phase 1 regulatory requirement. The largest potential benefit comes from friction reduction. In some cases, downsizing of the diesel engine may be beneficial, with potential fuel savings of 5% or more on vehicles with relatively light duty cycles.

Gasoline engines have traditionally suffered from a 25% to 30% fuel consumption penalty on a per gallon basis in medium trucks. About 13% of this penalty is due to the lower energy content of a gallon of E10 gasoline compared to diesel, but the rest of the penalty is due to lower brake thermal efficiency of the gasoline engines. However, with the technologies explored in this project, gasoline engines show considerable improvement potential. Both the small, boosted V-6 and the conventional, naturally aspirated V-8 show the potential for about 8% fuel consumption reduction from their respective baselines on the drive cycles evaluated in this project. The fuel consumption improvement is even larger at high loads, where enrichment can be eliminated. The downsized and boosted gasoline engine, with technologies such as EGR and VVA (P16), has the potential to match or beat the thermal efficiency of the 2019 baseline diesel on relatively low speed transient drive cycles, as shown in Table 6.1. The V-8 engine has GDI + EGR + cylinder deactivation + 10% FMEP reduction (P20). Data for the baseline 6.2 liter V-8 is provided in the following table for reference.

FUEL CONSUMPTION COMPARISON IN T270 TRUCK

Engine	**Fuel Consumption Penalty on Drive Cycle at 50% Payload vs. 2019 Baseline Diesel Engine**						
	CARB	**55 MPH**	**65 MPH**	**WHVC**	**CILCC**	**Parcel**	**Average**
2019 ISB (D)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
3.5 V-6 P16 (G)	9.9%	19.6%	18.4%	12.9%	3.7%	5.1%	11.6%
6.2 V-8 P20 (G)	18.6%	25%	21.7%	19.9%	13.9%	14.2%	18.9%
Base 6.2 V-8 (G)	31.2%	33.5%	36.3%	30.4%	28.3%	23.4%	30.5%

(D) = Diesel, (G) = Gasoline

The results in the tables here are in terms of fuel consumption on a volume basis (gallons). The fuel consumption of the gasoline engines in gallons is compared to the fuel consumption of the 2019 diesel in gallons. A fuel consumption increase of less than 13% would indicate that the gasoline engine is more efficient than the diesel, because of the lower energy content of a gallon of gasoline. A fuel consumption penalty of over 13% indicates that the gasoline engine is less efficient than the diesel.

The advantage for the downsized, boosted V-6 comes primarily from operating at a higher BMEP under light load conditions, due to the smaller displacement. At higher average loads, such as those found on the 55 and 65 MPH cruise cycles on the T270 truck with a high frontal area, the diesel engine retains a thermal efficiency advantage. Under extreme load, such as going up a grade at high speed or towing a heavy trailer, the diesel will retain a substantial efficiency advantage, but it will be less than the historical situation.

For medium-duty trucks, the fuel savings potential from a 20% reduction in rolling resistance and a transmission with more ratios (8) and higher mechanical efficiency is in the range of 4% to 6%. If an idle neutral feature is added to the transmission, the fuel savings exceed 14% on the Parcel cycle with the diesel engine, which includes 50% idle time. The V-6 achieves slightly higher fuel savings from the Crr reduction and 8-speed automatic than the diesel, and the V-8 slightly less. The gasoline engines benefit less from an idle neutral feature, because their looser torque converter allows less idle power demand on the gasoline engines.

PICKUP TRUCKS AND ENGINES

Heavy duty (3/4 and 1 ton) pickup trucks operate under a huge range of duty cycles. Some are primarily used for passenger transport, while others frequently tow heavy trailers with bulky loads. This makes evaluating technologies a challenge. For example, cylinder cutout on the gasoline V-8 may provide a significant benefit at zero payload on low speed drive cycles, but zero benefit on the highway with a load.

Based on the technologies evaluated in this project, it appears that medium duty diesel engines have the potential for fuel savings of 3% to 4% beyond the Phase 1 regulatory requirement. The largest potential benefit comes from friction reduction. In many cases, downsizing of the diesel engine may be beneficial, with potential fuel savings of 6% to 12% at ALVW over the full range of drive cycles. For most driving situations, 385 HP and 850 lb-ft are simply not needed, and downsizing could save significant fuel. However, for those few trucks that actually operate near GCW much of the time, the downsized engine will not provide a fuel savings, and the performance penalty will be substantial.

The fuel savings technologies applied to the small, boosted V-6 gasoline engine in the pickup truck yield similar benefits to those obtained in their medium truck applications. In the V-8, cylinder cutouts perform better than in the medium trucks, because with a smaller, lighter vehicle, there is more opportunity to shut cylinders down. Table 6.2 compares gasoline and diesel engine performance at ALVW payload (approximately 1,600 pounds in the cargo bed). Note that the 2019 ISB baseline is different from the one in the table above, because this is a 3,000 RPM pickup truck rating. The gasoline ratings are the same as for medium trucks.

FUEL CONSUMPTION COMPARISON IN PICKUP TRUCK

Engine	**Fuel Consumption Penalty on Drive Cycle at 50% Payload vs. 2019 Diesel Engine Baseline**						
	FTP-City	**FTP-Hwy**	**US06**	**SC03**	**WHVC**	**65 MPH**	**Average**
2019 ISB (D)	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
3.5 V-6 P16 (G)	-5.4%	9.0%	8.7%	-1.2%	-0.2%	13.5%	4.1%
6.2 V-8 P20 (G)	7.0%	17.1%	14.9%	10.6%	12.8%	19.6%	13.7%
Base 6.2 V-8 (G)	22.7%	32.7%	27.0%	29.4%	24.9%	33.3%	28.3%

(D) = Diesel, (G) = Gasoline

The advantage for the downsized, boosted V-6 comes primarily from operating at a higher BMEP under light load conditions, due to the smaller displacement. Compared to medium trucks, more of the drive cycle time is at light load, so the V-6 performs better in pickups. At higher average loads, such as those found on the 65 MPH cruise cycle, the diesel engine retains a slight thermal efficiency advantage. Under extreme load, such as going up a grade at high road speed or towing a heavy trailer, the diesel will retain a substantial efficiency advantage, but it will be less than the historical situation.

For pickup trucks, the fuel savings potential from a 10% reduction in aerodynamic drag and a 30% reduction in rolling resistance, plus a transmission with more ratios (8) and higher mechanical efficiency is in the range of 6% to 10% with the diesel and the V-6, and about 1% less with the V-8. If an idle neutral feature is added to the transmission, the fuel savings are an additional zero to 4% for the diesel, and zero to 2% for the gasoline engines on the drive cycles evaluated for this project. Note that the pickup truck was not run on the Parcel cycle, which has the highest portion of cycle time at idle.

Hybrid systems were also evaluated on the pickup trucks. These systems ranged from a small belt driven integrated starter generator, through a larger crank driven ISG, to a full parallel hybrid system. The fuel savings benefits vary with engine and payload. At ALVW payload (about 8,500 pounds vehicle test weight), the BISG provided a benefit of 5.6% to 7.7% on the city cycle. The CIGS provided 7.0% to 8.3% fuel savings on the city cycle, and the parallel system saved 25.2% to 29.5%. Fuel savings on the highway cycle were much smaller for all systems. Other drive cycles were not evaluated.

POTENTIAL OF GASOLINE ENGINES

Gasoline engines have several technologies which offer the potential for fuel consumption reduction. EGR is of particular interest, because it can eliminate the need for enrichment at high load and because it reduces in-cylinder and exhaust temperatures. The temperature reduction can help reduce the gap in durability between diesel and gasoline engines. Simulation results reported in Section 4 indicate that gasoline engines have the potential to compete with medium duty diesels on efficiency (on a per unit energy basis) and on fuel cost (with a gallon of diesel costing more than a gallon of gasoline). Gasoline engines also have the potential to compete with medium duty diesels on a GHG emissions basis. These results depend on the successful implementation of EGR in boosted gasoline engines, and as this technology has yet to be introduced into production, there is some risk associated with this approach. The primary market driver for gasoline engines is lower initial cost. Gasoline engines cost less because the engine and aftertreatment are less complex, and because their higher operating speeds and lower torques allow use of a lower cost transmission.

NATURAL GAS ENGINES

Natural gas offers several advantages, including the potential for lower, more stable fuel prices, simpler aftertreatment, and lower GHG emissions. Several states also offer tax incentives for the purchase of natural gas powered vehicles. Balanced against these advantages are a number of disadvantages. Class 2b and 3 trucks equipped for natural gas cost between $6,240 and $15,505 more than comparably equipped gasoline powered vehicles. Medium and heavy-duty trucks with natural gas engines are $37,549 to $76,354 more expensive than diesel powered trucks. A large portion of the cost penalty for natural gas vehicles is driven by fuel storage system cost. Natural gas must be stored either under very high pressure or in a well-insulated cryogenic tank. In addition to the purchase price penalty, natural gas requires specific equipment and training for the service shop.

Several other factors make natural gas a challenge for truck operations. The fuel tank size required to store a given amount of energy is about 1.8 times greater for LNG and 4.5 times greater for CNG. These larger tanks pose a significant packaging issue, and they are also substantially heavier than gasoline or diesel tanks. Often, a longer wheelbase is needed to package adequate fuel capacity, and natural gas vehicles typically offer a shorter range. Another issue is that the stoichiometric, spark-ignited engines that dominate the market have substantially lower thermal efficiency than diesel engines. This means that operators cannot just compare fuel cost on a gallon equivalent basis. They must also take the higher fuel consumption of natural gas engines into account. Engines that use direct injection of natural gas, with a diesel pilot to ignite the gas, can be as efficient as the best diesel. Unfortunately, these engines have challenges with meeting methane emissions standards. In addition, they are so expensive that they have recently been withdrawn from the market.

The number of natural gas fueling stations has increased over the last few years, but natural gas availability remains an issue for vehicles that need the flexibility to be able to travel away from a fixed location. The largest engine currently on the market is 12 liters, which limits the use of natural gas for long haul applications. OEM plans to introduce larger engines have been put on hold, partly due to the drop in diesel fuel prices in 2014.

OVERALL SUMMARY OF RESULTS

For the technologies evaluated in this project, the overall fuel savings potential beyond the Phase 1 standards are shown in the table below. Note that many of these technologies may not prove to be cost effective.

Overall, diesel engines offer a potential for 2% to 5% improvement beyond the requirements of the Phase 1 GHG regulations. Beyond that level, more exotic and untried technologies would be required. Gasoline engines show more potential for improvement, although they start from an efficiency level well below that of diesels. There is the potential for gasoline engines to become competitive with diesel in pickups and medium-duty truck applications.

SUMMARY OF RESULTS

Vehicle Category	Engine or Vehicle	Potential Fuel and CO_2 Savings
Long Haul	Engine	2% to 5% w/o WHR, 6% to 9% with WHR
	Vehicle	Up to 20% on long haul cycle
Medium Duty/Vocational	Engine	Diesel: 2% to 4%. Gasoline: 8%
	Vehicle	4% to 6%, more with idle neutral
Pickup Truck	Engine	Diesel: 3% to 4%. Gasoline: 8%
	Vehicle	6% to 10%

Long haul trucks offer the most potential for vehicle power demand reduction, and thus for improved fuel efficiency. There are several factors involved. Long haul drive cycles mean that power demand is dominated by aerodynamic drag and rolling resistance. There are known technologies to address these two sources of power demand. Vehicles that operate in more transient duty cycles have a larger share of total vehicle power demand used to overcome (accelerate) vehicle inertia. It is difficult to significantly reduce inertia, especially with a large payload. Any reduction in payload actually increases load specific fuel consumption. Smaller vehicles also have less frontal area than tractor-trailers, which makes the contribution of aerodynamic drag smaller, and which thus reduces the fuel economy improvement potential of aerodynamic treatments.

A wide range of both engine and vehicle individual technologies were explored in Final Report #1. After completion of that work, SwRI, NHTSA and EPA agreed on combinations of technologies to evaluate for the second phase of the project, which are now detailed in this report. Since it was not possible to simulate packages with every permutation of the many individual technologies, the staffs selected packages of technologies that were considered appropriate, cost-effective, and technologically feasible in the projected Phase 2 timeframe for the particular vehicles studied and their duty cycles. Other technologies or packages of technologies not included in this study may also offer pathways to increasing MD/HD vehicle fuel efficiency.

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LIST OF ABBREVIATIONS AND ACRONYMS

6X2....................Tractor with a front axle, a drive axle, and a non-driven axle
6X4....................Tractor with a front axle and dual drive axles (tandem)
A/C....................Air Conditioning
AES...................Automatic Engine Shutdown
AFR ....Air/Fuel Ratio
ALVW……….. Vehicle test weight for pickup trucks equal to the empty weight plus half of the payload that can go in the bed, with no trailer
AMT ....Automated Manual Transmission
APU ....Auxiliary Power Unit
BMEP...............Brake Mean Effective Pressure (A unit to compare the relative load on engines of different size)
BSFC ....Brake Specific Fuel Consumption
BTE...................Brake Thermal Efficiency
CAFE................Corporate Average Fuel Economy
CARB ....California Air Resources Board
Cd ....Coefficient of Drag (Aerodynamic drag)
CFD ....Computational Fluid Dynamics
CH_4 ....Methane
CILCC.............Combined International Local and Commuter Cycle
CNG..................Compressed Natural Gas
CO.....................Carbon Monoxide
CO_2 ....Carbon Dioxide
Crr ....Coefficient of Rolling Resistance (Tire rolling resistance)
DD15.................Detroit 15 liter heavy duty truck engine (formerly Detroit Diesel)
DEF...................Diesel Exhaust Fluid (Urea mixture used in SCR catalysts)
DPF...................Diesel Particulate Filter
E10....................Gasoline with 10% ethanol content
ECM ....Engine Control Module
EGR..................Exhaust Gas Recirculation
EPA...................United States Environmental Protection Agency
EVO..................Exhaust Valve Opening (Valve timing)
F-650.................Ford Class 5 and 6 truck model
FMEP ....Friction Mean Effective Pressure (Unit for comparison of friction between different engines)
GDI ....Gasoline Direct Injection
GEM.................Greenhouse gas Emissions Model (EPA tool for determining compliance with truck GHG regulations)
GCW.................Gross Combination Weight (Weight of the vehicle and trailer combined)
GHG ....Greenhouse Gas (CO_2, N_2O, CH_4, and others. In this report, CO_2 is the focus)
GT-POWER ....Commercial 1-dimensional engine simulation code. Part of GT-SUITE.
GVW.................Gross Vehicle Weight
GVWR.............Gross Vehicle Weight Rating (Vehicle mass with maximum allowed payload)

LIST OF ABBREVIATIONS AND ACRYONYMS (CONT'D)

HCCI ....Homogeneous Charge Compression Ignition
HD.....................Heavy Duty (Typically refers to Class 8 trucks with engine of 10 liters or more displacement)
HPCR ....High Pressure Common Rail (Diesel fuel system)
HPDI.................High Pressure Direct Injection (Natural gas is directly injected into the cylinder, followed by a diesel pilot injection that serves to ignite the gas)
ICCT.................International Council on Clean Transportation
IEA ....International Energy Agency
ISB ....Cummins 6.7 liter diesel engine (also available as a 4.5 liter 4-cylinder)
IVC ....Intake Valve Closing (Valve timing)
LD ....Light Duty (Typically refers to Class 2b and 3 trucks. Note that to passenger car manufacturers, Class 2b and 3 are called "Heavy Duty". This leads to considerable confusion between people with car and truck backgrounds.
LNG..................Liquefied Natural Gas
LTC ....Low Temperature Combustion
MD....................Medium Duty (Typically refers to Class 4 through "Baby 8" trucks with engine displacements below 10 liters)
mm....................millimeter
MY....................Model Year
N_2 ....Nitrogen
N_2O ....Nitrous Oxide
NOx...................Nitrogen Oxides
NAS...................National Academy of Science
NESCCAF........Northeast States Center for a Clean Air Future
NH_3 ....Ammonia
NHTSA............National Highway Traffic Safety Administration (Responsible for fuel economy regulations)
NREL ....National Renewable Energy Laboratory
NMHC..............Non-Methane Hydrocarbons
NO.....................Nitric Oxide
NO_2 ....Nitrogen Dioxide
NOX..................Oxides of Nitrogen
O_2 ....Oxygen
DOC..................Diesel Oxidation Catalyst
ppm...................Parts per Million
PFI ....Port Fuel Injection
PM ....Particulate Matter
RCCI ....Reactivity Controlled Compression Ignition
rpm ....revolutions per minute
SCR...................Selective Catalytic Reduction
SwRI ....Southwest Research Institute
T270..................Kenworth Class 6 truck model
T700..................Kenworth Class 8 long haul tractor model
TCPD................Turbocompound
VIUS ....Census Bureau Vehicle Inventory and Use Survey

VMT ....Vehicle Miles Traveled (per year)
VSL...................Vehicle Speed Limiter (also called road speed governor)
VVA..................Variable Valve Actuation (Variable lift and duration)
VVT ....Variable Valve Timing (Typically cam phasing, but constant lift and duration)
WHR.................Waste Heat Recovery
WHSC ....World Harmonized Steady-State Cycle (An engine dyno test cycle)
WHTC..............World Harmonized Transient Cycle (An engine dyno test cycle)
WHVC..............World Harmonized Vehicle Cycle (Truck test cycle with urban, rural, and motorway segments)

1.0 INTRODUCTION

In 2011, the National Highway Traffic Safety Administration (NHTSA) and Environmental Protection Agency (EPA) jointly issued a first phase of fuel efficiency and greenhouse gas (GHG) standards that apply to medium- and heavy-duty on-highway engines and vehicles for model years (MY) 2014 to 2018 and beyond. These regulations are commonly referred to as "Phase 1" of the Heavy-Duty National Program. The standards cover all vehicles in weight classes 2b through 8, which encompasses most vehicles with gross vehicle weight ratings (GVWR) over 8,500 pounds except for a limited number of passenger vehicles covered under the light duty corporate average fuel economy (CAFE) standards, and recreational vehicles, which were included in EPA's GHG standards but not NHTSA's fuel efficiency standards. Phase 1 has two implementation stages. EPA's greenhouse gas emission standards are mandatory beginning with model year 2014. NHTSA's fuel consumption standards are voluntary in model years 2014 and 2015, becoming mandatory with model year 2016 for most regulatory categories. Commercial trailers were not regulated in Phase 1. The Phase 1 GHG and fuel consumption standards were developed using input from a number of studies that evaluated the fuel saving technologies that are available, such as the NESCCAF 2009 report [1] and the NHTSA and NAS 2010 reports [2], [3].

This is the third report in a series of research reports completed for NHTSA to help to inform the next phase ("Phase 2") of the regulations, which would set MD/HD standards in coordination with EPA for model years beyond Phase 1. In order to prepare for Phase 2, NHTSA directed SwRI to update prior research on fuel saving technologies to reflect the effects of the Phase 1 regulations, as well as to include technical progress that has been made over the last few years. In particular, Southwest Research Institute (SwRI) was tasked with assessing the current commercial fleet technology baseline at the time of contract award (MY 2011/2012) and assessing the effectiveness and cost of potential fuel efficiency/GHG improving technologies for the Phase 2 timeframe (post MY 2018).

The first report from this project was produced by SwRI [4]. This report provides a detailed analysis of the fuel savings potential of both engine and vehicle technologies for Class 2b through Class 8 trucks. Each technology is evaluated on an individual, stand-alone basis. Report #1 also looks at the trade-off between emissions and fuel consumption. The second report was prepared by Tetra Tech [5]. This report provides a cost analysis for each of the technologies that are evaluated in the other two reports, as well as certain technologies that are not directly addressed by the other reports. The cost report does not include cost/benefit analysis, since this analysis was beyond the project scope. Cost/benefit analysis is being performed by the agencies as they develop the Phase 2 regulations. This report is the third and final report from the project. This report has been prepared by SwRI, and it covers an analysis of several engine and vehicle technology combinations, and compares their performance to the baseline vehicle performance mandated at the end of Phase 1 implementation in 2018. In addition, this report provides input on a parameter study of vocational trucks, and a study of natural gas vehicle costs and implementation issues. This report also includes a look at the potential for gasoline engines to become competitive with diesel engines in medium trucks.

Section 2 of this report covers the results of a task in which SwRI created packages of engine and vehicle technologies by combining individual technologies that are described in Final Report #1. These combinations were meant to explore questions regarding which technologies provide benefits that are additive, which are not additive, and whether any technologies are synergistic. In addition, a range of hybrid systems are evaluated on the Class 2b/3 pickup truck in Section 2.

Section 3 of this report covers the results of a task in which SwRI performed sweeps of vehicle parameters (also called parameter sensitivity analysis) to determine their effect on vehicle fuel consumption. These sweeps included changes to the aerodynamic drag coefficient (Cd), the tire rolling resistance (Crr), the vehicle empty weight, and the axle ratio. The vehicle performance and fuel consumption has been evaluated over a range of driving cycles. In addition, the bottoming cycle model developed and reported on in Final Report #1 was extended to include a wider range of working fluids, and the option of a recuperator. The recuperator is a device that has the effect of increasing bottoming cycle power output and reducing heat rejection, both at the expense of additional cost, weight, and system complexity.

In Section 4 of this report, results presented in Sections 2 – 4 are used to evaluate how vehicle specification can affect performance and fuel consumption of vocational trucks. The fuel economy of these trucks has been given much less attention by researchers than tractor-trailer trucks, so there is a need to evaluate vocational trucks in more detail.

Section 5 of this report describes a survey of current truck market costs for natural gas engines and natural gas fuel storage systems. The engines studied are the Cummins ISL-9G, a 9 liter, spark ignited, stoichiometric engine, and the Cummins ISX-12G, a 12 liter engine which uses similar technology. These two engines represent over 90% of the current medium and heavy-duty natural gas engine market for trucks. Both compressed natural gas (CNG) and liquefied natural gas (LNG) truck fuel storage systems were included in the study. The study also includes a brief survey of subsidies and tax advantages that are offered by local, state, and federal governments, as well as a survey of CNG and LNG fuel availability.

Overall project conclusions are described in Section 6. Section 6.1 covers project conclusions related to long haul tractor-trailer trucks, Section 6.2 covers medium-duty vocational trucks and engines, and Section 6.3 provides project conclusions for Class 2b and 3 pickup trucks and their engines. Section 6.4 wraps up the main body of this report with some overall project conclusions.

Appendix A provides technical details regarding all of the gasoline engine technology packages addressed in this report. Appendix B does the same for the diesel engine packages, including packages with waste heat recovery systems. Appendix C describes the vehicle simulation approach and provides details on all vehicle technology packages. Appendix D describes the hybrid system evaluations that were done on the Class 2b/3 pickup truck model. Finally, Appendix E details some corrections, specifically on the 2019 heavy-duty baseline engine, that have been made since the draft report was released to the public.

Table 1.1 below summarizes how the selected vehicles and engines fit into the US vehicle classification system, and Table 1.2 summarizes the fundamental characteristics of the engines in their baseline form. See Table 2.10 for a summary of the drive cycles used with each vehicle.

TABLE 1.1 VEHICLE AND ENGINE CLASSIFICATION

Class	Vehicle	Diesel	Gasoline	Base Transmission
2b	Ram Pickup	Cummins 6.7 Liter 385 HP (base), 4.5 Liter 256 HP	3.5 L V-6, 6.2 L V-8	6-Speed Automatic
3				
4				
5	F-650 Tow Truck	Cummins 6.7 Liter 300 HP (base), 4.5 Liter 256 HP	3.5 L V-6, 6.2 L V-8	5-Speed Automatic
6	T270 Box Truck			
7				
8	T700 Tractor-Trailer	Detroit 14.8 L DD15 (base), 12.3 L Derivative	None	10-Speed AMT

TABLE 1.2 2011 – 2013 BASELINE ENGINE CHARACTERISTICS

Engine	Displacement, Liters	Rated HP @ RPM	Torque Peak lb-ft @ RPM	Best BSFC g/kW-hr	Other
ISB Pickup	6.7	385 @ 3000	850 @ 1600	198.6	Part load EGR
ISB MD	6.7	300 @ 2500	750 @ 1300	207.8	Full time EGR
V-6	3.5	370 @ 5500	420 @ 3500	238.0	Turbo, DI
V-8	6.2	316 @ 5500	400 @ 4200	236.5	NA, PFI
DD15	14.6	485 @ 1800	1650 @ 1240	185.7	Turbocompound

Report #1 provides background information, details, and results for all of the individual engine and vehicle technologies that were evaluated in the first phase of this project. This report covers selected combinations of those technologies over appropriate duty cycles for each segment. Other technologies or packages of technologies not included in this study may also offer pathways to increasing MD/HD vehicle fuel efficiency.

2.0 COMBINED BENEFITS SIMULATIONS

2.1 Technology Combinations

A wide range of both engine and vehicle individual technologies were explored in Final Report #1. After completion of the work covered by Report #1, SwRI, NHTSA and EPA agreed on combinations of technologies to evaluate for the second phase of the project. Since it was not possible to simulate packages with every permutation of the many individual technologies, the staffs selected packages of technologies that were appropriate, cost-effective, and technologically feasible in the projected timeframe and for the particular vehicles and their duty cycles. Cost information from this project was not available at the time the selections were made, but values from previous studies were taken into account. A certain amount of engineering judgment was necessary to select packages of technologies that were potentially additive and would not impose excessive penalties in terms of weight, drivability, utility, cost, or complexity. The engine technology combinations selected for the task are listed in tabular form below. Additional details are provided in Appendix A (gasoline engine technologies), Appendix B (diesel engine technologies and waste heat recovery systems), Appendix C (vehicle technologies), and Appendix D (hybrid systems).

While this report examines the effects of packages of technologies on fuel consumption, vehicle and engine manufacturers must also comply with pollutant emission regulations. For a discussion of the trade-off between criteria emissions and fuel consumption, see section 3.4 of Report #1 [4].

2.1.1 Engine Technology Combinations

The tables below list technology combinations that were applied to the engines in the program. For 2019 baseline diesel engines, an assumption was made that there would be a 1% efficiency improvement due to combustion system development. This assumption represents any engine improvement developed and implemented by 2019. There are many forms this improvement could take, and simulating them all in GT-POWER is not possible. For this work, the 1% improvement was simply implemented in GT-POWER as a reduction in combustion duration. This change in combustion duration does not represent the application of any one specific technology, but was selected to represent a combination of improvements that are likely to be implemented over the next few years – improvements that do not lend themselves to 1-D simulation.

TABLE 2.1 ENGINE TECHNOLOGY COMBINATIONS EVALUATED ON THE DD15

Technology	Hardware Content	Comments
2011 Baseline DD15	Production 2011 DD15	Complies with 2014 GHG requirement, but with zero margin
2019 Baseline DD15	Turbocompound system deleted, asymmetric fixed geometry turbocharger, combustion duration decreased to provide a 1% efficiency improvement	Represents the 2013 production engine, plus a 1% efficiency improvement from shorter combustion duration. Complies with the 2018 GHG requirement, but with zero margin
DD15 Combo Package 1 (P1)	2019 baseline engine + FMEP reduction	10% engine friction reduction at high engine speed and load, increasing to 35% near idle
DD15 Combo Package 2 (P2)	2019 baseline engine + Downspeed B + partial FMEP reduction	Reduce cruise RPM at 65 MPH from 1368 RPM to 1050 RPM. 5% engine friction reduction at high engine speed and load, increasing to 17.5% near idle
DD15 Combo Package 3 (P3)	Combo Package 2 + bottoming cycle with water as the working fluid	See Appendix B for bottoming cycle details
DD15 Combo Package 3a (P3a)	Combo Package 2 + bottoming cycle with R245 as the working fluid	See Appendix B for bottoming cycle details
DD15 Combo Package 3b (P3b)	Combo Package 2 + bottoming cycle with a recuperator, using R245 as the working fluid	See Appendix B for bottoming cycle details
DD15 Combo Package 3c (P3c)	Combo Package 2 + bottoming cycle with methanol as the working fluid	See Appendix B for bottoming cycle details
DD15 Combo Package 3d (P3d)	Combo Package 2 + bottoming cycle with a recuperator, using methanol as the working fluid	See Appendix B for bottoming cycle details
DD15 Combo Package 3e (P3e)	Combo Package 2 + bottoming cycle with ethanol as the working fluid	See Appendix B for bottoming cycle details
DD15 Combo Package 3f (P3f)	Combo Package 2 + bottoming cycle with a recuperator, using ethanol as the working fluid	See Appendix B for bottoming cycle details
DD15 Combo Package 4 (P4)	No EGR, no turbocompound, conventional fixed geometry turbo, FMEP reduction	Combine a non-EGR engine with 10% - 35% friction reduction. Would require very high conversion efficiency SCR to meet NOx requirement. OBD could be a major issue.
DD15 Combo Package 5 (P5)	Optimized turbocompound, Downspeed B, partial FMEP reduction, 1% BSFC reduction due to combustion duration reduction	The only combo using turbocompound. Adds downspeeding, 5% - 17.5% friction reduction, and BSFC reduction due to combustion duration reduction

TABLE 2.2 ENGINE TECHNOLOGY COMBINATIONS EVALUATED ON THE ISB 6.7 MEDIUM-DUTY ENGINE

Technology	**Hardware Content**	**Comments**
Baseline ISB	Production 2012 ISB	Most popular MD truck engine
2019 Baseline ISB	Partial FMEP reduction, combustion duration decreased to provide a 1% efficiency improvement	Complies with the 2017 GHG requirement
MD ISB Combo Package 6 (P6)	2019 baseline ISB + partial turbo efficiency improvement + Downspeed	Assume a 2.5% improvement in turbine and compressor efficiencies, reduce rated speed from 2500 RPM to 2200, increase torque and BMEP to compensate for lower rated speed.
MD ISB Combo Package 7 (P7)	No EGR + full turbo efficiency improvement + full FMEP reduction	Would require a very high conversion efficiency SCR to meet NOx requirement. OBD could be a major issue
MD ISB Combo Package 8 (P8)	No EGR + full turbo efficiency improvement + partial FMEP reduction + Downspeed	Would require a very high conversion efficiency SCR to meet NOx requirement. OBD could be a major issue
MD ISB Combo Package 9 (P9)	2019 Baseline ISB + partial turbo efficiency improvement + full FMEP reduction	Compare to Package 6. Package 9 trades away downspeeding to get additional friction reduction
MD ISB Combo Package 10 (P10)	4-cylinder with Pickup torque curve, EGR across the full engine speed/load range	3,000 RPM rated rather than 2500, to help compensate for the displacement, power, and torque reduction. Full range EGR required for HD engine certification emissions compliance.

TABLE 2.3 ENGINE TECHNOLOGIES EVALUATED ON THE ISB 6.7 ENGINE FOR CLASS 2B/3 PICKUPS

Technology	**Hardware Content**	**Comments**
Baseline ISB	Production 2012 ISB for Ram	Higher power and torque than MD version, no EGR at high loads, chassis certified
2019 Baseline ISB	Partial FMEP reduction, combustion duration decreased to provide a 1% efficiency improvement	Complies with the 2017 GHG requirement
Pickup ISB Combo Package 11 (P11)	2019 baseline ISB + partial turbo efficiency improvement + Downspeed	Assume a 2.5% improvement in turbine and compressor efficiency, reduce rated speed from 3000 RPM to 2500
Pickup ISB Combo Package 12 (P12)	No EGR + full turbo efficiency improvement + full FMEP reduction	Would require a very high conversion efficiency SCR to meet NOx requirement. OBD could be a major issue
Pickup ISB Combo Package 13 (P13)	No EGR + full turbo efficiency improvement + partial FMEP reduction + Downspeed	Would require a very high conversion efficiency SCR to meet NOx requirement. OBD could be a major issue
Pickup ISB Combo Package 14 (P14)	2019 Baseline ISB + partial turbo efficiency improvement + full FMEP reduction	Compare to Package 11. Package 14 trades away downspeeding to get additional friction reduction
Pickup ISB Combo Package 15 (P15)	4-cylinder with same BMEP as 6 + full FMEP reduction + 2019 combustion	Power and torque are reduced 33% compared to 6-cylinder baseline ISB

TABLE 2.4 ENGINE TECHNOLOGY COMBINATIONS EVALUATED ON THE 3.5 LITER V-6 TURBO GDI

Technology	Hardware Content	Comments
Baseline 3.5 V-6	2012 Ford EcoBoost 3.5 used in F-150 (Class 2a)	Not used in heavier applications yet, but the potential is there; used as a representative of a downsized, boosted engine for heavier duty applications
3.5 Combo Package 16 (P16)	Baseline V-6 + VVA + EGR	Combines 2 technologies from Report #1
3.5 Combo Package 17 (P17)	Package 16 + Downspeed	Rated speed reduced from 6,000 RPM to 4,500, torque and BMEP increased to maintain performance.
3.5 Combo Package 18 (P18)	Package 16 + Lean GDI at part load	Requires lean NOx aftertreatment. Exhaust temperature is a problem
3.5 Combo Package 19 (P19)	Baseline V-6 + EGR + Downspeed	Combines 2 technologies from Report #1

TABLE 2.5 ENGINE TECHNOLOGIES EVALUATED ON 6.2 LITER PORT-INJECTED V-8

Technology	Hardware Content	Comments
Baseline 6.2 V-8	2012 6.2 V-8 used in Class 2b/3 pickup trucks	Not used in heavier applications yet, but the potential is there
6.2 Combo Package 20 (P20)	GDI + EGR + Cylinder Deactivation + 10% FMEP reduction	Combines 4 technologies from Report #1
6.2 Combo Package 21 (P21)	Package 20 + VVA	Combines 5 technologies from Report #1
6.2 Combo Package 22 (P22)	GDI + EGR + Two Cam Phasers + 10% FMEP reduction	Lower cost alternative to VVA Note: there is no Combo Package 3
6.2 Combo Package 23 (P23)	GDI + EGR + Cylinder Deactivation	Combines 3 technologies from Report #1
6.2 Combo Package 24 (P24)	GDI + EGR + 10% FMEP reduction	Combines 3 technologies from Report #1 Note: there is no Combo Package 6

2.1.1.1 Vehicle Technology Combinations

Similar to the approach with engine technologies, combinations of vehicle technologies were chosen for evaluation by SwRI, NHTSA and EPA. In many cases, several vehicle features (such as aerodynamic drag reduction, weight reduction, and rolling resistance reduction) are combined, but these combinations are run with the original baseline engine(s). There are other combinations where vehicle features are combined with an engine technology package. The selected technology packages for each vehicle type are shown in the tables below.

TABLE 2.6 VEHICLE TECHNOLOGY COMBINATIONS ON THE KENWORTHT700 TRACTOR (CLASS 8)

Technology	Hardware Content	Comments
2019 Baseline	Production 2013 T700 truck with 2019 baseline DD15 engine	Complies with 2017 GHG requirement, but with zero margin
T700 Combo Package 1 (VP1)	15% Cd reduction, 10% Crr reduction, 3% weight reduction. 2019 baseline DD15 engine.	Combines 3 vehicle technologies from Report #1
T700 Combo Pack. 2 (VP2)	25% Cd reduction, 30% Crr reduction, 6.5% weight reduction. 2019 baseline DD15 engine.	Aggressive combination of 3 vehicle technologies from Report #1
T700 Combo Package 3 (VP3)	P1 + 40% A/C power reduction + 20% chassis friction reduction + 6X2 drive axles + 18-spd AMT. 2019 DD15 baseline engine.	Combines vehicle 7 technologies from Report #1
T700 Combo Package 4 (VP4)	25% Cd reduction, 30% Crr reduction, 40% A/C power reduction, 20% chassis friction reduction, 6X2 Axles, 18-spd AMT. Engine package 3b (P2 + R245 BC w/ recuperator).	Combines 6 vehicle technologies from Report #1 with an engine technology package. Note that significant weight reduction efforts would be needed to compensate for aero features and WHR system.
T700 Combo Package 5 (VP5)	Vehicle technology combo 3, but with 10-spd AMT. Engine combo package 5	Combines 6 vehicle technologies with an engine technology package.

TABLE 2.7 VEHICLE TECHNOLOGY COMBINATIONS ON THE KENWORTHT270 BOX TRUCK (CLASS 6)

Technology	Hardware Content	Comments
2019 Baseline	Production 2013 T270 truck with 2019 baseline ISB diesel engine	Complies with 2017 GHG requirement, but with zero margin
T270 Combo Package 6 (VP6)	Sweep of Cd (5%, 10%, 15% reductions). Sweep of Crr (10%, 20%, 30% reductions). Baseline 2019 ISB engine.	Evaluates the effect of Cd and Crr changes.
T270 Combo Package 7 (VP7)	20% Crr reduction, 8-spd automatic transmission. Evaluated with 2019 baseline ISB and gasoline engines.	Combines two vehicle technologies from Report #1
T270 Combo Package 8 (VP8)	VP7 + Idle Neutral feature on transmission. Evaluated on 2019 baseline ISB and gasoline engines.	Evaluate the effect of an idle neutral feature for both diesel and gasoline applications.
T270 Combo Package 9 (VP9)	20% Crr reduction, 6-spd AMT transmission. Evaluated on 2019 baseline ISB and gasoline engines.	Combines 2 vehicle technologies from Report #1. Compares AMT fuel efficiency against automatic transmission (Vehicle Package 7) and automatic with idle neutral (Vehicle Package 8).
T270 Combo Package 10 (VP10)	VP8 + 40% A/C power reduction + 800 weight reduction	Combines 4 vehicle technologies from Report #1 with the idle neutral feature.

TABLE 2.8 VEHICLE TECHNOLOGY COMBINATIONS ON THE FORD F-650 TOW TRUCK (CLASS 5)

Technology	Hardware Content	Comments
2019 Baseline	Production 2013 F-650 truck with 2019 baseline ISB diesel engine	Complies with 2017 GHG requirement, but with zero margin
F-650 Combo Package 11 (VP11)	Sweep of Cd (5%, 10%, 15% reductions). Sweep of Crr (10%, 20%, 30% reductions). Baseline 2019 ISB engine.	Evaluates the effect of Cd and Crr changes.
F-650 Combo Package 12 (VP12)	20% Crr reduction, 8-spd automatic transmission. Evaluated with 2019 baseline ISB and gasoline engines.	Combines two vehicle technologies from Report #1
F-650 Combo Package 13 (VP13)	VP12 + Idle Neutral feature on transmission. Evaluated on 2019 baseline ISB and gasoline engines.	Evaluate the effect of an idle neutral feature for both diesel and gasoline applications.
F-650 Combo Package 14 (VP14)	20% Crr reduction, 6-spd AMT transmission. Evaluated on 2019 baseline ISB and gasoline engines.	Combines 2 vehicle technologies from Report #1. Compares AMT fuel efficiency against automatic transmission (VP12) and automatic with idle neutral (VP13).
F-650 Combo Package 15 (VP15)	VP13 + 40% A/C power reduction + 800 weight reduction	Combines 4 vehicle technologies from Report #1 with the idle neutral feature.

TABLE 2.9 VEHICLE TECHNOLOGY COMBINATIONS ON THE RAM PICKUP (CLASS 2B/3)

Technology	Hardware Content	Comments
2019 Baseline	Production 2013 Ram pickup with 2019 baseline ISB pickup diesel engine	Complies with 2017 GHG requirement, but with zero margin
Ram Combo Package 16 (VP16)	Sweep of Cd (5% and 10% reductions). Sweep of Crr (10%, 20%, 30% reductions). Baseline 2019 ISB pickup engine.	Evaluates the effect of Cd and Crr changes.
Ram Combo Package 17 (VP17)	10% Cd reduction, 30% Crr reduction, 8-spd automatic transmission. Evaluated with 2019 baseline ISB and gasoline engines.	Combines three vehicle technologies from Report #1
Ram Combo Package 18 (VP18)	VP17 + Idle Neutral feature on transmission. Evaluated on 2019 baseline ISB and gasoline engines.	Evaluate the effect of an idle neutral feature for both diesel and gasoline applications.
Ram Combo Package 19 (VP19)	10% Cd reduction, 30% Crr reduction, baseline 6-spd automatic transmission. Evaluated on 2019 baseline ISB and gasoline engines.	Combines 2 vehicle technologies from Report #1. Compares baseline transmission fuel efficiency against 8-spd automatic (VP17) and 8-spd automatic with idle neutral (VP18).
Ram Combo Package 20 (VP20)	VP18 + 40% A/C power reduction + 600 weight reduction	Combines 4 vehicle technologies from Report #1 with the idle neutral feature.

2.2 Modeling Methodology

As in Report #1, the engines and engine technologies were modeled in GT-Power, which is a commercially available simulation tool. Each baseline engine model was calibrated using experimental engine data. Appendices A and B of Report #1 [4] include assumptions made for each technology for gasoline and diesel engines, respectively. The technology inputs were derived from literature on existing technologies, and physical validation of each technology on the modeled engines and vehicles was often not possible. Wherever possible, experimental results from similar engines were used to help validate simulation results. In many cases, detailed combustion heat release data was available from engine testing. This allowed heat release to be input directly into the model, rather than estimated by GT. Actual turbocharger efficiency maps were used as an input, although these maps were not necessarily from the engine being simulated. The turbo maps were scaled up or down to achieve the required air flow for each specific engine technology simulated.

One dimensional CFD tools such as GT-POWER have certain advantages and limitations. Some advantages relative to 3-D CFD tools include:

- Rapid solution time
- Accurate calculation of engine air flows, pressures, and temperatures (provided the input geometry data is correct)
- Very useful for predicting the effects of basic parameters such as compression ratio, combustion timing, air/fuel ratio, intake and exhaust restriction, etc.
- Very useful for determining required turbocharger match
- Fairly accurate representation of overall fuel consumption and CO_2 emissions (typically within +/- 3%)
- More accurate representation of small changes in fuel consumption and CO_2 as a result of a technology change (differences of less than 1% can often be reliably predicted)

Areas of weakness in tools like GT-Power include:

- Unreliable predictions of NOx, PM, and other criteria emissions
- Predictions of combustion parameters such as rate of heat release are simplified unless experimental data is available to use as an input. Wherever possible, measured heat release data was used to simulate the technologies that involve changes to the combustion process.
- Predictions of turbocharger performance are based on the maps that are provided to the program, which sometimes do not reflect real-life performance on the engine. This can be improved if measured engine data is available to verify and adjust the turbo maps to match actual, on-engine turbo performance.

One issue with simulating turbocharger performance is the fact that compressor and turbine efficiency maps are measured on a gas stand. The gas stand has steady flow, unlike the pulsating flow seen by the turbine in an actual engine. As a result, the gas stand will miss performance that is a function of fluctuating flow, such as the benefit of a dual entry turbine housing, which utilizes the pulsation energy from blow-down pulses in the exhaust manifold. If engine test data is available, the turbine performance maps determined on a gas stand can be modified to reflect actual on-engine performance.

To address the limitations of GT-Power, SwRI used measured combustion heat release data whenever it was available. All of the engine models used measured heat release for the baseline technology, and in many cases, experimental data was available for specific technologies that had an effect on combustion. Except in specific cases that are noted in the discussion, EGR rates and air/fuel ratios were controlled to match the baseline engine performance. Technologies that would affect heat release rates and combustion duration will have effects on efficiency that are not captured in the GT-POWER models used in this project. Technologies where assumptions had to be made regarding combustion are noted in the results section. SwRI also used actual turbocharger performance maps as a basis, and scaled them to match given engines and technologies. This approach provides turbocharger performance that matches at given points and has the right characteristics across the engine speed/load range. Having data on a full family of turbochargers that would be applied to the engine being simulated would be even better. Unfortunately, full turbo map data was not available for all of the engine permutations in this study.

For each engine and engine technology, the GT-Power model was run over a range of engine speed and load conditions. The resulting fuel consumption and CO_2 data were used to create a fuel consumption map. The map provides projected fuel consumption over a range of 20 engine speeds and 20 loads, for a total of 400 data points. Not all of these data points were actually simulated – many were generated by interpolation between simulated speed/load points. Appendices A and B provide details on the number of speed/load points that were simulated for each engine. The 20 X 20 point fuel maps were then provided to the vehicle simulation tool to represent the engine performance. In addition to the fuel maps, the full load torque curve and motoring torque curve (the torque required to spin the engine with zero fuel) were provided to the vehicle simulation tool.

Appendix A includes details of each gasoline engine model, including sources of input data and comparisons to experimental results. The assumptions made for each technology combination are also described. Appendix A also includes the fuel map results for each gasoline engine and technology. Appendix B includes the same information for the two diesel engines.

Vehicles and vehicle technologies were modeled using the SwRI Vehicle Simulator tool. This MATLAB-based tool is similar to the NREL tool called Advisor. The Vehicle Simulator tool has the ability to handle a wide range of vehicle technologies including automatic transmissions, automated manual transmissions, hybrid systems, etc. One advantage of the SwRI tool is that features can easily be ported to the EPA’s greenhouse gas emissions certification tool, GEM. Any desired drive cycle can be put into the Vehicle Simulator tool. The following drive cycles were used for this program:

TABLE 2.10 VEHICLES AND DRIVE CYCLES USED IN STUDY

Vehicle	Drive Cycles
Dodge Ram Pickup	FTP City, FTP Highway, US06, SC03, WHVC, 65 MPH
Kenworth T270 Box Truck	GEM Cycles, CILCC, Parcel Delivery Cycle, WHVC
Ford F-650 Tow Truck	GEM Cycles, CILCC, Parcel Delivery Cycle, WHVC
Kenworth T700 Tractor	GEM Cycles, WHVC, NESCCAF Long Haul Cycle

The cycles listed above are described in detail in Appendix C. The current version of GEM includes 3 cycles. One is a low speed urban cycle developed by CARB. The second is a constant 55 MPH with no grade or wind. The final cycle is a 65 MPH constant speed with no grade or wind. For the 55 and 65 MPH cycles, only data from the steady-state portion of the cycle is reported. The US06 and SC03 cycles are carried over from light-duty applications. Since heavy-duty pickup trucks are often used in the same way as a passenger car, it is appropriate to evaluate their performance on car-like drive cycles. The acronym CILCC stands for Combined International Local and Commuter Cycle. This cycle is primarily a low vehicle speed cycle with numerous stops. The CILCC includes very gentle accelerations and decelerations which may not be representative of real-world operation, but which would give very favorable results for hybrid vehicles. The decelerations are gradual enough to allow a hybrid system to recover most or all of the braking energy. The parcel delivery cycle was derived from the operations of a Class 6 parcel delivery truck in the US market. This cycle was developed by the HTUF organization, based on real-world data measurements. HTUF was formerly known as the Hybrid Truck Users Forum, and is now the High-efficiency Truck Users Forum. The CILCC and Parcel Delivery cycles were used to represent the local operations that are typical for many vocational trucks.

WHVC stands for World Harmonized Vehicle Cycle. This cycle is intended for medium- and heavy-duty vehicles, and includes a low speed urban segment, a moderate speed suburban segment, and a highway cruise segment. The highway segment of the WHVC does not include grade or wind, and the vehicle speeds on this segment reflect the European practice of installing road speed governors on trucks to limit maximum vehicle speed to 90 km/h (56 MPH). The WHVC is the only cycle other than the 65 MPH cycle that was applied across the complete range of Class 2b through Class 8 vehicles. The NESCCAF long haul cycle includes brief urban/suburban segments and four extended highway cruise segments at 65 to 70 MPH. One of the highway cruise segments includes a cyclic grade of +/- 1%, and another highway cruise segment includes a cyclic grade of +/- 3%. Like all the other cycles, the NESCCAF cycle does not include the effect of any wind.

The reason for exploring several duty cycles is to develop an understanding of how different engine and vehicle technology combinations perform across a range of drive cycles. Certain technologies may be insensitive to payload or drive cycle, while others can be extremely sensitive.

Appendix C of Report #1 lists the input data required by the SwRI Vehicle Simulator tool. In most cases, SwRI used measured data from test vehicles and components, or information provided by OEMs and component suppliers as inputs. In certain cases, such as axle and transmission efficiency, SwRI used test data from other SwRI projects as inputs to the simulation. This existing data is proprietary to SwRI and its specific clients, and was not created or derived from federally funded work. In these limited cases, SwRI cannot provide the actual input data used in the simulation runs.

2.3 Results

The following sections review the results derived for the engine and vehicle technology combinations described in Sections 2.1.1 and 2.1.2.

2.3.1 Class 8 Tractor-Trailer Truck and Engine Technology Combination Results

The Kenworth T700 truck and trailer, and the DD15 heavy duty engine, have been described in Section 3 of Report #1. Only the technology combination results will be discussed here.

2.3.2 Summary of DD15 Engine Technology Combinations in the T700 Truck

The engine technology combinations listed previously in Table 2.1 were all evaluated using the baseline tractor-trailer vehicle configuration. Appendix B describes the details of the DD15 model, its calibration, as well as the assumptions and parameters involved in simulating each of the considered technology combinations.

The results presented in this section have been revised since the original draft version of the report. Three errors were discovered during the independent peer review and public release of the draft report that have been corrected in this final version. The first error was the use of the wrong fuel map to represent the model year 2019 DD15 engine baseline. The fuel map inadvertently used was a model year 2011 baseline turbocompound engine with a 1% benefit from combustion duration, but otherwise unchanged. The analysis for this section should have used a fuel map representative of the more efficient 2013 DD15 engine as the baseline to allow exploration of improvements beyond the Phase 1 standards. The 2013 DD15 replaced the turbocompound system with an asymmetric turbocharger and includes other changes which increase efficiency. The second error was an Excel lookup reference which pointed to the wrong vehicle frontal area. The frontal area for the T700 truck used in the draft version of this report was about 5% low. This had the effect of making all technology combination fuel consumption results look slightly better than they should have. This error had the largest effect (up to 2%) on the high speed cruise cycles, where aerodynamic load plays the largest role. The final error was that several of the technology packages were run by mistake with preliminary rather than final fuel maps.

In addition to correcting the errors described above, one other change was made in the interest of providing the most accurate possible comparison. The original 2011 DD15 GT model was revised to include a fueling controller (which defines the torque curve) and an exhaust backpressure controller (which defines an orifice in the exhaust to achieve a target backpressure). These controllers were used in all subsequent technology simulations, so they were applied to the baseline engine model in an effort to guarantee consistency in the modeling approach.

The revised results included in this version of the report show the following effects:

- There is now a larger difference between the 2011 and 2019 DD15 baseline engine results, particularly on the CARB and WHVC cycles
- The fuel savings benefits of all the DD15 technology combination packages are reduced by up to 3.3% depending on the technology packages and driving cycles compared to the original draft, primarily because the post-Phase 1 2019 DD15 baseline now has lower fuel consumption
- The relative benefit of waste heat recovery is essentially unchanged

Additional information on these corrections can be seen in Appendix E of this report.

Table 2.11 summarizes the results of engine technology combination simulations. Results are provided for each technology on five drive cycles. Each drive cycle was run at three payloads, to provide information on how sensitive a given technology is to payload. As a result, the table provides 15 data points for each of the 12 technology combinations that were evaluated. The results shown are in terms of percent reduction in fuel consumption compared to the baseline projected 2019 DD15 engine GT model.

The results shown in Table 2.11 can also be presented in graphical form. To simplify the graph, only results for the 50% payload are shown in Figures 2.1 and 2.2. There is one important difference between Table 2.11 and Figure 2.1. In the table, the values for Combo 3 (the bottoming cycles) includes the benefits of Combo 2, since the bottoming cycles were added to the Combo package 2 technologies. However, in Figure 2.1, the performance of the bottoming cycles is shown in reference to Combo 2. This allows the reader to see the contribution of each bottoming cycle type on a stand-alone basis. Figure 2.2 presents the same information, but shows the full value of Combo 3, including the technologies in Combo 2, plus the bottoming cycle.

Because bottoming cycles have very slow transient response, there is a large drop-off in fuel savings between a steady-state test cell evaluation and real, on-road performance under transient conditions. The model does not include the effects of transient response, so the bottoming cycles were not run on the more transient drive cycles (CARB and WHVC). Real world performance of the bottoming cycles will be hurt by transient response issues, even at steady speed operation. Steady speed rarely involves steady load.

TABLE 2.11 FUEL SAVINGS RESULTS OF DD15 ENGINE TECHNOLOGY COMBINATIONS VS. 2019 BASELINE

Engine Technology Combos	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload														
	CARB			55 MPH			65 MPH			WHVC			NESCCAF		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
1. 2011 Base DD15	-3.0%	-2.7%	-2.5%	-2.5%	-2.4%	-2.3%	-2.8%	-2.7%	-2.5%	-2.8%	-2.6%	-2.4%	-2.8%	-2.6%	-2.5%
2. DD15 Combo 1	5.5%	3.9%	3.0%	2.9%	2.2%	1.7%	1.6%	1.2%	1.0%	4.6%	3.1%	2.2%	2.0%	1.4%	1.1%
3. DD15 Combo 2	8.1%	5.6%	4.1%	2.2%	2.4%	2.3%	4.0%	3.3%	2.9%	6.3%	4.4%	3.2%	4.8%	3.2%	2.6%
4. DD15 Combo 3	8.1%	5.6%	4.1%	6.8%	7.2%	7.3%	8.6%	8.1%	7.9%	6.3%	4.4%	3.2%	9.5%	8.1%	7.7%
5. DD15 Combo 3a	8.1%	5.6%	4.1%	5.7%	5.9%	5.9%	7.3%	6.7%	6.3%	6.3%	4.4%	3.2%	7.9%	6.4%	5.7%
6. DD15 Combo 3b	8.1%	5.6%	4.1%	6.7%	6.9%	6.9%	8.7%	8.0%	7.7%	6.3%	4.4%	3.2%	9.3%	8%	7.1%
7. DD15 Combo 3c	8.1%	5.6%	4.1%	7.4%	7.7%	7.8%	9.2%	8.6%	8.4%	6.3%	4.4%	3.2%	10%	8.4%	7.9%
8. DD15 Combo 3d	8.1%	5.6%	4.1%	7.4%	7.8%	8.0%	9.3%	8.8%	8.6%	6.3%	4.4%	3.2%	10%	8.7%	8.3%
9. DD15 Combo 3e	8.1%	5.6%	4.1%	7.1%	7.5%	7.5%	9.0%	8.4%	8.1%	6.3%	4.4%	3.2%	10%	8.1%	7.5%
10. DD15 Combo 3f	8.1%	5.6%	4.1%	7.4%	7.8%	7.9%	9.4%	8.8%	8.7%	6.3%	4.4%	3.2%	10%	8.7%	8.3%
11. DD15 Combo 4	6.4%	4.9%	4.1%	5.9%	5.0%	4.2%	5.2%	4.7%	4.3%	6.0%	4.6%	3.7%	5.2%	4.4%	3.9%
12. DD15 Combo 5	7.6%	5.4%	6.5%	1.3%	1.6%	1.8%	4.3%	3.4%	2.7%	5.6%	4.1%	3.3%	5.0%	3.6%	3.2%

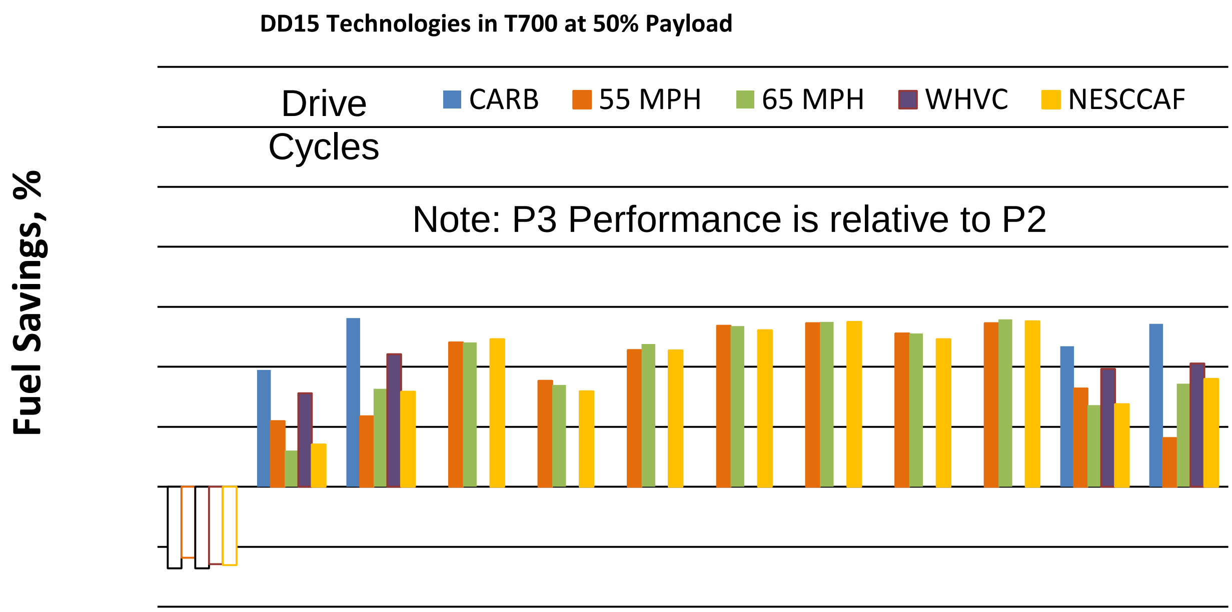

FIGURE 2.1 FUEL SAVING PERFORMANCE OF DD15 TECHNOLOGY PACKAGES, WITH P3 RESULTS DISPLAYED RELATIVE TO THE P2 RESULTS RATHER THAN TO THE 2019 BASELINE

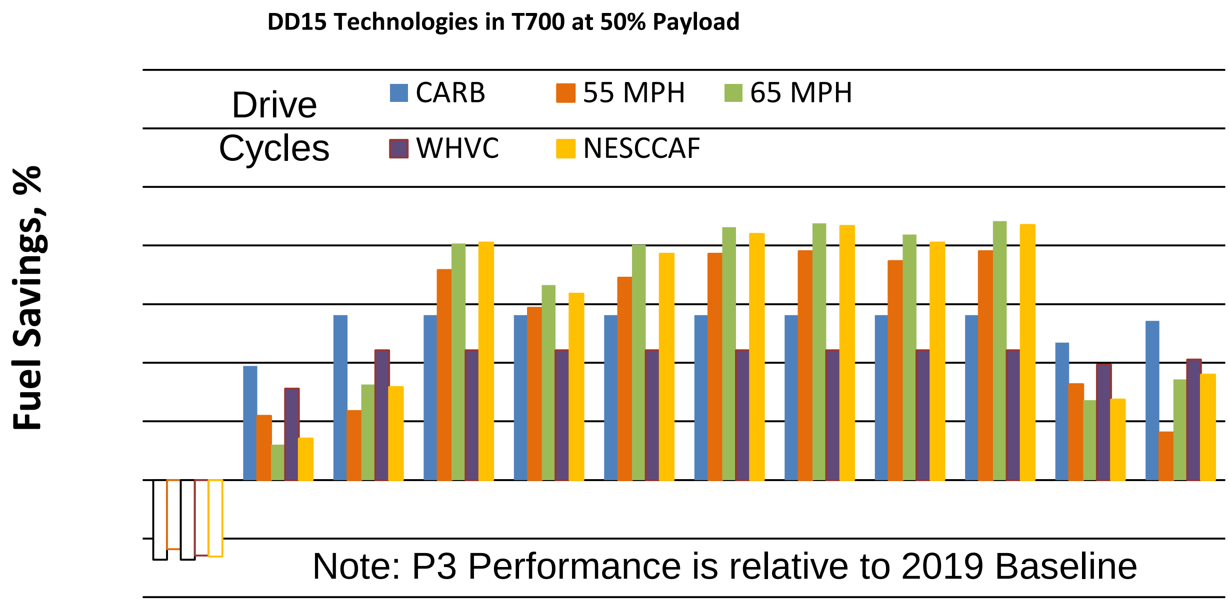

FIGURE 2.2 FUEL SAVING PERFORMANCE OF THE DD15 TECHNOLOGY PACKAGES, SHOWING THE FULL VALUE OF ALL TECHNOLOGY PACKAGES

In the following subsections, each engine technology is given its full name in the section heading, along with the abbreviated name used in Figure 2.1. The abbreviations are provided in parentheses.

2.3.2.1 Comparison of 2019 Baseline engine to original 2011 baseline (2011 Base)

In 2019, heavy duty engines must meet the MY 2017 and later GHG requirements. The MY 2017 standard calls for a 3% fuel consumption reduction compared to the MY 2014 requirements from the first stage of the Phase 1 regulation. The original baseline 2011 DD15 engine just meets the MY 2014 requirements, so a 3% improvement was needed. The asymmetric turbocharger, non-turbocompound engine was selected from the original technology evaluation for the 2019 baseline. This GT-POWER model represents (as closely as possible) the current production 2014 model DD15 non-turbocompound engine. Some additional improvement was needed to comply with 2017 GHG requirements, so a shortened combustion duration was applied to achieve a 1% BSFC reduction across the engine speed/load range. See Appendix B for details of the 2019 baseline engine configuration and performance.

Across all drive cycles and payloads, fuel savings of 2% to 3.4% are achieved, compared to the 2011 baseline DD15 engine. Fuel savings are generally higher with light payloads, and lower at 100% payload.

2.3.2.2 DD15 Technology Package 1: 2019 Baseline + FMEP Reduction (P1)

Package 1 adds an engine friction reduction (FMEP reduction) to the 2019 baseline DD15 engine. The friction reduction is identical to that explored in Section 3.3.1.12 of the first report, which is10% at high engine speeds and loads, increasing to 35% at low speed, light load. FMEP encompasses the cylinder kit, bearing, and valve train friction, but also the power demand of the engine fuel, oil, and water pumps. Thus, a feature that turns off piston cooling nozzle flow at light load, and that reduces oil pump flow and power accordingly, would contribute to lower FMEP. A more efficient fuel system high pressure pump would also reduce FMEP. Any accessory not essential to engine operation is not considered as a contributor to FMEP, but rather as an accessory power demand. Examples of these non-FMEP accessories include the air conditioner compressor, alternator, power steering pump, air compressor, and engine cooling fan. See Appendix B for details of the friction reduction assumptions, and for the resulting changes in the engine fuel map. Development of this package to production readiness would require significant engineering effort, but a production package should have only limited cost and complexity impact.

The FMEP reduction in Package 1 provides a 1% to 2.9% benefit on the higher load drive cycles, with the larger benefits coming at zero payload. On the lightly loaded cycles, benefits as high as 5.5% can be found at zero payload.

2.3.2.3 DD15 Technology Package 2: 2019 Baseline + Downspeed B + ½ FMEP Reduction (P2)

Package 2 applies Downspeed B to the 2019 baseline DD15, which reduces engine cruise speed at 65 MPH road speed from 1368 to 1051 RPM. A friction reduction is also assumed, but because of the higher BMEP of this engine (the torque curve was increased to maintain vehicle performance), only 50% of the friction reduction assumed for Package 1 was applied here. Development of this package would require engineering effort to achieve durability targets, but a production package should have only limited cost and complexity impact.

Package 2 provides fuel savings over the 2019 baseline DD15 of just under 3% (under the most highly loaded conditions) to as much as 8.1% on the CARB cycle at zero payload.

It should be mentioned that the overall final drive ratio for this study is 1.88, with the top transmission gear ratio at 0.73 and the axle ratio at 2.58. With such a low final drive ratio, driveline torsional vibration problems may need to be resolved. In addition, at 55 MPH the engine speed in top gear would be reduced to 880 RPM. This is not practical, so the results presented in this report assume that the vehicle runs at 55 MPH in 9th gear, one gear down.

2.3.2.4 DD15 Technology Package 3: Package 2 + Water Based WHR (P3)

Because WHR showed significant promise when evaluated as a stand-alone technology in Report #1, and because OEMs are considering a number of working fluid options, WHR systems were explored in more detail in this part of the project. The choice of working fluid can affect WHR system efficiency and hardware requirements. The working fluid can also introduce technical challenges, such as freezing when not in use or a combination of high temperature, high pressure, and flammable fluid when in use. Package 3 adds a water-based bottoming cycle to the Package 2 engine. This system does not include a recuperator. Details of the bottoming cycle modeling, assumptions, and results can be found in Appendix B. Package 3 was only run on the 55 MPH, 65 MPH, and NESCCAF cycles, because of transient response limitations described in Section 2.3.2. WHR systems will require extensive analysis, design, and development effort. They will add substantial cost and complexity to the powertrain. Package 3 provides fuel savings over Package 2 of 4.6% to 5.2% over the range of drive cycles and payloads. The performance improves slightly with increasing payload.

2.3.2.5 DD15 Technology Package 3a: Package 2 + R245 Based WHR (P3a)

Package 3a adds an R245-based bottoming cycle to the Package 2 engine. This system does not include a recuperator. Details of the bottoming cycle modeling, assumptions, and results can be found in Appendix B. Package 3a was only run on the 55 MPH, 65 MPH, and NESCCAF cycles, because of transient response limitations described in Section 2.3.2. Package 3a provides fuel savings over Package 2 of 3.1% to 3.6% over the range of drive cycles and payloads. This is about 1.5% less than the water-based system.

2.3.2.6 DD15 Technology Package 3b: Package 2 + R245 Based WHR with Recuperator (P3b)

Package 3b adds an R245-based bottoming cycle with a recuperator to the Package 2 engine. Details of the bottoming cycle modeling, assumptions, and results can be found in Appendix B. Package 3b was only run on the 55 MPH, 65 MPH, and NESCCAF cycles, because of transient response limitations described in Section 2.3.2.

Adding a recuperator to the R245-based system improves the fuel savings by 1% to 1.5% over the non-recuperator version, bringing the refrigerant-based system close to the water-based system in fuel savings performance. Note, however, the added cost, package space, and complexity imposed by the recuperator.

2.3.2.7 DD15 Technology Package 3c: Package 2 + Methanol Based WHR (P3c)

Package 3c adds a bottoming cycle with methanol as the working fluid to the Package 2 engine. Details of the bottoming cycle modeling, assumptions, and results can be found in Appendix B. Package 3c was only run on the 55 MPH, 65 MPH, and NESCCAF cycles, because of transient response limitations described in Section 2.3.2. The methanol-based bottoming cycle performs slightly better than the water-based cycle, with fuel savings of 5.1% to 5.5%

2.3.2.8 DD15 Technology Package 3d: Package 2 + Methanol WHR with Recuperator (P3d)

Package 3d adds a recuperator to the methanol-based system of Package 3c. With methanol as the working fluid, the benefit of a recuperator is very limited (0 to 0.4% additional fuel savings over Package 3c).

2.3.2.9 DD15 Technology Package 3e: Package 2 + Ethanol Based WHR (P3e)

Package 3e adds a bottoming cycle with ethanol as the working fluid to the Package 2 engine. Details of the bottoming cycle modeling, assumptions, and results can be found in Appendix B. Package 3e was only run on the 55 MPH, 65 MPH, and NESCCAF cycles, because of transient response limitations described in Section 2.3.2. The fuel savings with ethanol as a working fluid are about 0.3% lower than those of methanol, and very similar to those of the water-based system.

2.3.2.10 DD15 Technology Package 3f: Package 2 + Ethanol WHR with Recuperator (P3f)

Package 3f adds a recuperator to the ethanol-based system of Package 3e. With ethanol as the working fluid, the fuel savings benefit of a recuperator ranges from 0.3% to 0.7% over Package 3e. This is a larger recuperator benefit than was observed with methanol, but less than was found with R245. The overall fuel savings performance of the P3f system is similar to that of the P3d methanol + recuperator system. These represent the two highest performing bottoming cycle waste heat recovery systems. Note, however, the added cost, package space, and complexity imposed by the recuperator.

2.3.2.11 DD15 Technology Package 4: No Turbocompound, Conventional Fixed Geometry Turbine, No EGR, full FMEP Reduction (P4)

This package represents a high engine-out NOx option that would rely heavily on a high conversion efficiency SCR system for NOx control. Since EGR flow is not required, the asymmetric turbine is replaced by a conventional fixed geometry turbine. Downspeeding was not applied in this package, so the full FMEP reduction described in Section 2.3.2.2 was employed. While the FMEP reduction will require substantial engineering development, the overall package should be less complex and expensive than the baseline turbocompound engine. Fuel savings benefits compared to the 2019 baseline DD15 range from under 4% in the most highly loaded cycles up to over 6% on the CARB cycle at zero payload.

2.3.2.12 DD15 Technology Package 5: Turbocompound + Downspeed B + 1% Combustion Improvement + ½ FMEP Reduction + Reduced Intake, Exhaust, and Charge Air Cooler Restrictions (P5)

DD15 Package 5 represents an effort to achieve maximum possible fuel savings using the engine’s 2011 turbocompound configuration. All the technologies listed above were combined in this package. See Appendix B for details on the technology implementation and the resulting fuel map. This package has an engine cost and complexity similar to Package 2, with the addition of turbocompound. The air handling requirements drive significantly larger and more expensive intake, charge air cooling, and aftertreatment systems. Packaging will be a major challenge. DD15 Package 5 provides fuel savings benefits similar to those of Package 2, but at the expense of significantly increased cost and complexity. Packaging the reduced restriction intake, exhaust, and charge air cooler systems in a practical vehicle would prove very difficult, for example, because these components would need to grow substantially in size to achieve the desired reduction in restriction.

2.3.2.13 DD15 Engine Technology Synergies/Interferences

Downspeeding and downsizing both have the effect of driving BMEP and cylinder pressure up, as well as increasing demands on the air handling system, so there are limitations on how far either approach can be pursued without impacting durability and reliability. These limitations also constrain any combination of downspeeding and downsizing. The two approaches have similar benefits, so OEMs may select either approach or a combination, depending on their available hardware platforms. Another constraint applies to combinations of downspeeding or downsizing with FMEP reduction. Higher cylinder pressures require larger bearings and piston changes which will increase friction, so any change which increases cylinder pressure makes achieving an FMEP reduction more difficult.

The performance of waste heat recovery systems is dependent on the heat sources used. Many base engine improvements would actually reduce the benefits of WHR. As manufacturers move to reduce EGR flow (and push up engine-out NOx) to improve the efficiency of the base engine, this reduces the availability of a high quality (high temperature) heat source for the WHR system. Advancing fuel injection timing can improve brake thermal efficiency, but at the cost of a reduction in exhaust energy. Many air handling system improvements, such as improving turbocharger efficiency and reducing EGR flow circuit loss, can improve engine brake thermal efficiency, but it can also reduce EGR flow, thus reducing the heat available to the WHR. Given a choice between making the base engine more efficient or increasing the waste heat available to the WHR system, improving the base engine is usually the more effective solution. This is because WHR systems typically have thermal efficiencies of 20% or less, so the portion of waste heat converted to useful work is smaller than the portion of fuel energy converted to useful work in the base engine. Another issue with WHR is its slow transient response, which makes it unsuitable for applications that involve highly transient operation.

The complete elimination of EGR is an attractive approach to higher efficiency, and is used by several European OEMs to comply with the Euro VI standards. However, this approach depends entirely upon very high conversion efficiency in the SCR system. This poses significant technical challenges, especially in terms of achieving OBD compliance (i.e., detecting SCR degradation that would cause the engine to exceed the NOx limit).

There is a trade-off between compression ratio and engine friction. Increasing the compression ratio can improve thermal efficiency. However, a higher compression ratio also increases cylinder pressure. Features added to the engine to enable it to tolerate higher cylinder pressure, plus the direct effect of cylinder pressure itself, mean that at some point the benefit of higher compression ratio is entirely lost due to the penalty of higher friction.

There really are no engine technologies that combine to provide fuel savings greater than the sum of the individual contributions. Rather, it would be less than the sum of the individual contributions for most of the technology combinations.

2.3.3 Summary of T700 Truck Technology Combination Results

The vehicle technology combinations listed in Table 2.6 above were all evaluated using the baseline DD15 engine configuration. Appendix C describes the details of the T700 vehicle model, its calibration, as well as the assumptions and parameters involved in simulating each of the considered technology combinations. All vehicle technology packages are compared to the original baseline vehicle, as defined in Report #1. This study simulated the fuel efficiency benefits over theoretical ranges of aerodynamic drag, rolling resistance, empty weight, etc. improvements that were informed by current literature values. This study did not attempt to determine what value of aero, Crr, etc. improvement was possible for any particular vehicle or tire model, nor the design changes necessary to accomplish the improvements (which can vary significantly across models). The value of simulating over a range of values is to allow manufacturers and regulators to determine the fuel efficiency benefits for any achievable value in the range.

Table 2.12 below summarizes the results of vehicle technology combination simulations. Results are provided for each technology on five drive cycles. Each drive cycle is run at three payloads, to provide information on how sensitive a given technology is to payload. As a result, the table provides 15 data points for each of the five technology combinations that were evaluated. The results shown are in terms of percent fuel consumption reduction compared to the baseline projected 2019 T700 vehicle simulation model. Since the 2017 fuel consumption/GHG regulations do not require any trailer aerodynamic or tire rolling resistance features, the original baseline vehicle model is assumed to be appropriate for compliance with the 2017 regulatory requirements. Note that the market, with a push from CARB regulations requiring SmartWay trailer features for vehicles operating in California, may in many cases offer vehicles that perform better than this baseline.

TABLE 2.12 VEHICLE TECHNOLOGY COMBINATION FUEL SAVINGS RESULTS

Vehicle Technology Combos	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload														
	CARB			55 MPH			65 MPH			WHVC			NESCCAF		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
1. T700 Combo 1	3.4%	3.2%	3.1%	11%	11%	11%	12%	12%	12%	6.0%	5.6%	5.2%	10.9 %	10.1 %	9.6%
2. T700 Combo 2	7.4%	7.6%	7.6%	21%	22%	23%	22%	23%	24%	12%	12%	12%	20%	20%	20%
3. T700 Combo 3	5.9%	5.6%	5.3%	13%	13%	14%	14%	14%	14%	8.1%	7.0%	6.7%	13%	12%	12%
4. T700 Combo 4	20%	18%	17%	29%	30%	30%	32%	33%	33%	23%	21%	20%	31%	29%	28%
5. T700 Combo 5	13%	11%	9%	14%	14%	14%	19%	18%	17%	14%	12%	10%	18%	16%	15%

The results shown in Table 2.12 can also be presented in graphical form. To simplify the graph, only results for the 50% payload are shown in Figure 2.3 below. Note that Vehicle

Technology Combinations 4 and 5 include engine technology packages, while Vehicle Technology Combinations 1, 2, and 3 use the 2019 baseline DD15 engine.

Vehicle Package 4 includes Engine Package 3b, which is the R245-based WHR system with a recuperator. Because bottoming cycles have very slow transient response, there is a large drop-off in fuel savings between a steady-state test cell evaluation and real, on-road performance under transient conditions. The bottoming cycle model does not include the effects of transient response, so the bottoming cycles were not run on the more transient drive cycles (CARB and WHVC). This explains why Vehicle Package 4 performs much better on the 55 MPH, 65 MPH, and NESCCAF cycles than on the transient cycles.

In the following subsections, each engine technology is given its full name in the section heading, along with the abbreviated name used in Figure 2.3. The abbreviations are provided in parentheses.

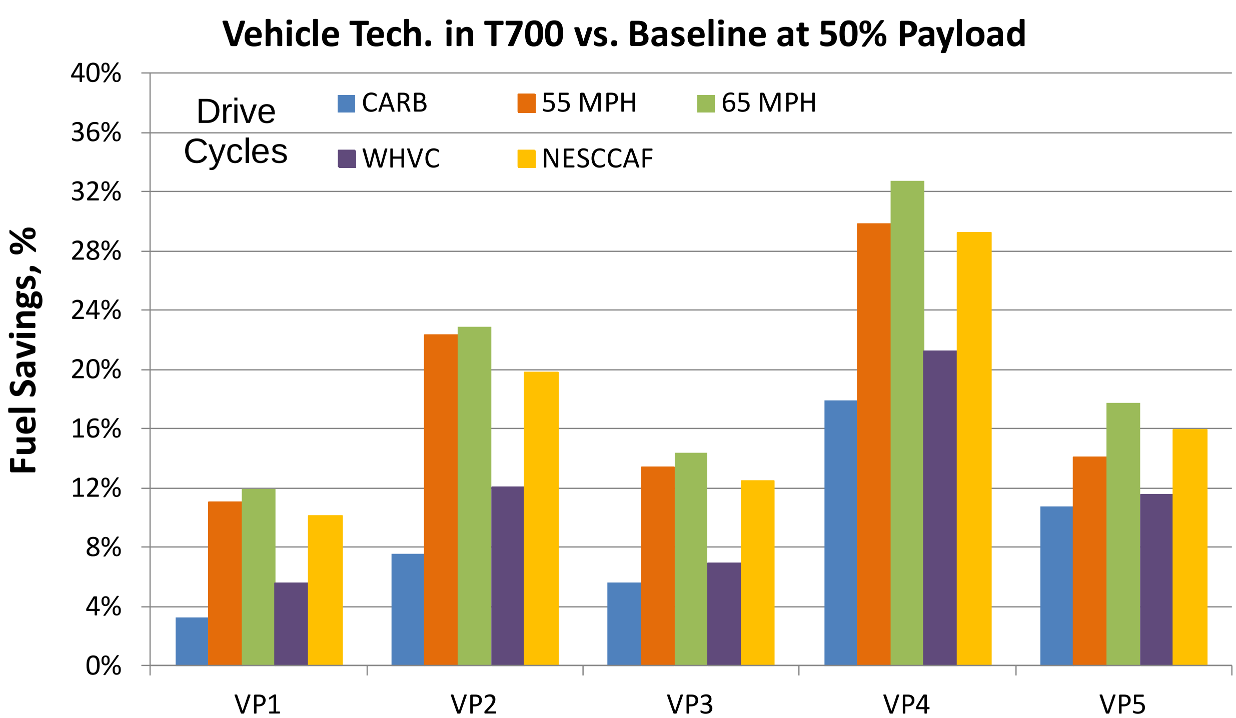

FIGURE 2.3 T700 VEHICLE TECHNOLOGY COMBINATION FUEL SAVINGS RESULTS

2.3.3.1 T700 Technology Package 1: 15% Cd reduction + 10% Crr reduction + 3% weight reduction (VP1)

Package 1 specifies a 15% aerodynamic drag reduction, which would require some form of aerodynamic treatment of the trailer, in addition to tractor treatments beyond those of the baseline tractor. A 10% reduction in Crr is specified. This target could be met with an aggressive reduction in tractor tire rolling resistance, but it would be easier to meet if the target was spread between the tractor and trailer tires. The 3% weight reduction target applies to the empty weight of both the tractor and trailer. This target could be met by any combination of tractor and trailer weight reductions. Note, however, that many fuel saving technologies (such as aerodynamic treatments) add weight, so achieving a weight reduction often requires a larger than specified weight reduction, to make up for new components that are added. The cost and complexity associated with the aerodynamic and rolling resistance components are similar to those experienced by SmartWay certified trucks. The weight reduction requirement will add significant cost, as higher cost materials are substituted for low cost steel.

Package 1 provides a range of fuel savings benefits between 3.1% and 12%. The benefits are largest for the 65 MPH cruise cycle, where aerodynamic drag plays a large role. The benefits are smallest on the transient cycles at 100% payload, where the power demand to overcome vehicle inertia is more important than either aero or rolling forces.

2.3.3.2 T700 Technology Package 2: 25% Cd reduction + 30% Crr reduction + 6.5% weight reduction (VP2)

Package 2 is a more aggressive version of Package 1, with larger reductions in all 3 categories. The Package 2 targets could only be met by applying aggressive aerodynamic, tire rolling, and weight reduction features to the trailer as well as the tractor. These features will have a substantial cost and complexity impact. Note again that the aerodynamic features involve a weight increase, which makes achieving the weight target a greater challenge. Package 2 provides a range of fuel savings from 7.4% to 24%. As with Package 1, the benefits are largest for the 65 MPH cruise cycle, and smallest on the CARB cycle.

2.3.3.3 T700 Technology Package 3: Package 1 + 40% AC power reduction + 20% chassis friction reduction + 6X2 axles + 18-speed AMT (VP3)

Package 3 adds several vehicle power demand reducing features to Package 1. Cost and complexity increase moderately from Package 1. The 18-speed transmission adds weight, which must be compensated for. The benefit of the 18-speed AMT is only a small part of the improvement provided by this package (see Section 3.3.2.8 of Report #1). Package 3 provides an additional fuel savings of 1.4% to 2.7% over Package 1. On the transient cycles, the benefits are largest at zero payload, and smallest at full payload. However, on the more steady state cycles, the benefits are largest at 100% payload. Considering T700 Package 3 as a complete system, the fuel savings benefits cover a range from 5.3% on the CARB cycle at 100% payload, up to 14% on the 65 MPH cycle at full payload.

2.3.3.4 T700 Technology Package 4: 25% Cd reduction + 30% Crr reduction + 40% AC power reduction + 20% chassis friction reduction + 6X2 axles + 18-spd AMT + DD15 Package 3b (VP4)

T700 vehicle Package 4 includes the aero and rolling improvements of Package 2 with the vehicle power demand reduction features of Package 3, and an engine with downspeeding and a WHR system, along with some additional features. Note that this package does not include a weight reduction, but the features being added would require a significant weight reduction effort just to hold weight constant. This package borders on that of a SuperTruck [6, 7], and it provides benefits approaching what are being reported in the SuperTruck program. It includes the combination of the best tractor and trailer, while the regulation on the tractor vehicle always refers to a reference trailer, which is much less advanced than the SuperTruck-type of trailer. Vehicle Package 4 would demand a large increase in cost and complexity. Also, the overall final drive ratio used in this package is extremely aggressive at a value of 1.88, which may not be practical in GHG Phase 2 timeframe. Fuel savings benefits for this package range from 17% on the CARB urban cycle at 100% payload, to 33% at 65 MPH. Note that in the SuperTruck program, results are presented in terms of fuel economy rather than fuel consumption. The 33% fuel consumption reduction achieved by T700 vehicle Package 4 represents a 50% increase in fuel economy or load-specific fuel economy.

The benefits on transient cycles are smaller than those at steady state, for several reasons. First, the WHR system is not used on transient cycles because of its transient response constraints. Second, the Cd and Crr improvements have less effect on transient cycles, where vehicle power demand from inertia loads tend to predominate.

2.3.3.5 T700 Technology Package 5: Vehicle Package 3 + DD15 Package 5 (VP5)

Vehicle Package 5 for the tractor-trailer combines a previous vehicle package with the turbocompound engine technology package. The cost and complexity of this package is equal to the sum of VP3 with engine package 5. Comparing P5 to P3, the smallest fuel savings (just under 1%) are on the 55 MPH cruise cycles, where the engine has to run one gear down compared to the 2019 baseline DD15 engine. On the other cycles, the fuel savings relative to vehicle Package 3 are 3% to 5%, and 7.1% on the CARB cycle at zero payload. Compared to the baseline vehicle, the Package 5 fuel savings range from 9% on the CARB cycle at 100% payload to 19% on the 65 MPH cycle at zero payload.

2.3.3.6 T700 Vehicle Technology Synergies/Interferences

The vehicle technologies explored in this section tend to have little synergy or interference. Each technology contributes to a reduction in vehicle power demand, and each addresses a different source of vehicle power demand. As a result, the improvements tend to sum in a linear way. One factor worth remembering is that once improvements are made in one area, the remaining sources of power demand gain in relative importance. For example, if aerodynamic drag is reduced, tire rolling resistance and other power demand sources would be a larger percentage of the remaining (smaller) total vehicle power demand. The comments in this section regarding the T700 truck also apply to all the other vehicles in this study.

2.3.4 Medium Duty Vocation Truck Engine and Vehicle Technology Combinations

The Ford F-650 tow truck and Kenworth T270 delivery truck, as well as the ISB diesel engine, have been described in Section 3 of Report #1 [4]. The two gasoline engines, a 3.5 liter turbocharged V-6 and a naturally aspirated V-8, are also described in Section 3 of Report #1 [4]. Only the technology combination results will be discussed here.

2.3.5 Summary of Engine Technology Package Results in the F-650

The engine technology combinations previously listed in Tables 2.2, 2.4, and 2.5 were all evaluated using the baseline F-650 vehicle configuration. Appendix B describes the details of the ISB medium-duty diesel model, its calibration, as well as the assumptions and parameters involved in simulating each of the considered technology combinations. Appendix A provides details of the gasoline engine models, calibrations, assumptions, and parameters used.

Table 2.13 summarizes the results of engine technology combination simulations. Results are provided for each technology on six drive cycles. Each drive cycle is run at three payloads, to provide information on how sensitive a given technology is to payload. As a result, the table provides 18 data points for each of the 15 technology combinations that were evaluated. The results shown in Table 2.13 are in terms of percent fuel consumption reduction compared to the baseline projected 2019 engine GT-POWER models for all three engine types. Each engine is compared to its own respective 2011 baseline. The results from Table 2.13 can also be presented in graphical form. To simplify the graphs, only results for the 50% payload are shown in Figures 2.4 to Figure 2.6 below.

TABLE 2.13 FUEL SAVINGS RESULTS OF ENGINE TECHNOLOGY COMBINATIONS IN THE F-650

	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload																	
	CARB -City			55 MPH Cruise			65 MPH Cruise			WHVC			CILCC			Parcel		
Technology	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
ISB 2011 Base	-4.7	-4.4	-4.2	-3.4	-3.2	-3.1	-2.9	-2.8	-2.7	-4.1	-3.8	-3.6	-5.1	-4.8	-4.6	-4.3	-4.1	-3.9
ISB Package 6	-0.4	-0.3	0.0	5.6	4.9	4.4	7.1	6.6	6.1	0.8	0.7	0.6	0.8	0.7	1.0	-6.0	-5.4	-5.4
ISB Package 7	7.4	6.9	6.6	6.3	5.7	5.3	5.5	5.0	4.6	7.2	6.7	6.3	8.7	8.4	8.0	5.9	5.6	5.3
ISB Package 8	2.0	2.0	2.1	7.9	7.2	6.5	8.9	8.3	7.8	3.5	3.2	3.0	3.6	3.5	3.7	-4.0	-3.5	-3.5
ISB Package 9	4.2	3.9	3.7	3.4	3.1	2.9	2.8	2.6	2.4	3.8	3.5	3.3	4.6	4.4	4.2	3.6	3.4	3.2
ISB Pack. 10	6.5	6.0	5.7	2.9	2.6	2.3	1.9	1.6	1.4	5.8	5.3	4.9	14	9.5	9.2	4.9	5.0	4.7
3.5 Package 16	6.0	6.2	6.5	5.8	6.0	6.2	7.1	7.2	7.3	5.9	6.1	6.3	6	6	6.6	5.1	5.5	6.0
3.5 Package 17	10	9.7	9.3	8.9	8.7	8.6	11	9.9	9.4	9.3	8.8	8.6	11	11	9.9	3.2	3.3	3.9
3.5 Package 18	11	11	10	14	12	11	10	8.6	7.4	12	11	10	12	12	11	9.0	8.7	8.7
3.5 Package 19	8.4	7.7	7.2	8.0	7.8	7.6	9.4	9.0	8.6	7.5	7.0	6.8	8.9	8.3	7.7	1.5	1.6	2.1
6.2 Package 20	11	10	9.9	9.5	8.4	7.4	6.7	6.6	6.5	10	9.4	8.7	13	12	12	8.2	7.8	7.6
6.2 Package 21	12	12	11	10	9.3	8.7	11	10	9.6	11	10	9.8	14	13	13	9.0	8.6	8.4
6.2 Package 22	8.9	8.6	8.4	6.5	6.4	6.2	6.6	6.8	7.0	8.2	7.8	7.6	9.8	9.6	9.3	6.8	6.7	6.8
6.2 Package 23	9.4	8.7	8.3	7.4	6.5	5.7	5.2	5.2	5.2	8.4	7.7	7.2	11	10	9.9	6.8	6.5	6.4
6.2 Package 24	5.0	5.2	5.4	5.9	5.9	5.9	6.2	6.4	6.6	5.3	5.4	5.6	4.7	4.8	4.9	3.9	4.3	4.7

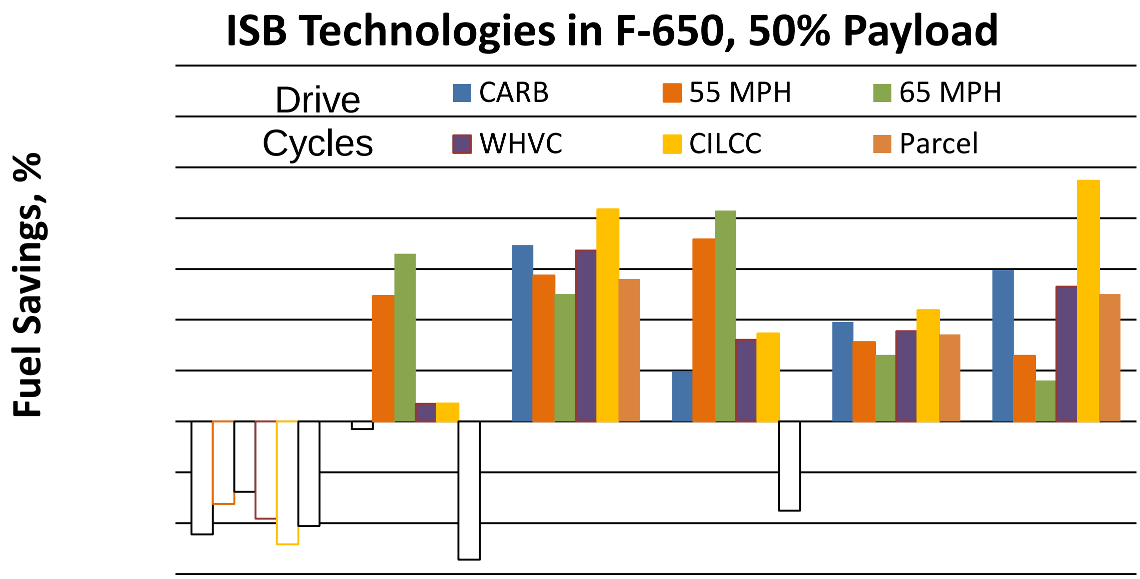

FIGURE 2.4 FUEL SAVING PERFORMANCE OF ISB TECHNOLOGY PACKAGES IN THE F-650 TRUCK

In the following subsections, each engine technology is given its full name in the section heading, along with the abbreviated name used in Figure 2.4. The abbreviations are provided in parentheses.

2.3.5.1 Comparison of 2019 ISB Baseline engine to original 2013 baseline (ISB 2013)

The combination of shorter combustion duration (imposed to provide a 1% BSFC benefit across the fuel map), and a partial friction reduction (5% at high speed/high load, increasing to 17.5% at low speed and light load) provides benefits of 2.7% to 5.1% over the range of drive cycles and payloads. The largest benefits are on the gentle low speed drive cycles at zero payload.

2.3.5.2 ISB Package 6: 2019 Baseline ISB + 2.5% Turbo Efficiency + Downspeed (ISB P6)

This package reduces the rated speed from 2500 RPM to 2200 RPM, with a corresponding increase in engine torque to maintain vehicle performance. The package also includes a 2.5% improvement of both the compressor and turbine maps of the turbocharger. This means, for example, that a 50% turbocharger combined efficiency operating point would improve to 51.25% combined efficiency. This represents approximately the maximum turbocharger efficiency improvement that can be achieved without losing control of EGR flow (and thus NOx emissions). Because of the lower rated speed and higher torque, a tighter torque converter match is required. The tight converter imposes a higher torque on the engine when the vehicle is stationary, and this exacts a significant fuel consumption penalty on the Parcel cycle, which includes 50% idle time. There is also a slight penalty on the CARB cycle, which has only

12.1% idle time, and on the CILCC cycle, which has 8% idle time. ISB Package 6 provides a significant benefit at 55 and 65 MPH (4.4% and 7.1% respectively).

2.3.5.3 ISB Package 7: No EGR + Full Friction Reduction + Full Turbo Improve (ISB P7)

ISB Package 7 is a high engine-out NOx package that would require approximately 99% conversion efficiency from the SCR system to meet 2010 emissions requirements. This package provides shorter combustion duration (due to the elimination of EGR). The friction (FMEP) reduction is twice that assumed in the 2019 ISB baseline package (10% at high speed/load, up to 35% at low speed/load). Note the discussion of FMEP reductions in Section 2.3.2.2. Both the turbo compressor and turbine maps see a 5% efficiency increase, so a 50% combined efficiency point becomes 52.5%.

ISB Package 7 provides benefits of 4.6% to 8.7% on all drive cycles and payloads. The benefits are greatest on the low speed cycles (CILCC, CARB, and WHVC) at zero payload. This is typical for the introduction of an engine friction reduction.

2.3.5.4 ISB Package 8: No EGR + ½ Friction Reduction + Turbo Improve + Downspeed (ISB P8)

ISB Package 8 is another high engine-out NOx package that would require approximately 99% conversion efficiency from the SCR system to meet 2010 emissions requirements. This package provides shorter combustion duration (due to the elimination of EGR). The friction (FMEP) reduction is the same as that assumed in the 2019 ISB baseline package (5% at high engine speed/load, up to 17.5% at low speed/load). Note the discussion of FMEP reductions in Section 2.3.2.2. Both the turbo compressor and turbine maps see a 5% efficiency increase, so a 50% combined efficiency point becomes 52.5%. Rated speed is reduced from 2500 RPM to 2200 RPM, with a corresponding increase in engine torque to maintain vehicle performance. The differences between Package 7 and 8 are that Package 8 has less FMEP reduction, but it includes downspeeding.

Package 8 provides greater fuel consumption benefits than Package 7 on the steady state drive cycles (55 MPH and 65 MPH), but less benefit on the lower vehicle speed cycles that include some idle time. There is a significant fuel penalty on the Parcel cycle, which includes 50% idle time. This result is driven by the higher idle torque imposed by the tighter torque converter match that is required to compensate for the lower engine speed and higher torque peak value.

2.3.5.5 ISB Package 9: 2019 ISB Baseline + Full Friction Reduction + 2.5% Turbo Efficiency (ISB P9)

ISB Package 9 adds another increment of FMEP reduction, compared to the 2019 baseline ISB engine. It also includes a 2.5% improvement in both compressor and turbine map efficiency. This means, for example, that a 50% combined efficiency operating point would improve to 51.25% combined efficiency. This represents approximately the maximum turbocharger efficiency improvement that can be added without losing control of EGR flow (and thus NOx emissions). This package provides benefits of 2.4% to 4.4%, with the larger benefits coming on low speed cycles at zero payload.

2.3.5.6 ISB Package 10: 4-Cylinder Engine + Pickup Torque Curve + Full Range EGR (ISB P10)

ISB Package 10 is based on the 4-cylinder downsized engine (4.5 liters). Because this engine has significantly lower power and torque than the 6-cylinder baseline ISB, the pickup truck BMEP and torque curves are used. This results in a 3,000 RPM rated speed, up from the 2,500 RPM baseline ISB engine. The vehicle axle ratio is shorter (numerically higher) to help retain vehicle performance at a lower torque level. Because this engine needs to meet the heavy duty engine dynamometer emissions certification cycle, it uses EGR at high loads (unlike the chassis certified pickup truck version). This drives higher cylinder pressures.

Package 10 provides benefits up to 10% on the most lightly loaded cycle, the CILCC cycle. On the other transient cycles, the benefits are around 4% to 5%. At 65 MPH cruise, the fuel savings are under 2%. The 4 cylinder engine benefits from lower friction and higher operating BMEP on the lightly loaded cycles. At higher loads, the increased engine speed required to make power starts to take a toll, driving the fuel savings down.

2.3.5.7 ISB Engine Technology Synergies/Interferences

The technology synergies and interferences for the medium truck diesel are similar to those described in section 2.3.2.13 for the larger DD15 engine. One exception is that waste heat recovery was not considered for medium-duty engines, because they typically operate in transient conditions which do not suite the characteristics of a WHR system. Another difference is that in the medium-duty case, a reduction in vehicle performance was accepted in the case of engine downsizing. For the heavy-duty case, BMEP was increased enough to maintain vehicle performance. This was not practical for a 33% size reduction of the medium duty engine (see section 2.3.5.6).

There are limitations on the increase of turbocharger efficiency. If EGR flow is to be retained, turbo efficiency cannot reach the point where the intake manifold pressure is higher than the exhaust manifold pressure, because this will eliminate EGR flow. In practice, turbo efficiency is deliberately limited to maintain EGR flow. This limitation does not apply to turbocompound engines, where the power turbine imposes sufficient backpressure to allow EGR flow regardless of turbo efficiency. The comments here regarding the ISB diesel in the F-650 truck also apply to applications in the T270 truck and the Ram pickup.

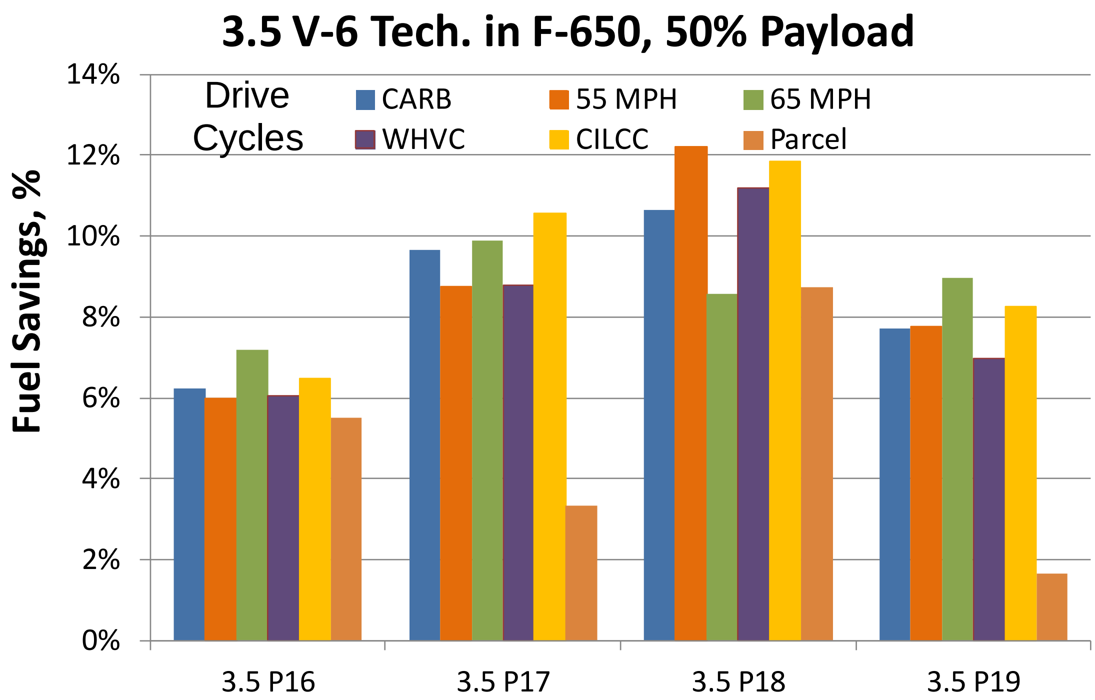

FIGURE 2.5 FUEL SAVING PERFORMANCE OF 3.5 V6 TECHNOLOGY PACKAGES IN THE F-650 TRUCK

2.3.5.8 3.5 V6 Package 16: VVA + EGR (3.5 P16)

All 3.5 liter V-6 technology packages are compared to the original 3.5 liter V-6 engine baseline, as defined in Report #1. The combination of full authority VVA and EGR works out to a bit less than the sum of the two individual technologies. In Report #1, Table 3.21, VVA provided benefits of 2.2 – 3.5%, while EGR provided benefits of 3.4% to 4.5%. The combined benefit of the two technologies is on the order of 6%. This is less than the sum of the individual technology benefits because part of the benefit of EGR is reduced pumping work at light loads, which is also part of the benefit of VVA.

The 3.5 V-6 with VVA and EGR provides impressive results compared to the 6.2 V-8 engine with Cylinder Deactivation and EGR (Package 20). Averaging across all the drive cycles at 50% payload, the V-8 uses 7.3% more fuel than the V-6. This result is driven by two factors: BSFC differences and BMEP differences. For a given road load and engine speed, the V-6 runs at a 77% higher BMEP level than the V-8. If the road load is relatively small, this difference in BMEP causes the smaller V-6 to operate at a much more efficient part of its fuel map. The V-6 also achieves slightly better BSFC values across much of the speed/load range.

Comparison of the 3.5 V-6 with VVA and EGR to the 2019 baseline diesel is also instructive. The V-6 uses 11.6% more fuel than the diesel, on an average of all 6 drive cycles at 50% payload. The difference in energy content between diesel and gasoline is about 13%, so this result indicates that the gasoline engine is on average slightly more efficient (on a brake thermal efficiency basis) than the diesel. This surprising result can be attributed to three factors:

- The V-6 with EGR and VVA has low pumping losses compared to conventional gasoline engines
- The V-6 with EGR and VVA does not need timing retard or enrichment at high BMEP to avoid knock
- The diesel has 91% more displacement than the V-6, which means the V-6 runs at much more efficient BMEP when the road load is low

Note that on the drive cycles with higher average road load (55 and 65 MPH cruise), the V-6 uses 18.4% to 19.6% more fuel than the diesel. In general, heavier vehicle power demand drives a larger fuel consumption advantage for the diesel engine.

2.3.5.9 3.5 V6 Package 17: Package 16 + Downspeed (3.5 P17)

3.5 V-6 Package 17 adds downspeeding to Package 16. In Report #1, Table 3.21, EGR + Downspeed had provided benefits in the 7% to 9% range, except for the Parcel cycle, where benefits are below 2% (note that this is also the 3.5 V6 Package 19 configuration, described below). Adding VVA to the overall package increases fuel savings to a range of 8.6% to 11% on all cycles except the Parcel. Performance on the Parcel cycle is poor, at 3.2% to 3.9%, but this is still better than the fuel savings without the benefit of VVA. The relatively modest fuel savings on the parcel cycle are related to the tighter torque converter match required by the downspeed engine. This increases idle fuel consumption.

2.3.5.10 3.5 V6 Package 18: Package 16 + Lean Burn (3.5 P18)

Package 18 of the 3.5 V6 adds lean burn at light to moderate load to the Package 16 engine with VVA and EGR. EGR is used to prevent rich operation at high loads. This package provides the most impressive fuel saving results for the V6 engine: 10% to 14% fuel savings on the CARB, 55 MPH, WHVC, and CILCC cycles, 7.4% to 10% at 65 MPH, and around 9% on the Parcel cycle. The key issue here is that exhaust aftertreatment is required to control NOx. A 3-way catalyst cannot be used, because of lean operation. Existing SCR systems would have inadequate durability, given the high exhaust temperatures compared to a diesel. As a result, implementation of an engine like this awaits the development of an improved high temperature NOx reduction system.

2.3.5.11 3.5 V6 Package 19: EGR + Downspeed (3.5 P19)

Package 4 represents Package 17 with the VVA removed. This technology combination was already run for Report #1 (Table 3.21). This package provides benefits in the 7% to 9% range, except for the Parcel cycle, where the benefits are below 2%. This is because of the tighter torque converter match required by the downspeed engine, which increases idle fuel consumption. Overall, the fuel consumption penalty for removing VVA from 3.5 V-6 Package 17 is in the 1% to 2% range.

2.3.5.12 3.5 V6 Engine Technology Synergies/Interferences

VVA, lean burn, and EGR all have the effect of reducing pumping work at light load, so the introduction of all of these features will have an effect less than the sum of the benefits at light loads. At higher load, the effects are still mostly independent, so they are mostly additive. Comments made regarding downspeeding (increased cylinder pressure) of diesel engines and the trade-off against reduced friction (FMEP) apply to gasoline engines as well. See section 2.3.2.13. The comments in this section also apply to the application of the 3.5 V-6 in the T270 truck and the Ram pickup.

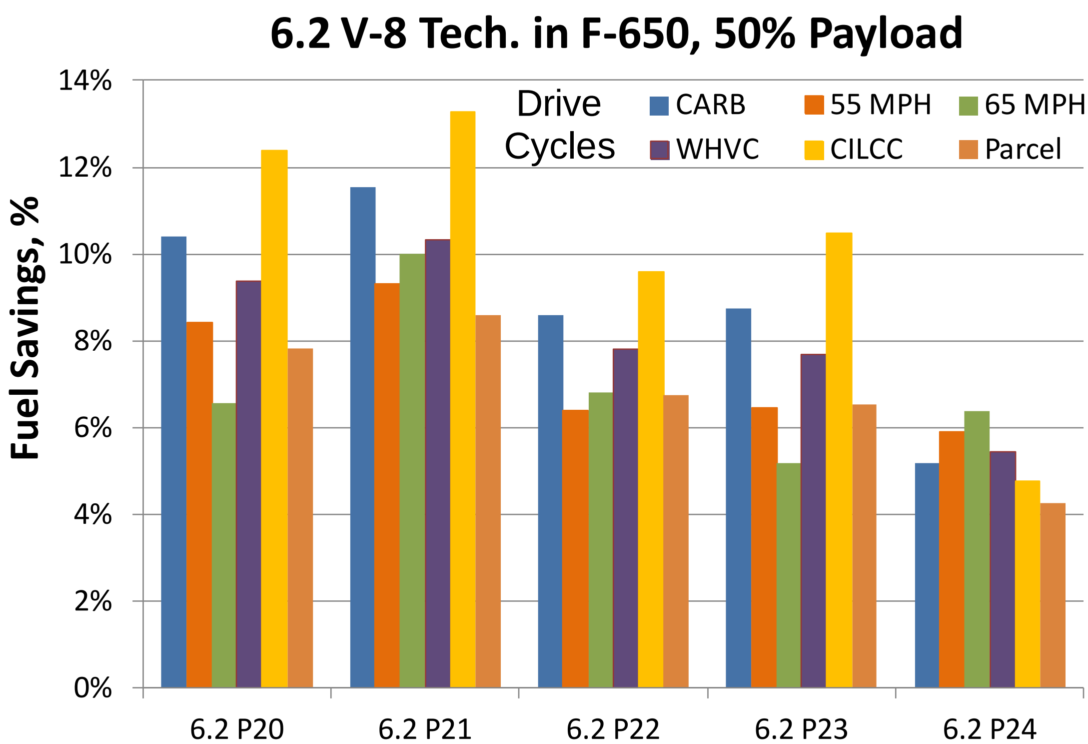

FIGURE 2.6 FUEL SAVING PERFORMANCE OF 6.2 V8 TECHNOLOGY PACKAGES IN THE F-650 TRUCK

2.3.5.13 6.2 V8 Package 20: GDI + Cylinder Deactivation + EGR + 10% FMEP Reduction (6.2 P20)

All 6.2 liter V-8 technology packages are compared to the original 6.2 liter V-8 engine baseline, as defined in Report #1. Package 20 combines four technologies from Report #1. The fuel savings range from 6.5% to 13% over the drive cycles and payload, with the biggest benefits on the CILCC cycle, which features very gentle accelerations.

2.3.5.14 6.2 V8 Package 21: Package 1 + VVA (6.2 P21)

V8 Package 21 adds VVA to the combo Package 20. Overall fuel savings range from 8.4% to 14%. The additional contribution from VVA is generally in the 1% to 2% range, except at 65 MPH, where the benefit is 3% to 4%. The primary benefit of VVA is to reduce pumping work at light to moderate load. Cylinder deactivation also reduces pumping work at light load, so the addition of VVA on top of cylinder deactivation at light load provides only a small additional benefit. At 65 MPH cruise, the engine power demand is too high for cylinder deactivation to be active, so VVA provides a larger benefit.

2.3.5.15 6.2 V8 Package 22: GDI + 2 Cam Phasers + EGR + 10% FMEP Reduction (6.2 P22)

Package 22 starts with Package 20 as the basis. The cylinder deactivation feature used in Package 20 is replaced by dual cam phasers, as an alternative approach to reduce pumping work. Package 22 performs less well than Package 20 on all cycles except 65 MPH cruise, where cylinder deactivation does not come into play. At 65 MPH, the dual cam phasers give a slight advantage over the Package 20 setup. Dual cam phasers are unable to provide as large a pumping work reduction at light load as the cylinder deactivation system.

2.3.5.16 6.2 V8 Package 23: GDI + Cylinder Deactivation + EGR (6.2 P23)

V8 Package 23 is also based on Package 20, with the deletion of the 10% FMEP reduction. Package 23 provides fuel savings of 1% to 2% less than Package 20. This result shows that the incremental benefit of a 10% FMEP reduction for this engine is on the order of 1% to 2%.

2.3.5.17 6.2 V8 Package 24: GDI + EGR + 10% FMEP Reduction (6.2 P24)

Package 24 is based on Package 23. The cylinder deactivation is deleted from the Package 23 setup, and a 10% FMEP reduction is added. Except at 65 MPH, where cylinder deactivation is not active, the FMEP reduction provides a smaller benefit than cylinder deactivation. Thus, on cycles other than 65 MPH cruise, Package 24 provides fuel savings which are 0% to 6% smaller than those of Package 5. The biggest differences between Package 23 and 24 come on the very gentle CILCC cycle, where Package 23 has an advantage of up to 6%, while Package 24 has an advantage of up to 1.4% at 65 MPH. On the CILCC cycle, the accelerations are so gentle that cylinder deactivation can remain active. Since cylinder deactivation provides a larger fuel savings than a 10% FMEP reduction, the result is that Package 23 with cylinder deactivation outperforms Package 24 with the friction reduction on the CILCC cycle. On the other hand, at 65 MPH, cylinder deactivation is not active, but an FMEP reduction will still provide some benefit. As a result, Package 24 outperforms Package 23 at 65 MPH.

2.3.5.18 6.2 V8 Engine Technology Synergies/Interferences

Cylinder deactivation, VVA, EGR, and lean burn all address light load pumping work, so their benefits are not fully additive. FMEP reductions have the largest effect at light load, so an FMEP reduction will be synergistic with any vehicle power demand reduction. The comments in this section also apply to the application of the 6.2 V-8 in the T270 truck and the Ram pickup truck.

2.3.5.19 Comparison of the Three Baseline Engines in the F-650

Figure 2.7 shows the comparison of the three 2019 baseline engines in the F-650 truck. Keep in mind that diesel fuel has about 13% higher energy content than E-10 gasoline on a per unit volume basis. The figure compares the fuel consumption of the V6 gasoline engine and the medium duty diesel to a baseline of the V8 gasoline engine.

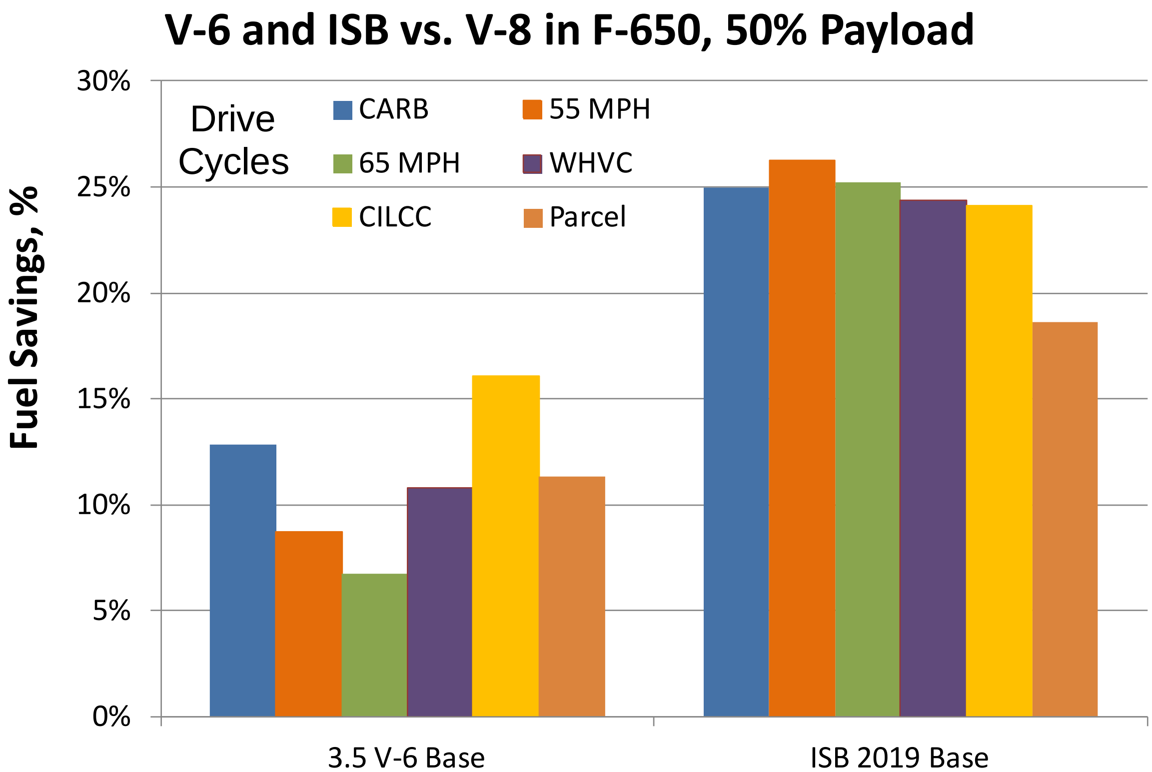

FIGURE 2.7 FUEL CONSUMPTION COMPARISON OF 3.5 V6 AND 2019 DIESEL TO THE V8

2.3.5.20 Summary of Vehicle Technology Package Results in the F-650

The vehicle technology combinations previously listed in Table 2.8 were all evaluated using the baseline ISB 2019 engine configuration. In addition, F-650 vehicle packages 12 through 15 were also evaluated using the baseline V6 and V8 gasoline engines. Appendix C describes the details of the F-650 vehicle model, its calibration, as well as the assumptions and parameters involved in simulating each of the considered technology combinations.

Table 2.14 summarizes the results of vehicle technology combination simulations. Results are provided for each technology on 6 drive cycles. Each drive cycle is run at three payloads, to provide information on how sensitive a given technology is to payload. As a result, the table provides 18 data points for each of the 6 technology combinations that were evaluated. The results shown are in terms of percent fuel consumption reduction compared to the baseline F-650 vehicle simulation model with the projected 2019 baseline diesel, except as noted. Since the 2017 fuel consumption/GHG regulations do not require any vocational truck aerodynamic features, the original baseline vehicle model is assumed to be appropriate for compliance with the 2017 regulatory requirements. In Table 2.14, the Package 13 results are compared to Package 12, and Package 15 results are compared to Package 13. These results are shaded in green. This allows the reader to see the marginal benefits of Package 13 over P12, and Package 15 over P13.

The results shown in Table 2.14 can also be presented in a form that shows the full fuel savings for Packages 13 and 15 compared to the baseline. These results are shown in Table 2.15. The results shown in Tables 2.14 and 2.15 can be further presented in graphical form. To simplify the graphs, only results for the 50% payload are shown in Figures 2.8 through 2.11 below. Note that all Vehicle Technology Combinations use only the baseline engines. In Figures 2.8 and 2.9, the results for VP13 (VP12 + idle neutral) are presented relative to the VP12 results, so that the incremental benefit of idle neutral can be seen. The results for VP15 (VP13 + 40% A/C power demand reduction + 700 pound empty weight reduction) are shown relative to VP13, so that the incremental benefit of the A/C power demand reduction and the weight reduction can be seen. This approach is similar to that of Table 2.14.

In Figures 2.10 and 2.11, all packages are compared to the 2019 vehicle baseline, so that the full benefit of F-650 vehicle packages 13 and 15 can be seen. This approach is similar to that of Table 2.15.

TABLE 2.14 FUEL SAVINGS RESULTS OF VEHICLE TECHNOLOGY COMBOS IN THE F-650. GREEN CELLS DENOTE COMPARISON BETWEEN PACKAGES RATHER THAN TO THE BASELINE

	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload																	
	CARB - City			55 MPH Cruise			65 MPH Cruise			WHVC			CILCC			Parcel		
Technology	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100 %
VP11 ISB Cd 5%	0.4	0.3	0.3	1.9	1.8	1.7	2.1	2.1	2.0	0.9	0.8	0.8	0.3	0.3	0.3	0.3	0.3	0.2
VP11 ISB Cd 10%	0.7	0.7	0.6	3.8	3.6	3.4	4.3	4.2	4.1	1.8	1.7	1.6	0.7	0.6	0.6	0.5	0.5	0.5
VP11 ISB Cd 15%	1.1	1.0	0.9	5.6	5.4	5.1	6.4	6.2	6.1	2.7	2.5	2.4	1.0	0.9	0.9	0.8	0.8	0.7
VP11 ISB Crr 10%	1.7	1.9	2.1	2.4	2.7	3.0	1.9	2.3	2.6	2.0	2.3	2.5	2.0	2.1	2.3	1.1	1.3	1.4
VP11 ISB Crr 20%	3.5	3.8	4.2	4.7	5.4	6.1	3.8	4.5	5.2	4.1	4.6	5.0	4.1	4.2	4.6	2.3	2.6	2.8
VP11 ISB Crr 30%	5.2	5.8	6.3	7.1	8.1	9.1	5.7	6.7	7.7	6.1	6.8	7.6	6.1	6.5	6.9	3.4	3.9	4.2
VP12 ISB	4.7	5.2	5.8	5.7	6.3	6.8	4.7	5.3	5.8	6.2	6.5	7.0	9.4	9.9	10	4.7	5.5	6.0
VP12 3.5 V-6	4.1	4.9	5.8	7.1	7.8	8.3	6.1	6.4	6.9	6.4	7.0	7.6	3.4	5.0	6.1	5.7	6.1	6.6
VP12 6.2 V-8	2.3	3.9	4.9	6.2	6.8	7.3	5.5	6.1	6.7	5.6	6.2	6.6	1.9	3.3	4.4	5.6	6.0	6.2
VP13 ISB vs. P2	2.6	2.4	2.2	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.2	1.1	1.9	1.8	1.7	12	11	10
VP13 3.5 V-6 vs. P2	1.4	1.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.6	0.6	1.0	0.9	0.9	6.7	6.2	5.8
VP13 6.2 V-8 vs. P2	1.0	1.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.7	0.7	0.7	5.3	5.0	4.7
VP14 ISB	7.6	7.4	7.1	9.3	9.8	10	7.8	8.3	8.8	10	9.9	9.8	14	13	13	13	13	13
P14 3.5 V-6	6.4	5.7	5.9	10	11	11	8.7	8.7	8.9	8.6	8.6	7.7	8.4	8.5	8.0	9.0	8.6	8.1
VP14 6.2 V-8	3.7	3.5	2.4	8.0	8.7	9.2	7.5	8.0	8.4	5.8	6.0	6.1	5.0	4.9	4.7	5.6	4.0	3.6
VP15 ISB vs. P3	4.1	3.8	3.5	1.8	1.7	1.7	1.4	1.3	1.3	3.3	3.1	2.9	4.1	3.8	3.6	4.6	4.3	4.0

VP15 3.5 V-6 vs. P3	4.4	4.1	3.8	2.1	2.0	2.0	1.7	1.5	1.4	3.6	3.5	3.3	4.1	3.9	3.8	5.2	4.8	4.6
VP15 6.2 V-8 vs. P3	3.4	3.2	3.2	1.6	1.6	1.6	1.4	1.4	1.3	2.8	2.7	2.7	3.1	3.0	2.9	4.0	3.9	3.8

TABLE 2.15 FUEL SAVINGS RESULTS OF VEHICLE TECHNOLOGY COMBINATIONS IN THE F-650

Technology	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload																	
	CARB City			55 MPH Cruise			65 MPH Cruise			WHVC			CILCC			Parcel		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
VP13 ISB Total	7.3	7.5	8.0	5.7	6.3	6.8	4.7	5.3	5.8	7.4	7.7	8.1	11	12	12	16	17	16
VP13 3.5 V-6 Total	5.5	6.2	7.0	7.1	7.8	8.3	6.1	6.4	6.9	7.1	7.7	8.1	4.4	5.9	7.0	12	12	12
VP13 6.2 V-8 Total	3.4	4.9	5.8	6.2	6.8	7.3	5.5	6.1	6.7	6.1	6.7	7.1	2.7	4.0	5.1	11	11	11
VP15 ISB Total	11	11	12	7.5	8.0	8.5	6.0	6.6	7.2	11	11	11	15	15	16	21	21	20
VP15 3.5 V-6 Total	9.8	10	11	9.2	9.8	10	7.8	7.9	8.4	11	11	11	8.5	9.9	11	18	17	17
VP15 6.2 V-8 Total	6.7	8.1	9.0	7.8	8.4	8.8	7.0	7.5	8.0	9.0	9.4	9.8	5.8	7.1	8.0	15	15	15

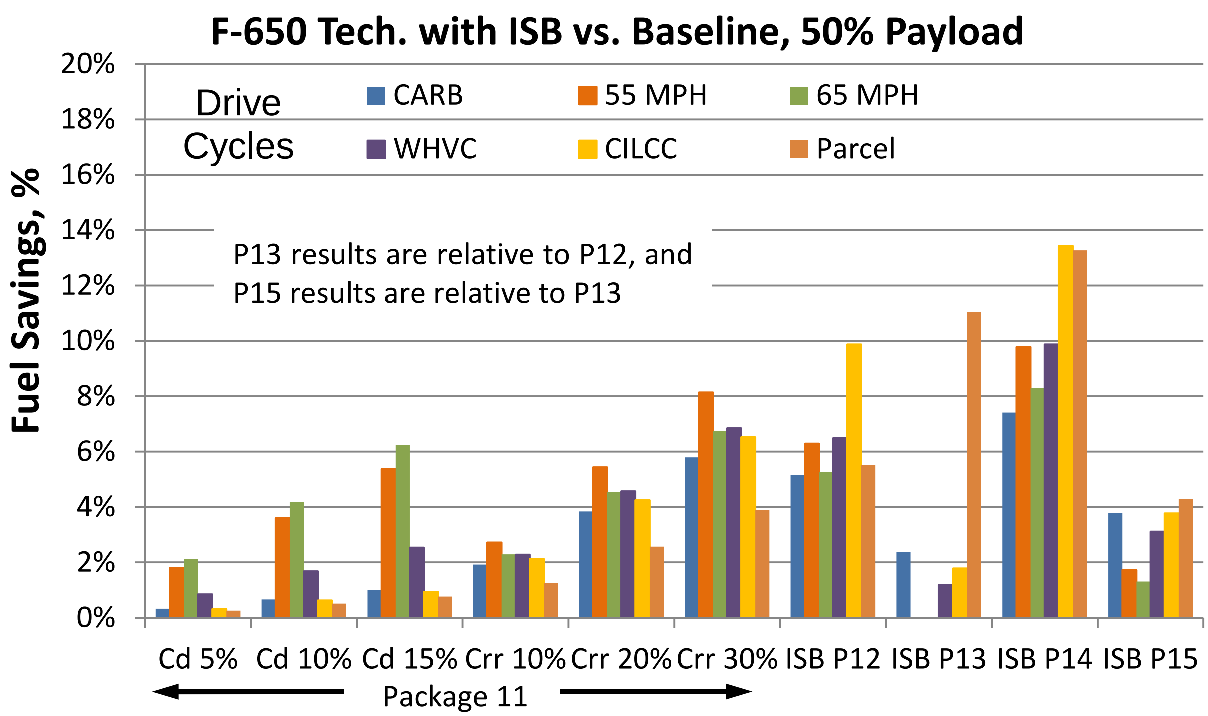

FIGURE 2.8 F-650 VEHICLE TECHNOLOGY COMBINATION FUEL SAVINGS RESULTS WITH THE 2019 BASELINE ISB ENGINE. VP13 RESULTS ARE RELATIVE TO VP12, AND VP15 TO VP13

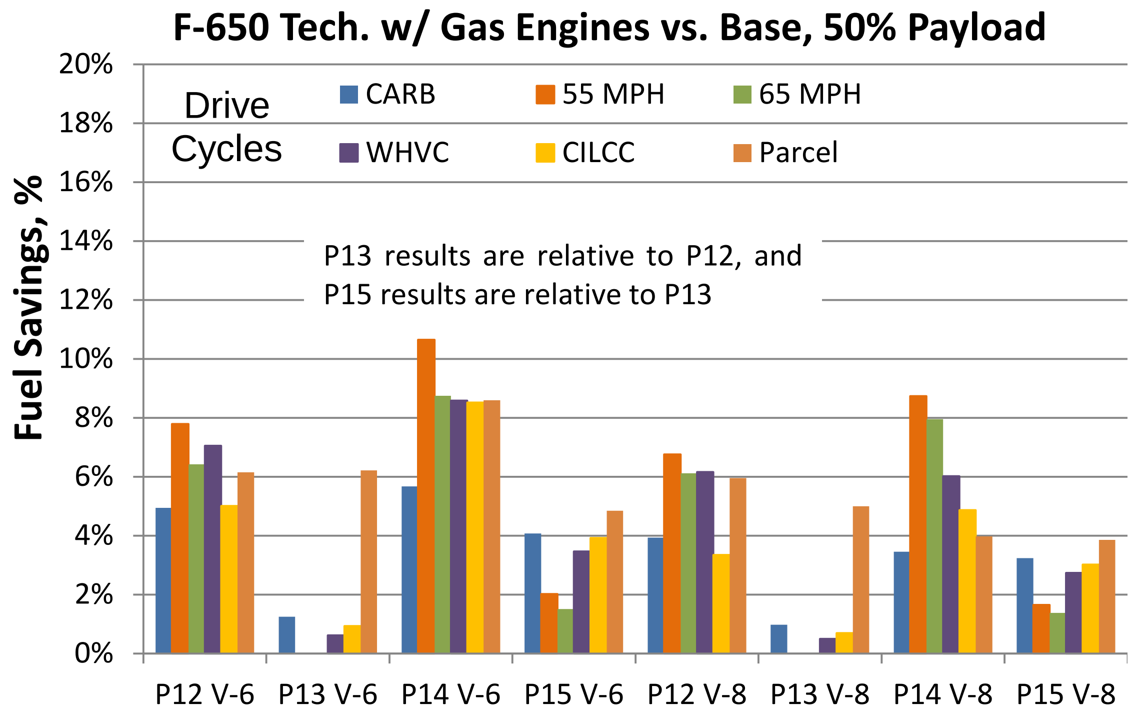

FIGURE 2.9 F-650 TECHNOLOGY COMBO FUEL SAVINGS RESULTS WITH BASE GASOLINE ENGINES

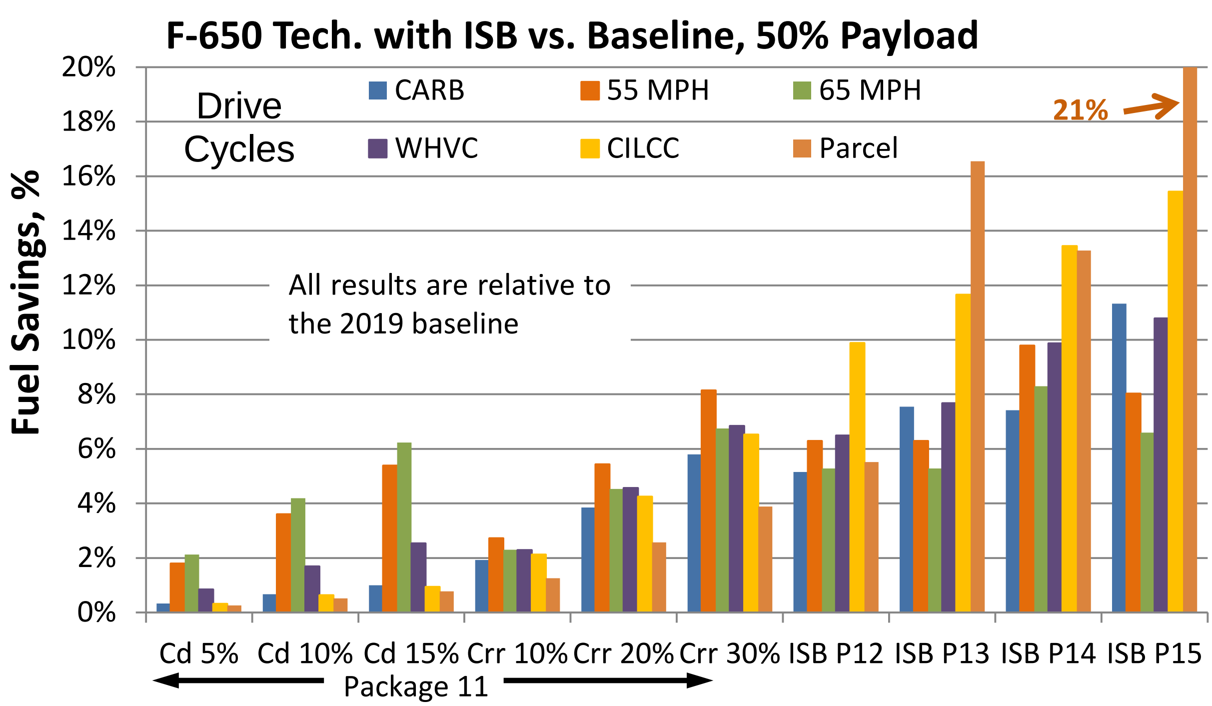

FIGURE 2.10 F-650 VEHICLE TECHNOLOGY COMBINATION FUEL SAVINGS RESULTS WITH THE 2019 BASELINE ISB ENGINE. ALL RESULTS ARE RELATIVE TO THE 2019 ISB BASELINE

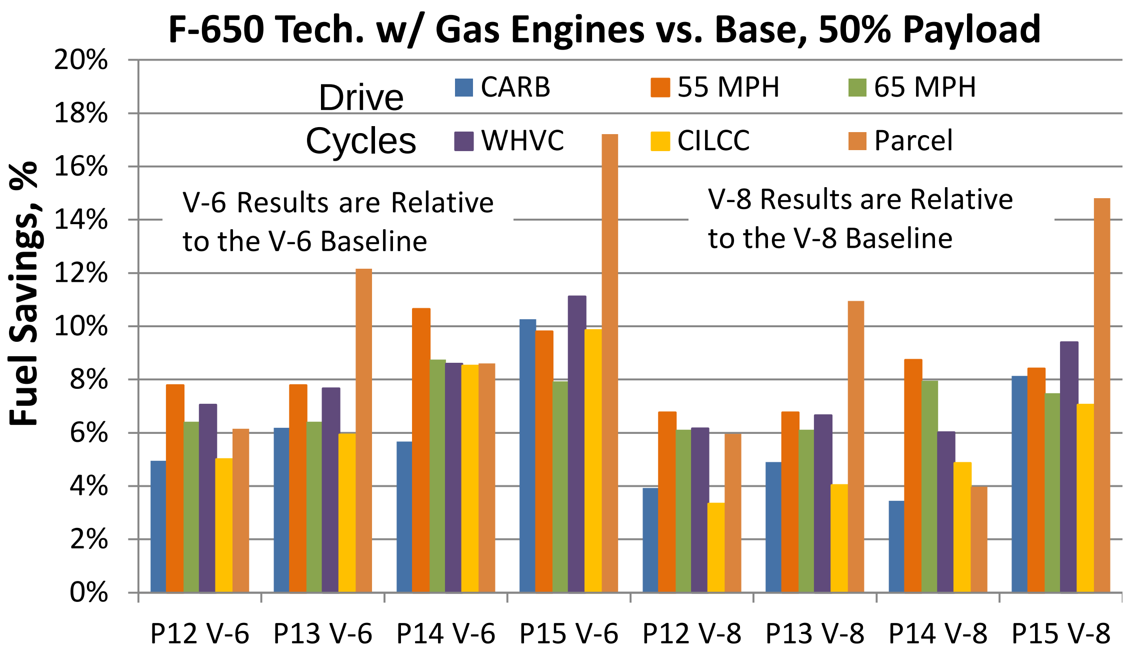

FIGURE 2.11 F-650 VEHICLE TECHNOLOGY COMBINATION FUEL SAVINGS WITH BASELINE GASOLINE ENGINES. ALL RESULTS ARE RELATIVE TO THE BASELINE FOR EACH ENGINE

2.3.5.21 F-650 Package 11: Cd and Crr Sweeps (Parameter Sensitivity Analysis)

All F-650 vehicle technology packages were evaluated against the baseline F-650 truck, as described in Report #1. Sweeps of drag coefficient (Cd) and tire rolling resistance coefficient (Crr) were run only with the baseline ISB engine. As could be expected, the results are very linear. As the Cd and Crr reductions increase, there is a linear increase in fuel consumption reduction. A 15% Cd reduction provides a 6% fuel savings on the 65 MPH cruise cycle, but under 1% on the lower vehicle speed cycles. A 30% reduction in tire rolling resistance provides over 8% fuel savings at 55 MPH. The savings are reduced to about 6.5% at 65 MPH, where aerodynamic drag is the main vehicle power demand. The smallest benefit for tire rolling resistance reduction is found on the parcel cycle, which has a high inertia power demand (power to accelerate the vehicle from frequent stops) as well as significant idle fuel consumption due to 50% idle time in the cycle.

2.3.5.22 F-650 Package 12: 20% Crr Reduction + 8-Speed Automatic (P12)

F-650 vehicle package 12 reduces the tire rolling resistance by 20% and replaces the original 5-speed automatic transmission with an 8-speed unit. The 8-speed transmission provides a wider ratio range, closer ratio steps, and improved mechanical efficiency compared to the baseline 5-speed automatic. Package 12 provides a 4.7% to 10% benefit with the diesel engine.

By far the largest benefit is on the CILCC cycle, where the increased mechanical efficiency of the 8-speed transmission helps significantly on this very gentle (low power demand) cycle. With the V-6 gasoline engine, benefits range from 4.1% to 8%, with the largest benefits coming at 65 MPH.

The V-8 gasoline engine sees the smallest improvements: 1.9% to 7.3%. For the V-8, the smallest benefits come on the most lightly loaded cycles: the CARB and CILCC cycles at zero payload. With zero payload, tire rolling resistance is a smaller factor, and the gentle accelerations of the CARB and CILCC cycles do not emphasize the benefits of the 8-speed transmission. All fuel savings at higher payload and on other cycles are 3.3% or more. Benefits are largest for the V-8 on the 55 MPH cycle.

2.3.5.23 F-650 Package 13: Package 12 + Idle Neutral Features (P13)

F-650 package 13 adds an idle neutral feature to Package 12. This feature reduces fuel consumption any time the vehicle is stationary and the accelerator pedal is at idle. There will only be a benefit on drive cycles where the vehicle spends some time at idle. The diesel engine benefits most from an idle neutral feature, because of the higher torque converter load at idle. For the ISB, the benefit is zero at 55 and 65 MPH, and 1.1 to 2.6% on the CARB, WHVC, and CILCC cycles. The benefits are largest for the ISB on the Parcel cycle, which includes 50% idle time (10% to 12%). The gasoline engines see benefits of 0.7% to 1.4% on the CARB, WHVC, and CILCC cycles. The V-6 sees slightly larger benefits than the V-8. On the Parcel cycle, the V-6 gains 5.8% to 6.7%, while the V-8 gains 5.6% to 6.2%.

2.3.5.24 F-650 Package 14: 20% Crr Reduction + 6-Speed AMT (P14)

F-650 Package 14 is the same as Package 12, except the 8-speed automatic of P12 is replaced by an automated manual transmission. The AMT has mechanical efficiency benefits over the automatic, although the automatic will provide faster acceleration and better drivability. Package 14 can also be compared to Package 13, which adds an idle neutral feature to the automatic.

Comparing P14 to P13, the AMT generally has a fuel consumption penalty compared to the automatic for the CARB urban cycle with all 3 engines. At 55 and 65 MPH, the AMT is clearly better than the automatic, with benefits of 3% to 3.5% over the automatic with all 3 engines. On the WHVC, the AMT has a slight advantage with the diesel, and a slight penalty with the gasoline engines. On the Parcel cycle, the automatic has about a 3% advantage over the AMT, the 3.5 V-6 sees a 3% to 4% benefit with the automatic, while the V-8 gains a 5% to 7% advantage with the automatic on the Parcel cycle.

The AMT and 8-speed automatic are geared to provide identical engine speed in top gear. The advantage held by the AMT on the steady speed cruise cycles is driven by its higher mechanical efficiency. The penalty for the AMT on transient cycles, especially the CARB and Parcel cycles, is related to the fact that the 8-speed automatic does a better job of keeping the engine in its best BSFC range. This is partly a function of having more gear ratios available, but mostly a function of shift schedule. Careful tailoring of the AMT shift schedule could potentially reduce or eliminate the fuel consumption deficit on transient cycles.

2.3.5.25 F-650 Package 15: P13 + 40% A/C reduction + 700 pound weight reduction (P15)

F-650 Package 15 adds reduced accessory power demand (a 600 watt reduction in A/C power) and a 700 pound empty vehicle weight reduction to Package 13. Payloads remain unchanged. At 55 and 65 MPH cruise, the benefits of Package 15 over Package 13 are generally under 2%. On the more transient cycles, the benefits are in the range of 2.7% to 5.2%. The V-6 gasoline engine tends to see larger benefits than the other engines, which indicates that it is very power demand sensitive.

2.3.6 Summary of Engine Technology Package Results in the T270

The engine technology combinations listed in Tables 2.2, 2.4, and 2.5 were all evaluated using the baseline T270 vehicle configuration. Appendix B describes the details of the ISB medium-duty diesel model, its calibration, as well as the assumptions and parameters involved in simulating each of the considered technology combinations. Appendix A provides details of the gasoline engine models, calibrations, assumptions, and parameters used.

Table 2.16 summarizes the results of engine technology combination simulations in the T270 truck. Results are provided for each technology on 6 drive cycles. Each drive cycle is run at three payloads, to provide information on how sensitive a given technology is to payload. As a result, the table provides 18 data points for each of the 15 technology combinations that were evaluated. The results shown are in terms of percent fuel consumption reduction compared to the three baseline projected 2019 engine GT-POWER models. Each engine is compared to its own respective baseline. These results can be compared with the engine technology combination results for the F-650 truck, shown in Table 2.13. The same engine technology combinations have been evaluated in two different medium duty vocational trucks. The T270 is heavier and has a larger frontal area, so it imposes higher loads on the engine.

The results shown in Table 2.16 can also be presented in graphical form. To simplify the graphs, only results for the 50% payload are shown in Figure 2.12 to Figure 2.14. Because of the similarity in results between the T270 and the F-650, there will not be a discussion of the performance of each engine technology package in the T270. Only significant differences due to the larger and heavier T270 will be noted.

TABLE 2.16 FUEL SAVINGS RESULTS OF ENGINE TECHNOLOGY COMBINATIONS IN THE T270

Technology	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload																	
	CARB Urban			55 MPH Cruise			65 MPH Cruise			WHVC			CILCC			Parcel		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
2012 ISB	-4.4	-4.1	-3.9	-2.8	-2.7	-2.7	-2.3	-2.3	-2.3	-3.6	-3.4	-3.2	-4.7	-4.4	-4.2	-4.1	-3.8	-3.6
ISB Package 6	0.2	0.3	0.2	3.0	2.6	2.3	4.2	4.0	3.6	0.6	0.4	0.1	2.5	2.2	1.5	-5.3	-5.5	-4.6
ISB Package 7	6.9	6.4	6.1	4.2	4.1	4.0	3.2	3.1	3.1	6.2	5.8	5.4	8.1	7.6	7.2	5.7	5.3	5.0
ISB Package 8	2.4	2.4	2.4	4.7	4.3	3.9	5.7	5.4	5.1	3.0	2.6	2.2	5.1	4.9	4.1	-3.4	-3.6	-2.9
ISB Package 9	3.9	3.6	3.3	2.3	2.2	2.1	1.7	1.7	1.6	3.3	3.1	2.9	4.3	4.0	3.8	3.4	3.2	3.0
ISB Package 10	6.3	5.7	4.9	1.5	1.4	1.1	-1.5	-2.5	-3.4	5.1	4.4	3.8	15	10	8.4	4.8	4.2	4.9
3.5 Package 16	6.3	6.7	7.7	6.6	6.8	7.0	11	12	13	6.4	6.8	7.3	6.5	6.6	7.1	5.5	6.2	7.4
3.5 Package 17	7.7	7.5	8.5	7.9	7.3	7.0	9.9	11	12	7.6	7.5	7.6	8.8	8.2	7.8	2.0	2.6	3.8
3.5 Package 18	10	9.9	10	8.0	7.5	7.1	8.8	10	12	9.9	9.5	9.4	11	11	11	8.8	8.7	9.3
3.5 Package 19	6.0	6.2	7.2	5.2	5.5	5.6	9.6	10	11	5.2	5.5	6.1	6.1	5.9	5.9	1.1	1.9	3.1
6.2 Package 20	11	9.7	9.5	6.2	6.4	6.8	9.8	11	12	8.5	8.1	8.1	12	11	11	7.7	7.5	7.8
6.2 Package 21	12	11	10	7.4	7.4	7.5	10	11	12	9.6	9.1	9.0	13	12	12	8.5	8.2	8.5
6.2 Package 22	9.1	8.4	8.6	6.6	6.9	7.3	10	11	12	7.8	7.7	8.0	9.5	9.2	9.1	6.7	6.8	7.4
6.2 Package 23	9.1	8.1	8.1	4.9	5.2	5.7	8.9	9.8	11	7.0	6.7	6.9	10	9.5	9.2	6.4	6.3	6.7
6.2 Package 24	5.7	5.5	6.0	6.3	6.5	6.9	9.9	11	12	5.6	6.0	6.5	4.9	5.1	5.5	4.3	4.8	5.7

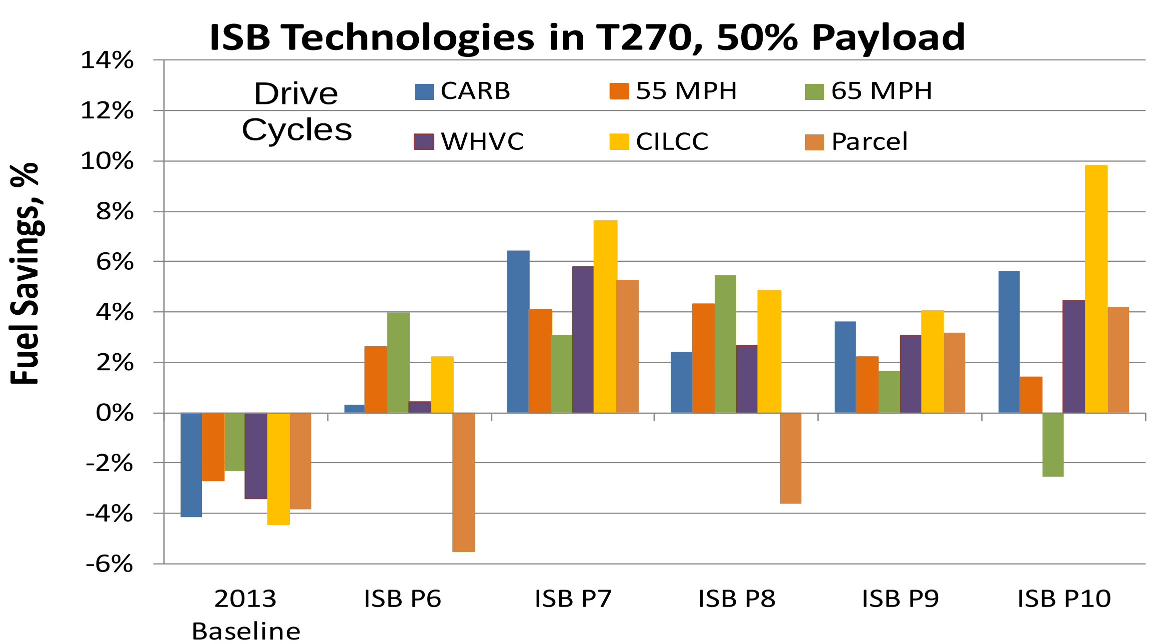

FIGURE 2.12 FUEL SAVING PERFORMANCE OF ISB TECHNOLOGY PACKAGES IN THE T270 TRUCK

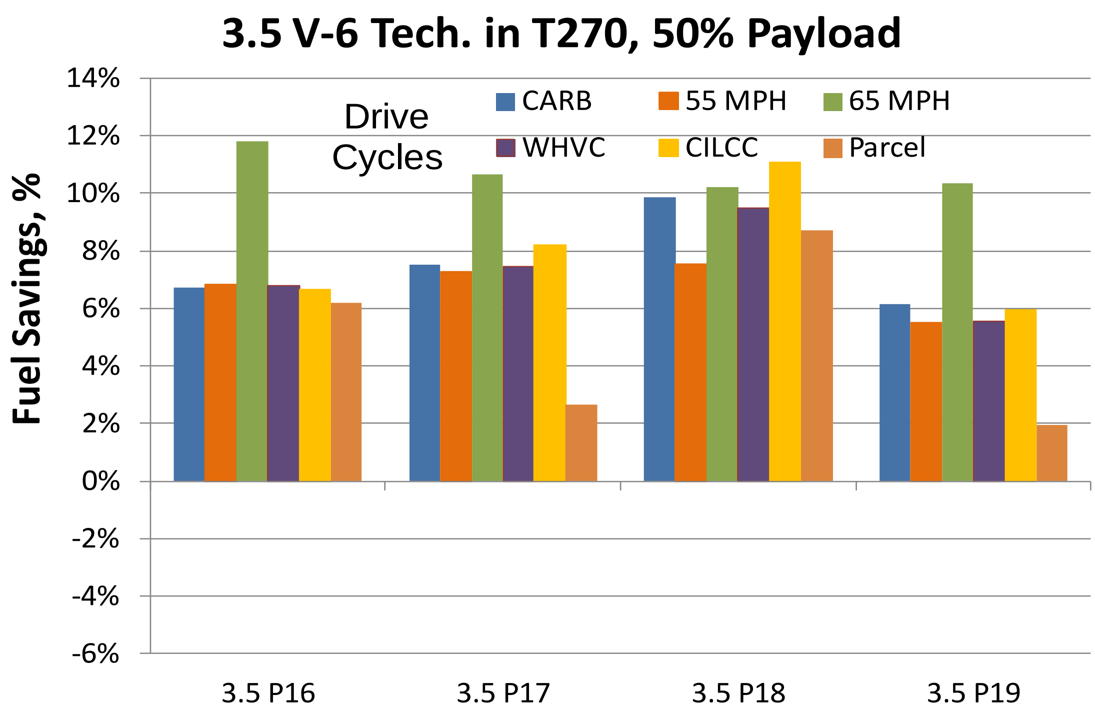

FIGURE 2.13 FUEL SAVING PERFORMANCE OF 3.5 V6 TECHNOLOGY PACKAGES IN THE T270 TRUCK

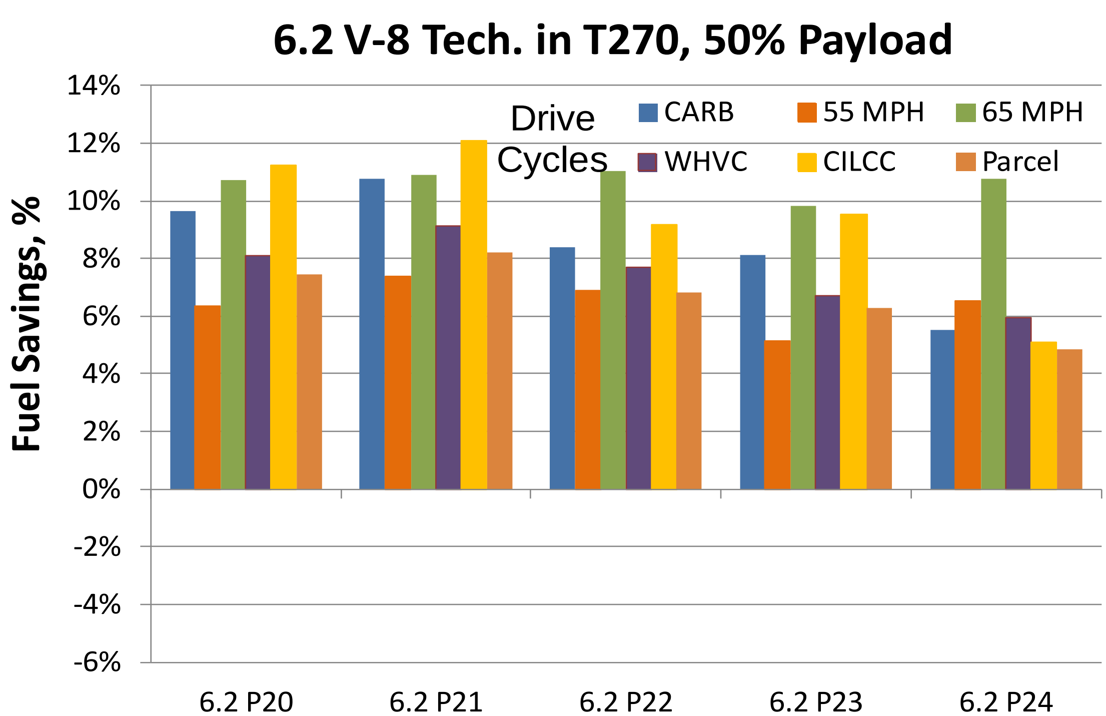

FIGURE 2.14 FUEL SAVING PERFORMANCE OF 6.2 V8 TECHNOLOGY PACKAGES IN THE T270 TRUCK

2.3.6.1 Comparison of engine technology results between the T270 and F-650

Because the T270 truck is heavier and has a much larger frontal area, it imposes higher loads on the engine on all drive cycles. This provides an opportunity to look at the load sensitivity of engine technologies. Table 2.13 for the F-650 can be compared to Table 2.16 for the T270. Also, Figures 2.4, 2.5, and 2.6 for the F-650 can be compared to Figures 2.12, 2.13, and 2.14 respectively for the T270. A summary of noteworthy differences in technology performance between the two trucks is shown in Table 2.17.

ISB Packages 6 and 8 include downspeeding. The fuel savings benefits of downspeeding are not very load dependent, except at cruise. At cruise, the benefit is greater on the lightly loaded F-650. ISB Packages 7 and 9 have full engine friction reduction. Reducing engine friction has the largest benefits at light loads, so there is a slight advantage for the F-650 on all drive cycles. ISB Package 10 is the downsized 4-cylinder engine. The smaller engine brings both a friction reduction (from smaller displacement) and higher BMEP for a given road load, which is an advantage under light load conditions. However, under higher loads, the downsized engine must work harder (higher BMEP at a higher engine speed), so fuel consumption suffers at higher loads. As a result, the downsized engine works better on the smaller, lighter F-650, especially at 65 MPH cruise, where the road load of the T270 is high.

TABLE 2.17 DIFFERENCES IN ENGINE TECHNOLOGY PERFORMANCE BETWEEN THE F-650 AND T270, AT 50% PAYLOAD

Engine	Package	Important Fuel Savings Differences	In Truck
ISB	P6	About 2% better at 55 and 65 MPH	F-650
ISB	P7	0.5% to 1.5% better on all cycles, largest benefit at 55 and 65	F-650
ISB	P8	About 3% better at 55 and 65 MPH	F-650
ISB	P9	0.5% to 1% better on all cycles	F-650
ISB	P10	About 5% better at 65 MPH, modest benefit on other cycles	F-650
3.5 V-6	P16	About 4.5% better at 65 MPH only, less on other cycles	T270
3.5 V-6	P17	About 2% better on all cycles except 65 and parcel	F-650
3.5 V-6	P18	Similar performance with minor variations	Both
3.5 V-6	P19	About 2% better on all cycles except 65 and parcel	F-650
6.2 V-8	P20	About 3% better at 65 MPH only	T270
6.2 V-8	P21	Similar performance with minor variations	Both
6.2 V-8	P22	About 4% better at 65 MPH only	T270
6.2 V-8	P23	About 4% better at 65 MPH only	T270
6.2 V-8	P24	About 4% better at 65 MPH only	T270

For the 3.5 liter V-6 gasoline engine, all four packages include EGR. Packages 17 and 19 also include downspeeding. Package 18 adds lean burn operation at part load. For 3.5 V-6

Package 16, there is a distinctly larger fuel consumption reduction on the larger, heavier T270 truck, especially at 65 MPH, the highest load cycle. This is because the vehicle power demand is sufficient to push the baseline V-6 engine into the rich operating zone in the T270, so EGR provides a larger benefit in this case. The situation is different in the downspeed versions of the 3.5 V-6 (Packages 17 and 19), because with the lower engine speed, both trucks have sufficient power demand to push the baseline V-6 engine into rich operation.

All four 6.2 liter V-8 gasoline engine packages also include EGR. As a result, most packages provide better results on the larger, heavier T270 at 65 MPH, where the baseline V-8 engine would have to run rich. On the lighter F-650, the fuel savings at 65 MPH are less, because enrichment is less or is not required. V-8 Package 21 performs about equally on both trucks. This package has full authority VVA in addition to EGR, which enables good savings at both light load and at full load.

2.3.7 Summary of Vehicle Technology Combination Packages in the T270

The vehicle technology combinations listed in Table 2.7 were all evaluated using the baseline ISB 2019 engine configuration. In addition, T270 vehicle packages 7 through 10 were also evaluated using the baseline V6 and V8 gasoline engines. Appendix C describes the details of the T270 vehicle model, its calibration, as well as the assumptions and parameters involved in simulating each of the considered technology combinations.

Table 2.18 summarizes the results of vehicle technology combination simulations. Results are provided for each technology on six drive cycles. Each drive cycle is run at three payloads, to provide information on how sensitive a given technology is to payload. As a result, the table provides 18 data points for each of the six technology combinations that were evaluated. The results shown are in terms of percent fuel consumption reduction compared to the baseline T270 vehicle simulation model with the 2019 baseline diesel engine, except as noted below. Since the 2018 fuel consumption/GHG regulations do not require any vocational truck aerodynamic features, the original baseline vehicle model is assumed to be appropriate for compliance with the 2018 regulatory requirements.

In Table 2.18, the Package 8 results are compared to Package 7, and Package 10 results are compared to Package 8. These comparisons are shown in green shading, to indicate that the comparison is not to the baseline vehicle results. This allows the reader to see the marginal benefits of Package 8 over P7, and Package 10 over P8. In The results shown in Table 2.18 can also be presented in a form that shows the full fuel savings for Packages 8 and 10 compared to the baseline. These results are shown in Table 2.19 below.

The results shown in Table 2.18 and 2.19 can also be presented in graphical form. To simplify the graphs, only results for the 50% payload are shown in Figures 2.15 through 2.18 below. Note that all vehicle technology combinations use only the baseline engines. In Figures 2.15 and 2.16, the results for P8 (P7 + idle neutral) are presented relative to the P7 results, so that the incremental benefit of idle neutral can be seen. The results for P10 (P8 + 40% A/C power demand reduction + 700 pound empty weight reduction) are shown relative to P8, so that the incremental benefit of the A/C power demand reduction and the weight reduction can be seen. This approach is similar to that of Table 2.18.

TABLE 2.18 FUEL SAVINGS RESULTS OF VEHICLE TECHNOLOGY COMBOS IN THE T270. GREEN CELLS DENOTE COMPARISON BETWEEN PACKAGES RATHER THAN TO THE BASELINE

Technology	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload																	
	CARB Urban			55 MPH Cruise			65 MPH Cruise			WHVC			CILCC			Parcel		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
P6 Cd 5%	0.6	0.5	0.5	2.5	2.4	2.3	3.0	2.9	2.8	1.3	1.2	1.1	0.5	0.5	0.4	0.5	0.4	0.5
P6 Cd 10%	1.1	1.0	0.9	5.0	4.8	4.6	6.0	5.7	5.7	2.7	2.4	2.2	1.1	0.9	0.9	0.9	0.8	1.0
P6 Cd 15%	1.7	1.5	1.4	7.5	7.2	6.8	8.8	8.6	8.4	4.0	3.6	3.3	1.6	1.4	1.3	1.3	1.2	1.4
P6 Crr 10%	1.9	2.1	2.3	2.2	2.7	3.1	1.9	2.4	2.7	2.1	2.4	2.7	2.1	2.1	2.3	1.3	1.5	2.3
P6 Crr 20%	3.7	4.2	4.7	4.5	5.4	6.2	3.8	4.6	5.5	4.2	4.9	5.3	4.3	4.3	4.6	2.6	3.0	4.2
P6 Crr 30%	5.6	6.3	7.0	6.7	8.1	9.3	5.7	6.9	8.2	6.3	7.3	8.0	6.5	6.8	6.9	3.9	4.5	5.8
P7 ISB	5.4	6.1	6.7	4.9	5.8	6.4	4.0	4.8	5.6	6.3	6.8	7.3	11	11	12	5.2	5.6	7.1
P7 3.5 V-6	4.6	5.8	7.1	5.7	6.7	7.7	5.5	6.4	7.4	5.9	7.1	7.5	4.2	5.8	6.8	6.0	6.6	6.6
P7 6.2 V-8	3.4	4.9	5.8	4.8	5.6	6.4	4.5	5.3	6.2	5.2	5.9	7.0	2.5	4.0	4.9	5.9	6.3	7.0
P8 ISB	2.3	2.1	1.9	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.0	0.9	1.7	1.6	1.5	11	10	9.2
P8 3.5 V-6	1.2	1.1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.4	0.9	0.8	0.8	6.1	5.5	4.9
P8 6.2 V-8	1.0	0.9	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.7	0.6	0.6	4.9	4.5	4.1
P9 ISB	7.7	7.6	7.9	8.2	8.9	9.5	7.2	7.8	8.6	9.3	9.3	9.3	15	14	14	13	12	13
P9 3.5 V-6	5.4	6.0	6.4	8.4	9.3	10	8.2	9.0	9.8	7.6	7.1	6.8	8.2	7.3	6.6	8.2	7.8	6.0
P9 6.2 V-8	4.0	1.5	2.2	7.2	7.9	8.5	6.8	7.4	8.2	5.1	4.4	4.3	4.8	4.5	2.8	4.2	3.1	1.7
P10 ISB	4.0	3.6	3.3	1.6	1.6	1.5	1.3	1.2	1.2	3.1	2.8	2.6	3.9	3.5	3.3	4.5	4.1	3.8
P10 3.5 V-6	4.3	3.9	3.7	1.8	1.7	1.7	1.7	1.6	1.5	3.4	3.2	3.2	4.0	3.8	3.7	5.1	4.7	4.5
P10 6.2 V-8	3.4	3.2	3.0	1.5	1.5	1.4	1.3	1.3	1.2	2.7	2.7	2.6	3.1	3.0	2.9	4.0	3.9	3.7

TABLE 2.19 FUEL SAVINGS RESULTS OF VEHICLE TECHNOLOGY COMBINATIONS IN THE T270

Technology	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload																	
	65 MPH Cruise			WHVC									CILCC			Parcel		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
P8 ISB	7.8	8.3	8.6	4.9	5.8	6.4	4.0	4.8	5.6	7.4	7.8	8.2	13	13	13	16	16	16
P8 3.5 V-6	5.8	6.9	8.0	5.7	6.7	7.7	5.5	6.4	7.4	6.5	7.5	8.0	5.0	6.7	7.6	12	12	12
P8 6.2 V-8	4.4	5.8	6.6	4.8	5.6	6.4	4.5	5.3	6.2	5.6	6.4	7.4	3.2	4.6	5.5	11	11	11
P10 ISB	12	12	12	6.6	7.3	8	5.3	6.0	6.8	10	11	11	17	17	17	21	20	20
P10 3.5 V-6	10	11	12	7.5	8.4	9.3	7.2	8.0	8.9	9.9	11	11	9.1	11	11	17	17	16
P10 6.2 V-8	7.8	9.0	9.6	6.4	7.1	7.8	5.9	6.6	7.4	8.3	9.0	10	6.3	7.6	8.4	15	15	15

In Figures 2.17 and 2.18, all packages are compared to the 2019 vehicle baseline, so that the full benefit of Packages 8 and 10 can be seen. This approach is similar to that of Table 2.19.

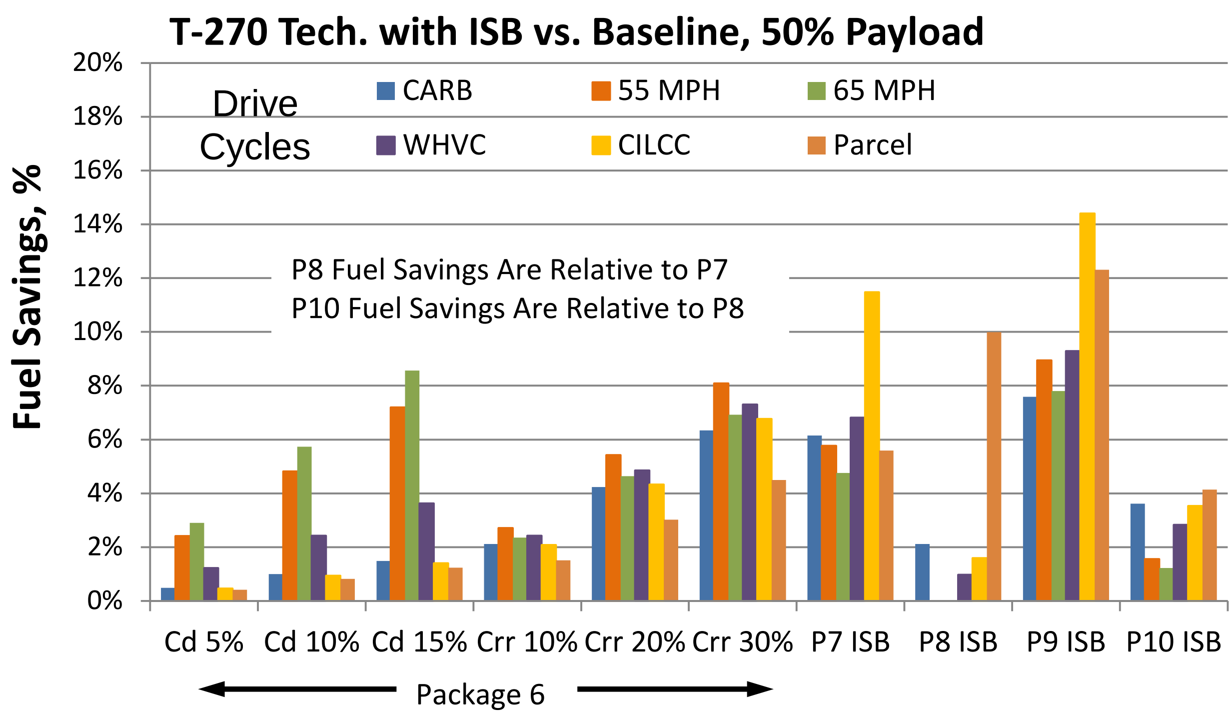

FIGURE 2.15 T270 VEHICLE TECHNOLOGY COMBINATION FUEL SAVINGS RESULTS WITH THE 2019 BASELINE ISB ENGINE. P8 RESULTS ARE RELATIVE TO P7, AND P10 TO P8

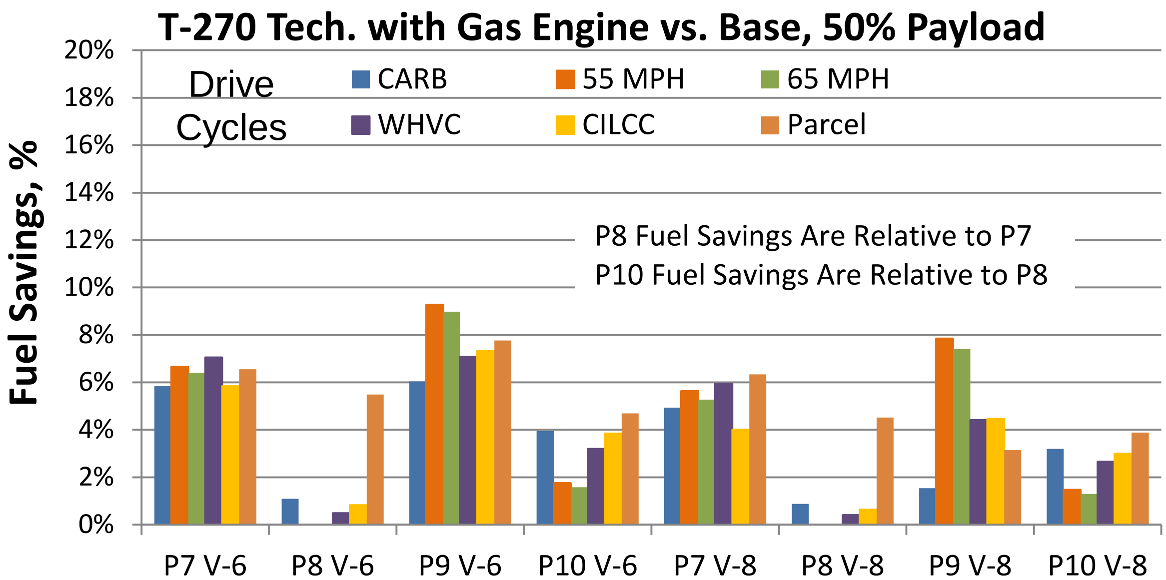

FIGURE 2.16 T270 TECHNOLOGY COMBO FUEL SAVINGS RESULTS WITH BASE GASOLINE ENGINES

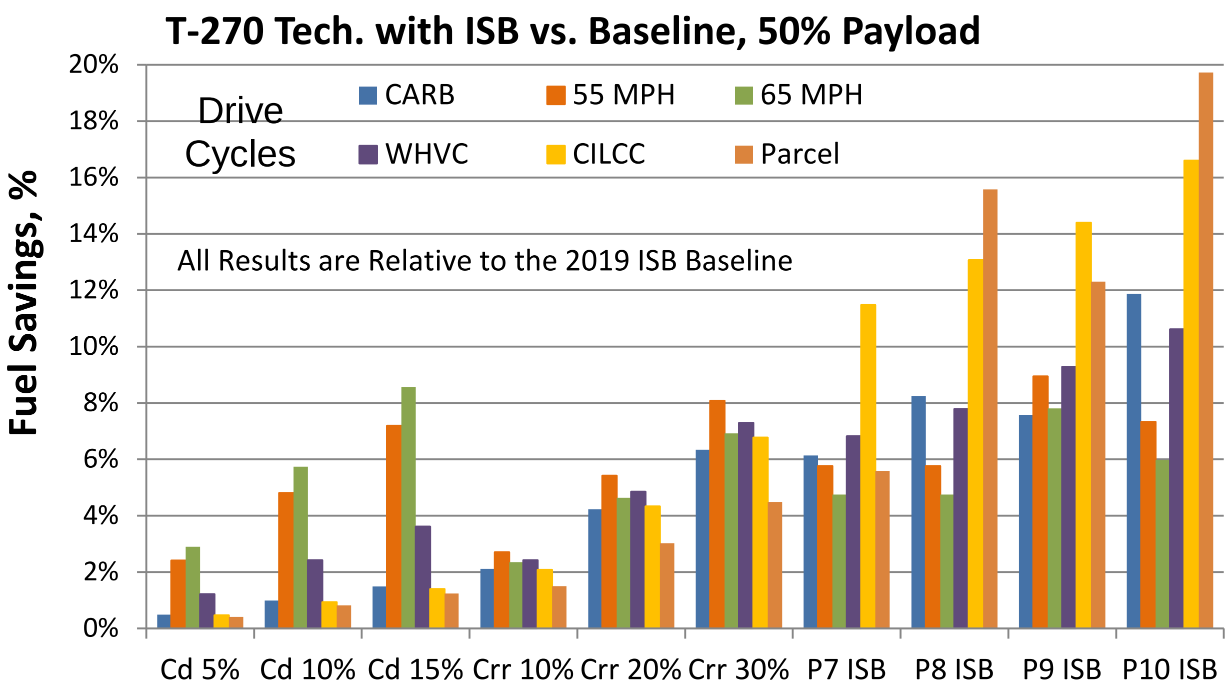

FIGURE 2.17 T270 VEHICLE TECHNOLOGY COMBINATION FUEL SAVINGS RESULTS WITH THE 2019 BASELINE ISB ENGINE. ALL RESULTS ARE RELATIVE TO THE 2019 ISB BASELINE

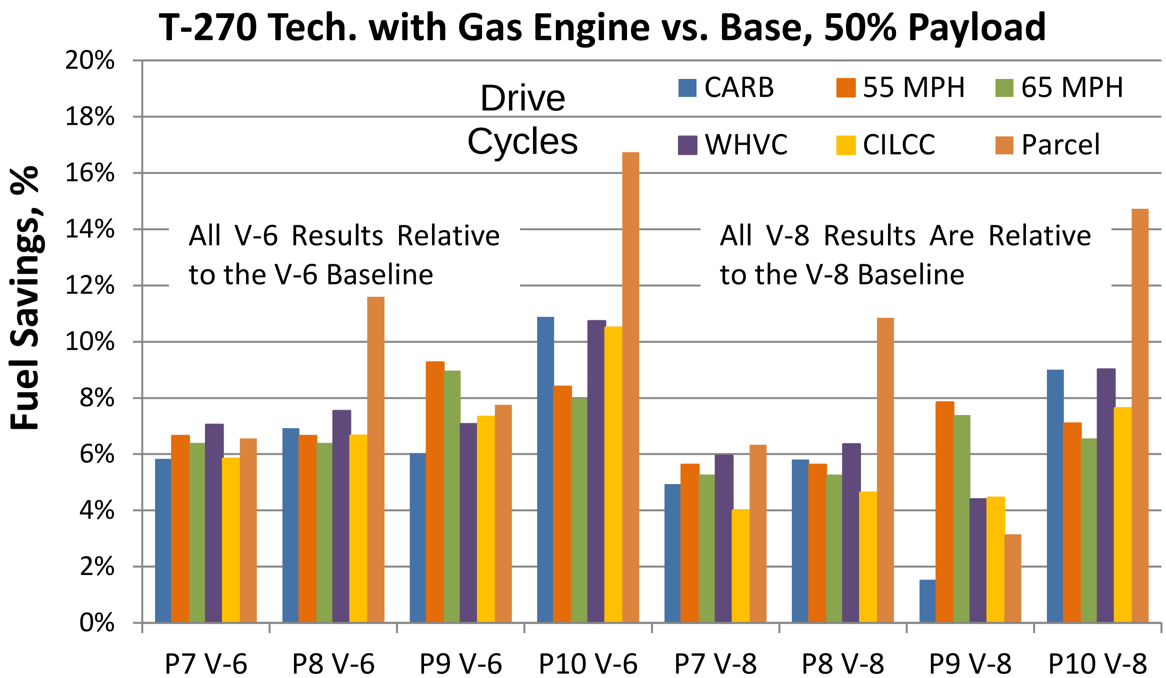

FIGURE 2.18 T270 VEHICLE TECHNOLOGY COMBINATION FUEL SAVINGS WITH BASELINE GASOLINE ENGINES. ALL RESULTS ARE RELATIVE TO THE BASELINE FOR EACH ENGINE

2.3.7.1 Differences in Vehicle Package Performance Between T270 and F-650

The T270 is more sensitive to changes in aerodynamic drag than the F-650, because it has a much larger frontal area. The T270 is also more sensitive to changes in tire rolling resistance than the F-650, because of its greater weight.

With vehicle package 7 and the diesel engine (ISB with a 20% reduction in Crr + an 8-speed automatic), the heavier T270 sees about a 1% fuel consumption advantage on the CARB cycle and the CILCC cycle. On the other drive cycles, there is little difference in vehicle package 7 performance with the diesel engine between the two trucks. With the two gasoline engines, vehicle package 7 provides similar benefits on the two different trucks, with results for each drive cycle within 1% between the two trucks. The V-6 engine sees a slightly larger fuel savings from vehicle package 7 than the V-8, because the V-6 tends to be more load sensitive.

Vehicle package 8 adds an idle neutral feature to vehicle package 7. The idle neutral feature has no effect on the two cruise cycles. With the diesel engine, benefits are 1% to 2% on the CARB, WHVC, and CILCC cycles, but around 10% for the Parcel cycle, which has about 50% idle time. The F-650 sees a slightly larger improvement from vehicle package 8, because idle fuel consumption represents a larger portion of total fuel burned on this smaller, lighter truck. The results for the two gasoline engines are similar in trends, but smaller in magnitude, because of the lower idle power demand of the gasoline engine torque converter.

Vehicle package 9 includes a 20% Crr reduction, as in packages 7 and 8, but the automatic transmission is replaced by a 6-speed AMT. The fuel savings provided by vehicle package 9 for each engine type is nearly independent of vehicle, with variations of 1% or less between the F-650 and T270.

Vehicle package 10 builds on package 8, with the addition of an 800 pound empty weight reduction and a 40% reduction in A/C power demand. With the diesel engine, the larger, heavier T270 sees slightly less fuel savings than the F-650 all cycles except the CARB and the CILCC. This is because the accessory power demand constitutes a smaller portion of total vehicle power demand for the bigger T270. The trends are similar with the gasoline engines.

2.3.8 Pickup Truck Results

The Ram pickup truck, the ISB pickup diesel engine, the 6.2 liter V-8, and the 3.5 liter V-6 gasoline engines have been described in Section 3 of Report #1. Only the technology combination results will be discussed here. Results of the diesel engine technology packages are all expressed in comparison to the 2019 diesel baseline. The differences between the original pickup diesel baseline and the 2019 engine are described in Appendix B. Results for the gasoline engine technology packages are all expressed in comparison to the original (2012) baseline.

2.3.9 Engine Technologies in the Ram Pickup

The engine technology combinations previously listed in Tables 2.3, 2.4, and 2.5 were all evaluated in the Ram pickup vehicle configuration. Appendix B describes the details of the ISB pickup truck diesel model, its calibration, as well as the assumptions and parameters involved in simulating each of the considered technology combinations. Appendix A provides details of the gasoline engine models, calibrations, assumptions, and parameters used.

Table 2.20 summarizes the results of engine technology combination simulations. Results are provided for each technology on six drive cycles. Note that the drive cycles used for the pickup truck are not the same as those used for the medium-duty F-650 and T270. The 65 MPH cruise and the WHVC are in common, but the remaining cycles used on the pickup are light duty cycles. Each drive cycle is run at three payloads, to provide information on how sensitive a given technology is to payload. Zero payload represents the empty truck. ALVW represents 50% of the maximum payload in the cargo bed, but no trailer. The truck weight at ALVW is approximately 8,500 pounds. GCW represents a total vehicle + trailer weight of 25,000 pounds, and the frontal area is increased by 50% to account for the aerodynamic drag of the trailer. The overall result is that there is a big step in weight between ALVW and GCW.

Table 2.20 provides 18 data points for each of the 15 technology combinations that were evaluated. The results shown are in terms of percent fuel consumption reduction compared to the three baseline projected 2019 engine GT-POWER models. Each engine is compared to its own respective baseline. Note that the results for the US06 cycle at GCW are shown in RED type. This is because the vehicle was not able to follow the drive cycle, because the power demand exceeded the available power. As a result, these results cannot reliably be used for comparison. Rows in the table labeled 2019 ISB are highlighted in green. The 2019 ISB row near the center of the table gives fuel consumption values relative to the 3.5 V-6 baseline engine, while the 2019 ISB row at the bottom of the table provides values relative to the 6.2 V-8 baseline. The fuel consumption comparisons are on a volume basis (gallons), not a mass basis.

The results shown in Table 2.20 can also be presented in graphical form. To simplify the graphs, only results for ALVW are shown in Figures 2.19 to Figure 2.21.

In the following subsections, each engine technology is given its full name in the section heading, along with the abbreviated name used in Figure 2.4. The abbreviations are provided in parentheses.

TABLE 2.20 ENGINE TECHNOLOGY RESULTS IN THE RAM PICKUP TRUCK

Technology	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload																	
	FTP-City			FTP-Highway			US06			SC03			WHVC			65 MPH		
	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW
ISB 2013	-6.4	-6.1	-3.5	-5.7	-5.3	-2.8	-3.6	-3.2	-1.9	-5.8	-5.4	-3.0	-6.6	-6.3	-3.8	-4.0	-3.8	-2.3
ISB P11	1.7	1.3	0.9	-0.9	-0.3	1.8	3.8	3.6	3.2	0.6	1.0	-0.1	0.6	1.0	1.7	6.1	5.3	-0.5
ISB P12	6.0	5.9	3.9	7.0	6.8	3.3	4.5	4.0	2.5	5.9	5.6	3.4	6.7	6.6	4.3	6.7	6.1	2.2
ISB P13	2.9	2.6	1.9	1.1	1.6	2.9	5.0	4.7	3.9	1.9	2.2	0.8	2.0	2.4	2.8	7.9	7.1	0.2
ISB P14	4.6	4.5	2.7	4.9	4.7	2.3	3.1	2.8	1.2	4.5	4.2	2.3	5.1	5.0	3.1	4.4	4.0	1.7
ISB P15	14	13	8.2	9.5	9.0	5.3	5.8	5.2	10	12	12	6.6	13	12	8.2	6.3	5.9	1.5
3.5 P16	6.1	6.1	9.5	6.0	6.0	9.1	6.6	7.6	18	6.0	6.1	12	6.2	6.1	6.9	5.0	5.1	7.4
3.5 P17	9.5	9.3	9.1	12	11	11	9.1	9.6	22	10	9.5	12	11	10	8.1	9.0	8.7	6.5
3.5 P18	13	12	12	15	13	10	11	11	18	13	12	13	14	14	9.7	15	14	7.3
3.5 P19	7.2	7.0	7.0	10	9.5	7.9	7.5	8.0	20	8.1	7.5	10	6.6	6.8	5.5	8.2	8.0	5.6
2019 ISB	-1.5	0.7	14	13	14	22	13	15	27	3.8	4.9	19	4.8	5.9	15	16	16	23
6.2 P20	14	13	10	13	12	8.8	10	10	13	13	12	10	15	13	8.1	11	10	7.4
6.2 P21	15	14	11	14	13	10	10	10	12	14	13	11	15	14	9.1	12	11	7.5
6.2 P22	10	9.9	9.5	10	10	9.1	7.9	8.4	13	10	9.6	10	11	10	7.9	7.8	7.2	7.7
6.2 P23	12	11	8.6	11	10	7.7	7.8	8.4	12	11	10	9.1	12	11	6.9	9.1	8.1	6.5
6.2P24	4.5	4.6	7.5	5.6	5.8	8.1	6.0	6.9	12	4.7	4.9	8.5	4.7	4.9	6.1	6.0	6.1	7.4
2019 ISB	18	18	19	26	25	24	21	21	31	21	21	23	24	23	20	26	25	23

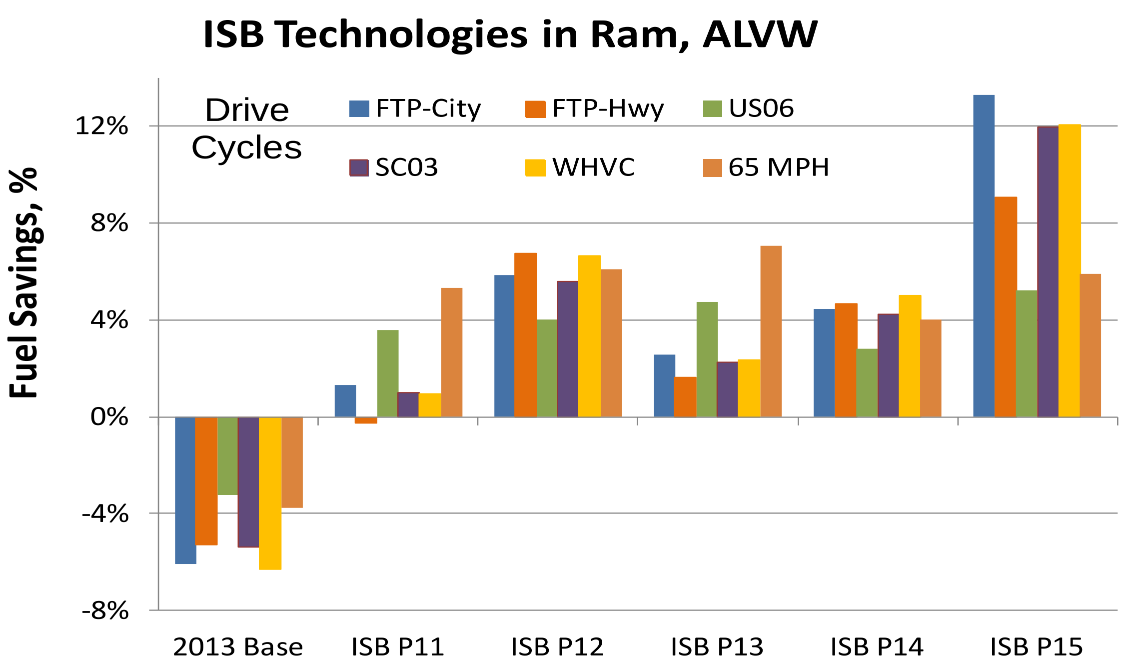

FIGURE 2.19 DIESEL TECHNOLOGY COMBINATIONS IN THE RAM PICKUP

2.3.9.1 Comparison of 2019 Diesel pickup Baseline to original 2013 baseline (2013 Base)

The combination of shorter combustion duration (imposed to provide a 1% BSFC benefit across the fuel map), and a partial friction reduction (5% at high engine speed/high load, increasing to 17.5% at low speed and light load) provides benefits of 2.3% to 4.6% over the range of drive cycles and payloads. The largest benefits are on the gentle low speed drive cycles at zero payload (FTP-City), while the smallest benefits is at 65 MPH and full GCW.

2.3.9.2 ISB Package 11: 2019 Baseline ISB + 2.5% Turbo Efficiency + Downspeed (ISB P11)

This package reduces the rated speed from 3000 RPM to 2500 RPM, with a corresponding increase in engine torque to maintain vehicle performance. The package also includes a 2.5% improvement of both the compressor and turbine maps of the turbocharger. This means, for example, that a 50% turbocharger combined efficiency operating point would improve to 51.25% combined efficiency. This represents approximately the maximum turbocharger efficiency improvement that can be achieved without losing control of EGR flow (and thus NOx emissions). Because of the lower rated speed and higher torque, a tighter torque converter match is required. The tight converter imposes a higher torque on the engine when the vehicle is stationary. ISB Package 11 provides modest benefits (-0.9% to 1.7%) on the FTP-City, FTP-Highway, SC03, and WHTC cycles. Larger benefits are seen on the more aggressive US06 cycle and 65 MPH cruise (3.6% to 6.1%), except for the 65 MPH cycle at GCW, where the vehicle needs to run a gear down in order to maintain speed.

2.3.9.3 ISB Package 12: No EGR + Full Friction Reduction + Full Turbo Improvement (ISB P12)

ISB Package 12 is a high engine-out NOx package that would require approximately 99% conversion efficiency from the SCR system to meet 2010 emissions requirements. This package provides shorter combustion duration (due to the elimination of EGR at part load conditions). The friction (FMEP) reduction is twice that assumed in the 2019 Baseline ISB package (10% at high engine speed/load, up to 35% at low speed/load). Note the discussion of FMEP reductions in Section 2.3.2.2. Both the turbo compressor and turbine maps see a 5% efficiency increase, so a 50% combined efficiency point becomes 52.5%.

At zero payload and at ALVW, ISB Package 12 provides benefits of 4% to 7% on all drive cycles. At full GCW, the benefit falls off to a range of 2.2% to 3.9%, with the smallest benefit at 65 MPH. This result is typical for the introduction of an engine friction reduction. As average engine load increases, the benefit of a friction reduction is reduced.

2.3.9.4 ISB Package 13: No EGR + ½ Friction Reduction + Turbo Improvement + Downspeed (ISB P13)

ISB Package 8 is another high engine-out NOx package that would require approximately 99% conversion efficiency from the SCR system to meet 2010 emissions requirements. This package provides shorter combustion duration (due to the elimination of EGR). The friction (FMEP) reduction is the same as that assumed in the 2019 Baseline ISB package (5% at high engine speed/load, up to 17.5% at low speed/load). Note the discussion of FMEP reductions in Section 2.3.2.2. Both the turbo compressor and turbine maps see a 5% efficiency increase, so a 50% combined efficiency point becomes 52.5%. Rated speed is reduced from 3000 RPM to 2500 RPM, with a corresponding increase in engine torque to maintain vehicle performance. The differences between Package 12 and 13 are that Package 13 has less FMEP reduction, but it includes downspeeding.

Package 13 provides less fuel consumption benefit than Package 12 on all of the more gentle drive cycles (FTP-City, FTP-Highway, SC03 and WHVC). Package 13 performs better on the US06 and 65 MPH cycles, except for 65 MPH at GCW. On this cycle, the downspeed engine has to run in a lower gear to maintain vehicle speed at full GCW.

2.3.9.5 ISB Package 14: 2019 Baseline ISB + Full Friction Reduction + 2.5% Turbo Efficiency (ISB P14)

ISB Package 14 adds another increment of FMEP reduction, compared to the 2019 baseline ISB engine. It also includes a 2.5% improvement in both compressor and turbine map efficiency. This means, for example, that a 50% combined efficiency operating point would improve to 51.25% combined efficiency. This represents approximately the maximum turbocharger efficiency improvement that can be added without losing control of EGR flow (and thus NOx emissions). This package provides benefits of 4.2% to 5% on the four more gentle drive cycles with zero or ALVW payload. At full GCW and on the US06 and 65 MPH cruise cycle, the benefits are less.

2.3.9.6 ISB Package 15: 4-Cylinder Engine with same BMEP as 6 Cylinder + Full FMEP reduction (ISB P15)

ISB Package 15 is based on the 4-cylinder downsized engine (4.5 liters). Because this engine has 33% lower power and torque than the 6-cylinder baseline ISB, vehicle performance will be reduced. However, as a result of the power war that has been going on among pickup truck diesels, the 4-cylinder engine will have more power and torque than was available with the 6-cylinder engine until 2003. The 4-cylinder rating is 256 HP and 567 lb-ft.

Package 15 provides 12% to 15% benefits on the FTP-City, SC03, and WHVC at zero payload and ALVW. The benefits on these cycles drop off to 6.6% to 8.2% at full GCW, where power demands on the engine are higher. Benefits on the FTP-Highway, US06, and 65 MPH cycles are in the 5% to 8% range, except for 65 MPH at full GCW, where the benefit is only 1.5%. The primary benefit driver for the 4-cylinder engine is that for a given road load, the engine operates at higher BMEP. If the road load is low, this provides significant BSFC benefits.

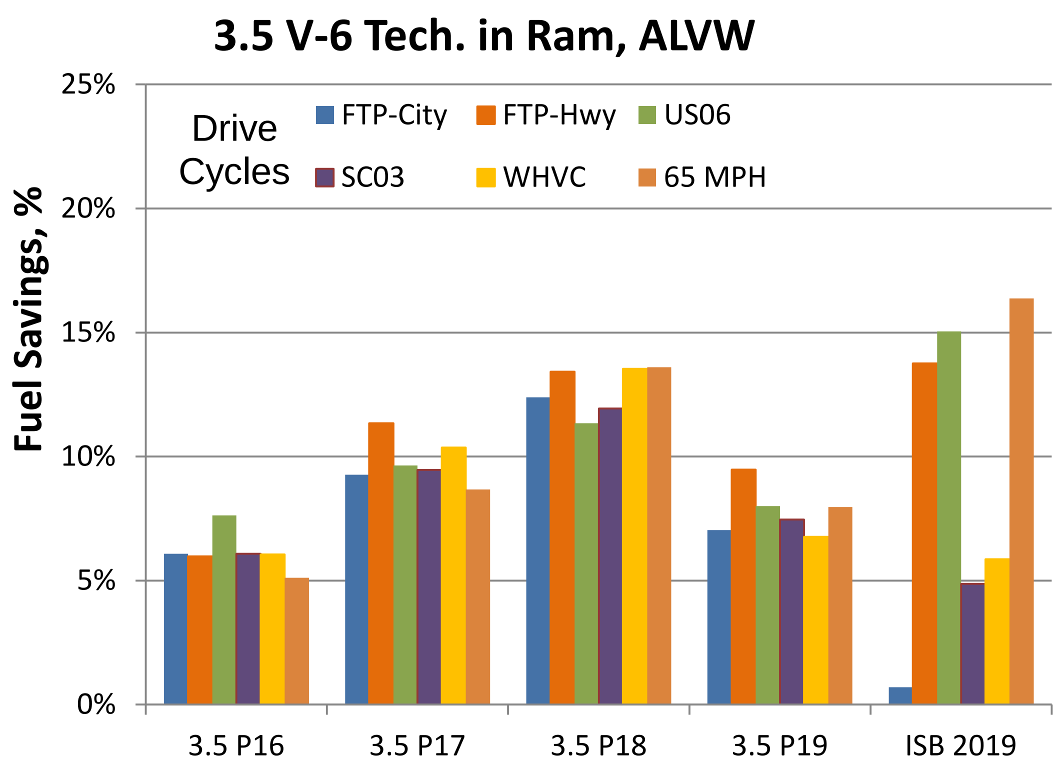

FIGURE 2.20 3.5 V6 TECHNOLOGY COMBINATIONS IN THE RAM PICKUP

2.3.9.7 5 V6 Package 16: VVA + EGR (3.5 P16)

The combination of full authority VVA and EGR provides 5% to 7% benefit on all drive cycles except the US06 with zero payload or at ALVW. On the US06, where average power demands are higher, the fuel savings is 6.6% at zero payload and 7.6% at ALVW. At full GCW, the EGR helps eliminate the need for enrichment, so the benefits are larger: from 6.9% on the very gentle HWVC cycle, to 12% on the SC03. Note that results for the aggressive US06 cycle are not considered at full GCW, because the vehicle was unable to follow the cycle.

The 3.5 V-6 with VVA and EGR provides impressive results compared to the 6.2 V-8 engine with Cylinder Deactivation and EGR (Package 20). Averaging across all the drive cycles at ALVW payload, the V-8 uses 9.6% more fuel than the V-6. This result is driven by two factors: BSFC differences and BMEP differences. For a given road load and engine speed, the V-6 runs at a 77% higher BMEP level than the V-8. If the road load is relatively small, this difference in BMEP causes the smaller V-6 to operate at a much more efficient part of its fuel map. The V-6 also achieves slightly better BSFC values across much of the speed/load range.

Comparison of the 3.5 V-6 with VVA and EGR to the 2019 baseline diesel is also instructive. The V-6 uses only 4.1% more fuel than the diesel, on an average of all six drive cycles at ALVW payload. The difference in energy content between diesel and gasoline is about 13%, so this result indicates that the gasoline engine is on average almost 9% more efficient (on a brake thermal efficiency basis) than the diesel. This surprising result can be attributed to three factors:

- The V-6 with EGR and VVA has low pumping losses compared to conventional gasoline engines
- The V-6 with EGR and VVA does not need timing retard or enrichment at high BMEP to avoid knock
- The diesel has 91% more displacement than the V-6, which means the V-6 runs at much more efficient BMEP when the road load is low

Note that on the drive cycles with higher average road load (65 MPH cruise at ALVW), the V-6 uses 13.5% more fuel than the diesel. In general, a higher vehicle power demand drives a larger fuel consumption advantage for the diesel engine. At 65 MPH and GCW, the V-6 uses 20.6% more fuel than the diesel. The diesel thus maintains a large advantage when towing heavy loads, but for vehicles which spend most of their life without a trailer or heavy payload, the high technology downsized gasoline engine can be very competitive.

2.3.9.8 3.5 V6 Package 17: Package 16 + Downspeed (3.5 P17)

3.5 V-6 Package 17 adds downspeeding to Package 16. At zero payload and ALVW, Package 17 saves 3% to 5% more fuel than Package 16, except on the aggressive US06 cycle, where the additional savings are closer to 2%. At full GCW, however, the downspeed version provides mixed results. Where the average power demand is still moderate, Package 17 has a slight advantage over Package 16, but on the FTP-Highway and 65 MPH cycles, Package 17 has a slight disadvantage compared to Package 16.

2.3.9.9 3.5 V6 Package 18: Package 16 + Lean Burn (3.5 P18)

Package 18 of the 3.5 V6 adds lean burn at light to moderate load to the Package 16 engine with VVA and EGR. EGR is used to prevent rich operation at high loads. This package provides the most impressive fuel saving results for the V6 engine: 12% to 15% fuel savings on all drive cycles (except the US06) with no payload or at ALVW. On the US06, the benefit is 11% with zero or ALVW payload. The worst performance is at 65 MPH and GCW, where Package 18 is 7.3% better than the baseline V-6. The key issue here is that exhaust aftertreatment is required to control NOx. A 3-way catalyst cannot be used, because of lean operation. Existing SCR systems would have inadequate durability, given the high exhaust temperatures compared to a diesel. As a result, implementation of an engine like this awaits the development of an improved high temperature NOx reduction system.

2.3.9.10 3.5 V6 Package 19: EGR + Downspeed (3.5 P19)

Package 4 represents Package 17 with the VVA removed. This technology combination was already run for Report #1 (Table 3.24). This package provides benefits in the 7% to 9% range, except for the WHVC and 65 MPH cycles at full GCW, where the benefits are around 6%. Overall, the fuel consumption penalty for removing VVA from 3.5 V-6 Package 17 is in the 5% to 6% range. This is much higher than was the case in the medium trucks, where the average load was high enough to minimize the pumping work reduction benefits of VVA.

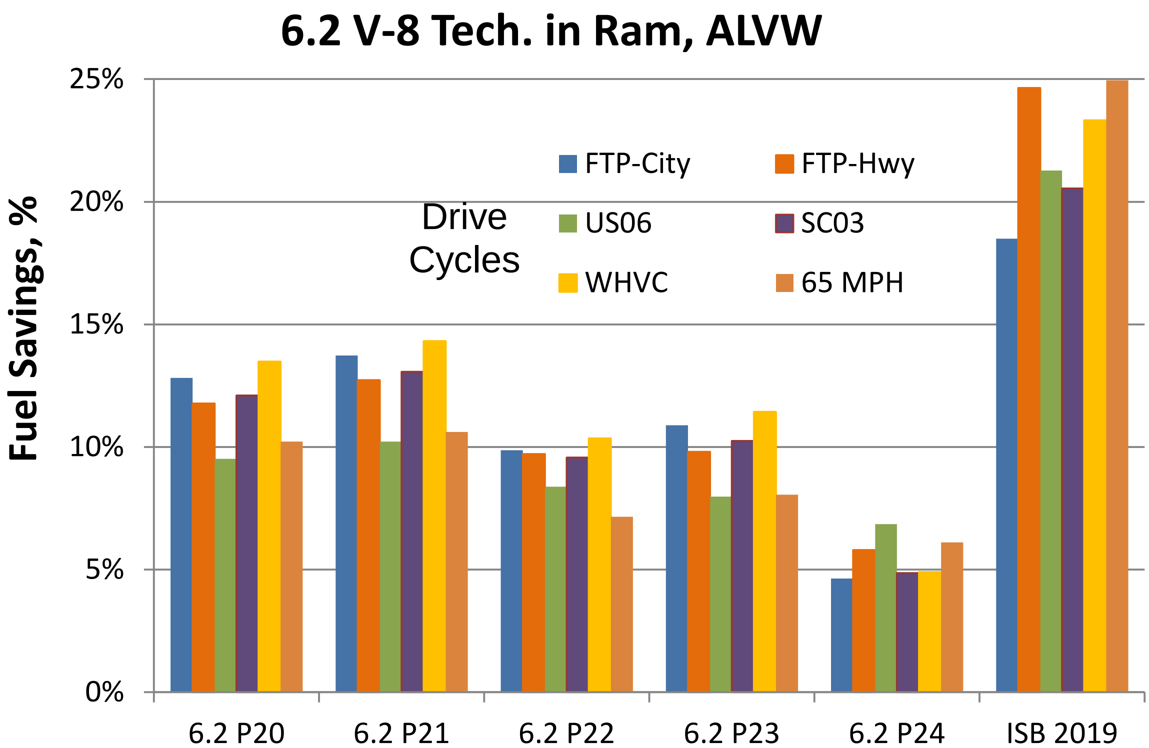

FIGURE 2.21 6.2 V-8 TECHNOLOGY COMBINATIONS IN THE RAM PICKUP

2.3.9.11 6.2 V8 Package 20: GDI + Cylinder Deactivation + EGR + 10% FMEP Reduction (6.2 P20)

Package 20 combines four technologies from Report #1. At zero payload and at ALVW, the fuel savings range from 12% to 15% on the FTP-City, FTP-Highway, SC03, and WHVC cycles. At full GCW, the fuel savings on these cycles is reduced to 8% to 10%. Fuel savings on the US06 cycle are 10%, and at 65 MPH, Package 20 saves 7.4% (full GCW) to 11% (empty), compared to the baseline V-8.

2.3.9.12 6.2 V8 Package 21: Package 1 + VVA (6.2 P21)

V8 Package 21 adds VVA to the combo Package 20. Overall fuel savings are generally about 1% better than those achieved by Package 20. The primary benefit of VVA is to reduce pumping work at light to moderate load. Cylinder deactivation also reduces pumping work at light load, so the addition of VVA on top of cylinder deactivation at light load provides only a small additional benefit.

2.3.9.13 6.2 V8 Package 22: GDI + 2 Cam Phasers + EGR + 10% FMEP Reduction (6.2 P22)

Package 22 starts with Package 20 as the basis. The cylinder deactivation feature used in Package 20 is replaced by dual cam phasers, as an alternative approach to reduce pumping work.

Package 22 performs less well than Package 20 on all cycles except the 65 MPH cruise at full GCW, where cylinder deactivation does not come into play. At 65 MPH and full GCW, the dual cam phasers give a slight advantage over the Package 20 setup. Dual cam phasers are unable to provide as large a pumping work reduction at light load as the cylinder deactivation system.

2.3.9.14 6.2 V8 Package 23: GDI + Cylinder Deactivation + EGR (6.2 P23)

V8 Package 23 is also based on Package 20, with the deletion of the 10% FMEP reduction. Package 23 provides fuel savings of 1% to 2% less than Package 20. This result shows that the incremental benefit of a 10% FMEP reduction for this engine is on the order of 1% to 2%. The benefit of reduced FMEP is largest on lightly loaded cycles.

2.3.9.15 6.2 V8 Package 24: GDI + EGR + 10% FMEP Reduction (6.2 P24)

Package 24 is based on Package 23. The cylinder deactivation is deleted from the Package 23 setup, and a 10% FMEP reduction is added. Except at 65 MPH and full GCW, where cylinder deactivation is not active, the FMEP reduction provides a smaller benefit than cylinder deactivation. Thus, on cycles other than 65 MPH cruise, Package 24 provides fuel savings which are 1% to 7.5% smaller than those of Package 23. The biggest differences between Package 23 and 24 come on the very gentle FTP-City cycle at zero payload, where Package 23 has an advantage of 7.5%, while Package 24 has an advantage of up to 1.2% at 65 MPH and full GCW.

2.3.9.16 Comparison of the Three Baseline Engines in the Ram Pickup

Figure 2.22 shows the comparison of the three 2019 baseline engines in the Ram pickup truck. Keep in mind that diesel fuel has about 13% higher energy content than E-10 gasoline on a per unit volume basis. The figure compares the fuel consumption of the V-6 gasoline engine and the pickup truck diesel to a baseline of the V-8 gasoline engine.

The V-6 offers over 15% fuel savings compared to the V-8 on the FTP-City, SC03, and WHVC cycles. These cycles all run at relatively low road speed, with gentle accelerations, so average engine power demand is quite low. The smaller size of the V-6 means that it runs at a higher BMEP than the V-8, which helps efficiency at light loads. The benefit of the V-6 is smallest on the US06 and 65 MPH cruise cycles, where vehicle power demand is higher. In fact, at 65 MPH and GCW, the V-6 uses about 1% more fuel than the V-8.

Figure 2.22 shows that the 2019 baseline diesel has about a 25% advantage over the V-8 on the FTP-Highway and 65 MPH cycles. The diesel has over a 20% advantage on all cycles except the FTP-City. However, note that the diesel has only a slight advantage over the V-6 on the FTP-City cycle. At zero payload, the V-6 beats the diesel on the FTP-City cycle, because its small displacement leads to higher BMEP operation.

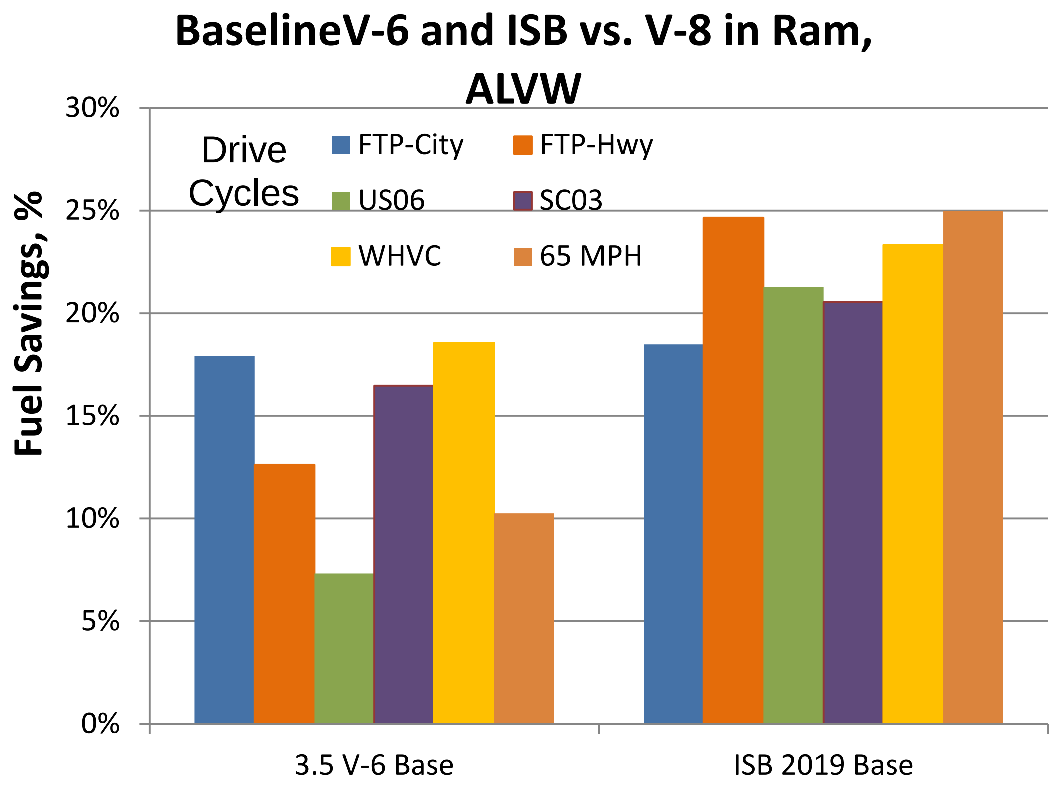

FIGURE 2.22 BASELINE V-6 AND DIESEL VS. V-8 IN RAM AT ALVW

2.3.10 Pickup Truck Vehicle Technology Results

The vehicle technology combinations previously listed in Table 2.9 were all evaluated using the baseline ISB 2019 engine configuration. The vehicle technology packages are all compared against the original baseline vehicle configuration, but with the 2019 baseline diesel engine. In addition, Ram vehicle packages 17 through 20 were also evaluated using the baseline V6 and V8 gasoline engines. Appendix C describes the details of the Ram vehicle model, its calibration, as well as the assumptions and parameters involved in simulating each of the considered technology combinations.

Table 2.21 summarizes the results of vehicle technology combination simulations. Results are provided for each technology on six drive cycles. Each drive cycle is run at three payloads, to provide information on how sensitive a given technology is to payload. As a result, the table provides 18 data points for each of the six technology combinations that were evaluated. The results shown are in terms of percent fuel consumption reduction compared to the baseline Ram vehicle simulation model with the projected 2019 baseline diesel engine, except as noted. No changes were made to the vehicle to account for the 2017 fuel economy and GHG requirements.

In Table 2.21, the Package 18 results are compared to Package 17, and Package 20 results are compared to Package 19. These results are shaded in green. This allows the reader to see the marginal benefits of Package 18 over P17, and Package 20 over P19.

TABLE 2.21 VEHICLE TECHNOLOGY PACKAGE RESULTS IN THE RAM PICKUP

Technology	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload																	
	FTP-City			FTP-Highway			US06			SC03			WHVC			65 MPH		
	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW
Cd - 5%	0.4	0.3	0.3	1.4	1.3	1.0	1.4	1.3	0.9	0.4	0.3	0.3	0.7	0.7	0.6	1.9	1.8	1.6
Cd - 10%	0.7	0.7	0.6	2.7	2.6	2.0	2.8	2.5	1.8	0.7	0.7	0.5	1.4	1.4	1.2	3.9	3.7	3.2
Crr - 10%	0.9	0.9	1.6	1.4	1.5	2.4	0.9	1.0	1.4	0.9	0.9	1.4	1.1	1.2	2.1	1.2	1.4	2.4
Crr - 20%	1.7	1.9	3.1	2.7	3.1	4.7	1.8	2.0	2.9	1.7	1.8	2.9	2.1	2.4	4.3	2.4	2.7	4.7
Crr - 30%	2.6	2.8	4.7	4.2	4.6	7.1	2.7	3.0	4.3	2.3	2.8	4.3	3.1	3.6	6.9	3.6	4.1	7.1
P17 ISB	7.6	7.4	8.8	11	11	11	6.3	6.6	7.9	5.7	6.1	7.5	8.5	8.6	9.6	9.4	9.6	11
P17 3.5	5.1	5.8	7.2	10	11	11	7.8	7.6	6.8	8.1	7.8	7.2	7.1	7.8	10	11	11	13
P17 6.2	3.6	4.6	7.1	8.4	8.7	11	6.5	6.8	7.7	7.4	8.2	8.3	5.5	6.0	8.6	8.2	8.4	10
P18 ISB	4.1	3.9	2.3	0.1	0.1	0.1	1.6	1.4	0.7	3.4	3.1	1.7	2.2	2.1	1.2	0.0	0.0	0.0
P18 3.5	2.3	2.1	1.5	0.1	0.1	0.1	0.8	0.7	0.6	1.8	1.7	1.0	1.1	1.0	0.7	0.0	0.0	0.0
P18 6.2	1.7	1.7	1.6	0.0	0.0	0.1	0.7	0.6	0.7	1.4	1.3	1.1	0.8	0.8	0.6	0.0	0.0	0.0
P19 ISB	3.4	3.4	5.2	6.9	7.2	9.2	5.4	5.5	6.1	3.0	3.5	4.9	4.5	5.0	8.0	7.5	7.8	10
P19 3.5	3.9	4.3	6.1	6.9	7.3	10	6.0	6.2	6.8	3.7	4.0	5.7	5.1	5.5	8.4	7.9	8.3	12
P19 6.2	3.2	3.7	5.6	5.3	5.8	9.5	5.0	5.2	6.6	2.8	3.8	5.1	3.7	4.1	7.1	5.9	6.4	9.5
P20 ISB	4.9	4.8	3.0	4.5	4.3	2.3	4.5	4.0	2.1	5.3	4.9	2.9	4.8	4.6	2.8	3.2	3.0	1.8
P20 3.5	6.0	5.7	3.6	4.8	4.5	2.9	5.6	5.2	2.4	6.6	6.2	3.4	5.3	5.1	3.3	3.6	3.4	2.1
P20 6.2	4.4	4.3	3.1	3.5	3.4	2.6	4.3	4.0	2.7	4.9	4.7	3.2	3.8	3.7	2.7	2.6	2.6	1.8

The results shown in Table 2.21 can also be presented in a form that shows the full fuel savings for Packages 18 and 20 compared to the Ram with the 2019 baseline ISB engine. These results are shown in Table 2.22 below.

TABLE 2.22 VEHICLE TECHNOLOGY PACKAGE P18 AND P20 RESULTS VS. BASELINE

Technology	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload																	
	FTP-City			FTP-Highway			US06			SC03			WHVC			65 MPH		
	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW
P18 ISB	12	11	11	11	11	11	7.9	8.1	8.6	9.0	9.3	9.2	11	11	11	9.4	9.6	11
P18 3.5	7.3	8.0	8.8	10	11	11	8.6	8.4	7.4	10	9.5	8.3	8.1	8.8	11	11	11	13
P18 6.2	5.3	6.3	8.7	8.4	8.8	11	7.1	7.4	8.3	8.8	9.5	9.4	6.3	6.8	9.2	8.2	8.4	10
P20 ISB	17	16	14	15	15	13	12	12	11	14	14	12	15	15	14	13	13	12
P20 3.5	13	14	12	15	15	14	14	14	9.8	17	16	12	13	14	14	14	14	15
P20 6.2	10	11	12	12	12	13	11	11	11	14	14	13	10	11	12	11	11	12

The results shown in Table 2.21 and 2.22 can also be presented in graphical form. To simplify the graphs, only results for the 50% payload are shown in Figures 2.23 through 2.26 below. Note that all Vehicle Technology Combinations use only the baseline engines. In Figures 2.23 and 2.24, the results for P18 (P17 + idle neutral) are presented relative to the P17 results, so that the incremental benefit of idle neutral can be seen. The results for P20 (P18 + 40% A/C power demand reduction + 600 pound empty weight reduction) are shown relative to P19, so that the incremental benefit of the A/C power demand reduction and the weight reduction can be seen. This approach is similar to that of Table 2.21. In Figures 2.25 and 2.26, all packages are compared to the 2019 vehicle baseline, so that the full benefit of Packages 18 and 20 can be seen. This approach is similar to that of Table 2.22.

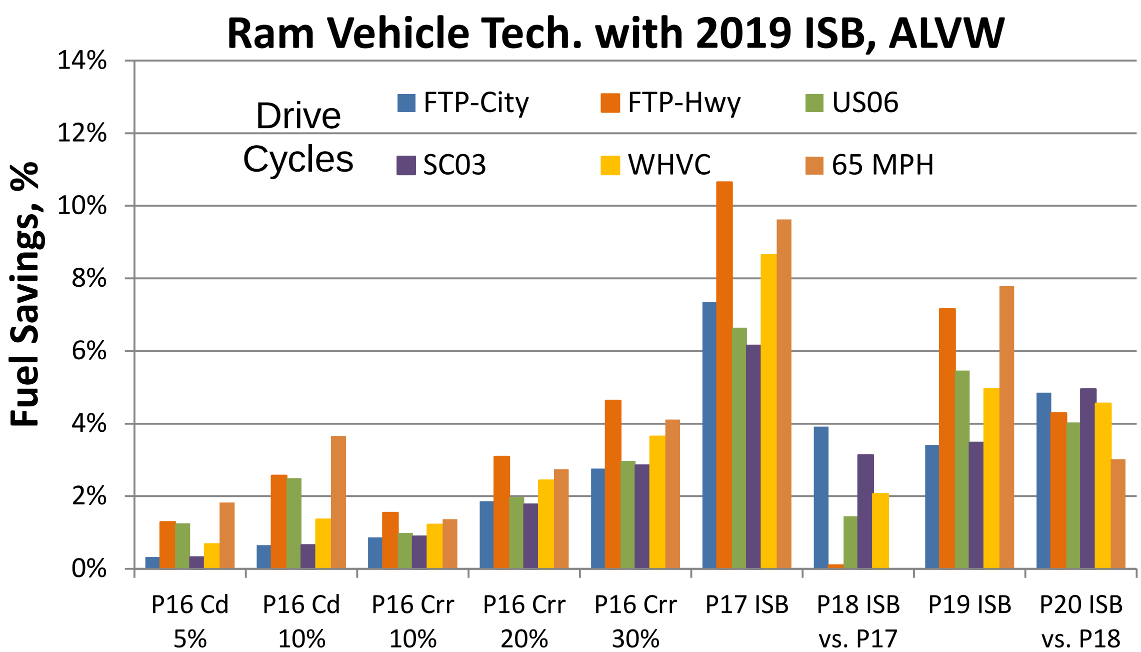

FIGURE 2.23 RAM VEHICLE TECHNOLOGY PACKAGE RESULTS WITH THE 2019 BASELINE DIESEL. P18 IS COMPARED TO P17, AND P20 TO P18

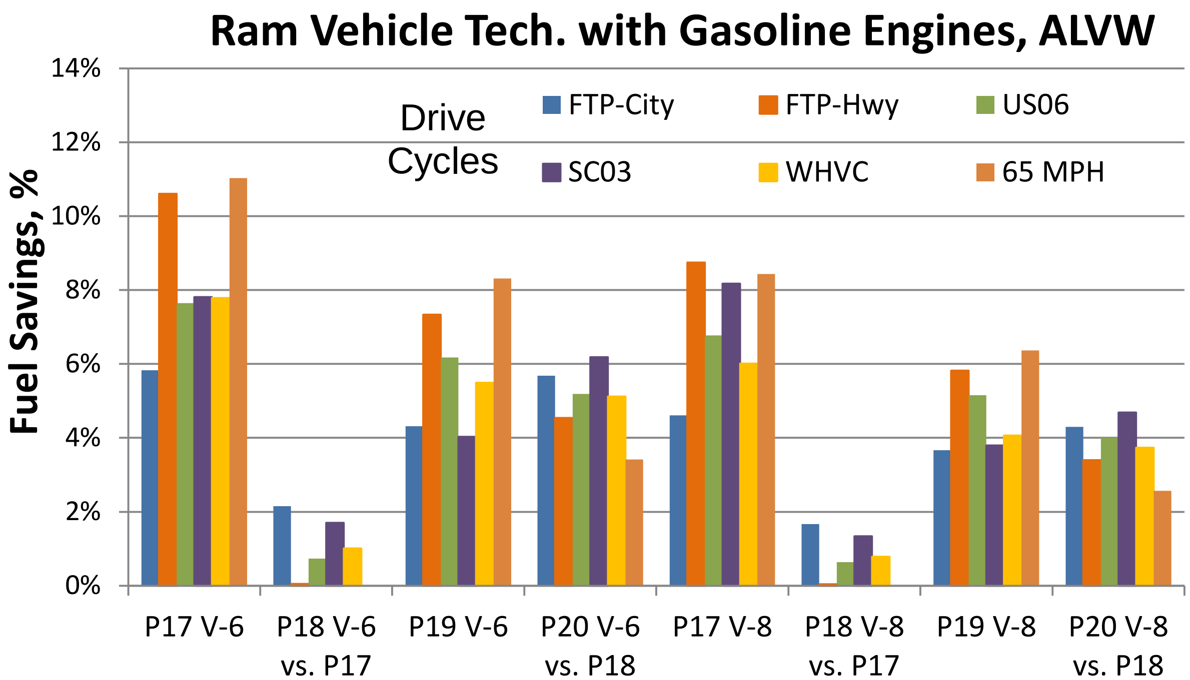

FIGURE 2.24 RAM VEHICLE TECHNOLOGY PACKAGE RESULTS WITH THE BASELINE GASOLINE ENGINES. P18 IS COMPARED TO P17, AND P20 TO P19

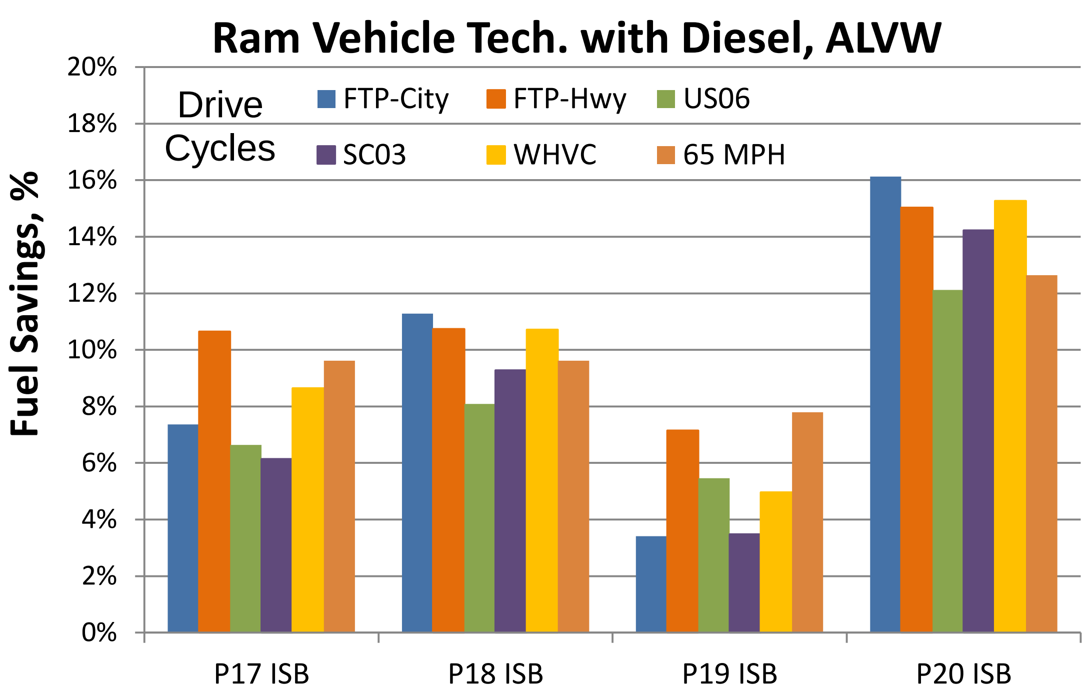

FIGURE 2.25 RAM VEHICLE TECHNOLOGY PACKAGE RESULTS WITH THE 2019 BASELINE DIESEL. THE FULL VALUE OF EACH PACKAGE IS SHOWN

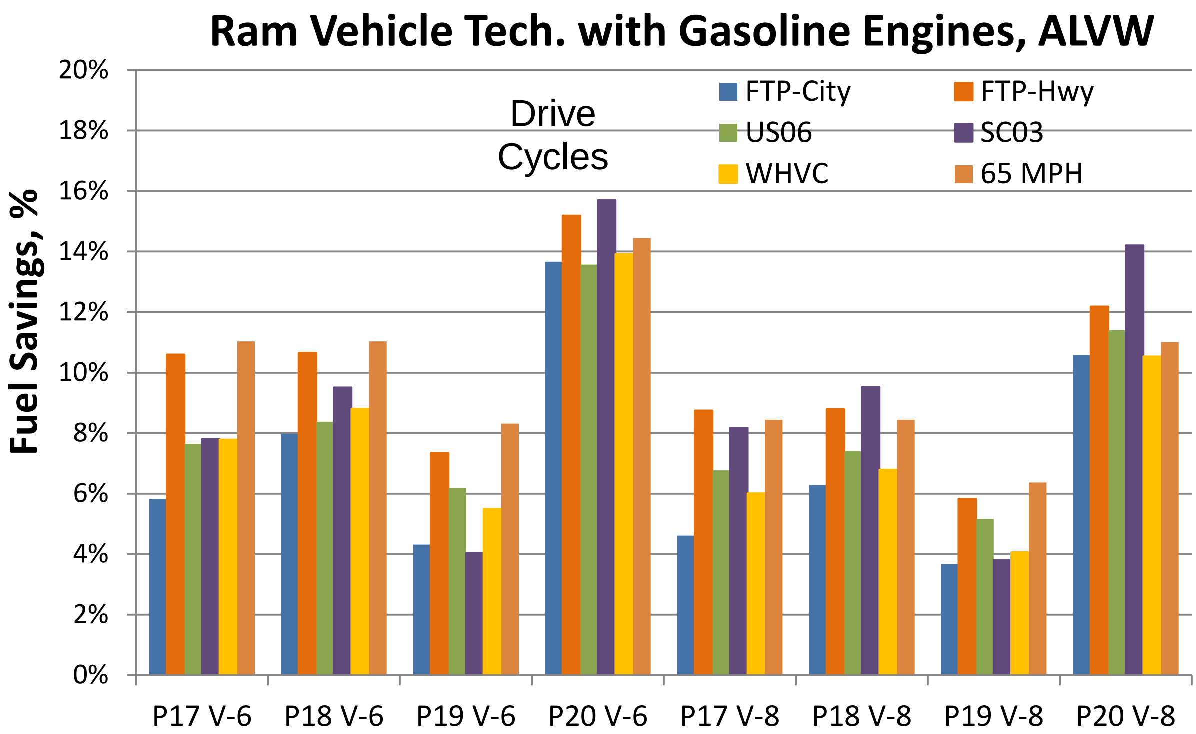

FIGURE 2.26 RAM VEHICLE TECHNOLOGY RESULTS WITH THE BASELINE GASOLINE ENGINES. THE FULL VALUE OF EACH PACKAGE IS SHOWN

2.3.10.1 Ram Vehicle Package 16: Cd and Crr Sweeps with Diesel Engine (P16)

As with the other vehicles, the response to changes in Cd and Crr is very linear. A larger reduction in Cd or Crr leads to a proportionally larger fuel savings. However, the sensitivity of the pickup truck to Cd and Crr is less than for the other vehicles. The vehicle frontal area is smaller, which makes aerodynamic drag less of a factor. The vehicle weight is also less, except in the case of towing a trailer. This makes tire rolling resistance a smaller factor. Accessory power demand becomes a larger factor, since the average vehicle power demand is lower than for larger trucks.

2.3.10.2 Ram Vehicle Package 17: 10% Cd reduction + 30% Crr reduction + 8-Speed Automatic (P17)

This combination of technologies provides the largest benefit on the FTP-Highway and 65 MPH cycles (9.4% to 11% with the diesel). The 8-speed transmission was geared to provide the same engine speed at 65 MPH as the baseline 6-speed, so a change in overall gearing in top gear is not a factor here. The 8-speed automatic does have higher mechanical efficiency, which does contribute to the fuel savings. On other drive cycles, the fuel savings due to Package 17 are generally in the 4% to 8% range. The benefit of Package 17 varies slightly based on engine. In general, there is slightly more benefit with the gasoline V-6 and the diesel than with the gasoline V-8, which is a bit less load sensitive.

2.3.10.3 Ram Vehicle Package 18: Package 17 + Idle Neutral Feature (P18)

The idle neutral feature reduces load on the engine whenever the transmission is in Drive and the vehicle is stationary. The largest benefit is on the FTP-City cycle, which spends 16.5% of the cycle at idle. The benefit compared to Package 17 is largest (up to 4.1% at zero payload) for the diesel. The V-6 sees a 2.3% benefit and the V-8 gets a 1.7% benefit under the same conditions. The reason for the larger benefit with the diesel is the tighter torque converter that is required to match the higher torque capability of the diesel. That tight torque converter causes a higher engine load at idle with the converter stalled (output speed = zero). Other drive cycles which spend less time at idle achieve smaller benefits than those on the FTP-City cycle.

2.3.10.4 Ram Vehicle Package 19: 10% Cd reduction + 30% Crr Reduction (P19)

P19 is effectively P17 with the baseline 6-speed automatic transmission rather than the 8-speed that is part of Package 17. Thus, the difference in results between P17 and P19 is the benefit of the upgrade transmission (more ratios and higher mechanical efficiency). Note that the two transmissions were geared so that cruise engine speed at 65 MPH is identical. P19 fuel savings are generally 2% to 3% less than P17, indicating the value of the upgrade transmission.

2.3.10.5 Ram Vehicle Package 20: P18 + 40% A/C Power Reduction + 600 lb empty weight reduction (P20)

Vehicle Package 20 includes reduced accessory power demand from the air conditioner compressor and a 600 pound empty weight reduction. This package is similar to Package 15 on the F-650 and Package 10 on the T270, although the 600 pound empty weight reduction for the Ram represents a larger percentage of the total vehicle empty weight than was applied to the larger trucks.

P20 provides incremental fuel savings of 3% to 5% for most drive cycles and payloads with the diesel engine. The smallest benefit is found on the 65 MPH cruise point at full GCW. On this cycle, the weight savings is only a (small) factor affecting rolling resistance, since there are no accelerations. Also, the accessory power demand is a small fraction of road load, since both aerodynamic drag and rolling resistance are much higher at GCW. The V-6 gasoline engine sees incremental fuel savings of 3.5% to over 6%, but the less load sensitive V-8 gets slightly less benefit than the diesel.

2.3.11 Hybrid System Results

In the last few years, large companies such as Eaton and Allison tried to break into the vocational truck market with both electric and hydraulic hybrid systems intended for refuse haulers, delivery trucks, and shuttle buses. This effort was supported by substantial federal and state subsidies for the purchase of trucks with hybrid systems. However, by the middle of 2014, before the oil price collapse, the large players had withdrawn from the market. The primary issues were that the systems showed poor payback, and they experienced numerous technical problems. A few smaller companies remain in the hybrid truck market, but the total market for hybrid systems in vocational trucks is very small. There has not yet been an effort to commercialize hybrid systems for long haul trucks, although there are battery based APU systems to handle hotel loads (air conditioning, TV, etc.) while the vehicle is parked. Because of budget and time constraints, SwRI and the agencies did not include medium- and heavy-duty truck hybrid systems in this study.

In the light duty vehicle market, hybrid systems have captured about a 3% market share after over 15 years on the market. The high cost and weight of batteries and power electronics has caused market penetration to grow slowly, with an average growth rate of about 0.2% gain in market share per year. The drop in oil prices in 2014 also has the effect of reducing the attraction of hybrids. On the other hand, battery and power electronic prices are coming down, and any future increase in fuel prices would make hybrids more attractive. Stringent fuel economy regulations may force manufacturers to ramp up the volume of hybrid systems, even if the cost/benefit ratio is not attractive. Since heavy-duty pickup trucks are the nearest market segment to light duty, they are likely to be in a position to take advantage of systems developed for the light duty market. Argonne National Laboratory was contracted to take the pickup truck model developed for this study and apply a range of potential hybrid systems to it. Three systems were evaluated:

A 7 kW belt driven integrated starter/generator (BISG)
A 15 kW crank drive integrated starter/generator (CISG)
A 50 kW parallel hybrid system

The fuel consumption levels and reductions provided by the three hybrid systems are summarized in Table 2.23 below. The values are in terms of percent reduction in fuel consumption on the light duty city and highway drive cycles. The fuel savings are much larger on the city cycle, where more regenerative braking energy is available. Fuel savings also increase as the size and complexity of the hybrid system increases. On both drive cycles and with all three engines, the fuel savings decline as the vehicle payload increases. The 3.5 liter V-6 gasoline engine benefits slightly more from the various hybrid systems than the other two engines.

Some of the vehicle parameter assumptions used in the hybrid system study varied from those used for the rest of this report. As a result, the fuel economy of the baseline pickup and hybrid alternatives will be somewhat higher (and fuel consumption will be lower) than is shown elsewhere in this report. Additional details of the assumptions made, simulation approach, and results can be found in Appendix D.

The hybrid systems have a much larger effect on the city cycle than on the highway cycle, where there are fewer opportunities for regenerative braking. The integrated starter generator systems generally provide a larger fuel consumption benefit when paired with one of the gasoline engines rather than with the diesel. The more powerful crankshaft mounted ISG tends to outperform the smaller, lower cost belt driven ISG. The fuel savings of all the hybrid systems declines with increasing vehicle payload. Finally, the full parallel hybrid system has a smaller benefit when paired with the 3.5 liter V-6, compared to its benefit in combination with either the diesel or the larger V-8.

TABLE 2.23 HYBRID SYSTEM PERFORMANCE IN THE RAM PICKUP TRUCK

Engine	Drive Cycle	Payload	FC w/ BISG, gal/100	FC w/ CISG, gal/100	FC w/ Parallel Gal/100	BISG % Benefit	CISG % Benefit	Parallel % Benefit
Diesel	FTP-Hwy	0%	3.4	3.4	3.23	0.30	0.23	5.8
Diesel	FTP-City	0%	4.5	4.3	3.4	5.8	8.6	29
3.5 V-6	FTP-Hwy	0%	3.7	3.6	3.5	0.80	2.7	5.0
3.5 V-6	FTP-City	0%	4.7	4.6	3.8	7.8	10	25
6.2 V-8	FTP-Hwy	0%	4.3	4.3	4.0	0.08	0.72	6.5
6.2 V-8	FTP-City	0%	5.8	5.6	4.4	7.0	10	30
Diesel	FTP-Hwy	ALVW	3.7	3.7	3.5	0.28	0.85	6.2
Diesel	FTP-City	ALVW	5.0	4.8	3.7	5.6	8.3	29
3.5 V-6	FTP-Hwy	ALVW	4.1	4.0	3.9	0.86	2.8	6.3
3.5 V-6	FTP-City	ALVW	5.3	5.3	4.3	7.7	7.6	25
6.2 V-8	FTP-Hwy	ALVW	4.6	4.6	4.3	0.99	0.76	7.0
6.2 V-8	FTP-City	ALVW	6.4	6.3	4.8	6.1	7.0	30
Diesel	FTP-Hwy	GCW	6.9	6.8	6.5	0.40	1.5	6.3
Diesel	FTP-City	GCW	11	11	9.2	3.1	5.1	19
3.5 V-6	FTP-Hwy	GCW	9.2	9.1	8.7	0.46	0.92	5.9
3.5 V-6	FTP-City	GCW	14	14	12	4.7	7.1	16
6.2 V-8	FTP-Hwy	GCW	9.4	9.4	8.8	0.73	1.3	7.8
6.2 V-8	FTP-City	GCW	14	14	12	4.7	5.0	21

Both integrated starter generator systems have little effect on highway cycle results, regardless of the engine or payload. The full parallel hybrid system provides a 5% to 7% fuel savings on the highway cycle, regardless of engine or payload.

The hybrids provide much larger benefits on the city cycle. The smallest system, the belt driven ISG, saves 7% or more in fuel consumption with the gasoline engines at zero payload, and nearly 6% with the diesel. As payload increases, the benefit of the BISG declines into the 3% to 5% range. The more powerful crank mounted starter generator (CISG) provides about a 10% fuel savings with the gasoline engines and 8.6% with the diesel at zero payload. These benefits fall to a range of 5% to 7% at full payload. Finally, the full parallel hybrid reduces fuel consumption on the city cycle by 25% to 30% at zero payload. The best result is with the gasoline V-8, and the smallest benefit is with the turbocharged V-6. The benefits of the full hybrid system decline to a 16% to 21% range at full payload.

3.0 VEHICLE PARAMETER SWEEPS

Sweeps of several parameters have been conducted on the Ram pickup, the F-650 tow truck, and the T270 box delivery truck. The purpose of the parameter sweeps is to gain an insight into the sensitivity of vehicle fuel consumption to the various parameters considered. The list of parameters tested is:

- Aerodynamic drag coefficient (Cd)
- Tire rolling resistance coefficient (Crr)
- Axle ratio
- Vehicle empty weight

For all 3 vehicles, the axle ratio and empty weight sweeps were performed on all three applicable engines (the 2019 baseline ISB diesel, the baseline 3.5 V-6 turbocharged gasoline, and the baseline 6.2 V-8 gasoline). The aero and rolling resistance sweeps were performed using only the 2019 baseline diesel engine. Note that the baseline diesel engine is different in the Ram pickup than for the medium duty trucks, while the same baseline gasoline engines were used in all three vehicles.

3.1 Aerodynamic Drag Sweep

Figures 3.1 through 3.3 summarize the sensitivity of the three vehicles to a sweep in aerodynamic drag values. No specific list of features was specified for a given change in Cd value. The goal of these sweeps was to cover roughly the range of Cd improvements that might be feasible over the next 10 years. Readers are free to use their own assumptions regarding what Cd reduction is feasible to project a fuel consumption reduction, using the results provided here. Note that the Ram pickup has a different set of duty cycles than the medium trucks, but the WHVC and 65 MPH cycles are shared by all three vehicles. For the Ram pickup, ALVW represents a payload of 1,562 pounds in the bed, but no trailer. For the F-650, 50% payload is 3,180 pounds, while 50% payload for the T270 is 4,430 pounds.

Figure 3.3 shows data that is also included in Figure 2.25 and described in section 2.3.10.1. Figure 3.1 shows data that is also included in Figure 2.10 and described in section 2.3.6.1. Finally, Figure 3.2 presents data that is also included in Figure 2.17.

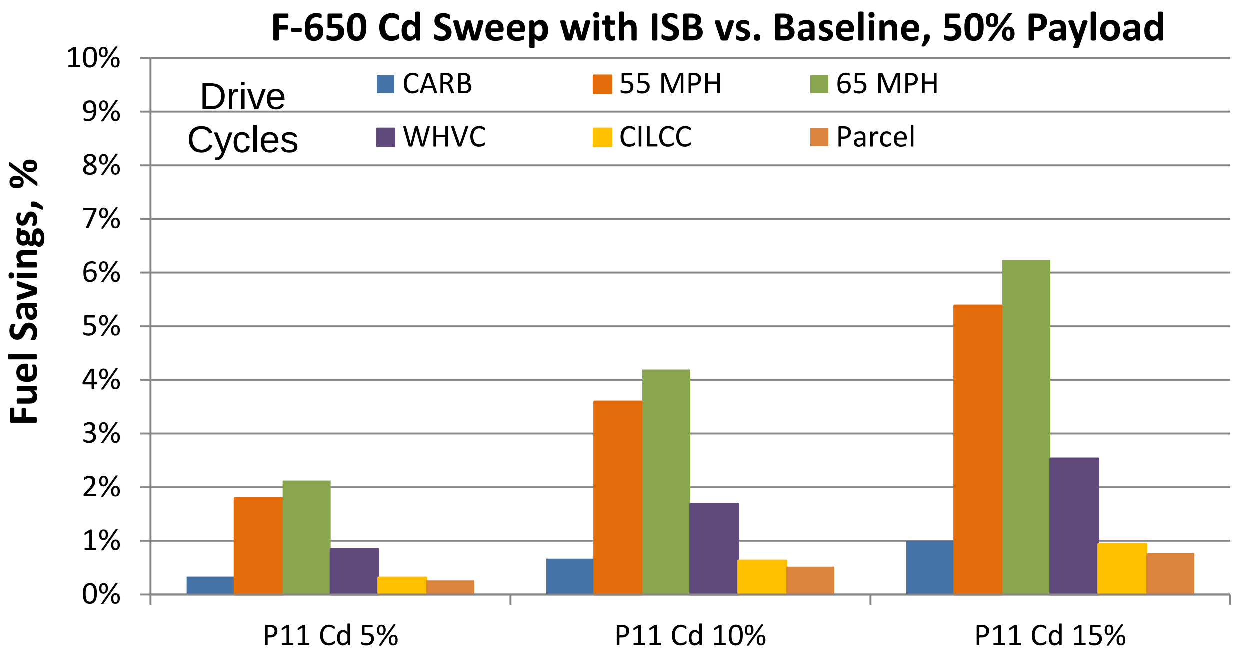

FIGURE 3.1 CD SWEEP OF F-650 TOW TRUCK

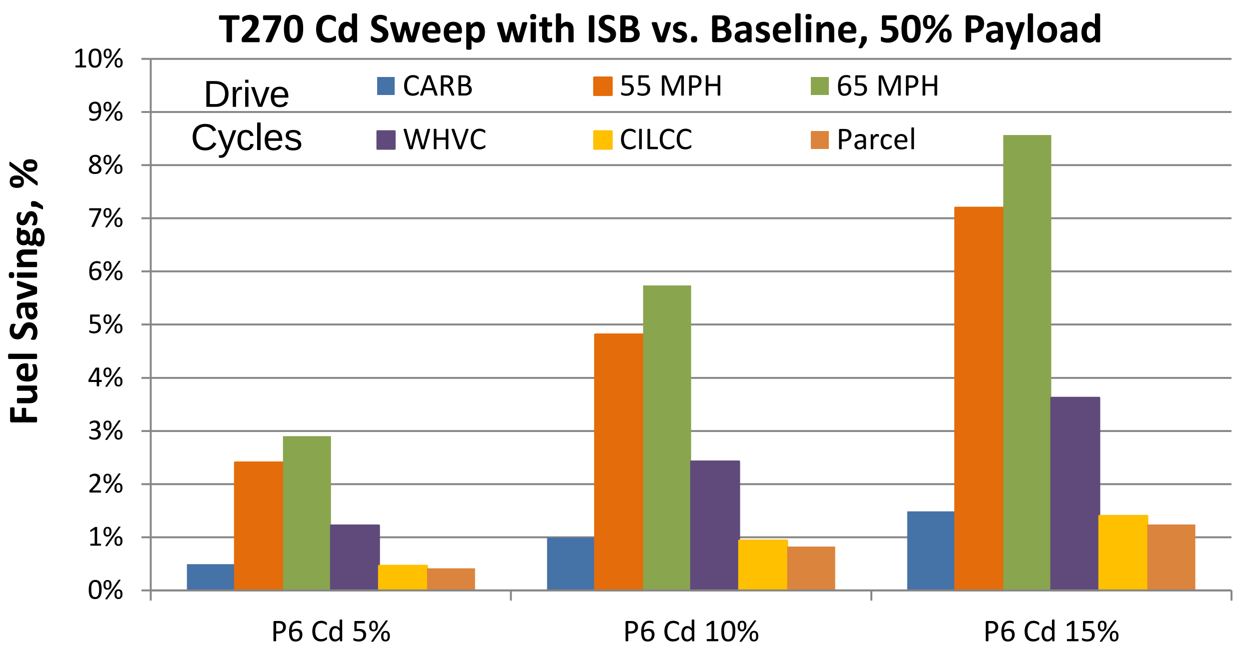

FIGURE 3.2 CD SWEEP OF T270 DELIVERY TRUCK

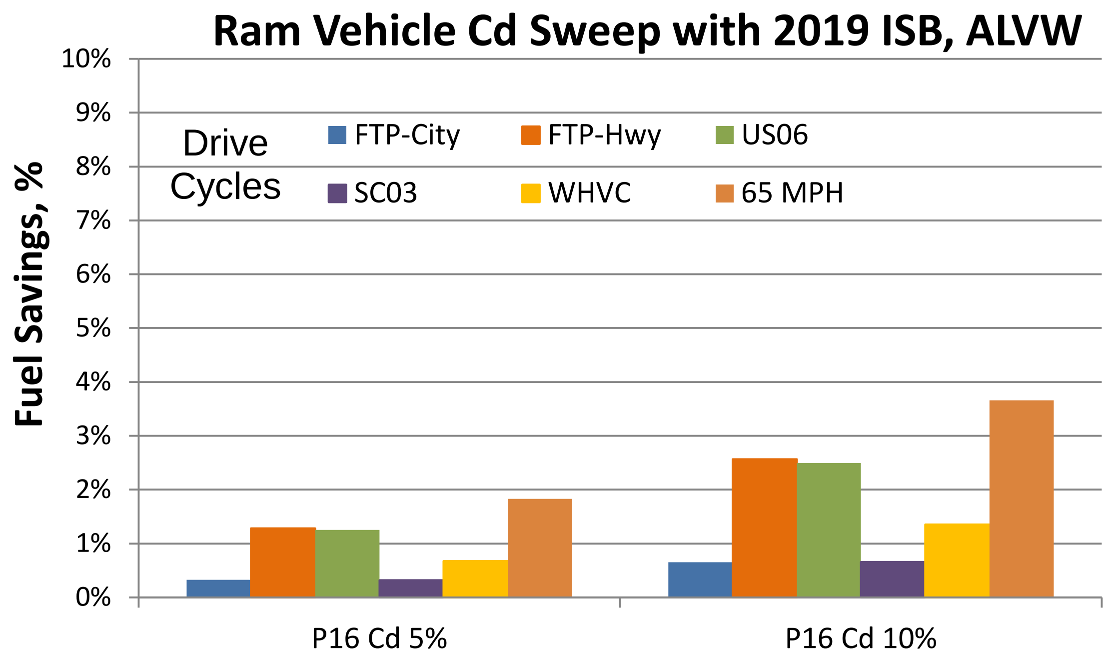

FIGURE 3.3 CD SWEEP OF RAM PICKUP

When comparing Figures 3.1 through 3.3, it becomes clear that frontal area has a large effect on the benefit of a Cd reduction. The Ram pickup, with the smallest frontal area, sees a 3.7% fuel consumption reduction at 65 MPH from a 10% Cd reduction. For the pickup, Cd reductions beyond 10% were not evaluated, on the assumption that larger improvements are not compatible with the basic vehicle configuration. The somewhat larger F-650 tow truck gains about 4.1% fuel savings on the same 65 MPH cycle, while the T270, which has nearly the frontal area of a long haul tractor-trailer truck, gains a 5.7% fuel savings at 65 MPH from a 10% Cd reduction.

For all three vehicles, the 65 MPH cycle produces the largest fuel savings, while low vehicle speed cycles such as the FTP-City (for the Ram) or the CARB cycle (for the F-650 and T270) yield very small fuel savings. This result is not surprising, since aerodynamic drag is a function of speed squared. High speed, steady state cycles will achieve the largest benefit from an aerodynamic improvement.

3.2 Tire Rolling Resistance Sweep

Figures 3.4 through 3.6 show the effects of a sweep in tire rolling resistance (Crr). As was the case for Figures 3.1 through 3.3, the Ram pickup shares only two drive cycles with the medium trucks: the WHVC and 65 MPH cruise.

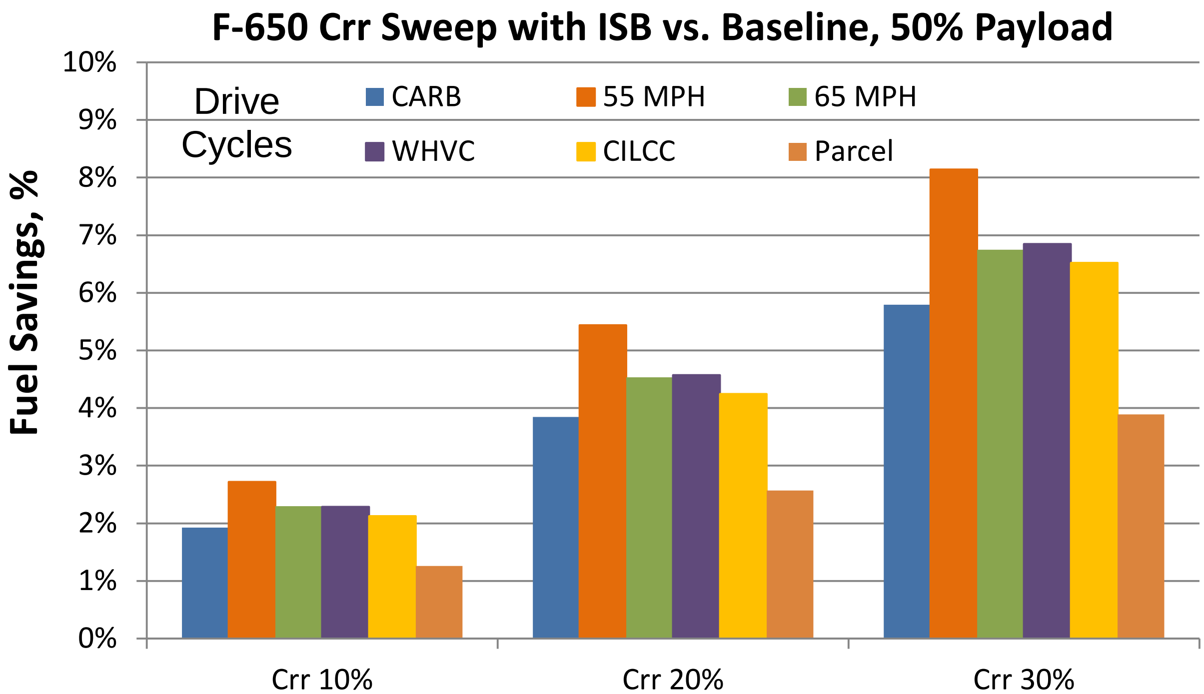

FIGURE 3.4 CRR SWEEP OF THE F-650 TOW TRUCK

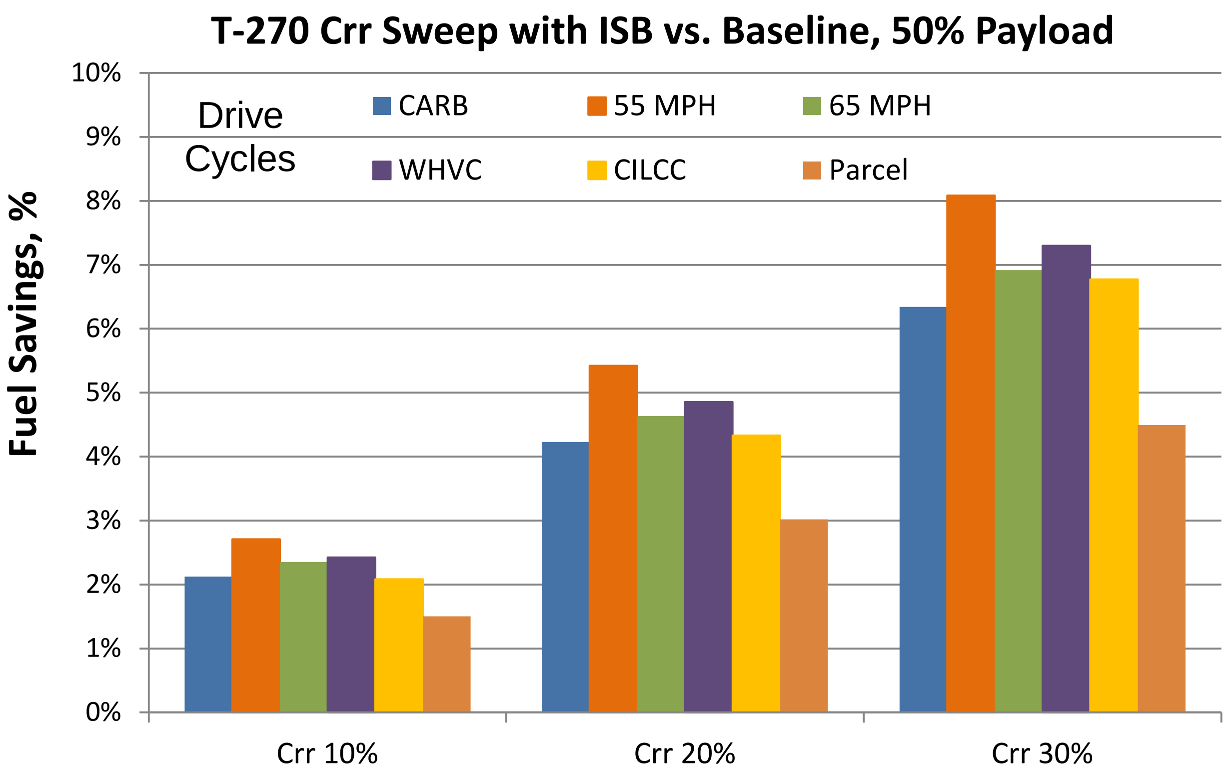

FIGURE 3.5 CRR SWEEP OF THE T270 DELIVERY TRUCK

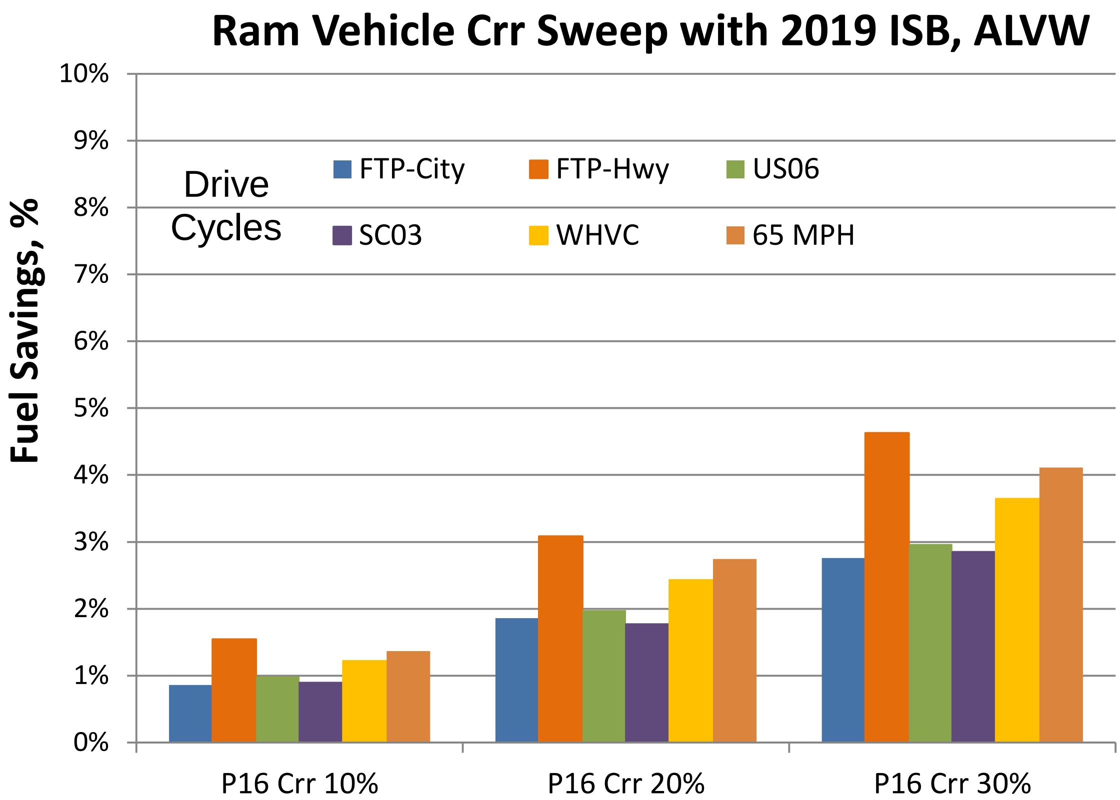

FIGURE 3.6 CRR SWEEP OF THE RAM PICKUP

On the Ram pickup, a reduction in tire rolling resistance has the largest benefit on the FTP-highway cycle, and the second largest benefit is seen at 65 MPH cruise. On the F-650 and T270 trucks, the largest fuel savings comes at 55 MPH, with the second largest benefit on the WHVC cycle. The results are similar on most cycles except the Parcel cycle, which is dominated by rapid accelerations and time at idle. At higher vehicle speed, aerodynamic drag becomes more dominant, thus reducing the impact of a tire rolling resistance improvement.

At 65 MPH, the relative light pickup truck gains a benefit of just over 4% from a 30% reduction in Crr. The heavier F-650 saves 6.8% at 65 MPH from a 30% Crr reduction, while the heaviest truck, the T270, sees almost a 7% benefit at 65 MPH. In general, the heavier the truck, the more important tire rolling resistance becomes. The only reason the T270 did not see a bigger fuel savings than 7% at 65 MPH is that this truck has significantly larger frontal area. The large frontal area of the T270 means that at high road speed, the vehicle power demand is dominated by aerodynamic drag. Since the portion of road load that comes from tire rolling resistance is smaller in the T270, the fuel savings provided by Crr reduction is smaller.

Rolling resistance reductions can come with trade-offs. One potential trade-off is against ride comfort. Low Crr tires tend to have lower deflections, which can make the ride harsher. This is mainly a concern for pickup trucks, which are often sold to consumers. Another potential trade-off is against traction and stopping distance. Although safety trade-offs from lower traction are theoretically possible, the literature search did not identify data on safety impacts of LRR tires in MD/HDVs, or reports of safety hazards from lower LRR road grip in snow, ice or wet conditions that could result in potential degraded handling or longer braking distance [8, 9].

3.3 Vehicle Empty Weight Sweep

Figures 3.7 through 3.9 show the impact of empty weight reductions on all three vehicles. In this case, the results are also shown for all three engines. The weight reductions are in absolute terms (pounds), so it is also useful to consider the results in terms of percent reduction in the empty weight of the vehicle. The percent reductions in empty vehicle weight are provided on each plot in small text boxes above the plotted values. Note that for this parameter sweep, the payload mass is not changed when empty weight is reduced. The weight reduction values that were evaluated are roughly proportional to the vehicle empty weights, but they are not a specific percentage of vehicle empty weight. The resulting sensitivity to weight can be used to predict the benefit of any specific percentage weight reduction.

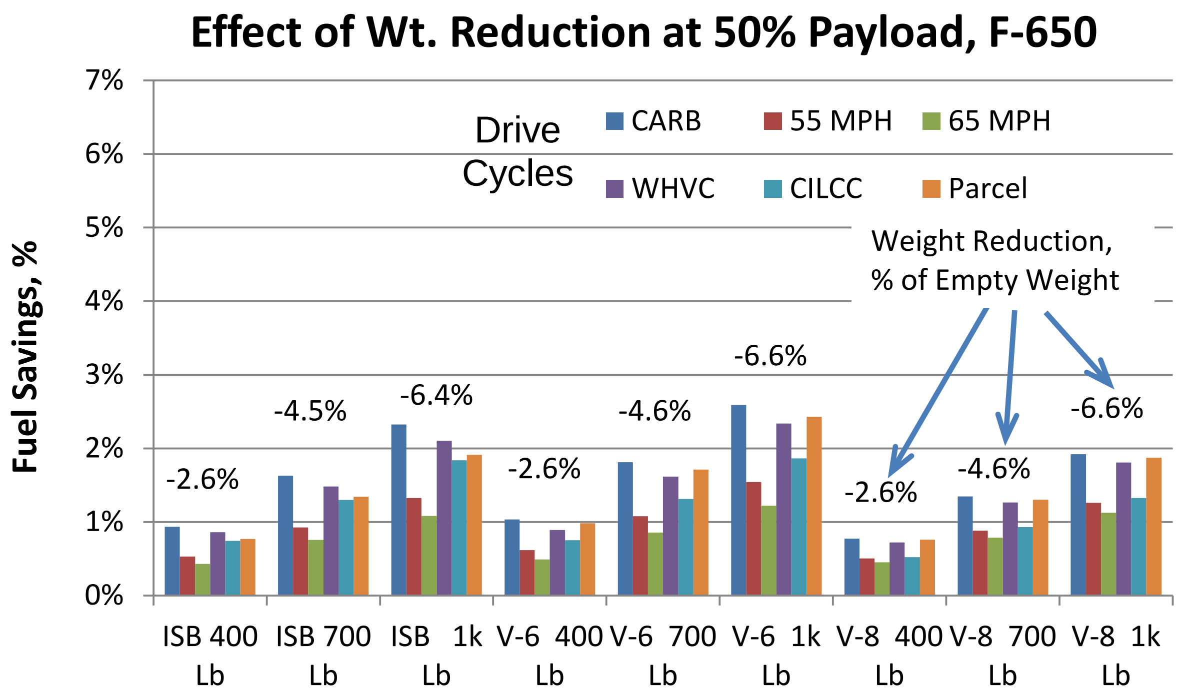

FIGURE 3.7 EFFECT OF EMPTY WEIGHT REDUCTION ON F-650

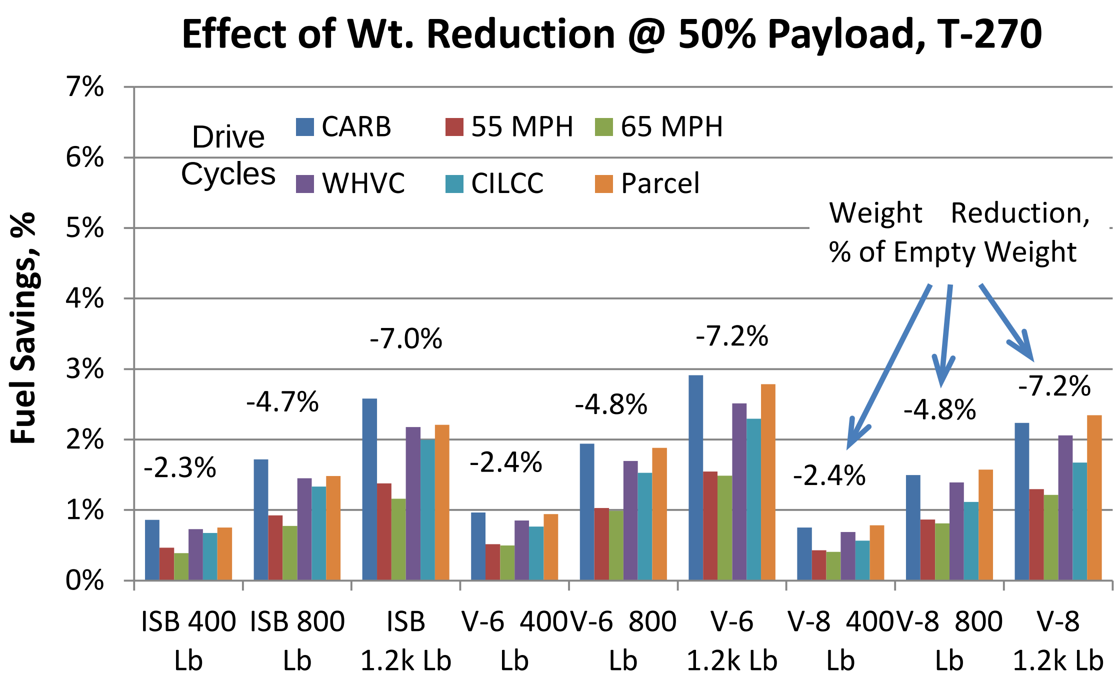

FIGURE 3.8 EFFECT OF EMPTY WEIGHT REDUCTION ON T270

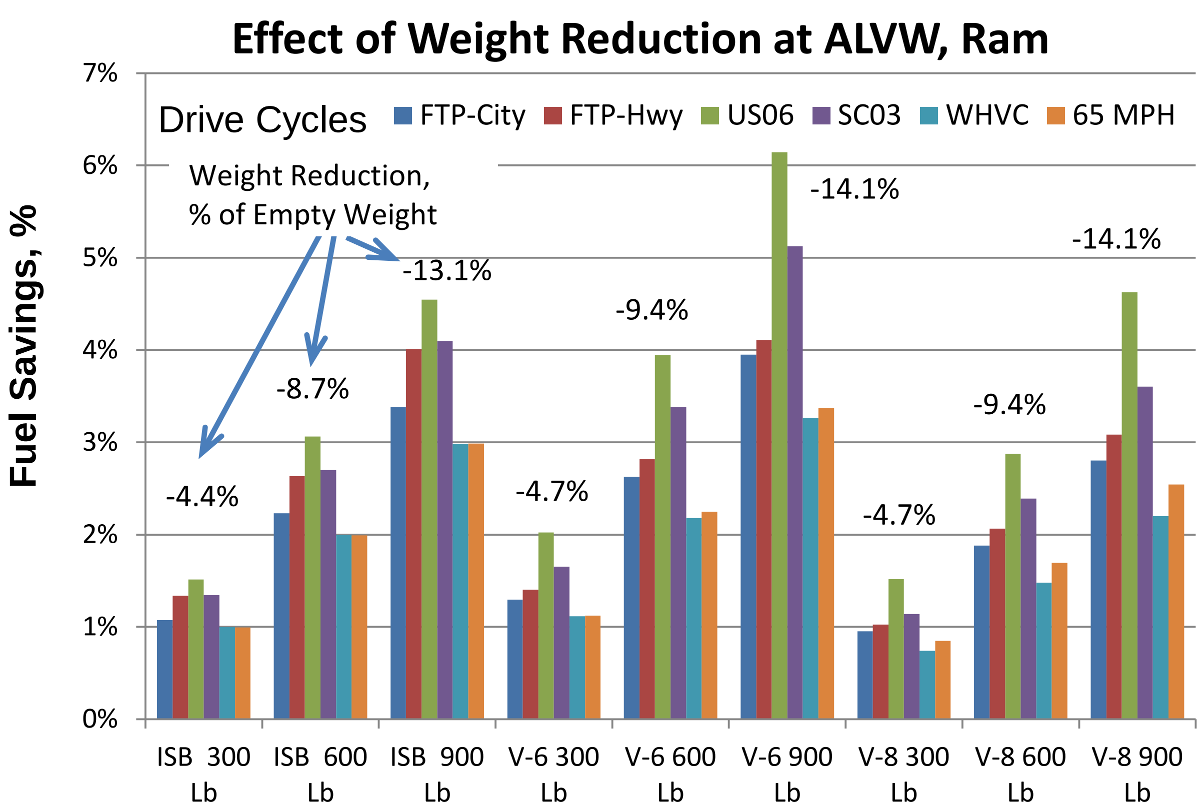

FIGURE 3.9 EFFECT OF EMPTY WEIGHT REDUCTION ON RAM PICKUP

The figures above appear to show that the Ram pickup is more sensitive to empty vehicle weight reductions than the two medium duty trucks. However, this is primarily because the pickup weight reductions are larger in percentage terms. Drive cycles with a lot of accelerations, such as the US06 and the CARB cycle, show the greatest sensitivity to empty weight reductions. This is because an empty weight reduction has two benefits on highly transient cycles: tire rolling resistance is reduced, and power demand to accelerate vehicle inertia is also reduced. On steady state cycles such as the 55 and 65 MPH cycles, the benefit of an empty weight reduction is smaller, because only rolling resistance power demand is reduced. Note that the 55 and 65 MPH cycles used in this study have no grade. With a grade, weight would have more of an impact on cruise cycles. There is no inertia power demand to be reduced.

In general, the V-6 gasoline engine sees the largest fuel savings benefit from any given reduction in vehicle power demand (either aerodynamic or rolling resistance). The V-8 gasoline engine tends to be the least sensitive to changes in vehicle power demand, with the diesel falling in between the two gasoline engines.

3.4 F-650 Axle Ratio Sweep

Figures 3.13 through 3.15 show the effect of an axle ratio sweep on the F-650 tow truck with all three engines. For the F-650, 50% payload represents a payload of 3,180 pounds on the bed, but no trailer. 100% payload is 6,360 pounds, again with no trailer.

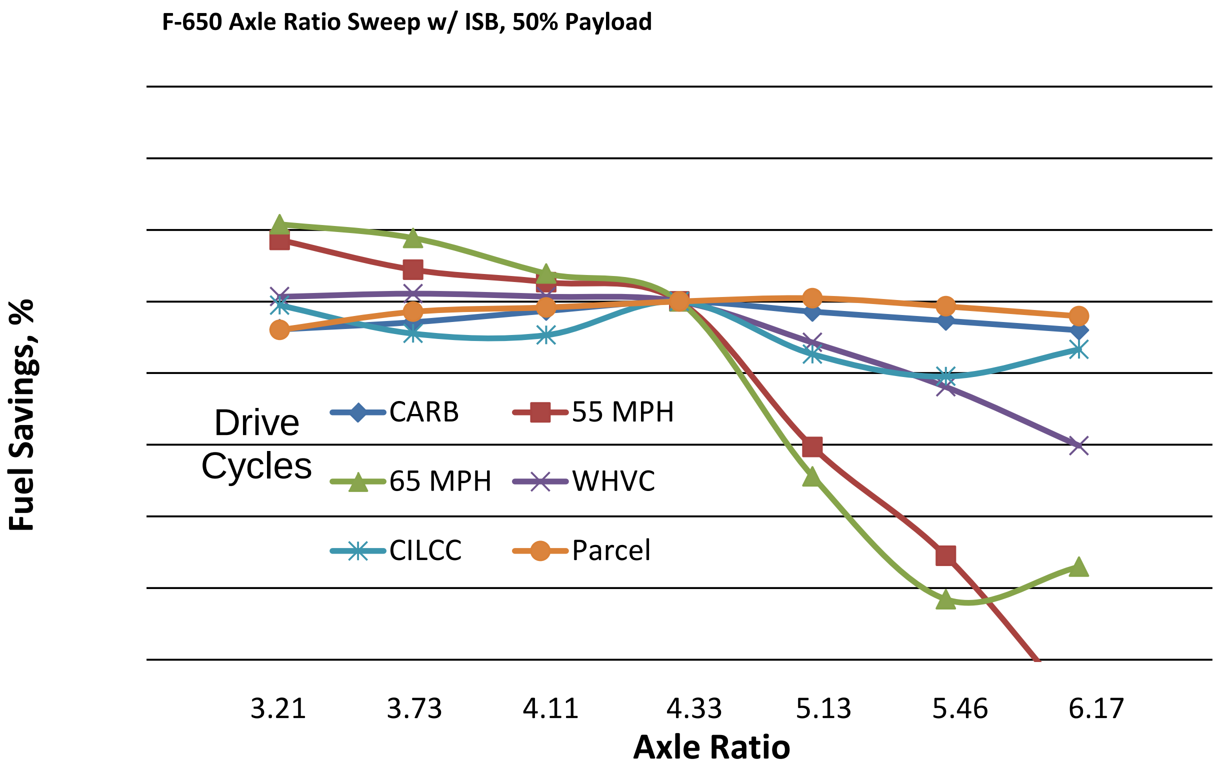

FIGURE 3.10 AXLE RATIO SWEEP ON F-650 WITH THE DIESEL

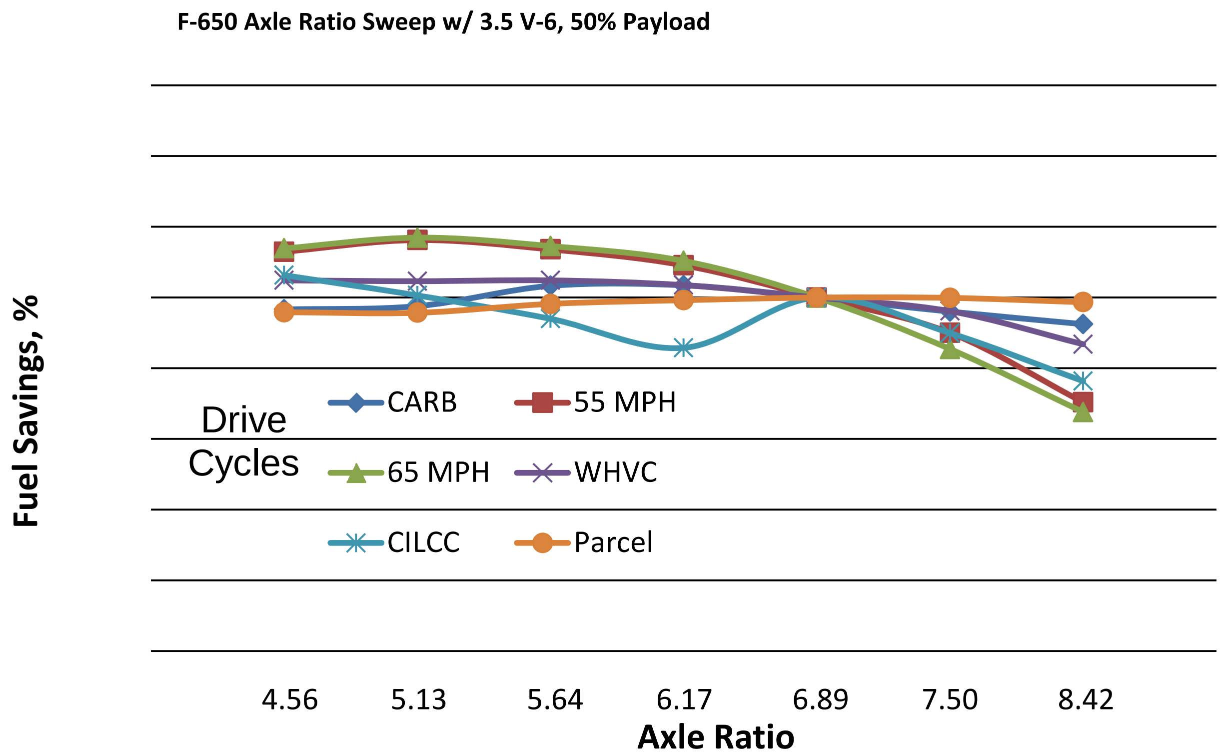

FIGURE 3.11 AXLE RATIO SWEEP ON F-650 WITH THE 3.5 V-6

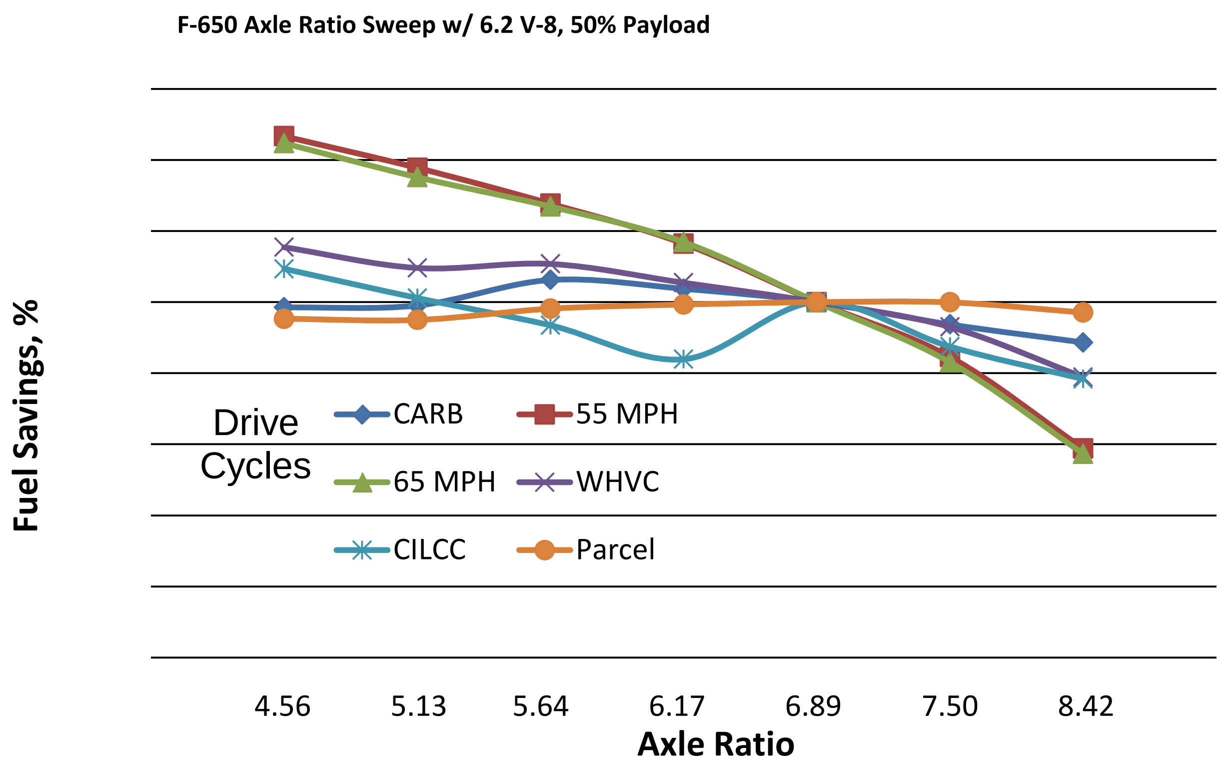

FIGURE 3.12 AXLE RATIO SWEEP ON F-650 WITH THE 6.2 V-8

All engines show similar overall trends. High speed drive cycles, such as the 55 and 65 MPH cruise, are very sensitive to axle ratio. Taller ratios (lower numerical ratios) provide better fuel economy on these high speed cycles. This is because the high speed cycles spend most of their time in top gear. If the axle ratio gets shorter (numerically higher), then engine speed at a given vehicle cruise speed will go up, penalizing fuel consumption.

On the other hand, low speed cycles, such as the CARB, Parcel, and CILCC, are almost completely indifferent to axle ratio. The reason for this is that on low speed cycles, if the axle ratio is made shorter, the transmission will automatically select a higher gear. This cancels the effect of the shorter axle ratio.

The baseline 4.33 axle ratio selected for the F-650 diesel application appears to be near the optimum. Shorter ratios cause a significant increase in fuel consumption on the higher vehicle speed drive cycles, but taller axle ratios offer little benefit. Similarly, the 6.89 axle ratio selected for the V-6 engine also appears to be near the optimum. Note that the V-6 engine is less sensitive to axle ratio than either the diesel or the V-8. The 6.2 V-8 appears to be likely to benefit from a somewhat taller axle ratio than the selected baseline of 6.89. However, a taller axle for the V-8 would mean reduced acceleration and grade capability, as Table 4.2 will show.

Table 3.2 helps explain how axle ratio affects F-650 vehicle performance. As was observed with the Ram pickup, there are two primary impacts from changing the axle ratio. One is that acceleration times, such as zero to 60 MPH times, tend to increase with taller axle ratios. The simulation tool used for this project does not have enough fidelity to accurately predict acceleration times. The other effect is that the ability of the vehicle to climb a grade without downshifting is reduced as the axle ratio gets taller. Other factors that will not be considered here include engine cooling system performance and transmission cooler heat rejection loads. It is possible, however, to predict how much grade a vehicle can go up before a downshift is required.

Table 3.2 shows the range of axle ratios that were evaluated for each engine. The engine speed at 65 MPH in 8th gear is provided in the third column of the table. The next three columns show the maximum grade in top gear at 65 MPH for each axle ratio. Values are provided for the empty truck, the truck at 50% payload (approximately 3,180 pounds of cargo on the bed, but no trailer), and at the full payload of 6,360 pounds. All results were calculated with Vehicle Technology package 12, which includes the 8-speed automatic transmission.

The results in Table 3.2 are color coded. In situations where the transmission has to drop from top gear to 7th gear, the data are shown in red. All black results indicate data for 8th gear. Note that it may be physically possible for the vehicle to run on completely level ground at 65 MPH in 8th gear with the tallest axle ratio, even at 100% payload. The transmission shift schedule does not allow this, however, in order to avoid excessive “hunting”, i.e., up- and down-shifting. Another situation demonstrated in Table 3.2 is the concept of being “Gear Bound”.
This is the situation that arises when the axle ratio is so short that the truck cannot reach 65 MPH within the speed range of the engine. This happens for the F-650 diesel with an axle ratio of 6.17.

The peak torque of the diesel is nearly twice that of the gasoline engines, and this translates into an ability to go up hills or accelerate without needing to downshift. Note, however, that the medium duty diesel has less power and torque than the pickup version of the diesel, so the advantages of the diesel are smaller in the F-650 than in the pickup. At 100% payload, the diesel with the baseline 4.33 axle can climb a 3.7% grade without downshifting. Even with the tallest axle that was simulated (3.21), the diesel can climb a 1.2% grade without downshifting. Note, however, that this performance would be considered inadequate by truck operators.

TABLE 3.1 EFFECT OF F-650 AXLE RATIOS ON GRADE PERFORMANCE

Engine	Axle Ratio	Engine RPM @ 65 MPH	Maximum% Grade in Top Gear @ 65 MPH			Gear @ 65 MPH
			0% Payload	50% Payload	100% Payload	
ISB	3.21	1722	2.0	1.5	1.2	8th
ISB	3.73	1674	4.1	3.3	2.7	8th
ISB	4.11	1844	5.0	4.1	3.4	8th
ISB	4.33	1941	5.5	4.5	3.7	8th
ISB	5.13	2302	7.2	5.8	4.9	8th
ISB	5.64	2531	5.8	4.7	4.0	8th
ISB	6.17	2769	Gear Bound	Gear Bound	Gear Bound	8th
3.5 V-6	4.56	2046	2.4	1.8	1.4	7th
3.5 V-6	5.13	2302	1.7	1.3	1.0	8th
3.5 V-6	5.64	2531	2.3	1.7	1.3	8th
3.5 V-6	6.17	2769	2.9	2.2	1.8	8th
3.5 V-6	6.89	3092	3.9	3.0	2.5	8th
3.5 V-6	7.5	3365	4.7	3.7	3.1	8th
3.5 V-6	8.42	3778	5.6	4.5	3.7	8th
6.2 V-8	4.56	2046	1.6	1.2	1.9	7th
6.2 V-8	5.13	2302	2.4	1.8	1.4	8th
6.2 V-8	5.64	2531	3.0	2.4	2.0	8th
6.2 V-8	6.17	2769	3.7	2.9	2.4	8th
6.2 V-8	6.89	3092	4.6	3.6	3.0	8th
6.2 V-8	7.5	3365	5.3	4.3	3.5	8th
6.2 V-8	8.42	3778	6.7	5.4	4.5	8th

Table 3.2 illustrates another issue that is common to diesel powered vocational trucks, especially trucks meant to operate both on and off-highway such as dump trucks, cement trucks, and refuse haulers. These trucks often use very short axle ratios to get adequate off-road performance on very steep grades and on soft ground. The penalty for these short axle ratios is that the truck is "gear bound". This means that it is unable to reach a high road speed, even at maximum engine speed. The diesel F-650 with the 5.64 axle ratio runs at 2,531 RPM @ 65 MPH, which is just above rated speed. With the shortest axle ratio of 6.17, the engine would run at 2,769 RPM @ 65 MPH, which is near high idle. Since the power available at this engine speed is very low, the vehicle cannot reach 65 MPH on level ground. The reason that gear bound vehicles are sold is that it is expensive to use transmissions with a very wide ratio range. When a wide ratio range is used, the transmission itself gets more complex and expensive. The driveline

and axle also need to be made stronger, to handle a very short (numerically high) first gear ratio. Tall overdrive ratios in a transmission also lead to more expensive drivelines (more, shorter driveshaft sections with more U-joints and carrier bearings, to achieve the required driveshaft speed capability). To achieve adequate off-road performance with a lower cost transmission and driveline, the buyer sacrifices high speed fuel economy.

The gasoline engines achieve acceptable 2.5% (V-6) or 3.0% (V-8) grade capability on the "standard" 6.89 axle ratio. Shorter axle ratios provide improved grade capability, but at the expense of a high speed fuel consumption penalty.

3.5 T270 Axle Ratio Sweep

Figures 3.16 through 3.18 show the effect of an axle ratio sweep on the T270 box delivery truck with all three engines. For the T270, 50% payload represents a payload of 4,430 pounds in the box, but no trailer. 100% payload is 8,860 pounds, again without a trailer.

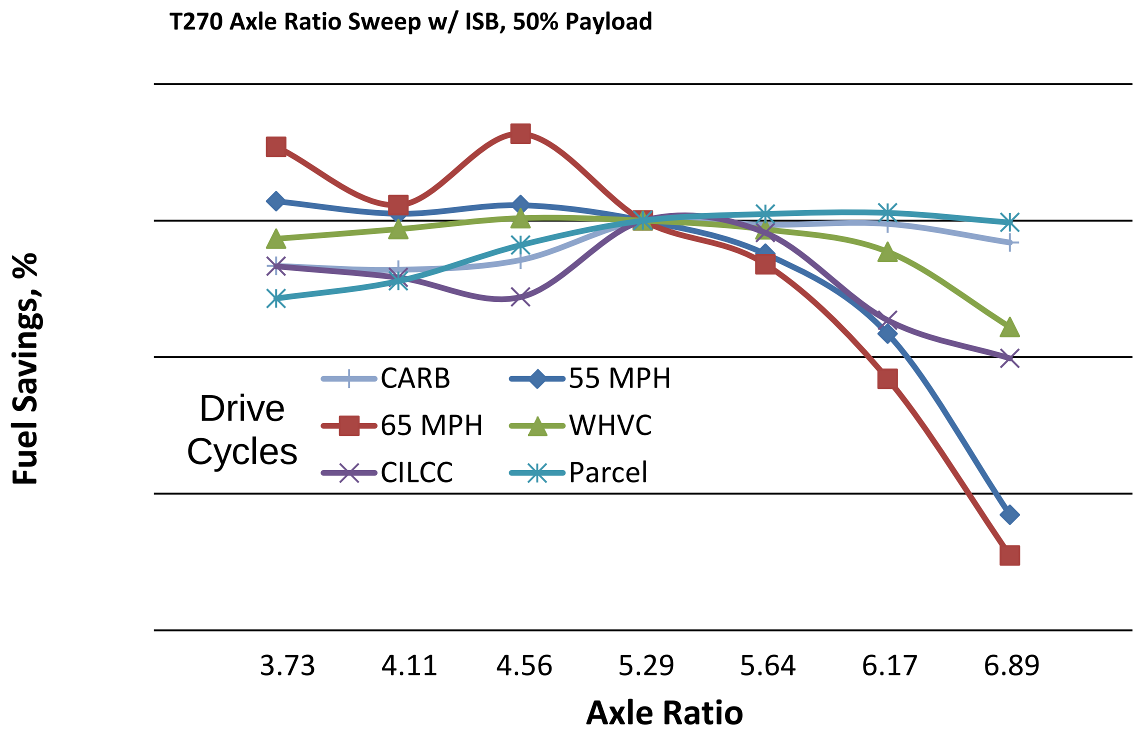

FIGURE 3.13 AXLE RATIO SWEEP ON T270 WITH THE DIESEL

All engines show similar overall trends. High speed drive cycles, such as the 55 and 65 MPH cruise, are very sensitive to axle ratio. Taller ratios (lower numerical ratios) provide better fuel economy on these high speed cycles. This is because the high speed cycles spend most of their time in top gear. If the axle ratio gets shorter (numerically higher), then engine speed at a given vehicle cruise speed will go up, penalizing fuel consumption. Note that unlike the lighter trucks (the Ram and F-650), the fuel savings plots in Figures 4.16 – 4.18 show several non-linear trends. This larger, heavier vehicle imposes higher road load on the engines, so with many of the taller axles, the transmission is running a gear or two down from top gear (8^{th}).

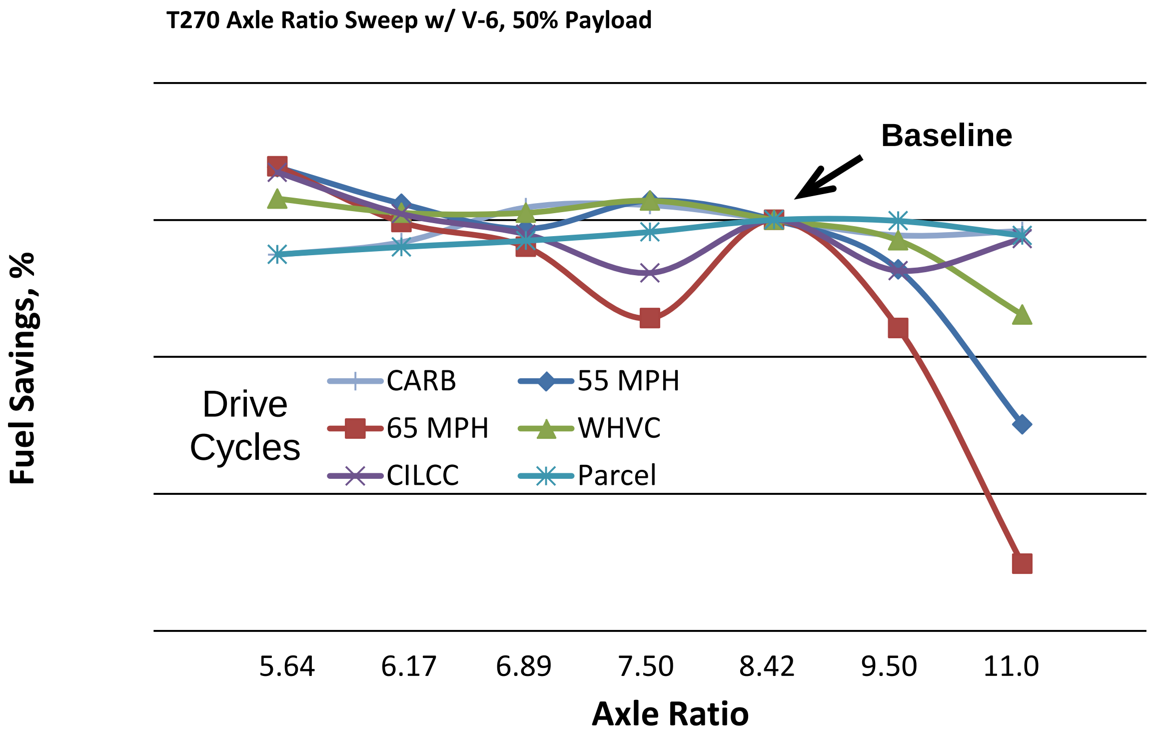

FIGURE 3.14 AXLE RATIO SWEEP ON T270 WITH THE 3.5 V-6

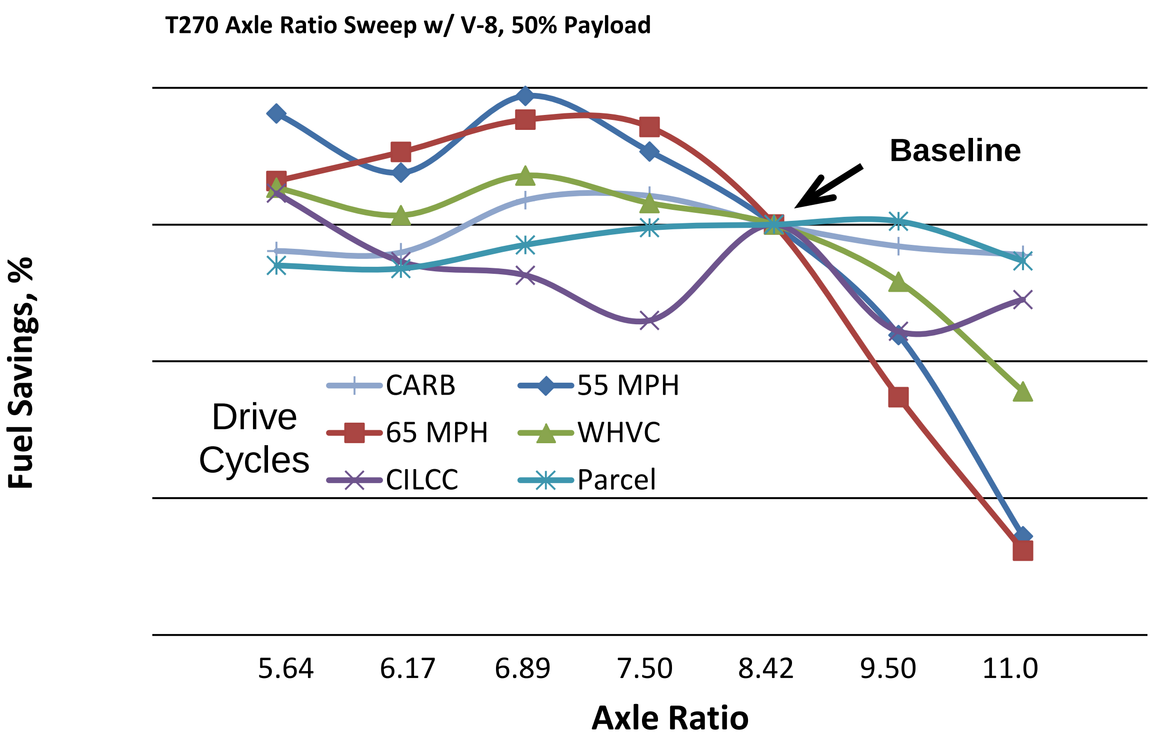

FIGURE 3.15 AXLE RATIO SWEEP ON T270 WITH THE 6.2 V-8

As with the other vehicles, low speed cycles, such as the CARB, Parcel, and CILCC, are almost completely indifferent to axle ratio. The reason for this is that on low speed cycles, if the axle ratio is made shorter, the transmission will automatically select a higher gear. This cancels the effect of the shorter axle ratio. There is more variation from one axle ratio to another, and from one drive cycle to another, with this larger, heavier truck. The CILCC cycle uses a few fixed speeds that the vehicle accelerates to during the cycle. As the axle ratio is changed, the gear achieved in a given steady speed segment of the cycle (such as 15 MPH) changes. As a result, the engine speed at 15 MPH steady state operation fluctuates up and down as the axle ratio sweeps and different gears are selected. This causes fuel consumption to fluctuate from one axle ratio to the next.

The baseline 5.29 axle ratio selected for the T270 diesel application appears to be near the optimum. Shorter ratios cause a significant increase in fuel consumption on the higher speed drive cycles, but taller axle ratios offer little benefit, and penalties on some cycles. Similarly, the 8.42 axle ratio selected for the V-6 engine also appears to be near the optimum. The 6.2 V-8 appears likely to benefit from a somewhat taller axle ratio than the selected baseline of 8.42. However, a taller axle for the V-8 would mean reduced acceleration and grade capability, as Table 3.3 will show. There is also a fuel penalty on the CILCC cycle for a taller axle ratio.

Table 3.3 helps explain how axle ratio affects T270 vehicle performance. There are two primary impacts from changing the axle ratio. One is that acceleration times, such as zero to 60 MPH times, tend to increase with taller axle ratios. The other effect is that the ability of the vehicle to climb a grade without downshifting is reduced as the axle ratio gets taller. Other factors that will not be considered here include engine cooling system performance and transmission cooler heat rejection loads.

Table 3.3 shows the range of axle ratios that were evaluated for each engine. The engine speed at 65 MPH in 8th gear is provided in the third column of the table. The next three columns show the maximum grade in top gear at 65 MPH for each axle ratio. Values are provided for the empty truck, the truck at 50% payload (approximately 4,430 pounds of cargo on the bed, but no trailer), and at the full payload of 8,860 pounds. All results were calculated with Vehicle Technology package 7, which includes the 8-speed automatic transmission.

The results in Table 3.3 are color coded. In situations where the transmission has to drop from top gear to 7th gear, the data are shown in red. In situations where the transmission needs to drop to 6th gear, the data are shown in blue. All black text indicates data for 8th gear. Note that it may be physically possible for the vehicle to run on completely level ground at 65 MPH in 8th gear with axle ratios that run in 7th gear. The transmission shift schedule does not allow this, however, in order to avoid excessive “hunting”, i.e., up- and down-shifting.

As was the case for the F-650, the peak torque of the diesel is much higher than that of the gasoline engines, and this translates into an ability to go up hills or accelerate without needing to downshift. Because the T270 is heavier and has more frontal area than the F-650, the grade capability advantages of the diesel are smaller in the T270. At 100% payload, the diesel with the baseline 5.29 axle can climb a 2.0% grade without downshifting. Note that this is far less than the 3.7% grade capability of the smaller, lighter F-650 with its standard axle ratio. With the tallest axle that was simulated (3.73), the diesel has to run in 7th gear at 65 MPH.

Table 3.3 illustrates another issue that is common to diesel powered vocational trucks, especially trucks meant to operate both on and off-highway such as dump trucks, cement trucks, and refuse haulers. These trucks often use very short axle ratios to get adequate off-road performance on very steep grades and on soft ground. The penalty for these short axle ratios is that the truck is "gear bound". This means that it is unable to reach a high road speed, even at maximum engine speed. The diesel T270 with the 6.89 axle ratio runs at 2,529 RPM @ 65 MPH, which is just above rated speed. As a result, a T270 with this axle ratio would not be able to drive at speeds much over 65 MPH. The reason that gear bound vehicles are sold is that it is expensive to use transmissions with a very wide ratio range. When a wide ratio range is used, the transmission itself gets more complex and expensive. The driveline and axle also need to be made stronger, to handle a very short (numerically high) first gear ratio. Tall overdrive ratios in a transmission also lead to more expensive drivelines (more, shorter driveshaft sections with more U-joints and carrier bearings, to achieve the required driveshaft speed capability).

TABLE 3.2 EFFECT OF T270 AXLE RATIOS ON GRADE PERFORMANCE

Engine	Axle Ratio	Engine RPM @ 65 MPH	Maximum% Grade in Top Gear @ 65 MPH			Gear @ 65 MPH
			0% Payload	50% Payload	100% Payload	
ISB	3.73	1722	2.4	1.7	1.2	7th
ISB	4.11	1508	0.9	2.3	1.8	7th
ISB	4.56	1673	2.2	1.6	1.2	8th
ISB	5.29	1941	3.5	2.6	2.0	8th
ISB	5.64	2070	4.1	3.0	2.4	8th
ISB	6.17	2264	4.8	3.7	3.0	8th
ISB	6.89	2528	3.8	2.9	2.3	8th
3.5 V-6	5.64	2604	2.0	1.4	1.0	6th
3.5 V-6	6.17	2848	1.3	2.0	1.5	6th
3.5 V-6	6.89	3181	2.1	1.4	1.0	7th
3.5 V-6	7.5	2752	1.0	1.9	1.5	7th
3.5 V-6	8.42	3090	1.9	1.3	0.9	8th
3.5 V-6	9.5	3486	2.9	2.1	1.6	8th
3.5 V-6	11	4037	4.0	3.0	2.3	8th
6.2 V-8	5.64	2604	2.6	1.9	1.4	6th
6.2 V-8	6.17	2848	1.8	1.3	0.9	7th
6.2 V-8	6.89	2529	1.2	0.8	1.4	7th
6.2 V-8	7.5	2752	1.8	1.2	0.9	8th
6.2 V-8	8.42	3090	2.6	1.8	1.4	8th
6.2 V-8	9.5	3486	3.6	2.7	2.1	8th
6.2 V-8	11	4037	5.3	4.0	3.2	8th

In achieving adequate off-road performance with a lower cost transmission and driveline, the buyer sacrifices high speed fuel economy. The maximum percent grade results provided for the 6.89 axle ratio are misleading, however. The engine is operating on the governor droop, so the ability to hold 65 MPH is less than for the next taller axle. However, in practice, when a grade is encountered, engine power will increase as road speed drops. Thus, the T270 with the 6.89 axle will actually be able to handle steeper grades without a downshift than with the taller ratio.

The gasoline engines achieve very marginal 0.9% (V-6) or marginal 1.4% (V-8) grade capability with the "standard" 8.42 axle ratio. Shorter axle ratios provide improved grade capability, but at the expense of a high speed fuel consumption penalty. Given the poor grade capability, many purchasers would select a shorter axle ratio than 8.42, to get acceptable acceleration and grade performance with the gasoline engines, especially the V-6. In order to achieve a significant increase in medium truck market share, gasoline engines will need to provide competitive performance, including grade capability. Achieving performance and efficiency parity may be technically feasible, but it will require analysis and development work.

3.6 Ram Pickup Axle Ratio Sweep

Figures 3.10 through 3.12 show the effect of an axle ratio sweep on the Ram pickup with all three engines. For the Ram pickup, ALVW represents a payload of 1,562 pounds in the bed, but no trailer.

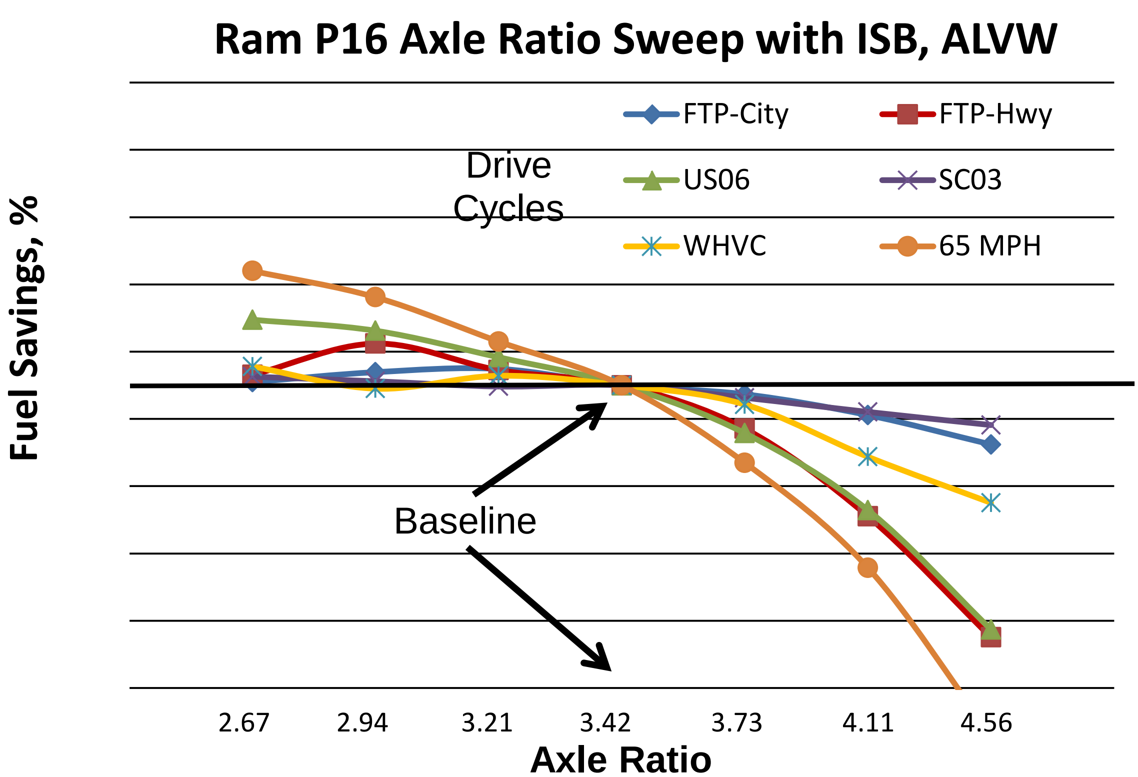

FIGURE 3.16 AXLE RATIO SWEEP ON RAM PICKUP WITH DIESEL

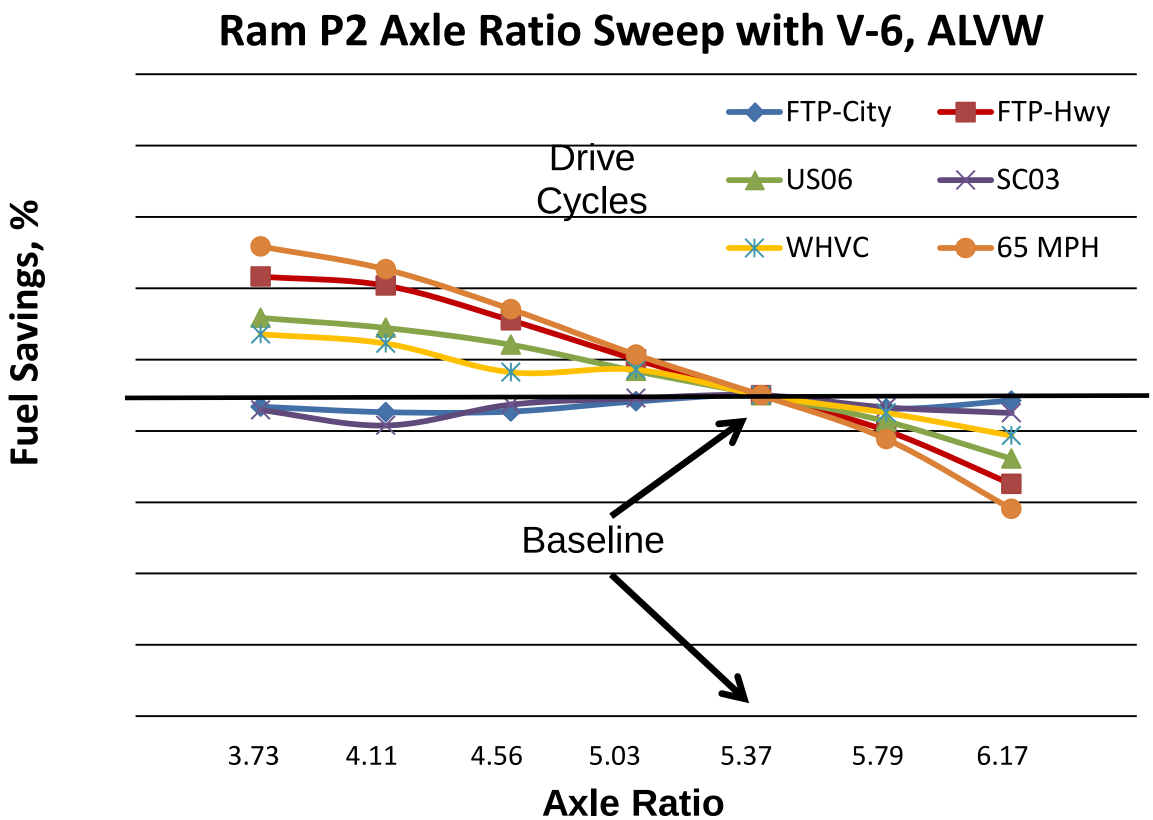

FIGURE 3.17 AXLE RATIO SWEEP ON RAM PICKUP WITH V-6 GASOLINE

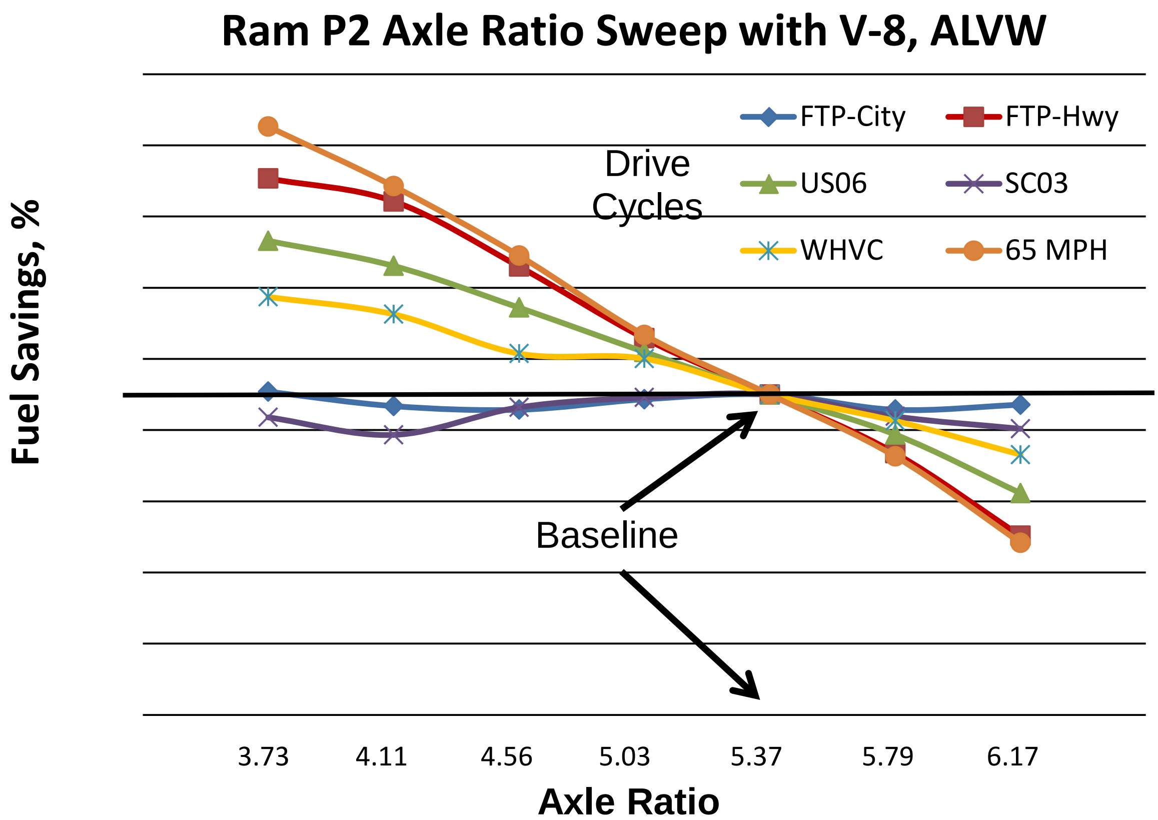

FIGURE 3.18 AXLE RATIO SWEEP ON RAM PICKUP WITH V-8 GASOLINE

All engines show similar overall trends. High speed drive cycles, such as 65 MPH cruise, FTP-Highway, and the US06, are very sensitive to axle ratio. Taller ratios (lower numerical ratios) provide better fuel economy on these high speed cycles. This is because the high speed cycles spend most of their time in top gear. If the axle ratio gets shorter (numerically higher), then engine speed at a given vehicle cruise speed will go up, penalizing fuel consumption.

On the other hand, low speed cycles, such as the FPT-City and SC03, are almost completely indifferent to axle ratio. The reason for this is that on low speed cycles, if the axle ratio is made shorter, the transmission will automatically select a higher gear. This cancels the effect of the shorter axle ratio.

The Ram pickup with a diesel engine is sold with axle ratios from 3.42 to 4.11. The 4.11 axle ratio has a noticeable fuel consumption penalty on higher speed drive cycles. The reason a buyer might select the 4.11 axle is related to vehicle performance when towing heavy loads. The Ram pickup with a gasoline engine is sold with the same range of axle ratios as the diesel: 3.42 to 4.11. However, the gasoline versions have much lower towing capacity than the diesel, so a gasoline axle ratio of 5.37 was chosen in order to achieve roughly comparable towing performance. As Figures 3.11 and 3.12 show, a gasoline engine with a 5.37 axle ratio will have much worse fuel consumption when running lightly loaded than a vehicle with a taller axle ratio. The penalty at 65 MPH is up to 7% for the V-6 engine, and up to 14% for the V-8.

Table 3.3 helps explain how axle ratio affects vehicle performance. There are two primary impacts resulting from changing the axle ratio. One is that acceleration times, such as zero to 60 MPH times, tend to increase with taller axle ratios. The other effect is that the ability of the vehicle to climb a grade without downshifting is reduced as the axle ratio gets taller. Other factors that will not be considered here include engine cooling system performance and transmission cooler heat rejection loads. The vehicle simulation tool used in this study does not provide reliable predictions for 0 – 60 MPH time. This is largely due to the fact that accurate estimates of acceleration time require engine derate information from the manufacturer. Typically, the engine torque curve is reduced in first gear, and often also in 2nd gear. It is possible, however, to predict how much grade a vehicle can tolerate before a downshift is required.

Table 3.3 shows for each engine the range of axle ratios that were evaluated. The engine speed in 8th gear at 65 MPH is provided in the third column of the table. The next three columns show the maximum grade in top gear at 65 MPH for each axle ratio. Values are provided for the empty truck, the truck at ALVW (approximately 1,560 pounds of cargo in the bed, but no trailer), and at the full GCW of 25,000 pounds. All results were calculated with Vehicle Technology package 17, which includes the 8-speed automatic transmission.

TABLE 3.3 EFFECT OF RAM AXLE RATIOS ON GRADE PERFORMANCE

Engine	Axle Ratio	Engine RPM @ 65 MPH	Maximum Percent Grade in Top Gear @ 65 MPH			Gear @ 65 MPH & GCW
			0% Payload	At ALVW	At GCW	
ISB	2.67	1326	5.6	4.3	3.4	7th
ISB	2.94	1460	10.2	8.0	1.4	8th
ISB	3.21	1594	16.0	12.7	3.0	8th
ISB	3.42	1699	18.1	14.4	3.6	8th
ISB	3.73	1853	20.5	16.2	4.2	8th
ISB	4.11	2042	23.1	18.3	4.9	8th
ISB	4.56	2265	26.3	20.8	5.6	8th
3.5 V-6	3.73	1853	5.3	4.0	1.6	6th
3.5 V-6	4.11	2042	6.6	5.0	1.1	7th
3.5 V-6	4.56	2265	7.9	6.0	1.6	7th
3.5 V-6	5.03	2499	9.2	7.1	1.0	8th
3.5 V-6	5.37	2667	10.3	8.0	1.3	8th
3.5 V-6	5.71	2836	11.4	8.8	1.6	8th
3.5 V-6	6.17	3065	13.0	10.1	2.0	8th
6.2 V-8	3.73	1853	6.2	4.7	1.2	7th
6.2 V-8	4.11	2042	7.5	5.8	1.7	7th
6.2 V-8	4.56	2265	9.1	7.1	1.1	8th
6.2 V-8	5.03	2499	10.8	8.4	1.6	8th
6.2 V-8	5.37	2667	11.9	9.3	1.8	8th
6.2 V-8	5.71	2836	13.1	10.2	2.1	8th
6.2 V-8	6.17	3065	14.6	11.4	2.5	8th

The results in Table 3.3 are color coded. In situations where the transmission has to drop from top gear to 7th gear, the data are shown in red. In the one case where the transmission has to drop to 6th gear, the data is shown in blue. All black data indicates that for 8th gear. Note that it may be physically possible for the vehicle to run on completely level ground at 65 MPH in 8th gear with the tallest axle ratio, even at maximum GCW. The transmission shift schedule does not allow this, however, in order to avoid excessive "hunting", i.e., up- and down-shifting.

Table 3.3 illustrates an important reason why diesel engines are popular with pickup truck owners who frequently tow heavy trailers. The peak torque of the diesel is roughly twice that of the gasoline engines, and this translates into an ability to go up hills or accelerate without needing to downshift. To match the grade climbing capability of the diesel, the gasoline engines would need to run at twice the speed of the diesel (to make the same power at 50% of the torque), but this would result in a very large fuel consumption penalty. This fact explains why the highest towing capacities offered by all the volume HD pickup models use a diesel engine.

At the full 25,000 pound GCW, the diesel with the baseline 3.42 axle can go up a 3.6% grade without downshifting. Using the optional 4.11 axle, the diesel can go up a 4.9% grade in top gear. It is only with a very tall axle ratio (2.67) that the diesel cannot maintain speed on level ground in top gear at 65 MPH. In this case, it retains a 3.4% grade capability, but in 7th gear rather than 8th. By contrast, even with the shortest axle ratio evaluated (6.17), the gasoline engines can only manage a 2.0% grade (V-6) or a 2.5% grade (V-8). At the shortest axle ratio offered in production, 4.11, the gasoline engines would need to stay down one gear at 65 MPH, and their grade capability is still only 1.1% (V-6) or 1.7% (V-8).

3.7 Comparison of Parameter Sensitivities

When evaluated at 65 MPH, long haul tractor-trailer trucks typically see about a 5% fuel consumption reduction for a 10% reduction in Cd. The situation for vocational trucks varies with their frontal area. At 65 MPH, the Ram pickup achieves a 3.7% benefit, the F-650 gets a 4.2% fuel savings, and the T270 achieves 5.7%. These values are for the Ram at ALVW payload, and the other trucks at 50% payload. The T270 has by far the largest frontal area of the vocational trucks considered in this report, and is thus most sensitive to Cd changes. Because the T270 has nearly the frontal area of a tractor-trailer, but is much lighter, it is a bit more sensitive to Cd than a tractor-trailer. It is important to keep in mind that few vocational trucks spend a large portion of their time at high road speeds, so overall, the effect of aerodynamics on vocational trucks is likely to be smaller than is the case for tractor-trailers.

Long haul tractor-trailers obtain about a 2.6% fuel savings for a 10% reduction in tire rolling resistance, when tested at 65 MPH and 50% payload. Under the same conditions, the Ram pickup achieves a 1.4% fuel savings at ALVW. At 50% payload, the F-650 gets a 2.3% benefit, and the T270 saves 2.4%. The lighter pickup truck has a smaller sensitivity to rolling resistance. On any vehicle, as payload increases, the fuel savings provided by a reduction in Crr will also increase. On more transient cycles, the effect of tire rolling resistance is lower, but not in the dramatic way that the benefit of aerodynamic drag falls off on transient cycles. For example, on the F-650 at 50% payload, the benefit from a 10% reduction in Cd is 4.2% on the 65 MPH cycle, but only 0.7% on the CARB urban cycle. That same truck saves 2.3% of fuel at 65 MPH for a 10% reduction in Crr, but it still has a 1.9% benefit on the CARB cycle. The lowest benefit for a rolling resistance reduction is on the Parcel cycle, which has frequent rapid accelerations.

The effect of a vehicle empty weight reduction is determined by the change in rolling resistance for a steady speed cycle. In transient cycles, a weight reduction also reduces the power demand required to accelerate the vehicle. Therefore, transient cycles such as the CARB cycle for medium trucks and the US06 cycle for pickups show the greatest benefits for a vehicle weight reduction. The three vehicles evaluated in this project show similar sensitivities to weight reductions. A 10% weight reduction provides fuel savings of 2.3% to 3.6% for the pickup truck, depending on drive cycle, 1.7% to 3.6% for the F-650, and 2.1% to 4.0% for the T270. All of these results are for ALVW (pickup) or 50% payload. As payload increases, the effect of an empty weight reduction diminished in percent terms, but the absolute fuel savings in gallons is generally independent of payload.

The selection of axle ratio depends on many factors. A short (numerically high) axle ratio provides better acceleration and better grade climbing capability. A short axle ratio also involves a fuel consumption penalty for high speed driving cycles. This fuel penalty with a short axle tends to be larger for the diesel engine and the 6.2 V-8 engine than it is for the small 3.5 liter V-6. A very short axle, combined with the narrow speed range of a diesel engine, can lead to a situation where the top speed of the truck is limited by maximum engine speed rather than by vehicle power demand. This situation is known as being “gear bound”.

Excessively tall (numerically low) axle ratios often require the transmission to downshift to put sufficient power to the wheels at cruising speed, so the fuel consumption advantage is small or even negative in most cases. The performance (acceleration and grade capability) penalties of a tall axle are significant. However, the 6.2 V-8 sees continuing fuel savings as the axle ratio is made taller, except in the largest truck, the T270. The result is that with a conventional gasoline V-8, there is a sharp trade-off between high towing capacity (which requires a short axle) and fuel economy (which requires a tall axle).

4.0 VOCATIONAL TRUCK FUEL CONSUMPTION AND PERFORMANCE

Results presented in the previous sections can be used to review the effect of vehicle specifications on vocational truck fuel consumption and performance.

4.1 Diesel vs. Gasoline

Fifty years ago, gasoline engines were almost universal in vocational trucks. In the 1980s, diesel engines rapidly gained market share, driven primarily by two factors: lower fuel cost (both fuel consumption and fuel price), and greater durability of diesel engines compared to the available gasoline engines. Today, Class 4 – 7 trucks are about 92% diesel powered [Polk], and Class 8 vocational trucks are 100% diesel powered. Ford is the only volume manufacturer offering gasoline powered trucks in Classes 4 – 7. The 6.8 liter V-10 used by Ford in these trucks is a derivative of an old engine that was originally designed for use in pickup trucks and vans, but which is no longer used in pickup trucks.

There are several reasons why the market share of gasoline engines in vocational trucks could start increasing again in the future. These include:

- The large price differential between gasoline engines, with inexpensive 3-way catalysts, and diesel engines with DOC+DPF+SCR.
- The price differential between gasoline and diesel fuel
- There are technologies on the horizon which reduce the fuel consumption penalty for gasoline engines
- Technology is available to reduce the gap in durability between gasoline and diesel engines
- Diesel engines, with their higher torque and narrow speed range, require more expensive transmissions than gasoline engines do

On December 30, 2014, the Ford commercial truck web site showed a price increase of $10,965 for an F-650 Pro Loader XL with a diesel engine, compared to the same truck with a gasoline engine. There are similar price differences for other Ford trucks that are available with both gasoline and diesel engines. This large price differential is driven by the higher aftertreatment cost for a diesel engine, higher fuel system cost for the diesel (high pressure common rail for the diesel vs. port injection for the gasoline engine), higher base engine cost for the diesel, and a more expensive transmission that is required with the diesel.

According to data from the eia.gov web site, diesel fuel averaged 4.3 cents per gallon cheaper than gasoline from March 1994 (the beginning of their data series) through September 2005. From October 2005 through December 2014, diesel averaged 23.8 cents higher than gasoline. For 2014, diesel averaged 37 cents more than gasoline, and at the end of December 2014, diesel had reached 82 cents higher than gasoline, and the largest price gap in the 20 year data series. Figure 4.1 shows the cost differences between gasoline and diesel over the last 20 years, using US Energy Administration data. The recent trend towards a volatile but increasing cost disadvantage of diesel fuel is driven by worldwide demand trends. Demand for diesel has been growing faster than demand for gasoline, which has tended to drive up the cost of diesel vs. gasoline.

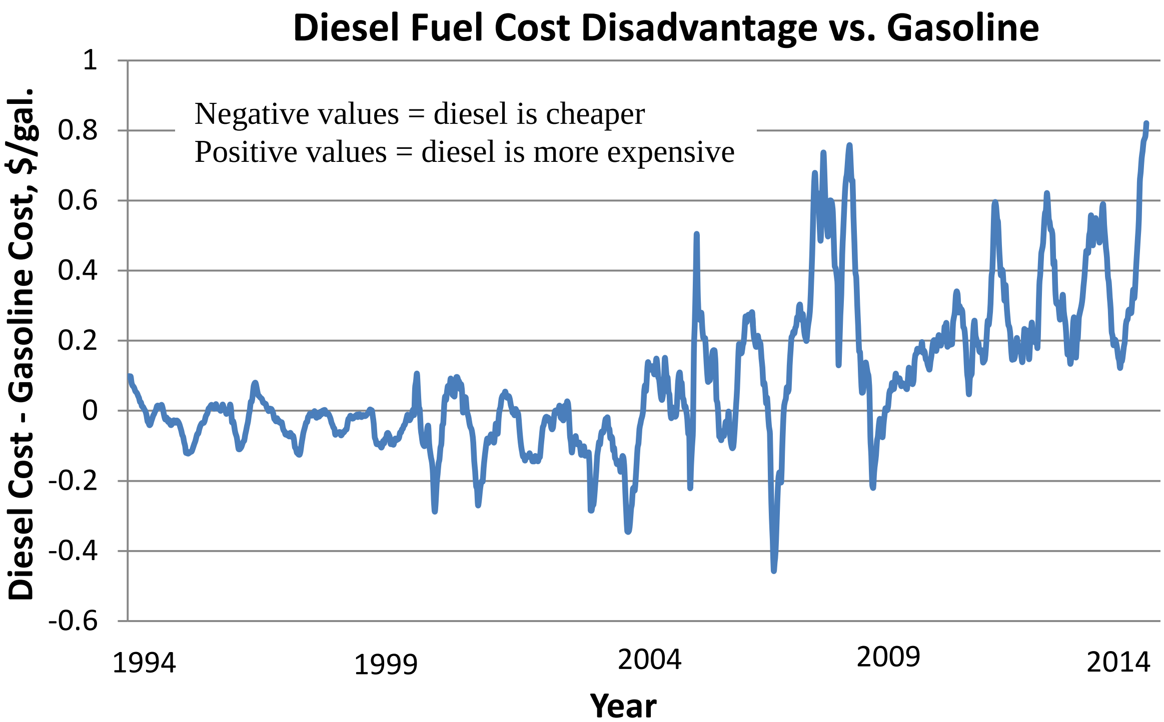

FIGURE 4.1 COST DIFFERENCES BETWEEN DIESEL FUEL AND GASOLINE

Table 4.1 below shows the fuel consumption penalty for gasoline engines in the T270 delivery truck. The engines compared are the 2019 baseline diesel, the Package 16 V-6 (EGR + VVA), the Package 20 V-8 (GDI + Cylinder Deactivation + EGR + 10% FMEP Reduction), and the baseline V-8. The percent fuel consumption penalty is shown for each gasoline engine on all six drive cycles, as well as an average penalty calculated from the six drive cycles. All results are for the T270 box delivery truck at 50% payload.

TABLE 4.1 FUEL CONSUMPTION PENALTIES OF FUTURE GASOLINE TECHNOLOGIES IN THE T270

Engine	Percent Fuel Consumption Penalty @ 50% Payload						
	CARB	55 MPH	65 MPH	WHVC	CILCC	Parcel	Average
2019 ISB	Base	Base	Base	Base	Base	Base	Base
3.5 V-6 P16	10%	20%	18%	13%	3.7%	5.1%	12%
6.2 V-8 P20	19%	25%	22%	20%	14%	14%	19%
V-8 Base	31%	34%	36%	30%	28%	23%	31%

Table 4.1 shows that for the T270 delivery truck, the average fuel consumption penalty for a downsized and boosted gasoline engine with EGR and VVA is less than 12%, compared to a 2019 diesel baseline. The fuel consumption penalty for a naturally aspirated V-8 is about 19%,

even when a wide range of technologies are applied. For the conventional baseline V-8, the penalty is over 30%. The advantage for the small, boosted V-6 can be tracked to the difference in displacement. For a given road load, the small engine runs at a higher BMEP. When the road load is relatively low, an increase in BMEP moves the engine into a much more efficient portion of the operating map. This drives lower fuel consumption over the drive cycle. Note that the results shown in Table 4.1 compare gasoline engine fuel consumption in gallons against a reference of diesel consumption in gallons. In Section 2, results for each gasoline engine technology package was compared to the baseline consumption for that particular engine. Thus, the results shown here are different from the results in Section 2.

The values from Table 4.1 can be combined with assumptions about future fuel price differentials and engine price differentials to calculate payback times for different engine options. The following assumptions will be used:

- Price difference between advanced gasoline engine and 2019 diesel: $9,000
  - Current upcharge for diesel engine in Ford F-650: $10,965
  - Estimated cost of high efficiency, durable gasoline vs. conventional: $1,965
- Fuel consumption difference between engines: average of simulated drive cycles
- Annual driving distance: 13,116 miles [12]
- Baseline T270 fuel consumption with V-6 P16 engine: 13.7 gallons per 100 miles (7.3 mpg)
- Gasoline prices of $2, $3, $4, and $5 per gallon
- No interest rates or discount rates are applied

Given the assumptions above, Table 4.2 shows potential payback times over a range of diesel vs. gasoline price differences. These results are for simple payback with no discount rate. The payback time is calculated by determining the annual fuel cost for both the diesel and gasoline options. The assumed price for a diesel upgrade ($9,000) is divided by the difference in annual cost for diesel fuel and gasoline to determine the payback time in years. The second column in Table 4.2 shows payback times for the case where diesel fuel is 25 cents cheaper than gasoline, while the 6th column gives payback times for the case where diesel fuel is 75 cents higher than gasoline (roughly the December 2014 price situation). Payback times greater than 20 years are labeled ">Life" in Table 4.2 to indicate times longer than the expected vehicle life.

Results in Table 4.2 show that the payback time for upgrading from gasoline to diesel power depends very strongly on three factors:

- The fuel consumption difference between engine options
- The price of fuel
- The price difference between gasoline and diesel

Payback times for upgrading from a conventional V-8 engine with current technology to the 2019 diesel are short, unless gasoline prices are low and/or the price of diesel is equal to or less than the price of gasoline. This illustrates the reason for the historical shift from gasoline to diesel power, even with the high cost of modern diesels with aftertreatment.

TABLE 4.2 PAYBACK TIMES FOR THE 2019 BASELINE DIESEL ENGINE OVER ADVANCED TECHNOLOGY GASOLINE ENGINES IN THE T270

Engine	Payback Time for Diesel vs. Fuel Cost Difference, Years					Gasoline Price, $/Gal
	-25 Cents	0 Delta	+ 25 Cents	+50 Cents	+75 Cents	
V-6 P16	12	>Life	Never	Never	Never	$2
V-8 P20	9.5	16	>Life	Never	Never	$2
Base V8	5.8	8.1	14	>Life	Never	$2
V-6 P16	9.3	16	>Life	Never	Never	$3
V-8 P20	7.2	11	19	>Life	Never	$3
Base V8	4.3	5.5	7.5	12	>Life	$3
V-6 P16	7.8	12	>Life	Never	Never	$4
V-8 P20	5.9	7.8	12	>Life	>Life	$4
Base V8	3.4	4.1	5.2	7.0	11	$4
V-6 P16	6.7	9.7	17	>Life	Never	$5
V-8 P20	5.0	6.3	8.6	13	>Life	$5
Base V8	2.8	3.3	3.9	4.9	6.4	$5

Payback times are significantly shorter for upgrading from the P20 V-8 to a diesel, since the P20 V-8 has over 7% higher fuel consumption than the P16 V-6. Payback times also come down rapidly as the price of fuel goes up. Doubling the fuel price cuts payback time in half when fuel prices are at parity. Payback time is very dependent on the price difference between gasoline and diesel fuel. At a fuel price of $2 per gallon and with diesel and gasoline prices identical, the payback time for a diesel powered vehicle compared to the V-6 is 24 years, greater than the total vehicle lifetime. Even at $4 per gallon for both fuels, the payback time for diesel over the P16 V-6 is 12 years. Most purchasers would probably buy the V-6 gasoline version if they anticipate gasoline prices of $5 or less (assuming fuel price parity), unless there are other compelling reasons (such as performance or durability) that also come into the decision. Another significant factor in determining payback time is annual vehicle miles traveled. The assumption of 13,116 miles per year comes from the FHWA estimated average VMT for straight trucks in 2013. If VMT doubles, the payback times would be half as long. Note that higher VMT will have no effect on situations where the payback is “Never”. In these cases, the gasoline engine will always have a lower annual fuel cost than the diesel.

From Table 4.2 it can be concluded that if diesel prices average 24 cents per gallon higher than gasoline prices (the average over the last 9 years), there is a powerful case to be made for vocational trucks switching to new technology gasoline engines, even if gasoline prices go to $5 per gallon. At the 2014 average price penalty of 37 cents per gallon for diesel, the case for gasoline engines becomes overwhelming. Note that this change will not occur overnight, because all-new or extensively revised engines would be required to achieve good fuel consumption and durability in a gasoline platform.

4.2 Vehicle Power Demand

As in any vehicle class, vehicle power demand has a large influence on fuel consumption. A 10% reduction in power demand will typically result in a fuel savings approaching 10%. However, reducing power demand often causes the engine to run at a slightly less efficient point on its fuel map, so the fuel savings is often slightly lower than the reduction in power demand would suggest.

The total potential for vehicle power demand reduction in vocational vehicles appears to be less than that found in Section 2 for tractor-trailer vehicles. There are several reasons for this:

- Vocational vehicle power demand tends to be less sensitive to Cd, because of smaller frontal areas
- Vocational vehicles often have drive cycles with less high speed operation, which reduces the sensitivity of fuel consumption to changes in Cd
- Improving the Cd of vocational vehicles is a big challenge, since there are a huge variety of body types, many of which are dictated by the truck's function. Addressing aerodynamics of the full range of vocational vehicles is likely to prove cost-prohibitive
- Vocational vehicles tend to operate on duty cycles where tire rolling resistance is a smaller portion of vehicle power demand than in long-haul applications
- The annual fuel consumption of vocational vehicles tends to be much lower than tractor-trailer trucks, primarily driven by lower VMT. This means that vocational trucks cannot support as much expense for fuel saving technologies

Many vocational vehicles have engine-driven accessories, such as the hydraulic pumps used on dump trucks and cement mixers. Engine cooling fans may have a high run time, driven by air conditioner use. These are examples of areas where additional vehicle power demand reduction can be achieved. The question will be: what level of technology is cost-effective in vocational vehicles? Because of the much lower average VMT of vocational trucks, the cost-effectiveness barrier is much more of a challenge for vocational vehicles.

4.3 Weight and Gearing

Section 3.3 addresses the sensitivity of vocational vehicle fuel consumption to changes in empty weight. The sensitivity is there, but it is not very strong. Given the relatively low VMT of most vocational trucks, only limited weight reduction efforts will be cost-effective.

Results presented in Sections 3.5 and 3.6 show the sensitivity of vocational vehicles to changes in axle ratio. These results make it clear that there is value in matching vocational truck gearing to the intended duty cycle. One unique area that deserves additional research is the issue of gear-bound trucks. These trucks require a very low (numerically high) first gear ratio, in order to achieve good off-road performance. Combining a very low first gear ratio with an efficient high speed cruise ratio introduces engineering challenges and additional costs. Additional research could determine what the potential fuel savings and costs would be, and what cost-effective improvements are possible.

4.4 Start-Stop

This technology has not been evaluated in this study. However, vocational trucks with drive cycles involving frequent stops could benefit significantly from start-stop systems. Start/stop systems have more limited potential benefits than hybrids, but the cost, complexity, and weight is far less than that of full hybrids. Start/stop technology is spreading in light duty applications, which should pave the way for applications on larger vehicles. Hybrid system results are discussed in Section 2.3.11.

5.0 NATURAL GAS VEHICLE COST SURVEY

Natural gas has become a widely discussed and occasionally implemented alternative fuel for on-highway vehicles. Natural gas has been fairly successful in the transit bus market, where central fueling eliminates issues regarding finding fuel on the road, and where there is political pressure for a cleaner fuel with lower GHG impact. Natural gas engines had a substantial edge in criteria emissions until 2010 requirements made diesel and natural gas criteria emissions similar. Natural gas retains a GHG advantage. In the truck market, however, natural gas has so far not been able to gain a market share beyond about two percent. Because of new techniques such as fracking for accessing previously uneconomic reserves of natural gas, natural gas prices in the United States have been well below prices for petroleum based fuels for several years, on a cost per unit of energy basis. There are two potential attractions for natural gas as an on-highway fuel:

- The fuel price is lower than that of gasoline or diesel fuel
- The lower carbon content of natural gas can lead to lower GHG emissions

From an extremely low base, the market share of natural gas in medium- and heavy-duty vehicles has climbed rapidly in the past couple of years. The overall share of natural gas vehicles in medium and heavy duty is still only about 2% for 2014 [Frost & Sullivan Powertrain Technology Forecast], but the natural gas share is much higher in certain applications such as transit bus and refuse haulers.

Three main factors have driven the recent increase in natural gas market share. Government subsidies are offered for natural gas vehicles in many markets, in an effort to achieve reductions in GHG emissions, criteria pollutant emissions, and petroleum use. The difference in fuel prices between diesel fuel and natural gas is another, even larger market driver. Third, some municipalities require that a certain percentage of vehicles such as transit buses and refuse haulers be powered by natural gas. Natural gas is used in one of two forms for transportation: compressed natural gas (CNG), or refrigerated, liquefied natural gas (LNG), with CNG being by far the most common. Balancing the subsidies and lower fuel cost for natural gas, there are some significant costs associated with conversion to natural gas. Some of the issues facing buyers of natural gas vehicles include:

- Lower density fuel = shorter range and/or much larger fuel tanks
- Higher vehicle empty weight and potentially impaired aerodynamics due to larger fuel tanks
- Limited availability of natural gas in some areas
- Higher vehicle prices, driven both by natural gas engines and fuel storage systems
- Need for parts and training to support the servicing of natural gas vehicles
- Need for service shops to be equipped to safely handle natural gas vehicles
- Very long fill time required to use full tank capacity (CNG)
- Extensive personal protective equipment and careful fill procedures required (LNG)
- Potential safety issues with underground and tunnel operations, where a fuel leak could lead to an explosion

5.1 Natural Gas Basics

Natural gas is currently sold on an energy equivalency basis. Compressed natural gas is typically sold either in gasoline gallon equivalent units (GGE), or diesel gallon equivalent units (DGE). Liquefied natural gas is normally sold in DGE. There is currently no standard specifying how natural gas is to be sold as a transportation fuel. There are some concepts for alternatives to the gallon equivalent units, such as selling gas by energy content units or by mass.

Compressed natural gas is normally stored at 3,000 to 3,600 PSI (20.5 to 25 mPa). To hold the energy equivalent of 10 gallons of gasoline, approximately 40 gallons of CNG compressed to 3,600 PSI (250 bar) is required. Thus, a 40 gallon CNG tank contains less energy than 9 gallons of diesel. The need for large, high pressure tanks drives very high tank empty weight for CNG, compared to gasoline or diesel. LNG is stored as a liquid refrigerated at about minus 260°F (-162°C). To provide the same energy content as 10 gallons of diesel, an 18 gallon LNG tank volume is needed. LNG thus has an advantage over CNG in terms of energy density, but both forms of gas suffer in comparison to the energy density of gasoline and diesel fuel, and both require a far more sophisticated storage tank. LNG typically costs more at the pump than CNG, and LNG tanks need to vent methane to the atmosphere if the vehicle is not driven for several days.

The type and size of the refueling station that is available determines how quickly a vehicle can be fueled, and how many vehicles can be refueled at one location. The Department of Energy has a report that describes fueling infrastructure costs and capabilities [11].

Rating the storage capacity of a CNG tank is not straightforward. The vehicle can’t run if the pressure drops below a certain point (generally 50 PSI or more), so the last bit of gas in a tank can’t be used. Also, if a CNG tank is filled rapidly, usable capacity is reduced by about 20%. Only a slow (typically overnight) fill will get the tank to full capacity. This issue is caused by thermal expansion. As compressed gas flows into a tank, it warms up and expands, reducing the energy content per unit volume. After the rapid fill is complete, the gas cools down, losing pressure. A slow fill happens at nearly constant temperature, so a loss in fuel density does not occur, and thus a loss of energy capacity does not occur. The capacity loss that occurs with rapid fill means that some users complain of shorter than expected range.

The Natural Gas Vehicles for America web site [10] offers a calculator that shows how much fuel storage can be achieved under different fueling conditions for a nominal 20 gasoline gallon equivalent CNG tank. The data is summarized in Table 5.1. Note that the nominal capacity cannot be achieved under any of the fueling conditions listed. There is also substantial fuel capacity degradation at high ambient temperatures.

TABLE 5.1 ACTUAL STORAGE CAPACITY OF A NOMINAL 20 GGE CNG TANK

Fill Type	GGE Capacity @ Fill Temperature		
	0° F	70° F	100° F
Fast Fill	16.0 Gal.	15.5 Gal.	14.0 Gal.
Time Fill	18.6 Gal.	18.0 Gal.	17.0 Gal.

LNG is available under two specifications. Blue Label (LNG-3) is slightly colder, to achieve a lower vapor pressure of the gas. LNG-3 is stored at 45 PSI or less, and with a proper tank, up to 10 days of hold time in a vehicle tank is possible before fuel venting is required. Because storage pressure is lower than the minimum pressure required by the engine, LNG-3 requires a cryogenic liquid fuel pump in the tank to deliver liquid fuel up to the engine fuel system. Green Label (LNG-7) is slightly warmer. It is stored at 100 PSI, and a proper tank can hold out for up to five days before venting methane to the atmosphere. LNG-7 is meant for use with spark ignited natural gas engines, which do not have a cryogenic pump in the tank. Some LNG facilities offer both types of LNG, but all facilities offer LNG-7, ensuring fuel delivery to the engine regardless of whether a pump is present in the tank or not. If LNG-7 is used in a truck with a cryogenic pump, there will be some sacrifice in hold time and range.

The figures below show examples of natural gas storage systems. Figure 5.1 shows a day cab tractor with a 40 gallon DGE compressed natural gas tank, mounted in the same location typically used for diesel tanks. Note that the CNG tank is quite large. A diesel tank mounted in this location would typically hold 75 or 100 gallons, but the CNG tank is much larger than a 100 gallon diesel tank, despite the 40 gallon DGE capacity. For vehicles requiring longer range, a different approach to natural gas storage is typically required.

Figure 5.2 shows a combination CNG storage system manufactured by a company called Agility. There is a back-of-cab mounted CNG storage system which holds 100 DGE, plus a 40 gallon DGE side-mount CNG tank. The two tanks together provide an estimated range of up to 600 miles. Note that the truck wheelbase must be increased to accommodate the back-of-cab CNG storage unit, which also increases vehicle weight and reduces maneuverability. The following tank weight information is provided by the manufacturer:

FIGURE 5.1 A 40 DGE COMPRESSED NATURAL GAS TANK INSTALLATION ON A DAY CAB TRACTOR

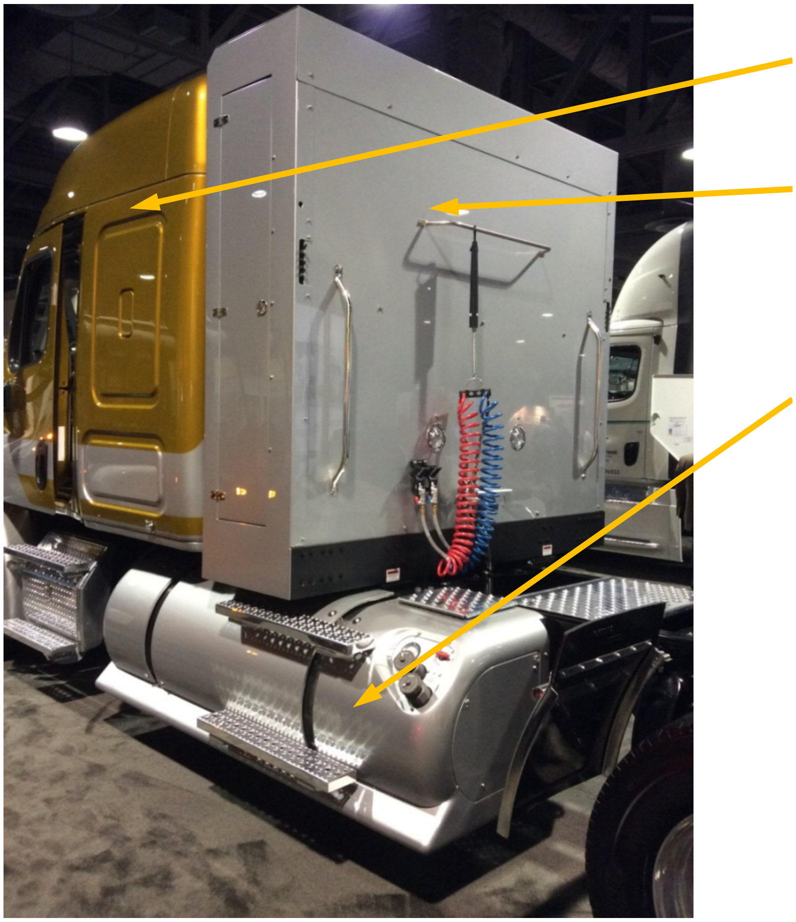

FIGURE 5.2 A 100 DGE BACK OF CAB SYSTEM, COMBINED WITH A 40 DGE SIDE MOUNT SYSTEM, ON A SLEEPER CAB TRACTOR

The CNG system suffers a weight penalty of 2,100 pounds with full tanks, and 2,358 pounds with empty tanks, not including the extra weight that will result from the increased wheelbase of the truck. The weight penalty for CNG is higher with empty tanks, because natural gas is lighter than an equivalent amount of energy in diesel fuel. The high weight of the CNG system is primarily due to a need to contain very high pressure gas, even in a crash situation. The full CNG system weighs 2.6 times more than a full diesel tank with equal energy content.

FIGURE 5.3 A 123 DGE CNG TANK, MOUNTED ON A DAY CAB TRACTOR

Another issue with large natural gas storage units can be aerodynamic drag. Figure 5.3 shows a back-of-cab system on a day cab tractor. In addition to requiring a longer wheelbase and added weight, this system penalizes vehicle aerodynamics.

Figure 5.4 below shows two examples of LNG storage systems. The system in the upper photo is produced by Westport, while the system in the lower photo is produced by Chart. The Chart system has a volume of 158 gallons, allowing a net storage of 135 gallons of LNG, plus space for gas. This represents the equivalent of 75 gallons of diesel. The Chart tank weighs 635 pounds empty and 1,108 pounds full, compared to a full 75 gallon tank of diesel at 712 pounds. The size and weight penalty of LNG systems is less than that of CNG systems, but there is a need for cryogenic liquid natural gas, and the risk of venting gas if the fuel is not used quickly enough. LNG refueling also requires extensive personal protective equipment and a careful fill procedure.

Tables 5.2 and 5.3 provide a weight comparison of various CNG and LNG tank systems to SwRI estimated weights for diesel tanks carrying an equivalent amount of energy. When full, CNG tanks weigh 50 – 90% more than LNG tanks. CNG tanks require more vehicle space, which can drive up vehicle length and weight. LNG tanks in turn are about 46% heavier than diesel for the same energy capacity. CNG tanks run 2.1 to 2.6 times heavier than diesel tanks, for the same energy capacity.

TABLE 5.2 COMPARISON OF AGILITY CNG AND DIESEL TANK WEIGHTS

Parameter	Back of Cab System	Side Mount System	140 Gal. Diesel Tank (SwRI est.)
Empty weight	2,100 pounds	578 pounds	320 pounds
Weight with fuel	2,600 pounds	820 pounds	1,320 pounds
Total system weight	3,420 pounds		1,320 pounds

FIGURE 5.4 EXAMPLES OF LNG STORAGE TANKS

TABLE 5.3 COMPARISON OF CNG, LNG, AND DIESEL TANK WEIGHTS

DGE	Type	Empty Weight (lbs)	Full Weight (lbs)
40	**CNG**	578	820
40	**LNG**	320	550
40	**Diesel**	100	386
63	**CNG**	752	1100
65	**LNG**	505	885
75	**CNG**	1650	2085
80	**LNG**	640	1100
80	**Diesel**	180	752
116	**CNG**	2080	2750
130	**LNG**	1010	1770
160	**LNG**	1230	2130
160	**Diesel**	360	1464

5.2 Current Natural Gas Engine and Vehicle Availability

A range of engines is available for natural gas applications. Engines require a natural gas fuel system and other modifications to ensure durability with natural gas operation. Table 5.4 shows the engine offerings.

TABLE 5.4 NATURAL GAS ENGINE OFFERINGS

Vehicle Class	Engine Offerings	Typical Applications
2a, 2b, 3,	GM 6.0 V-8, Ford 3.7 V-6, and 6.2 V-8, Ram 5.7 V-8	Pickup trucks, cab/chassis pickups, vans, cutaway vans
4, 5, 6, 7	Ford 6.8 V-10 Possible 2015 Cummins ISB6.7-G	Delivery trucks, utility service trucks, vocational trucks
7,8	Westport Cummins ISL-G 8.9	Vocational trucks, transit bus, local delivery tractors
8	Westport Cummins ISX12-G	Regional haul tractors, heavy vocational trucks
8	No 13 or 15 liter option at this time	Long haul tractors

Engines offered in Classes 2 and 3 are typically derivatives of gasoline engines. Typical conversion parts for natural gas operation include hardened valves and seats, specially coated piston rings, a bi-fuel or natural gas intake manifold, and ECM programming for either bi-fuel (gasoline and natural gas) or NG operation. Ford offers a naturally aspirated V-10 natural gas conversion of a gasoline engine for Class 4 – 7 trucks. No other manufacturer has a natural gas engine in these vehicle classes. There is a gap in the market for a durable, diesel-based natural gas engine suitable for Class 5 through 7 vehicles, such as delivery trucks, shuttle busses, and service trucks. As of December 2014, Cummins is still planning to launch a spark ignited, stoichiometric natural gas version of their 6.7 liter diesel engine for this market in 2015.

Westport had offered a 15 liter Cummins-based engine with diesel pilot ignition and direct natural gas injection, called the HPDI fuel system. For 2010 emissions, this engine required the full diesel aftertreatment system (DOC + DPF + SCR), even though about 95% of the fuel burned was natural gas. The high cost of this engine led to its withdrawal from the market in late 2013. Cummins had planned a lower cost, spark ignited stoichiometric version of their 15 liter engine, but this engine was put on hold in 2014 due to uncertain market conditions. Volvo had planned a 13 liter engine using a new generation of the Westport HPDI fuel system, but this was also put on hold in October 2014. As a result, there is no long haul natural gas engine option, although the Cummins 12 liter engine can potentially be stretched to fill the role, with some possible sacrifices in reliability and durability.

A fairly broad range of Class 2a - 4 vehicles are available with natural gas, as of December 2014. GM offers both cargo and passenger versions of its Express Van 2500 and 3500 (Class 2b and 3) as well as the 2500 HD pickup (Class 2b). GM’s natural gas systems are installed by IMPCO Automotive. Ford offers pickup trucks ranging from the F-150 (Class 2a) to the F-450/550 Chassis Cab (Class 4 and 5) and the Class 5 – 7 F-650 and F-750. Ford also offers the Class 2b Transit van. Ford’s natural gas systems are installed by Westport and Altech-Eco. Chrysler offers the Ram 2500 Class 2b pickup with a factory-installed natural gas system.

The Cummins Westport web site [http://www.cumminswestport.com/find-a-natural-gas-truck-or-bus] lists OEMs and vehicle models offering the 9 liter (ISL G) and 12 liter (ISX12 G) natural gas engines. Table 5.5 shows a partial listing as of December 19, 2014.

TABLE 5.5 CLASS 7 AND 8 NATURAL GAS VEHICLE OFFERINGS

Market Segment	Manufacturer	Engines Offered
School Bus	Blue Bird	ISL G
School Bus	Thomas Built	ISL G
Shuttle Bus	El Dorado	ISL G
Transit Bus	Gillig	ISL G
Transit Bus	NABI	ISL G
Transit Bus	New Flyer	ISL G
Transit Bus	Nova Bus	ISL G
Motor Coach	MCI	ISL G, ISX12 G
Refuse	Autocar	ISL G, ISX12 G
Refuse	Crane Carrier	ISL G
Refuse	Freightliner	ISX12 G
Refuse	Kenworth	ISL G
Refuse	Mack	ISL G
Refuse	Peterbilt	ISL G, ISX12 G
Tractor	Freightliner	ISL G, ISX12 G
Tractor	Kenworth	ISL G, ISX12 G
Tractor	Mack	ISX12 G
Tractor	Navistar	ISL G
Tractor	Peterbilt	ISL G
Tractor	Volvo	ISL G
Vocational	Peterbilt	ISL G, ISX12 G

5.3 Natural Gas Vehicle Prices

SwRI surveyed the prices of Class 2a, 2b, and 3 compressed natural gas vehicles in the summer of 2014. A total of nine vehicle families were surveyed from Ford, GM, and Chrysler. In each case, the cost of the natural gas fueled version was compared to the cost for the base gasoline engine. The average cost of the CNG option across this range of vehicles was $9,867. The lowest cost CNG option was $6,240, for an 8.9 GGE CNG system with a 3.7 liter V-6 in the Ford F-150 pickup truck. The highest price CNG option was $15,505 for a 23.1 GGE CNG system in a GM Express 2500 cargo van with a 6.0 liter V-8 engine.

For those vehicles where a diesel engine option was available, the diesel option was generally less expensive than the natural gas option. In one case, the Ford F-250/350 pickup, buyers can select a 6.2 V-8 CNG engine with a rather small 13.6 GGE tank for $386 less than the cost of the same truck with a diesel engine (and a much larger capacity fuel tank). The same F-250/350 with a 24.5 GGE CNG tank (still with much less range than the diesel) costs $2,535 more than the diesel option. For other vehicles, the natural gas option is typically $2,000 to $2,600 more than the diesel option, in vehicles where a diesel is available. See Appendix D for more details.

SwRI also found several companies offering retrofit kits to convert existing Class 2a – 4 trucks to CNG at prices around $11,000.

The situation with medium and heavy duty truck pricing is a bit more complex. The difference between list price and the price customers actually pay can be rather large, so list prices are not a reliable way to evaluate actual customer cost. SwRI worked with vehicle dealers to price comparably equipped trucks with standard diesel and natural gas power. Volume purchasers can expect slightly lower cost increments for a natural gas truck. Table 5.5 lists the prices quoted to SwRI by two different truck dealers representing two different OEMs.

TABLE 5.6 HEAVY DUTY NATURAL GAS TRUCK PRICES

Truck Type	Base Engine	NG Engine	Tank Type	Diesel Price	NG Price	NG Upcharge
Box Truck	8.9 L Diesel, 320 HP	ISL G 320 HP	45 DGE CNG	$ 97,757	$135,306	$37,549
Short Haul Tractor	10.8 L Diesel, 355 HP	ISL G 320 HP	90 DGE CNG	$131,234	$171,404	$40,170
Day Cab Tractor	11.9 L Diesel, 350 HP	ISX12 G 350 HP	120 DGE CNG	$141,214	$217,568	$76,354
Mixer / Refuse	11.9 L Diesel, 350 HP	ISX12 G 350 HP	45 DGE CNG	$147,464	$185,608	$38,144
Mixer / Refuse	11.9 L Diesel, 350 HP	ISX12 G 350 HP	90 DGE CNG	$147,464	$202,509	$55,045
Mixer / Refuse	11.9 L Diesel, 350 HP	ISX12 G 350 HP	38 DGE LNG	$147,464	$189,582	$42,118
Day Cab Tractor	12.8 L Diesel, 400 HP	ISX12 G 400 HP	150 DGE LNG	$134,594	$179,130	$44,536
Day Cab Tractor	12.8 L Diesel, 400 HP	ISX12 G 400 HP	300 DGE LNG	$134,594	$200,920	$66,326

The upcharge for converting from petroleum fuels to natural gas is mainly driven by two factors: the cost difference between engines, and the cost of the fuel storage system. In the case of conversion from gasoline to natural gas, it is reasonable to expect the natural gas engine to be more expensive than a gasoline engine. The natural gas engine requires some premium parts to retain durability, and the natural gas fuel system will be more expensive and complex than a standard port injection gasoline fuel system.

In the case of conversion from diesel to natural gas, it would be reasonable to expect the natural gas engine to be less expensive than the diesel. A natural gas fuel system and ignition system is less complex than a typical high pressure common rail fuel system, and a spark ignited stoichiometric natural gas engine only needs a 3-way catalyst for aftertreatment, compared to the DOC+DPF+SCR systems normally used for a diesel. However, these expectations of potential cost savings are not borne out in the truck quotes SwRI received. The quoted prices show about a $15,000 upcharge for the 9 liter ISL-G engine, compared to a standard diesel, and about $20,000 for the ISX-12G. There may be two sources of this higher cost for natural gas engines:

1. The volume of natural gas engines is very low, eliminating economy of scale
2. One manufacturer has a virtual monopoly on the US market for heavy duty natural gas engines, so there is no price competition between natural gas engines

If the volume of natural gas engines for medium and heavy trucks ever approaches the volume of diesel engines, SwRI would expect the cost premium for natural gas engines to shrink and perhaps disappear.

SwRI received a significant number of quotes for CNG and LNG fuel storage systems for vocational trucks and regional haul tractors. The price of CNG storage ranged from $2,735 to $6,610 per 10 DGE (energy storage equivalent to 10 gallons of diesel fuel). The price of LNG storage ranged from $1,616 to $5,924 per 10 DGE. These prices are at least an order of magnitude above those for a conventional gasoline or diesel fuel tank. Some of this price differential is due to the lack of significant production volume and thus economies of scale in the natural gas fuel storage market, but natural gas storage systems can never approach the price of a standard fuel tank. The requirements for natural gas storage (very high pressure or cryogenic storage at moderate pressure) are much greater than the requirements to store a smaller volume of gasoline or diesel at essentially atmospheric pressure. SwRI predicts that the cost penalty for natural gas fuel storage will become smaller if production volumes increase, but it will always make natural gas vehicles more expensive than conventionally fueled vehicles.

5.4 Fuel Price Comparison

SwRI conducted a survey of natural gas fuel prices in May 2014. The CNG survey covered 30 stations: 10 in Oklahoma, 10 in California, and 10 in New York. Because there are fewer public LNG stations, the LNG survey covered 10 stations nationwide. The results are summarized in Table 5.6 below. The CNG prices were posted in units of GGE, while LNG prices were in DGE. The table provides both for ease of comparison. A DGE has 1.14 times more energy (and thus price) than a GGE. At the time of the survey, the national average price for gasoline was $3.64 per gallon, and diesel was $3.94.

TABLE 5.7 NATURAL GAS FUEL PRICES, MAY 2014

Fuel Type	State	Price Range	Ave. Price	Ave. Price
CNG	Oklahoma	$1.19 to $1.99 per GGE	$1.59 per GGE	$1.81 per DGE
CNG	California	$1.77 to $2.90 per GGE	$2.45 per GGE	$2.79 per DGE
CNG	New York	$1.99 to $3.00 per GGE	$2.59 per GGE	$2.95 per DGE
LNG	Nation Wide	$2.64 to $2.79 per DGE	$2.35 per GGE	$2.68 per DGE

In May 2014, the price of crude oil represented 68% of the pump price for gasoline and diesel fuel. On the other hand, the price of natural gas from a pipeline only represented 37% of the pump price for CNG. These values were calculated using data from www.eia.gov and www.anga.us. As a result, gasoline and diesel prices are very sensitive to crude oil prices, while CNG and LNG prices are not as sensitive to wellhead gas prices. Table 5.7 shows the impact of a

50% increase in raw fuel cost, using the assumption that this will not affect other components of the fuel cost (refining, distribution and marketing, and taxes).

TABLE 5.8 SENSITIVITY OF PUMP PRICES TO RAW FUEL PRICES

Effect of a 50% Increase in Raw Fuel Price			
Fuel	**Initial Price**	**Final Price**	**% Increase**
Gasoline	$3.66	$4.91	34%
Diesel	$3.96	$5.31	34%
CNG	$2.41 DGE	$2.86 DGE	19%

The lower sensitivity of natural gas pump prices to raw fuel prices cuts two ways. On the one hand, when raw fuel prices go up, natural gas pump prices will rise more slowly. On the other hand, when raw fuel prices go down, as oil did in the last six months of 2014, gasoline and diesel fuel prices at the pump will fall much faster than natural gas prices at the pump. As a result, the cost advantage of natural gas as a transportation fuel is extremely sensitive to the price of oil, but only moderately sensitive to the wellhead price of natural gas itself. High oil prices lead to a large price advantage for natural gas. Low oil prices can make the natural gas price advantage disappear or even become a cost penalty. Since long term oil prices have proven to be very unpredictable, this makes it hard for companies to make long term equipment investment decisions with any confidence that today's difference between natural gas and gasoline or diesel prices is a reasonable estimate of the difference over the next few years.

Because of the large swing in fuel prices during the last half of 2014, the price survey was repeated on January 6, 2015. On this date, the national average price for gasoline was $2.21, and the average diesel price was $3.14. Table 5.8 provides the January 2015 prices for natural gas.

TABLE 5.9 NATURAL GAS FUEL PRICES, JANUARY 6, 2015

Fuel Type	State	Price Range	Ave. Price	Ave. Price
CNG	Oklahoma	$1.65 to $1.80 per GGE	$1.65 per GGE	$1.88 per DGE
CNG	California	$2.00 to $2.90 per GGE	$2.39 per GGE	$2.72 per DGE
CNG	New York	$1.90 to $2.84 per GGE	$2.58 per GGE	$2.94 per DGE
LNG	Nation Wide	$1.99 to $3.00 per DGE	$2.18 per GGE	$2.48 per DGE

Table 5.9 shows the price differences between natural gas, gasoline, and diesel in May 2014 and January 2015.

TABLE 5.10 FUEL PRICE DIFFERENTIALS, BASED ON NATIONAL AVERAGE PRICES

Difference between gasoline and CNG, $/GGE		Difference between diesel and CNG, $/DGE		Difference between diesel and LNG, $/DGE	
May 2014	January 2015	May 2014	January 2015	May 2014	January 2015
$1.53	$0.10	$1.53	$0.73	$1.26	$0.66

The data in Table 5.10 illustrates how recent swings in oil prices have affected the payback for natural gas vehicles. Gasoline prices have fallen much farther than diesel from May 2014 to January 2015, so the advantage of natural gas fuel cost over gasoline has nearly disappeared. Assuming the same engine efficiency with natural gas and gasoline, a driver would have saved 42% of his fuel cost by switching to natural gas in May 2014, but only 4.5% of a much smaller fuel cost in January 2015. Assuming a 15% efficiency penalty for natural gas engines compared to diesel, users of diesel fuel who converted to natural gas saw their fuel savings decrease from 30% of fuel cost in May 2014 to 12% of a smaller fuel cost in January 2015 (CNG), or from 22% to 9% (LNG). These numbers make it clear that to the extent that low oil costs persist, they will greatly reduce interest in converting vehicles to natural gas. Of course, an increase in oil prices would reverse this situation.

5.5 Natural Gas Availability

One of the constraints affecting natural gas vehicle sales is the availability of the fuel. A few areas (Oklahoma, Southern California, and parts of New York State) have reasonably good public access to natural gas fueling stations, at least for CNG. Other parts of the country have large areas with little or no availability. The availability situation is still improving, however. In May 2014, 705 CNG stations were listed. This number had increased to 799 by early January 2015, a 13% increase in 9 months. The number of LNG stations increased from 54 to 64 in the same time frame. It is not yet clear how the recent drop in oil prices will affect decisions regarding investment in new natural gas fuel stations.

5.6 Natural Gas Vehicle Incentives

SwRI surveyed natural gas vehicle incentives in May 2014. Some example results:

- Kansas has no natural gas vehicle incentives (Kansas incentivizes ethanol)
- Colorado offers a tax credit for new natural gas vehicles. The credit is $7,500 for vehicles up to Class 4, $15,000 for Classes 5 – 7, and $20,000 for Class 8
- New York offers a tax credit covering 80% of the upcharge for natural gas, up to a limit of $60,000, for Class 3 – 8 trucks. They also have a tax credit for refueling stations, and an exemption of CNG from state sales and road use tax. The state Energy R&D Authority provides funding for natural gas school buses, technical support for organizations considering natural gas vehicles or fuel stations, and low cost technician training on NG systems
- California offers $1000 rebates for NG powered vehicles up through Class 2a, and up to $25,000 for heavy duty vehicles. You can drive a NG vehicle in the HOV lane with

only the driver. There are numerous tax breaks, subsidies and grants (see Appendix D)

Overall, the incentive picture varies greatly from one state to another. It would be interesting to study how natural gas vehicle market penetration varies as a function of state incentives.

5.7 Other Barriers to Natural Gas Vehicle Adoption

In sections above, the effects of several parameters on adoption rates have been reviewed, including:

- Engine and vehicle availability
- Size and weight penalties for CNG and LNG fuel storage systems
- Engine, fuel storage system, and vehicle prices
- Fuel prices
- Fuel availability
- Government incentives

This final subsection will cover other issues that may limit the adoption of natural gas powered vehicles.

5.7.1 Engine Fuel Consumption/Thermal Efficiency

One factor that can significantly affect a vehicles fuel cost is the efficiency of the engine. In regional and long haul applications, where the number of miles traveled per year is very high, engine efficiency becomes an important factor in total cost of ownership. The natural gas engines currently offered in this market are stoichiometric, spark ignited engines. Their thermal efficiency cannot compete with that of diesel engines, and so their fuel consumption (in DGE terms) will be higher than a diesel.

SwRI attended the ACT Expo and NGV Global 2014 conferences in June 2014. Paper Transport, Inc. presented results for two tractors in their fleet. These are identical models with the same options, except one has a diesel engine and one is CNG. The diesel tractor averages 7.2 MPG in fleet service, while the natural gas tractor averages 4.3 MPGe on the same route. This represents a 33% fuel consumption penalty for the natural gas powered tractor. One component of the higher fuel consumption is a 1,000 pound empty weight increase. A second factor is the aerodynamically inefficient back-of-cab CNG storage box. The largest factor is the less efficient spark ignited, stoichiometric natural gas engine. The overall result, however, is that the natural gas price has to be low enough to make up for a 33% increase in fuel consumption.

A second example from the same conference compares two Class 8 vocational trucks in the Kroger fleet. Again, the same vehicle model is used for both diesel and CNG power. The natural gas truck suffers from 17 to 20% higher fuel consumption, which requires a fuel price advantage to compensate for the higher fuel consumption.

In SwRI's experience, a diesel pilot ignited natural gas engine can offer fuel consumption that is reasonably competitive with diesel engines. SwRI has measured brake thermal efficiency (BTE) of a lean burn HPDI natural gas engine in the 42% range. This compares to 2010 and newer heavy duty diesel engines that are in the 42 – 46% BTE range. However, these HPDI engines are complex and expensive, and are no longer available on the market. Efficient diesel pilot natural gas engines may return at some point in the future, but the currently available spark ignited stoichiometric engines have peak BTE values below 39%. Note that natural gas engines do not have an efficiency penalty compared to spark ignited gasoline engines. Some technologies for gasoline engines that are described in Section 2 could be applied to improve the efficiency of stoichiometric, spark ignited natural gas engines. EGR is already used, but VVA or cylinder cutouts could be considered to improve light load efficiency.

5.7.2 Vehicle Range

Vehicle range is important in applications where central fueling is not used. Longer range can allow the operator to seek out lower priced fuel or, in the case of natural gas vehicles, it can allow the operator to get to a location where fuel is available. Time spent fueling is time not spent delivering freight, so frequent fueling also causes a productivity penalty. In the tractor example from the section above, the diesel powered tractor had a 200 gallon tank, providing a range of 1,450 miles. The natural gas truck had a capacity of 140 DGE. Accounting for the lower fast-fill capacity and the higher fuel consumption, the range of the CNG truck is only 600 miles.

In the vocational truck example from section 5.7.1, the diesel powered truck has a 910 mile range from its 140 gallon tank, while the CNG powered truck has a 510 mile range from its 115 DGE tank. Again, this assumes 80% fast-fill capacity.

Along with vehicle range, the time required to refuel is also a productivity factor. Both fast-fill CNG and LNG vehicles generally take longer to fill than conventional diesel or gasoline vehicles. Slow fill CNG is only a viable option for centrally fueled vehicles that are not operated for several hours each day.

5.7.3 Vehicle weight

The CNG tractor in section 3.6.1 weighs 1,000 pounds more than the diesel version, while the CNG vocational truck is 1,471 pounds heavier than the diesel version. This weight penalty for natural gas vehicles has a modest negative effect on fuel consumption, and it also will reduce the maximum weight of freight that can be legally carried by the same amount as the vehicle weight increase. The fuel consumption penalty for a 1,000 pound weight increase ranges from 0.5% for an 80,000 pound tractor-trailer on a long-haul route to 2.5% for a Class 5 truck running with zero payload on the CARB urban drive cycle.

5.7.4 Vehicle Size and Maneuverability

The CNG powered vocational truck in section 5.7.1 has a wheelbase that is 26 inches longer than that of the diesel truck, in order to accommodate the back-of-cab CNG tank mounting system. The longer wheelbase results in a 3.5 foot larger turning radius, which is a significant impediment in city driving, and for operations in crowded loading dock areas.

5.7.5 Parts, Service, and Training

Operators who run both diesel and natural gas vehicles need to maintain parts for both vehicle types. Mechanics must be trained to work on both engine types, and drivers need training specific to each fuel type. Service shops that work on natural gas vehicles need expensive ventilation systems, to avoid the risk of an explosion in the event of a fuel leak. All of these factors lead to additional costs for operators of natural gas or mixed fuel fleets.

Overall, it appears that the prospects for increased natural gas market share in the truck market are limited, at least until diesel prices go up substantially. Experts disagree on whether this will happen in the short term, or not for many years.

6.0 PROJECT CONCLUSIONS

With the exception of the market research for the natural gas vehicle cost survey, this project involves simulation results that were supported to the greatest extent possible by experimental data. See Section 2.2 regarding the accuracy and limitations of the simulation techniques used in this project.

6.1 Long Haul Truck and Engine Results

The first step before evaluating engine technology packages was to look at what would be required to achieve compliance with the Phase 1 engine regulations. This required some technology assumptions that defined the 2019 baseline diesel engines (DD15 long haul truck engine, ISB medium-duty truck engine, and ISB pickup truck engine). With the 2019 baseline DD15 defined, a range of technology packages was simulated. These engine packages had the following content:

DD15 Package 1: 2019 Baseline + FMEP Reduction
DD15 Package 2: 2019 Baseline + Downspeed B + ½ FMEP Reduction
DD15 Package 3: Package 2 + Water Based WHR
DD15 Package 3a: Package 2 + R245 Based WHR
DD15 Package 3b: Package 2 + R245 Based WHR with Recuperator
DD15 Package 3c: Package 2 + Methanol Based WHR
DD15 Package 3d: Package 2 + Methanol WHR with Recuperator
DD15 Package 3e: Package 2 + Ethanol Based WHR
DD15 Package 3f: Package 2 + Ethanol WHR with Recuperator
DD15 Package 4: No Turbocompound, Conventional Fixed Geometry Turbine, No EGR, full FMEP Reduction
DD15 Package 5: Turbocompound + Downspeed B + 1% Combustion Improvement + ½ FMEP Reduction + Reduced Intake, Exhaust, and Charge Air Cooler Restrictions

The DD15 Package 1 added friction reduction to the 2019 baseline DD15 engine.[1] Friction reduction provides the largest benefits on lightly loaded drive cycles. Fuel savings of up to 5.5% were found on the CARB cycle at zero payload. The lowest benefit for Package 1 was 1% on the NESCCAF cycle at 100% payload. This is an operating cycle where friction reduction has less effect, because of the high average engine load.

DD15 Package 2 included Downspeed B (reduced engine speed @ 65 MPH from 1368 RPM to 1051 RPM) and half of the friction reduction applied in Package 1. DD15 Package 2 provides benefits from 2% to 5% on most drive cycles and payloads. Package 2 gave an 8.1% benefit on the CARB cycle at zero payload, where the lower operating speeds pushed engine

[1] The simulations with friction reduction assumed FMEP could be reduced by addressing any engine component needed for engine operation. Examples: Piston/ring/liner friction, bearing friction, valve train and gear train friction, variable speed/displacement oil and water pumps, on/off control of piston cooling nozzles, reduced power demand fuel pump, reduced viscosity engine oil, friction modifiers in oil, etc. Accessories required by the vehicle are addressed separately (A/C, power steering, air compressor, etc.).

load up into a more efficient range. Other gentle cycles with zero payload also saw fuel savings of over 5%.

DD15 Package 3 evaluated a range of waste heat recovery (bottoming cycle) systems. The WHR was applied to the Package 2 engine. Because WHR systems have very slow transient response, they contribute less useful work on highly transient cycles. Even on a high average power demand, but partly transient drive cycle such as NESCCAF, there are portions of the cycle where power demand will be zero. During these portions, the power from WHR is wasted, and WHR power recovers slowly after the vehicle power demand resumes. Thus, the simulation overstates the contribution of WHR on the NESCCAF cycle. On the other hand, the contribution of WHR on other transient cycles like CARB and WHVC is greater than zero. The simulation method used did not model transient activity, so the WHR systems were assumed to not operate on the CARB and WHVC cycles. Since the average power demand is not high and vehicle power demand fluctuates a lot, the WHR contribution will be small, but the assumption of zero contribution is definitely conservative. All WHR systems used both EGR flow and exhaust waste heat as energy sources. The systems were limited to a maximum of 80 kW additional heat rejection, to limit the impact on vehicle cooling systems and aerodynamics. The following systems were evaluated:

A system with methanol as the working fluid, with and without a recuperator
A system with ethanol as the working fluid, with and without a recuperator
A system with water as the working fluid, with no recuperator
A system with R245 refrigerant as the working fluid, with and without a recuperator

The R245 WHR system provides benefits of 3 to 3.5% over Package 2. Adding a recuperator to the R245 system increases the fuel savings to well over 4%. The water based system provides fuel savings of just under 5%. The methanol and ethanol systems provide fuel savings of around 5%. Adding a recuperator to these systems only gives a marginal improvement in performance. Comparing the Package 3 systems to the 2019 baseline DD15, the overall benefits at 55 and 65 MPH and on the NESCCAF cycle reach and sometimes exceed 9%, except in the case of the R245 system without a recuperator.

DD15 Package 4 is a high engine-out NOx package that would require a high performance NOx aftertreatment system to achieve compliance with the current criteria emissions standards. This package includes a high efficiency conventional fixed geometry turbocharger, no turbocompound, and the FMEP reduction. This package provides fuel savings that approach those of Package 2.

DD15 Package 5 is the only package to retain turbocompound. It adds downspeeding, a partial FMEP reduction, and the 1% BSFC reduction due to shorter combustion duration. Package 5 provides fuel savings results roughly comparable to those of Package 2, but at a higher engine cost because of the turbocompound.

The Kenworth T700 truck and trailer combination vehicle was evaluated with 5 vehicle technology packages:

T700 Package 1: 15% Cd reduction + 10% Crr reduction + 3% weight reduction
T700 Package 2: 25% Cd reduction + 30% Crr reduction + 6.5% weight reduction
T700 Package 3: Package 1 + 40% AC power reduction + 20% chassis friction reduction + 6X2 axles + 18-speed AMT
T700 Package 4: 25% Cd reduction + 30% Crr reduction + 40% AC power reduction + 20% chassis friction reduction + 6X2 axles + 18-spd AMT + DD15 Package 3b
T700 Package 5: Vehicle Package 3 + DD15 Package 5

The T700 tractor-trailer Package 1 includes a 15% Cd reduction, a 10% Crr reduction, and a 3% empty weight reduction, all with the 2019 baseline DD15 engine. This package provides 10% to 12% fuel savings on the three high speed cycles (55 and 65 MPH, and NESCCAF). The savings are just over 3% on the low speed CARB cycle, where aerodynamic drag is not a significant factor, and where the power required to accelerate the vehicle is more important than tire rolling resistance.

T700 Package 2 has a 25% Cd reduction, a 30% Crr reduction, and a 6.5% empty weight reduction, with the 2019 baseline DD15 engine. This package provides 20 to 23% fuel savings on the three high speed cycles, with the smaller values coming on the more realistic NESCCAF cycle, which includes grades and a small stop and go segment. Fuel savings are over 7% even on the low speed CARB cycle.

T700 Package 3 has all the features of Package 1, plus a 40% reduction in air conditioner power demand (a 600 Watt reduction), a 20% chassis friction reduction, 6X2 drive axles, and an 18-speed AMT transmission in place of the baseline 10-speed AMT. These additional features yield fuel savings that are 1.4% to 2.7% greater than those achieved by Package 1.

T700 Package 4 has the following content: 25% Cd reduction, 30% Crr reduction, 40% A/C power demand reduction, 20% chassis friction reduction, 6X2 drive axles, and the 18-speed AMT. This vehicle content is combined with DD15 engine Package 3b, which is the R245-based WHR system with a recuperator. The content of this package approaches that found in the SuperTruck program vehicles, and so do the results. Fuel consumption reductions of 28% to 33% are achieved on the three high speed drive cycles. Fuel savings are 17% to 20% on the low speed CARB cycle, despite the fact that the WHR system is not active on this cycle.

Finally, The T700 has vehicle Package 5. This package includes all the features of Package 3, except for two items. The 10-speed AMT is retained, and DD15 engine Package 5 is used. Previous work shows little change between the 10 and 18-speed transmissions, so the primary factor in this package compared to vehicle Package 3 is the engine change. Package 5 provides fuel savings of 9% to 19% across all the drive cycles and payloads, with the best results coming at high road speed and light payload.

6.2 Medium-Duty and Pickup Diesel Technology Combinations

Two versions of the 6.7 liter ISB diesel were evaluated. The pickup truck version has a higher engine speed and torque rating: 385 HP @ 3,000 RPM, and 850 lb-ft @ 1600 RPM. The medium truck version of this engine has a more modest 300 HP @ 2,500 RPM power rating, and a peak torque of 750 lb-ft. Packages 6 – 10 are medium duty engines, while Packages 11 – 15 are pickup truck versions. These engine packages had the following content:

ISB Package 6: 2019 Baseline ISB + 2.5% Turbo Efficiency + Downspeed
ISB Package 7: No EGR + 5% Turbo Efficiency + FMEP Reduction
ISB Package 8: No EGR + 5% Turbo Efficiency + ½ FMEP Reduction + Downspeed
ISB Package 9: 2019 Baseline ISB + 2.5% Turbo Efficiency + FMEP Reduction
ISB Package 10: 4-Cylinder + 3,000 RPM Rated + Full Range EGR
ISB Package 11: 2019 Baseline ISB + 2.5% Turbo Efficiency + Downspeed
ISB Package 12: No EGR + 5% Turbo Efficiency + FMEP Reduction
ISB Package 13: No EGR + 5% Turbo Eff. + ½ FMEP Reduction + Downspeed
ISB Package 14: 2019 Baseline ISB + 2.5% Turbo Efficiency + FMEP Reduction
ISB Package 15: 4-Cylinder + FMEP Reduction

Medium duty ISB Package 6 provides 2.3% to 4.2% fuel savings on the 55 and 65 MPH cycles with the T270. On the smaller, lighter F-650, the benefits range from 4.4% to 7.1% on the same two cycles. On the CARB, WHVC, and CILCC cycles, Package 6 provides less than a 1% benefit for both trucks, except the T270 gets about 2% on the CILCC cycle. On the Parcel cycle, downspeeding causes a fuel consumption increase of 4.5% to 6% on both trucks. The reason for this fuel penalty is that the downspeed engine has a higher torque, which requires a tighter torque converter match. The tight converter increases load on the engine at idle, which is 50% of the Parcel cycle time.

Medium duty ISB Packages 7 and 8 both eliminate EGR and thus depend upon extremely efficient aftertreatment to meet current criteria emissions regulations. P7 has a larger friction reduction than P8, while P8 adds downspeeding. P7 outperforms P8 on all drive cycles that include some idle time, partly because of the torque converter match penalty that comes with downspeeding. P7 provides 4.6% to 8.4% benefit on the F-650 across all drive cycles and payloads, while the larger T270 sees slightly smaller benefits. P8 provides slightly larger improvements on the 55 and 65 MPH cruise cycles, but falls short of P7 on all the other cycles. On the Parcel cycle, P8 is worse than the 2019 diesel baseline.

Medium duty ISB Package 9 drops the downspeed feature of P6, but adds a friction reduction. P9 beats the 2019 baseline ISB by 3% to 4.6% on all drive cycles in both trucks. P9 is better than P6 on all cycles except the two cruise cycles, where P6 is 2% to 4% better in the F-650, and 0.2% to 2.5% better in the T270. Downspeeding helps on cruise cycles, but not on cycles with significant idle time.

Medium duty ISB Package 10 is a downsizing option. Because BMEP is held constant, the rated speed is increased to 3,000 RPM to partly make up for the lower power and torque. This package has a very wide range of results. On the extremely gentle CILCC cycle at zero payload in the F-650, P10 provides a 14% fuel savings over the 2019 baseline ISB. At the other extreme, in the T270 at 65 MPH and full payload, the smaller engine incurs a 3.4% fuel consumption penalty. In general, downsizing works well when duty cycles are gentle, but not when they are aggressive.

Pickup ISB Package 11 provides 6.1% fuel savings at 65 MPH and zero payload. It provides about 3.5% on the aggressive US06 cycle. On the remaining cycles, the benefits are generally under 1%, with a few negative numbers. Downspeeding causes an idle fuel consumption penalty due to the torque converter match. Also, at 65 MPH and GCW, the truck needs to run in 5th gear to handle the road load. This causes a slight fuel consumption penalty compared to the 2019 baseline ISB.

Pickup ISB Packages 12 and 13 both eliminate EGR and thus depend upon extremely efficient aftertreatment to meet current criteria emissions regulations. P12 provides a fuel savings of 4% to 7% across the range of duty cycles and payloads except 65 MPH at GCW, where it gives a 2.2% benefit. P13 with downspeeding performs slightly better than P12 on the US 06 and 65 MPH cycles, but the idle fuel consumption penalty causes it to underperform P12 on the remaining cycles.

Pickup ISB Package 14 provides fuel savings of 4% to 5% on all drive cycles except the US06 with zero or ALVW payload. At GCW and on the US06, benefits are in the 2% to 3% range.

Medium duty ISB Package 15 is a downsizing option. Because the BMEP is held constant, both power and torque are reduced by 33% compared to the baseline 6-cylinder engine. For many pickup truck operators, this power penalty would be acceptable in light of the fuel savings. Savings of 9% to 14% are achieved on the City, Highway, SC03, and WHVC cycles at zero payload and at ALVW. On the US06 and 65 MPH cycles, fuel savings of about 6% are achieved at zero payload and at ALVW. At full GCW, the savings are less – 5.3% to 8.2%, except at 65 MPH, where the savings are only 1.5%. Users who normally tow very heavy loads would probably want to avoid the downsized option, but many users would see significant fuel savings.

6.3 Medium-Duty and Pickup Gasoline Technology Combinations

The 3.5 liter turbocharged gasoline V-6 engine and the 6.2 liter naturally aspirated V-8 engine technology packages were evaluated on three vehicles: the Ram pickup, the F-650 tow truck, and the T270 box delivery truck. These engine packages had the following content:

3.5 V-6 Package 16: Baseline V-6 engine + VVA + EGR
3.5 V-6 Package 17: Package 16 content + Downspeed
3.5 V-6 Package 18: Package 16 content + Lean Burn GDI at part load
3.5 V-6 Package 19: Baseline V-6 engine + EGR + Downspeed (Package 17 – VVA)

6.2 V-8 Package 20: GDI + EGR + Cylinder Deactivation + 10% FMEP reduction
6.2 V-8 Package 21: Package 20 + VVA

6.2 V-8 Package 22: GDI + EGR + 2 Cam Phasers + 10% FMEP Reduction
6.2 V-8 Package 23: GDI + EGR + Cylinder Deactivation (P20 – FMEP Reduction)
6.2 V-8 Package 24: GDI + EGR + 10% FMEP Reduction (P20 – Cyl Deactivation)

V-6 Package 16 provides fuel savings of 5% to 7% on all three vehicles on most drive cycles and payloads. In situations where the average road load is high, the savings increase. For example, fuel savings on the T270 at 65 MPH are 11% to 13%, and on the Ram pickup, fuel savings are 9% to 12% on the City, Highway, and SC03 cycles.

V-6 Package 17 adds downspeed to Package 16. Downspeeding helps most on the smaller, lighter Ram pickup, with 3% to 6% incremental improvement over P16 on all cycles except the aggressive US06 cycle. On the US06, the fuel savings drop into the 2% - 3% range. On the larger, heavier T270, the benefit of downspeeding is generally 1% or less. On the Parcel cycle, downspeeding actually causes a 3% to 4% increase in fuel consumption. It is possible that detailed optimization of the transmission shift schedule could reduce or eliminate this penalty.

V-6 Package 18 adds light load lean burn to Package 16. On the Ram pickup truck, this package provides incremental benefits of up to 10% at zero payload on gentle drive cycles. At full GCW, however, the engine is not able to take advantage of lean operation very often, so the fuel savings drop into the 0% to 3% range, depending on drive cycle. With the large, heavy T270, the largest fuel savings come on the very gently CILCC cycle (3% to 4%). On the other cycles, fuel savings range from 0 to 3%.

V-6 Technology Package 19 eliminates VVA from Package 17, so it can be used to determine the contribution of VVA to a small boosted engine with EGR. On the Ram pickup truck, P19 increases fuel consumption compared to P17 by 1% to 2% on most drive cycles, at most payloads. The fuel consumption penalty is under 1% on the 65 MPH cycle, but it is 3% to 4% on the very gentle (for a pickup) WHVC cycle. With the T270, the fuel consumption penalty for deleting VVA is also 1% to 2% on most cycles. It is less than 1% on the Parcel cycle, and about 3% on the very gentle CILCC cycle.

V-8 Package 20 combines 4 technologies from Final Report #1. With the Ram pickup, P20 provides fuel savings of 9% to 14% on most drive cycles and payloads. The smallest benefit was at 65 MPH and full GCW, where a 7.4% benefit is achieved. On the T270, fuel savings of 9% to 12% are achieved on the CARB, 65 MPH, and CILCC cycles. At 55 MPH, the savings are reduced to 6% to 7%, and on the WHVC and Parcel cycles savings are in the 7% - 9% range.

V-8 Package 21 adds VVA to P20. Savings on all vehicles and drive cycles were improved by less than 1% in most cases. The reason for this small benefit is that EGR and cylinder deactivation both serve to reduce pumping work, so there is little pumping work left for VVA to work with.

V-8 Package 22 is similar to Package 20, except twin cam phasers replace the cylinder cutout feature on P20. At light loads, the cylinder cutout feature provides a larger benefit than twin cam phasers. Thus, the Ram pickup sees an increase in fuel consumption from P20 to P22 of 3% to 4% on most cycles at zero payload and at ALVW. At GCW, the fuel consumption penalty of P22 compared to P20 drops to near zero. On the T270, P22 brings a 0% to 2% increase in fuel consumption compared to P20, with the largest penalties occurring at zero payload on gentle drive cycles.

V-8 Package 23 is also based on P20, with the 10% FMEP reduction eliminated. On all vehicles, drive cycles, and payloads, the change in friction is worth a 1% to 2% change in fuel consumption, with the slightly larger numbers coming on lightly loaded drive cycles.

Finally, V-8 Package 24 is P20 with cylinder deactivation eliminated. Cylinder deactivation is a very effective technology for reducing pumping work at light loads, but it shuts off above loads of about 4 bar BMEP, or roughly 30% of maximum torque for a naturally aspirated engine. Therefore, cylinder deactivation is very effective on lightly loaded duty cycles, but it has no effect when engine load is high. On the Ram pickup, the fuel consumption penalty for P24 compared to P20 is as much as 10% on the FTP-City cycle at zero payload. On the aggressive US06 cycle at ALVW, the difference is only 3%, and at 65 MPH and full GCW, there is no difference, because at that engine speed and load, cylinder cutout is not active. On the larger T270, there is no difference between P20 and P24 on the 55 and 65 MPH cycles at any payload, because the road load is high enough to keep cylinder deactivation turned off. On the CARB urban cycle at zero payload, the benefit of cylinder cutout is about 6%.

6.4 Medium-Duty and Pickup Vehicle Technology Packages

The Ram pickup, the F-650, and the T-270 were each evaluated with 5 vehicle technology packages. The packages are similar from vehicle to vehicle, but there are some variations. The vehicle technology packages are:

T270 Package 6: Cd and Crr Sweep
T270 Package 7: 20% Crr Reduction + 8-Speed Automatic
T270 Package 8: P7 + Idle Neutral Feature
T270 Package 9: 20% Crr Reduction + 6-speed AMT
T270 Package 10: P8 + 40% A/C Power Reduction + 800 lb Weight Reduction

F-650 Package 11: Cd and Crr Sweep
F-650 Package 12: 20% Crr reduction + 8-Speed Automatic
F-650 Package 13: P12 + Idle Neutral Feature
F-650 Package 14: 20% Crr Reduction + 6-speed AMT
F-650 Package 15: P13 + 40% A/C Power Reduction + 700 lb Weight Reduction

Ram Package 16: Cd and Crr Sweep
Ram Package 17: 10% Cd Reduction + 30% Crr Reduction + 8-Speed Automatic
Ram Package 18: P17 + Idle Neutral Feature
Ram Package 19: P17 Without 8-Speed Automatic
Ram Package 20: P18 + 40% A/C Power Reduction + 600 lb Weight Reduction

Vehicle Packages 6, 11, and 16 are Cd and Crr sweeps. Reductions in Cd have the largest effect at high, steady vehicle speeds such as the 65 MPH cruise cycle. The T270, with its greater frontal area, benefits more from a Cd reduction than the smaller F-650. At 50% payload, the T270 saves 5.7% fuel consumption with a 10% Cd reduction, while the F-650 saves 4.2% under the same conditions. The Ram, with even less frontal area, saves 3.7% at 65 MPH and ALVW. Fuel savings from Cd reductions on the other cycles are less for all vehicles.

Changes in tire rolling resistance (Crr) also tend to have the largest effect at steady cruise conditions at 100% payload. The T270 operating on the 65 MPH cycle at 50% payload saves 4.6% from a 20% Crr reduction, compared to 4.5% for the F-650 and 2.7% for the much lighter pickup operating at ALVW. The medium trucks saw the largest fuel savings at 55 MPH, where aerodynamic drag is a smaller factor, but the pickup was not run at 55 MPH. At full GCW, the pickup sees a 4.7% benefit at 65 MPH for a 20% Crr reduction.

Packages 7 and 12 are identical for the T270 and F-650, with a 20% Crr reduction and an 8-speed automatic in place of the baseline 5-speed. With the diesel engine, P7 and P12 are worth 4% to 7% across all the drive cycles and payloads, except for the very gentle CILCC cycle, where a 9% to 11% fuel savings is achieved. With the gasoline engines, P7 and P12 fuel savings are slightly higher than for the diesel at 65 MPH, but significantly less on the CILCC cycle. There may be some room to optimize the shift schedule at light loads to improve the performance of the gasoline engines on the CILCC.

Pickup Package 17 is more aggressive that P7 and P12 for the medium trucks. P17 has a 10% Cd reduction and a 30% Crr reduction, in addition to the 8-speed transmission. P17 provides 9.5% to 11% fuel savings on the 65 MPH cycle and the FTP-Highway cycle, across all payloads. Fuel consumption is reduced 6% to 9% on the remaining cycles.

Vehicle Packages 8, 13, and 18 add an idle neutral feature to the 8-speed automatic. This has zero effect on cycles with no idle time, such as the 55 and 65 MPH cycles. On the Parcel cycle, the idle neutral feature provides a 9% to 12% fuel consumption reduction with the diesel on the two medium-duty trucks. The gasoline engines have a much lower idle torque from the converter, so fuel savings are about half those obtained by the diesel.

Packages 9 and 14 have the same 20% Crr reduction as P7 and P12, but with an AMT transmission in place of the 8-speed automatic. P9 and P14 provide benefits of 12% to 14% on the CILCC and Parcel cycles at all payloads. 7% to 10% fuel savings are achieved on the remaining cycles. Fuel savings with the gasoline engines are similar to those of the diesel, except for smaller benefits on the CILCC and Parcel cycles. The tight torque converter of the diesel hurts idle fuel consumption, so there is a bigger benefit in switching to the AMT.

Package 19 shows the performance difference between the 8-speed automatic (P17) and the baseline 6-speed automatic. On lightly loaded cycles such as the two FTP cycles and the WHVC, the diesel uses 3% to 4% more fuel with the 6-speed of P19, compared to the 8-speed in P17. On more highly loaded cycles, the fuel savings diminish. In general, fuel savings differences are less for the gasoline engines, which have a different baseline transmission mechanical efficiency.

Packages 10, 15, and 20 apply the accessory power demand reduction and empty weight reduction to all 3 vehicles. The pickup benefits most from P20, for two reasons. Road load is less in the pickup than in the medium trucks, so the A/C power reduction is a larger portion of the road load. Also, the percentage reduction in empty weight is larger for the pickup. With zero payload and at ALVW, the diesel pickup gains a fuel consumption reduction from P20 of 4% to 5% on all drive cycles except 65 MPH cruise, which has a benefit of about 3%. The V-6 generally sees slightly larger fuel savings than the diesel, while the V-8 has slightly smaller fuel savings. The larger, heavier diesel T270 saves 2.6% to 4.5% in fuel consumption across the range of drive cycles and payloads, except for the 55 and 65 cruise cycles, where the benefits are between 1% and 2%. Savings for the gasoline V-6 are similar to those of the diesel, while the V-8 sees slightly smaller fuel savings.

The tables below summarize the fuel consumption reductions achieved by the technology packages, across a range of drive cycles. All results shown are at 50% payload or, for the pickup truck, at ALVW. These tables do *not* include results of parameter sweeps, such as sweeps of empty weight, Cd, or axle ratio. Results for the DD15 and ISB diesel engine packages are compared to the 2019 engine baselines, while the gasoline packages compare to the 2012 gasoline baselines. Note that most pickup drive cycles are different from the ones shown in the table, which explains the “N/A” entries.

6.5 Overall Summary of Engine and Vehicle Package Results

The tables below summarize the vehicle and engine technology results obtained in Section 2. Table 6.1 shows the engine technology combination results. The pickup truck only shares the 65 MPH cruise and WHVC cycles with the other trucks, so the other drive cycles are market “N/A” for the pickup. Table 6.2 summarizes the medium- and heavy-duty truck technology package results. Finally, Table 6.3 summarizes the pickup truck technology package results.

TABLE 6.1 ENGINE PACKAGES SUMMARY – MINIMUM TO MAXIMUM PERCENT IMPROVEMENTS FROM BASELINE (50% LOAD OR ALVW)

Engines	CARB – City	55 MPH Cruise	65 MPH Cruise	WHVC	CILCC	Parcel	NESCCAF
DD15 Packages 1-5	3.0% to 8.1%	1.3% to 8.0%	1.0% to 9.4%	3.1% to 6.3%	N/A	N/A	1.1% to 10.1%
ISB Medium Duty Packages 6-10	-0.4% to 6.9%	2.6% to 7.2%	-2.5% to 8.3%	0.4% to 12.1%	0.7% to 9.8%	-5.5% to 5.6%	N/A
ISB Pickup Packages 11 - 15	N/A	N/A	4.0% to 7.1%	1.0% to 12.1%	N/A	N/A	N/A
3.5L Packages 16-19	6.2% to 10.7%	5.5% to 12.2%	5.1% to 14%	5.5% to 14%	5.9% to 11.9%	1.9% to 8.7%	N/A
6.2L Packages 20-24	5.2% to 11.5%	5.2% to 9.3%	5.2% to 11%	4.9% to 14%	4.8% to 13.3%	4.3% to 8.6%	N/A

TABLE 6.2 CLASS 4-8 VEHICLE PACKAGES SUMMARY – MINIMUM TO MAXIMUM PERCENT IMPROVEMENTS FROM BASELINE (50% LOAD OR ALVW, NO SWEEPS)

Vehicles	CARB – City	55 MPH Cruise	65 MPH Cruise	WHVC	CILCC	Parcel	NESCCAF
T700 P1-5	3.1% to 17%	11% to 30%	12% to 33%	5.2% to 20%	N/A	N/A	9.6% to 31%
F-650 ISB P12-P15	5.8% to 11.5%	6.3% to 9.8%	5.3% to 8.3%	6.5% to 11%	9.9% to 15%	5.5% to 21%	N/A
F-650 3.5L P12-P15	4.9% to 10%	7.8% to 11%	6.4% to 8.7%	7.0% to 11%	5.0 to 9.8%	6.1% to 17%	N/A
F-650 6.2L P12-P15	3.9% to 9.2%	6.8% to 8.7%	6.1% to 8.0%	6.0% to 9.4%	3.3% to 7.0%	4.0% to 15%	N/A
T270 ISB P7-P10	6.1% to 12%	5.8% to 8.9%	4.8% to 7.8%	6.8% to 10%	12% to 17%	5.6% to 20%	N/A
T270 3.5L P7 – P10	5.8% to 11%	6.7% to 9.3%	6.4% to 9.0%	7.1% to 11%	5.8% to 10%	6.6% to 17%	N/A
T270 6.2L P7 - P10	1.5% to 9.0%	5.6% to 7.9%	5.3% to 7.4%	4.4% to 9.0%	4.0% to 7.6%	3.1% to 15%	N/A

TABLE 6.3 CLASS 2B-3 VEHICLE PACKAGES SUMMARY – MINIMUM TO MAXIMUM PERCENT IMPROVEMENTS FROM BASELINE (50% LOAD OR ALVW, NO SWEEPS)

Vehicles	FTP-City	FTP-Hwy	US06	SC03	WHVC	65 MPH
Ram ISB P17 - P20	3.4% to 16%	7.2% to 14%	5.5% to 12%	3.5% to 14%	5.0% to 14%	7.8% to 13%
Ram 3.5L P17 - P20	4.3% to 14%	7.3% to 16%	6.2% to 13%	4.0% to 16%	5.5% to 14%	8.3% to 14%
Ram 6.2L P17 - P20	3.7% to 11%	5.8% to 12%	5.2% to 11%	3.8% to 15%	4.1% to 11%	6.4% to 11%

6.6 Pickup Truck Hybrid System Evaluation

Argonne National Laboratory was contracted to take the pickup truck model developed for this study and apply a range of potential hybrid systems to it. Three systems were evaluated:

A 7 kW belt driven integrated starter/generator (BISG)
A 15 kW crank drive integrated starter/generator (CISG)
A 50 kW parallel hybrid system

The fuel consumption reductions provided by the three hybrid systems are summarized in Table 6.4 below. The values are in terms of percent reduction in fuel consumption. The fuel savings are much larger on the city cycle, where more regenerative braking energy is available. Fuel savings also increase as the size and complexity of the hybrid system increases. The fuel savings decline as the vehicle payload increases. The 3.5 liter V-6 gasoline engine benefits slightly more from the various hybrid systems than the other two engines.

TABLE 6.4 HYBRID SYSTEM RESULTS

Engine	Drive Cycle	Payload	BISG % Benefit	CISG % Benefit	Parallel % Benefit
Diesel	FTP-Hwy	0%	0.3	0.2	5.8
Diesel	FTP-City	0%	5.8	8.6	29
3.5 V-6	FTP-Hwy	0%	0.8	2.7	5.0
3.5 V-6	FTP-City	0%	7.8	10	25
6.2 V-8	FTP-Hwy	0%	0.1	0.7	6.5
6.2 V-8	FTP-City	0%	7.0	10	30
Diesel	FTP-Hwy	ALVW	0.3	0.9	6.2
Diesel	FTP-City	ALVW	5.6	8.3	29
3.5 V-6	FTP-Hwy	ALVW	0.9	2.8	6.3
3.5 V-6	FTP-City	ALVW	7.7	7.6	25
6.2 V-8	FTP-Hwy	ALVW	1.0	0.8	6.9
6.2 V-8	FTP-City	ALVW	6.1	7.0	30
Diesel	FTP-Hwy	GCW	0.4	1.5	6.3
Diesel	FTP-City	GCW	3.1	5.1	19
3.5 V-6	FTP-Hwy	GCW	0.5	0.9	5.9
3.5 V-6	FTP-City	GCW	4.7	7.1	16
6.2 V-8	FTP-Hwy	GCW	0.7	1.3	7.8
6.2 V-8	FTP-City	GCW	4.7	5.0	21

6.7 Vehicle Parameter Sweeps

Sweeps of several parameters have been conducted on the Ram pickup, the F-650 tow truck, and the T270 box delivery truck. The purpose of the parameter sweeps is to gain an insight into the sensitivity of vehicle fuel consumption to the various parameters considered. The list of parameters tested is:

- Aerodynamic drag coefficient (Cd)
- Tire rolling resistance coefficient (Crr)
- Vehicle empty weight
- Axle ratio

For all 3 vehicles, the axle ratio and empty weight sweeps were performed on all three applicable engines (the 2019 baseline ISB diesel, the baseline 3.5 V-6 turbocharged gasoline, and the baseline 6.2 V-8 gasoline). The aero and rolling resistance sweeps were performed using only the 2019 baseline diesel engine. Note that the baseline diesel engine is different in the Ram pickup than for the medium duty trucks, while the same baseline gasoline engines were used in all three vehicles.

The response to sweeps of Cd and Crr values provided very linear results. For example, a 20% reduction in Cd or Crr provides almost exactly twice the benefit of a 10% reduction. High vehicle speed cycles such as the 65 MPH cruise are most sensitive to changes in Cd, as would be expected. At 65 MPH, fuel savings from a 10% reduction in Cd range from 3.7% in the pickup truck to 5.8% in the T270, which has a frontal area nearly as large as a semi-tractor with a box van trailer. Medium vehicle speed cycles such as 55 MPH cruise and the FTP-Highway cycle are most sensitive to changes in Crr. At 65 MPH, fuel savings from a 10% reduction in Crr range from 1.3% in the pickup truck to 2.3% in the T270. Low vehicle speed stop and go cycles, such as the FTP-City and the Parcel cycle have the lowest sensitivity to both aerodynamic drag and tire rolling resistance. In stop-and-go cycles, a large portion of the engine power is devoted to accelerating the vehicle inertia.

Averaging across all the drive cycles at 50% payload, all three trucks show a similar sensitivity to empty weight reduction. A weight reduction of 3.5% to 4% is required to achieve an average fuel savings of around 1%. For the pickup truck, ALVW was used in this analysis.

Sweeps of rear axle ratios produced the following results:

Fuel consumption is not sensitive to axle ratio on low vehicle speed drive cycles, but at higher vehicle speeds, tall axles (numerically low ratios) save fuel.

The V-6 gasoline engine was generally less sensitive to axle ratio changes, while the V-8 was most sensitive.

The ability of the vehicle to maintain speed on a grade is very sensitive to axle ratio. Shorter (numerically high ratios) can handle steeper grades.

In general, the baseline axle ratios chosen for the project provide a reasonable combination of fuel consumption and grade capability. The one exception is the gasoline V-8, which could benefit from a slightly taller axle ratio

6.8 Vocational Truck Performance and Fuel Consumption

Before October 2005, diesel fuel was typically less expensive than gasoline. From October 2005 to the end of 2014, diesel averaged 23.8 cents per gallon higher than gasoline, with many large fluctuations in the price difference. By the end of 2014, diesel was a record 82 cents per gallon higher than diesel. This fuel price difference, combined with the potential of gasoline engine technologies that can improve the performance and reduce the fuel consumption penalty of gasoline engines, means that gasoline engines may become very attractive for heavy duty pickup trucks and medium duty trucks up through Class 7. Technologies are becoming available which will reduce the fuel consumption and durability penalties of gasoline engines relative to diesel, and gasoline engines will retain a substantial initial cost advantage.

The fuel consumption of vocational trucks tends to be less sensitive to Cd and Crr than is typical for a long-haul truck. Smaller frontal areas and lower speed duty cycles reduce sensitivity to Cd. Transient drive cycles reduce the sensitivity to Crr. There may be significant opportunities to reduce the power demand of engine-driven accessories in vocational trucks, such as the engine cooling fan and hydraulic driven auxiliaries. There are also opportunities worth exploring with start/stop systems, which are outside the scope of this report.

6.9 Natural Gas Vehicle Cost Survey

The cost of natural gas conversions from gasoline power for pickups and vans is typically in the range of ten to twelve thousand dollars. The upcharge for switching from diesel to natural gas in heavy-duty trucks is much higher: $37,000 to over $66,000 in our survey. A large portion of this cost is for the fuel storage system, which is much larger and more complex than a diesel fuel tank. In addition to the cost penalty, natural gas powered vehicles are heavier and sometimes less aerodynamic (because of the fuel storage system), and natural gas engines have a lower thermal efficiency than a diesel.

To provide a financial justification for buying a natural gas powered truck, there needs to be a large difference in price between conventional fuel and natural gas. As late as June 2014, when oil was over $100 per barrel, natural gas enjoyed a very attractive price difference compared to diesel or gasoline. By January 2015, the natural gas pump fuel price advantage has disappeared for gasoline, and has been reduced by more than half for diesel fuel. Natural gas pump prices are much less sensitive to well head prices than liquid fuels are to the price of crude oil. This means that natural gas can offer more price stability than oil-based fuels. However, at January 2015 oil prices, there is no way to achieve payback on the additional cost of a natural gas powered truck. Interest in converting to natural gas appears likely to be a strong function of crude oil prices, so interest is likely to wane in 2015, unless/until oil prices go back up.

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APPENDIX A

GASOLINE ENGINE TECHNOLOGY COMBINATIONS

GASOLINE ENGINE TECHNOLOGY COMBINATIONS

Objective: Simulate future gasoline engine technology combinations to demonstrate fuel economy improvement potential in Class 2b through 7 vehicles utilizing:

3.5L V6 turbocharged, direct injected gasoline engine

6.2L naturally aspirated, port injected V8 engine

1. **3.5L V6 turbo combination of technologies evaluation plan:**
   - **1.1. VVA/VVL with EGR Combo (Package 16)**
   - **1.2. VVA/VVL/EGR/Down speed Combo (Package 17)**
   - **1.3. VVA/VVL/Lean/EGR Combo (Package 18)**
   - **1.4. EGR/Down speed Combo (Package 19)**

2. **6.2L naturally aspirated V8 combination of technologies evaluation plan**
   - **2.1. Cylinder Deactivation/GDI/EGR/FMEP Combo (Package 20)**
   - **2.2. VVA/VVL/Cylinder Deactivation/GDI/EGR/FMEP Combo (Package 21)**
   - **2.3. VVA/GDI/EGR/FMEP Combo (Package 22)**
   - **2.4. Cylinder Deactivation/GDI/EGR Combo (Package 23)**
   - **2.5. GDI/EGR/FMEP Combo (Package 24)**

1 3.5L V6 turbo combination of technologies evaluation plan:

1.1 VVA/VVL with EGR Combo (Package 16)

- **Combo Benefits**
  - Reduced pumping losses (reduced or eliminated throttling)
  - Improved working fluid thermodynamic properties from EGR
  - Improved knock tolerance
    - Improved combustion phasing
    - Increased compression ratio
  - Reduce heat transfer
  - Eliminate enrichment for catalyst protection
- **Additional Components include:**
  - EGR Valves
  - EGR Cooler
  - High Energy Ignition
  - Special cams and actuators to allow for variable valve lift

Variable valve lift allows for improvement in efficiency during part load or "normally" throttled conditions. By closing the intake valve early and allowing the cylinders to pull a vacuum on the downward stroke, some of the energy is recovered as the piston comes back up. This is more evident at higher engine speeds, and the benefit phases out as load increases. Special cam actuators are required to allow for variable lift and phasing as shown in Report #1, Appendix A, Section 1.2. As the valve lift and duration are shortened, the in-cylinder charge motion may be affected negatively. This could cause unstable combustion at the low lift, or low load conditions. If the engine has two intake valves per cylinder, a potential solution might be to vary the lift on one valve much more than the other to keep the velocity high through at least one of the intake ports during low load operation. For the purposes of this simulation effort, charge motion was assumed not to be affected.

SwRI's High Efficiency Dilute Gasoline Engine (HEDGE) consortium has proven that engines with exhaust gas recirculation (EGR) show large benefits in efficiency and emissions. EGR engines require an EGR cooler and valve to recirculate the exhaust gasses, and a high energy ignition system to ignite the dilute mixture. EGR allows for less throttling at part loads and allows for stoichiometric operation throughout the engine operating range.

The VVA/VVL with EGR Combo model is a modified version of the EGR model from Report #1, Appendix A, section 1.5. The intake throttle was removed and the load was controlled by varying intake valve lift. Intake valve duration was a mathematical function of the lift that attempted to emulate a realistic VVL system. In addition to the variable valve lift, the intake and exhaust cams have independent phasing capability. To optimize fuel efficiency, more than 1400 intake and exhaust timing combinations were run for the 78 point test matrix.

Variable valve lift with EGR allows for improvement in BSFC at throttled conditions. The benefit is more evident at higher engine speeds, and it phases out as load increases. EGR not only aids in the throttled areas by improving the properties of the working fluid, but continues to improve BSFC in the mid to high load regions, where enrichment is avoided. Shown below are the BSFC and BSFC improvement over the baseline V-6 engine contour maps.

Gray area is less than -30%. Peak is -44%

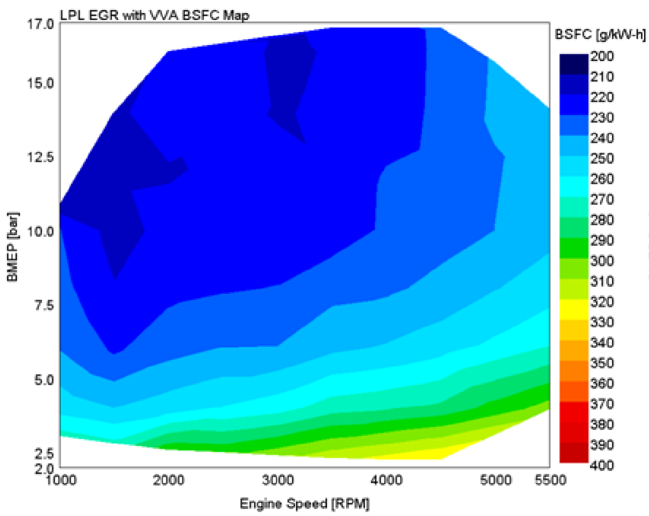


Figure A1 VVA/VL/EGR BSFC Map

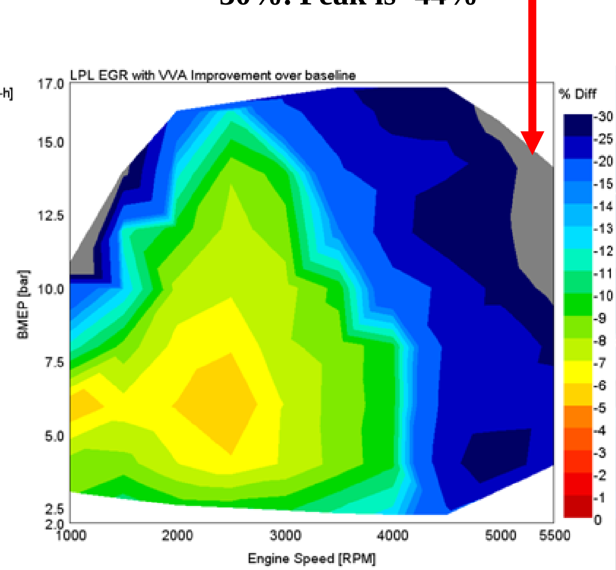


Figure A2 BSFC Improvement over Baseline

1.2 VVA/VVL/EGR/Down speed Combo (Package 17)

- **Combo Benefits**
  - Reduced pumping losses (reduced or eliminated throttling)
  - Improved working fluid thermodynamic characteristics from EGR
  - Improved knock tolerance
    - Improved combustion phasing
    - Increased compression ratio
  - Reduce heat transfer
  - Eliminate enrichment for catalyst protection
- **Additional Components include:**
  - EGR Valves
  - EGR Cooler
  - High Energy Ignition
  - Special cams and actuators to allow for variable valve lift
  - Improved cylinder pressure capability to allow higher BMEP

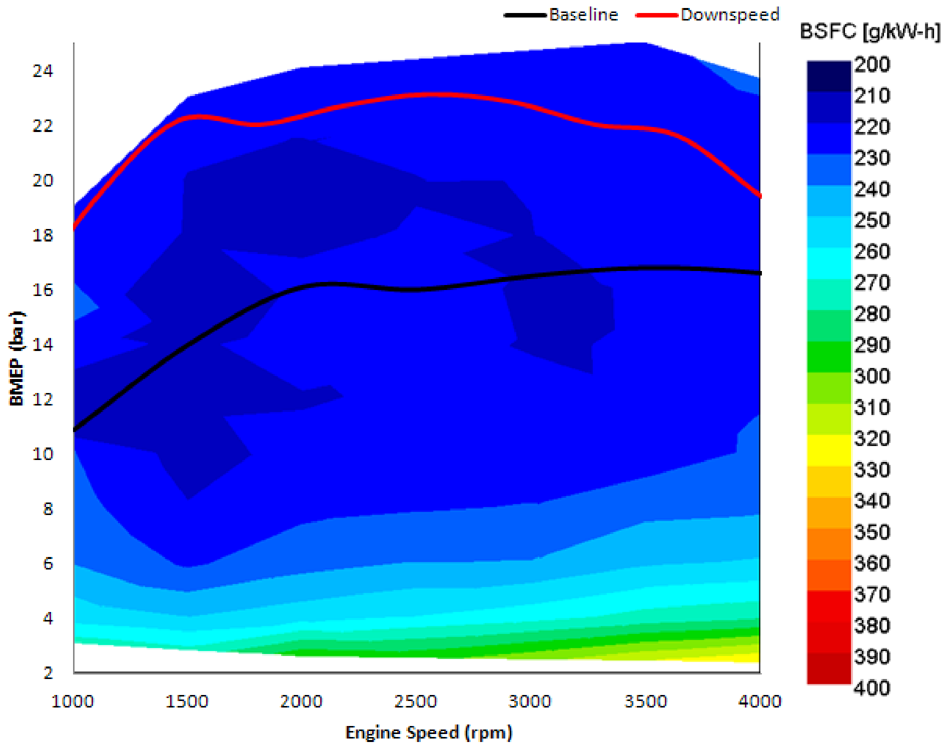


FIGURE A3 BMEP COMPARISON OF STANDARD AND DOWN SPEED TORQUE CURVES

A model based on the section 1.1 VVA/VVL/EGR Combo Package 16 engine model was developed to down speed the engine from 5,500 RPM rated to 4,000 RPM, while maintaining the same peak power. To accomplish this, the BMEP requirement of the engine becomes greater, as demonstrated by the red line in Figure A3 above. The model was allowed to run to even higher loads (areas above red line), but the final torque curve and fuel map was limited to keep the power levels the same as the baseline V-6 and to keep the maximum cylinder pressures below 105 bar. The baseline V-6 engine torque curve is shown by the black curve in Figure A3, while the Combo 2 torque curve is shown by the red curve.

Combo 17 does not affect the BSFC compared to Combo 16, except for an extension of the map to higher BMEP levels and the elimination of operation above 4,000 RPM. The vehicle level fuel savings comes from meeting a specific vehicle power demand at a lower engine speed, and thus at a higher BMEP. This effect is especially important under light load conditions, where BSFC is very sensitive to BMEP. There is a penalty when idling with an automatic transmission, however. This is because the lower speed, higher torque engine rating requires a tighter torque converter match. This drives a higher idle stall torque, and thus higher idle fuel consumption.

1.3 VVA/VVL/Lean/EGR Combo (Package 18)

- **Combo Benefits**
  - Reduced pumping losses (reduced or eliminated throttling)
  - Improved working fluid thermodynamic characteristics from EGR
  - Improved knock tolerance
    - Improved combustion phasing
    - Increased compression ratio
  - Reduce heat transfer
  - Eliminate enrichment for catalyst protection
  - Improved combustion efficiency during lean operation
- **Additional Components include:**
  - EGR Valves
  - EGR Cooler
  - High Energy Ignition
  - Special cams and actuators to allow for variable valve lift
  - SCR Catalyst/Lean NOx Trap
  - NOx sensor
  - Urea injector
  - Urea mixer
  - Exhaust gas temperature sensor

Lean burn operation can improve engine efficiency by reducing throttling losses and increasing combustion efficiency due to excess oxygen. To operate lean, additional components, such as a lean NOx traps and/or SCR systems, NOx sensors and Piezo fuel injectors for precise multiple injections will be needed. Some of the potential issues with operating in lean mode include degradation of the lean NOx traps at high load/temperature conditions, and using US fuels with high sulfur content. Both high temperature and high sulfur content will lead to a shortened life of the aftertreatment. There is the potential that future (post – 2017) US gasoline fuel quality specifications will reduce sulfur content, and thus minimize the damage caused by sulfur in the fuel, but that is not presently the case.

This engine model configuration has three operating modes, stratified lean mixture, homogeneous lean mixture, and stoichiometric EGR operation. Shown below in Figure A4, the engine operates at low speed/load, medium speed/load, and high load in stratified lean, homogeneous lean, and homogeneous stoichiometric modes respectively. Near full load, the engine operates with EGR which allows stoichiometric operation with the use of a three-way catalyst.

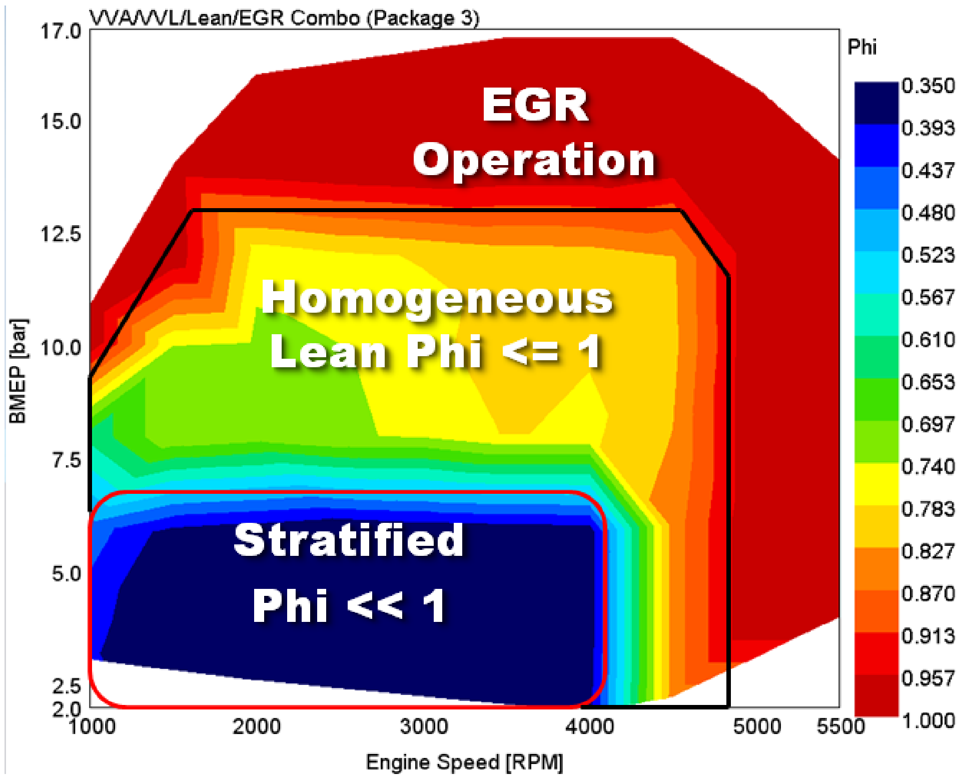


Figure A4 Package 3 Engine Operating Modes

The engine efficiencies for the three combustion modes were combined and a composite engine operating map was generated. Figures A5 and A6 show the composite engine BSFC map, and the percent BSFC improvement over the baseline V-6 engine.

Gray area is less than -30%. Peak is -44%

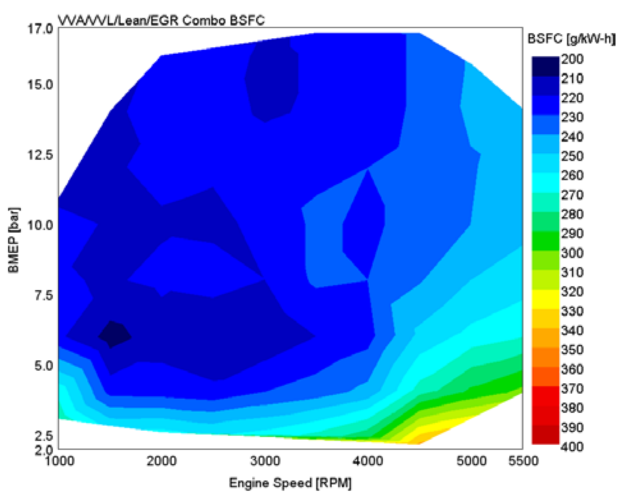


FIGURE A5 COMBINED BSFC MAP

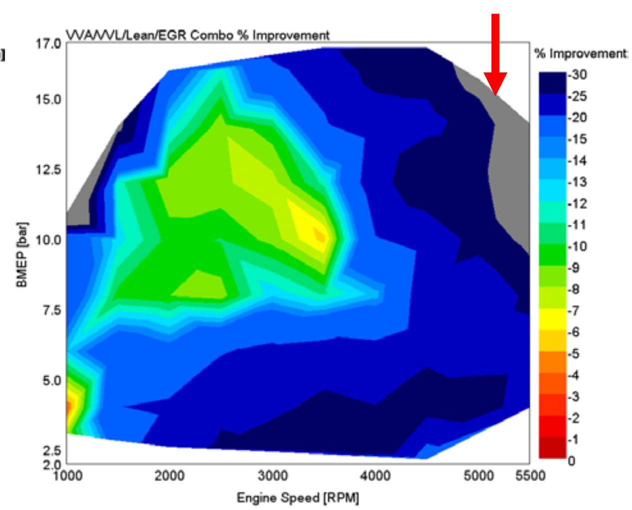


FIGURE A6 BSFC IMPROVEMENT OVER BASELINE

1.3 EGR + Down Speed (Package 19)

This package was already presented in Report #1. See Appendix A, Sec. 1.6 of Report #1.

2 6.2L naturally aspirated V8 combination of technologies evaluation plan

2.1 Cylinder Deactivation/GDI/EGR/FMEP Combo (Package 20)

- **Four Cylinder Deactivation. Examples include GM "Active Fuel Management" (pushrod engines) and Audi "cylinder on demand" (OHC engines). Honda has a system for OHC engines called "variable cylinder management".**
  - Eliminates pumping losses in deactivated cylinders
  - Deactivation of every second cylinder by firing order (1 5 4 8 6 3 7 2)
  - Reduced pumping losses in active cylinders (less throttling)
  - Reduced energy loss from deactivated valves
  - Possible at loads up to about 4 bar BMEP

- **GDI conversion**
  - Allows for in-cylinder charge cooling and better fuel control
  - Higher power output is available (but not used in this project)
  - Allows higher compression ratio
  - Requires higher parasitic power for fuel pump (disadvantage)

- **EGR Benefits**
  - Reduced pumping losses
  - Improved working fluid thermodynamic characteristics from EGR
  - Improved knock tolerance
    - Improved combustion phasing
    - Increased compression ratio
  - Reduce heat transfer
  - Eliminate enrichment for catalyst protection
- **Additional Components include:**
  - Special cams and actuators to allow for valve deactivation
  - Active Engine mounts/dampers
  - Special exhaust to handle 2nd and 4th order
  - High pressure pump
  - High pressure injectors
  - High pressure fuel lines
  - High voltage electronics
  - EGR Valves and Cooler
  - High Energy Ignition
  - Modifications to bores, rings, valve train, and bearings to reduce friction
  - Variable speed/variable displacement oil and/or water pumps

Engines that have eight cylinders have demonstrated operation with four cylinder deactivation such as General Motors Active Fuel Management and Audi Cylinder on Demand.

The engine at idle conditions will operate on all eight cylinders to minimize vibration, but between idle and approximately four bar BMEP, four cylinders will cut fuel injection and valve actuation. The EGR engine model from Report #1, Appendix A, Section 2.6 was modified to allow for cylinder deactivation and a 10% FMEP reduction and was run up to the maximum load the four-cylinder would allow, four bar BMEP (see Figure A7) and the areas that were less efficient than the baseline eight-cylinder operation were removed (see Figure A8). Loads above four bar BMEP will transition back to eight-cylinder operation.

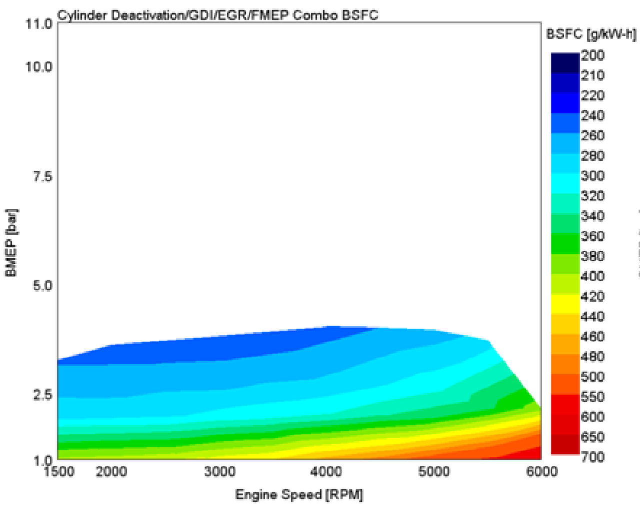


FIGURE A7 CYL. DEACT BSFC MAP

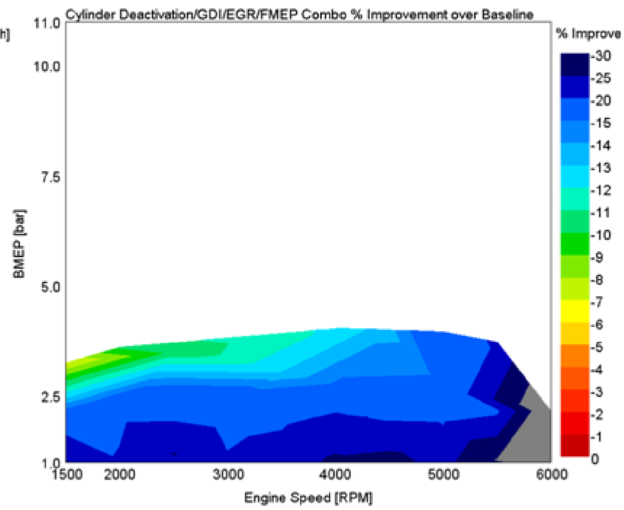


FIGURE A8 BSFC IMPROVEMENT OVER BASELINE

For loads greater than four bar BMEP, the engine turns on all eight cylinders with EGR and FMEP reduction. The combined maps can be seen below in Figures A9 and A10.

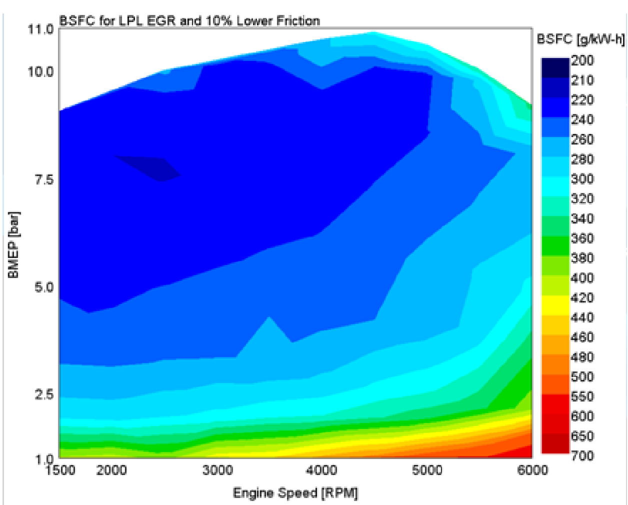


FIGURE A9 COMBINED BSFC MAP

Gray area is less than -30%. Peak is -36%

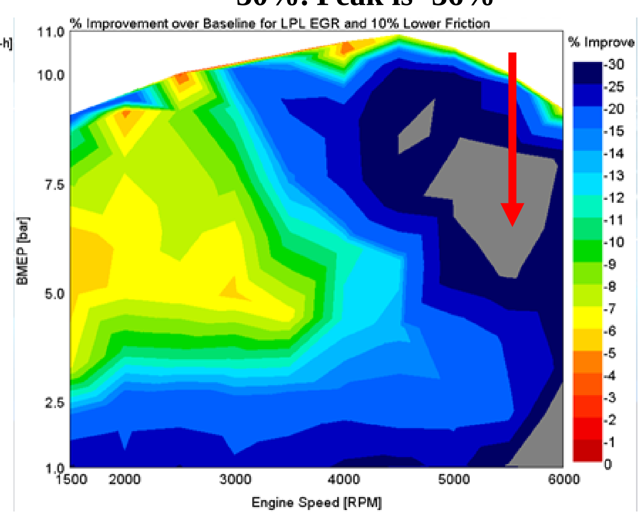


FIGURE A10 BSFC IMPROVEMENT

2.2 VVA/VVL/Cylinder Deactivation/GDI/EGR/FMEP Combo (Package 21)

- **Variable Valve Lift (VVL) and Phasing**
  - Reduced pumping losses (reduced or eliminated throttling)
- **Four Cylinder Deactivation. GM Active Fuel Management (pushrod engines) and Audi cylinder on demand (OHC engines)**
  - Eliminates pumping losses in deactivated cylinders
  - Deactivation of every second cylinder by firing order (1 5 4 8 6 3 7 2)
  - Reduced pumping losses in active cylinders (less throttling)
  - Reduced energy loss from deactivated valves
  - Possible at loads up to 4 bar BMEP

- **GDI conversion**
  - Allows for in-cylinder charge cooling
  - Better Fuel control
  - Higher power output is available (but not used in this project)
  - Allows higher compression ratio
- **EGR Benefits**
  - Reduced pumping losses
  - Improved working fluid thermodynamic characteristics from EGR
  - Improved knock tolerance
    - Improved combustion phasing
    - Increased compression ratio
  - Reduce heat transfer
  - Eliminate enrichment for catalyst protection
- **Additional Components include:**
  - Special cams and actuators to allow for valve deactivation
  - Active Engine mounts/dampers
  - Special exhaust to handle 2nd and 4th order
  - High pressure pump
  - High pressure injectors
  - High pressure fuel lines
  - High voltage electronics
  - EGR Valves
  - EGR Cooler
  - High Energy Ignition
  - Modifications to bores, rings, valve train, and bearings to reduce friction
  - Variable speed/variable displacement oil and/or water pumps

The configuration for Section 4.2 (Package 21) is similar to that in Section 4.1 (Package 20), but Package 21 has the added feature of variable valve lift and independent cam phasers. As stated previously, variable valve lift (VVL) allows for improvement in efficiency during part load or "normally" throttled conditions. By closing the intake valve early and allowing the cylinders to pull a vacuum on the downward stroke, some of the energy is recovered as the piston comes back up. The benefit is more evident at higher engine speeds, and it phases out as load increases. Special cam actuators are required to allow for variable lift and phasing as shown in Figure A 46 from Appendix A of Report #1. As the valve lift and duration are shortened, the in-cylinder charge motion may be affected negatively and cause unstable combustion at the low lift, or low load conditions. If the engine has two intake valves per cylinder, a potential solution for might be to vary the lift on one valve much more than the other to keep the velocity high through at least one of the intake ports during low load operation. For the purposes of this model, given the fact that this engine only has one intake valve, charge motion was assumed not to be affected.

The variable valve lift added model is a modified version of the model used in section 4.1 (Package 20). The throttle was removed and the load was controlled by the intake valve lift. Intake valve duration was a mathematical function of the lift that attempted to emulate a realistic VVL system. In addition to the variable valve lift, the intake and exhaust cams are now have independent phasing capability. To optimize fuel efficiency, more than 1300 intake and exhaust timing combinations were run for the 82 point test matrix. Variable valve lift allows for improvement in BSFC at throttled conditions which is more evident at higher engine speeds, but the benefit phases out as load increases. Figure A11 below shows the new engine BSFC map, while Figure A12 shows the percentage improvement in BSFC against the baseline engine.

Gray area is less than -30%. Peak is -41%

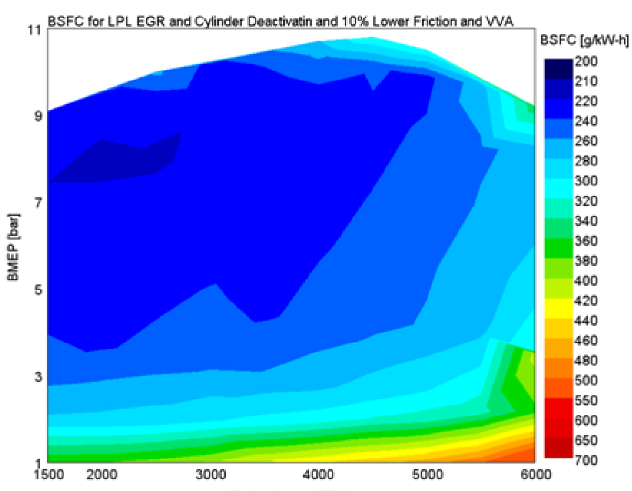


FIGURE A11 PACKAGE 2 COMBINED BSFC MAP

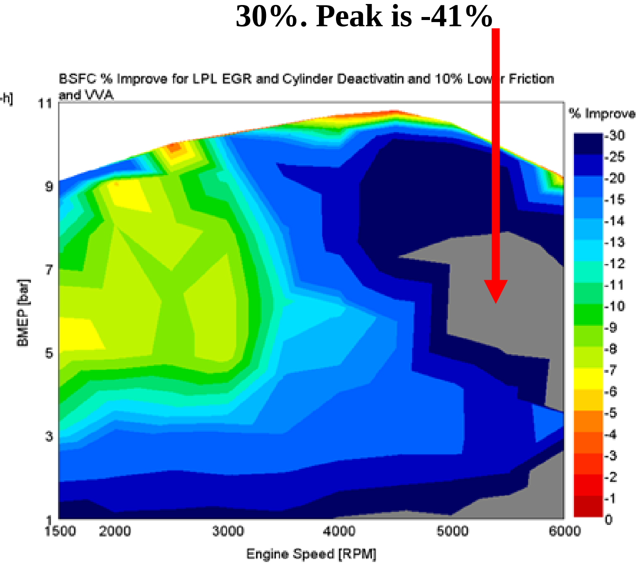


FIGURE A12 BSFC IMPROVEMENT OVER BASELINE

2.3 VVA/GDI/EGR/FMEP Combo (Package 22)

- **Independent Variable Valve Actuation (VVA)**
  - Optimal intake and exhaust valve phasing
- **GDI conversion**
  - Allows for in-cylinder charge cooling
  - Better Fuel control
  - Higher power output is available (but not used in this project)
  - Allows higher compression ratio
- **EGR Benefits**
  - Reduced pumping losses
  - Improved working fluid thermodynamic characteristics from EGR
  - Improved knock tolerance
    - Improved combustion phasing
    - Increased compression ratio
  - Reduce heat transfer
  - Eliminate enrichment for catalyst protection
- **Additional Components include:**
  - Independent cam actuators
  - Dual overhead cam or cam in cam technology
  - High pressure fuel pump
  - High pressure fuel injectors
  - High pressure fuel lines
  - High voltage electronics
  - EGR Valves
  - EGR Cooler
  - High Energy Ignition
  - Modifications to bores, rings, valve train, and bearings to reduce friction
  - Variable speed/variable displacement oil and/or water pumps

This technology combination is a lower cost package than Packages 20 and 21. The model from Section 2.1 (Package 20) was modified to run on all eight cylinders full time, and standard full valve lift operation is used. The throttle was reinstalled to control engine load and a second valve phaser was added to independently phase the exhaust cam. To optimize fuel efficiency, more than 4000 intake and exhaust timing combinations were run for the 82 point test matrix. Shown below in Figure A13 is the final intake and exhaust valve timing for the 82 speed/load conditions.

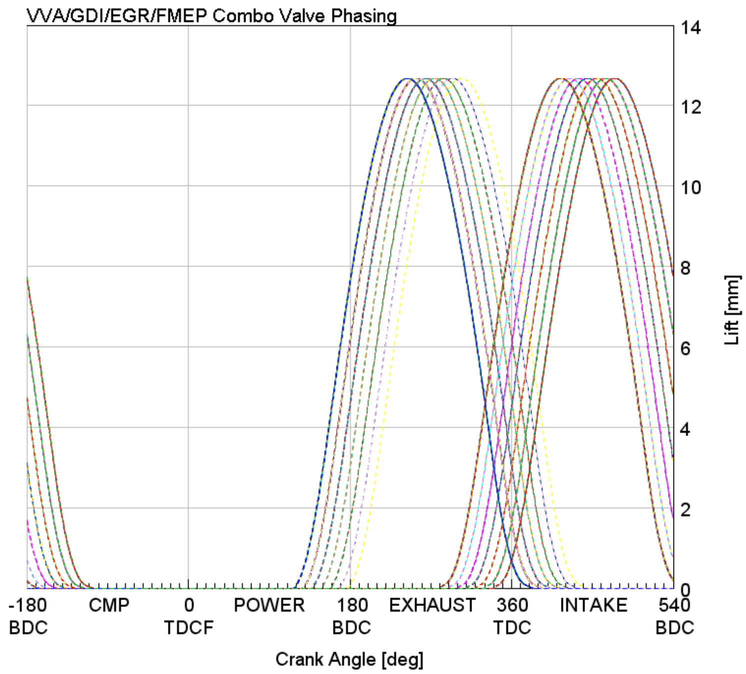


FIGURE A13 6.2L V8 INDEPENDENT CAM PHASING

Independent variable valve actuation allows for further improvement in BSFC with EGR and reduced PMEP by allowing optimized operation at every point. In addition, the ability to increase valve overlap will allow internal EGR to be trapped more effectively at low load conditions. Shown below in Figures A14 and A15 are the Package 4 BSFC map, and the BSFC improvement over the baseline V-8 engine.

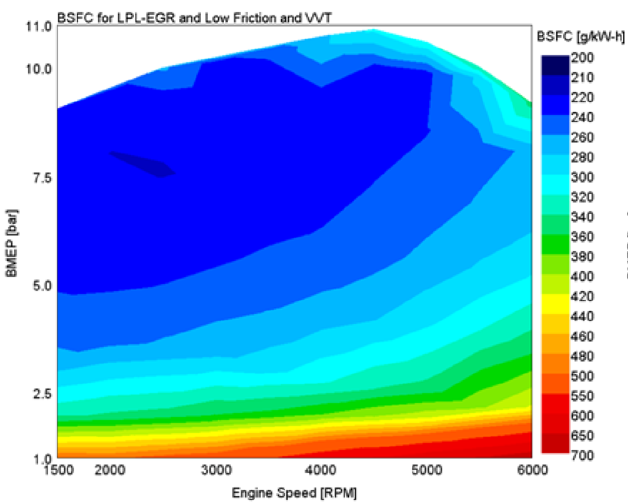


FIGURE A14 PACKAGE 4 COMBINED BSFC MAP

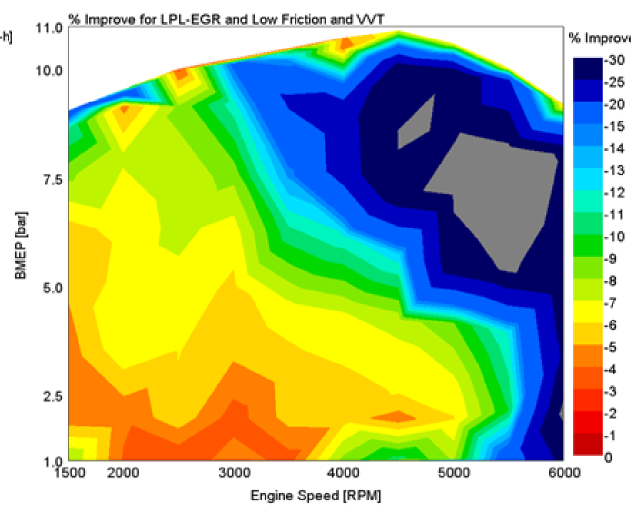


FIGURE A15 BSFC IMPROVEMENT OVER BASELINE

2.4 Cylinder Deactivation/GDI/EGR Combo (Package 23)

- **Four Cylinder Deactivation. GM Active Fuel Management (pushrod engines) and Audi cylinder on demand (OHC engines)**
  - Eliminates pumping losses in deactivated cylinders
  - Deactivation of every second cylinder by firing order (1 5 4 8 6 3 7 2)
  - Reduced pumping losses in active cylinders (less throttling)
  - Reduced energy loss from deactivated valves
  - Possible at loads up to 4 bar BMEP

- **GDI conversion**
  - Allows for in-cylinder charge cooling
  - Better Fuel control
  - Higher power output is available (but not used in this project)
  - Allows higher compression ratio
- **EGR Benefits**
  - Reduced pumping losses
  - Improved working fluid thermodynamic characteristics from EGR
  - Improved knock tolerance
    - Improved combustion phasing
    - Increased compression ratio
  - Reduce heat transfer
  - Eliminate enrichment for catalyst protection
- **Additional Components include:**
  - Special cams and actuators to allow for valve deactivation
  - Active Engine mounts/dampers
  - Special exhaust to handle 2nd and 4th order
  - High pressure fuel pump
  - High pressure fuel injectors
  - High pressure fuel lines
  - High voltage electronics
  - EGR Valves
  - EGR Cooler
  - High Energy Ignition

This Package 23 combines GDI, EGR, and cylinder deactivation. The 6.2 V-8 Package 23 is basically Package 20 with the lower friction features removed. Engines that have eight cylinders have demonstrated operation with four cylinder deactivation, such as General Motors Active Fuel Management and Audi Cylinder on Demand. The engine at idle conditions will operate on all eight cylinders to minimize vibration, but between idle and approximately four bar BMEP, four cylinders will cut fuel injection and valve actuation. The model from Section 2.1 with cylinder deactivation, EGR and FMEP reduction was modified to set the FEMP back to the stock conditions. The model was then run up to the maximum load the four-cylinder would allow, four bar BMEP (see Figure A16), and the areas that were less efficient than the baseline eight-cylinder were removed (see Figure A17). Loads above four bar BMEP will transition back to eight-cylinder operation.

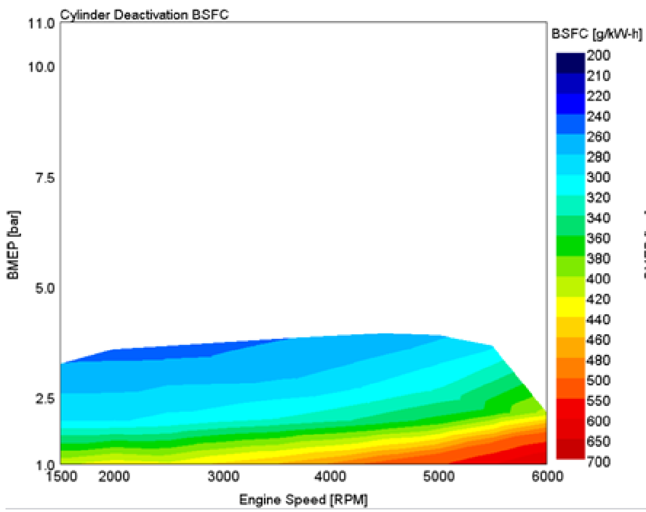


FIGURE A16 CYL. DEACT BSFC MAP

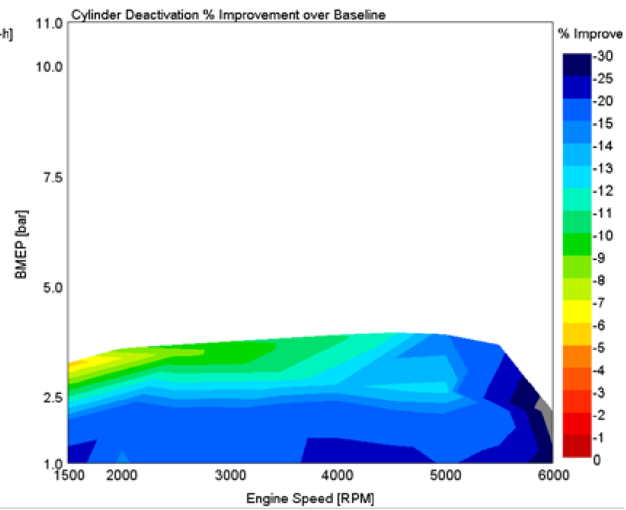


FIGURE A17 BSFC IMPROVEMENT OVER BASELINE

For loads greater than four bar BMEP, the engine turns on all eight cylinders with EGR. The combined maps can be seen below in Figures A 66 and A67.

Gray area is less than -30%. Peak is -34%

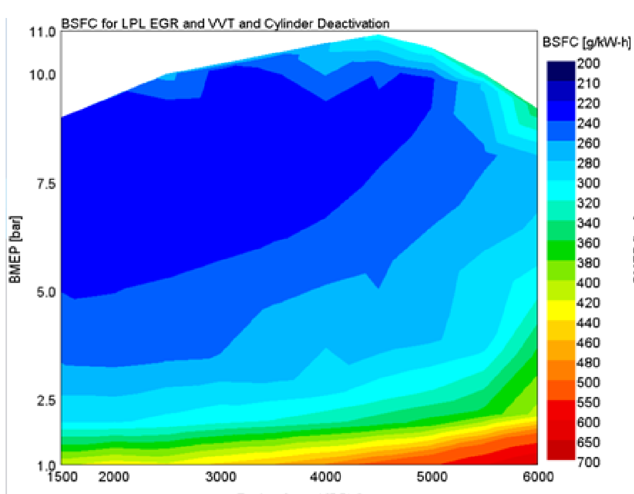


FIGURE A18 PACKAGE 5 COMBINED BSFC MAP

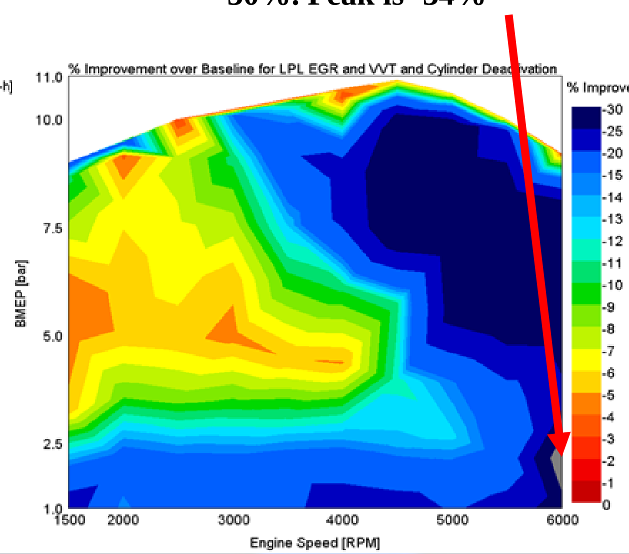


FIGURE A18 PACKAGE 5 COMBINED BSFC MAP

2.5 GDI/EGR/FMEP Combo (Package 24)

- **GDI conversion**
  - Allows for in-cylinder charge cooling
  - Better Fuel control
  - Higher power output is available (but not used in this project)
  - Allows higher compression ratio
- **EGR Benefits**
  - Reduced pumping losses
  - Improved working fluid
  - Improved knock tolerance
    - Improved combustion phasing
    - Increased compression ratio
  - Reduce heat transfer
  - Eliminate enrichment for catalyst protection
- **Additional Components include:**
  - High pressure fuel pump
  - High pressure fuel injectors
  - High pressure fuel lines
  - High voltage electronics
  - EGR Valves
  - EGR Cooler
  - High Energy Ignition

Package 24 for the 6.2 liter V-8 is basically Package 20 with cylinder deactivation removed. A model based on the Report #1, Appendix A, Section 2.6 LPL EGR engine model was modified to represent 10% lower FMEP over the full operating range of the engine.

EGR flow rates were defined as follows: at low speed and light load, 12% EGR is used. At high speed light load, 15 % EGR is used. Under full load, EGR is 15% at low speed, increasing to 18% at high speed. Linear interpolation is used to determine the EGR rate for any point in the map.

Intake cam phasing was altered from baseline cam timing to an EGR optimized cam timing based upon SwRI's EGR experience. At low loads more cam overlap is used with normal to late intake valve closing. Mid loads used low overlap and later intake valve closing. High loads operated at best volumetric efficiency positions with normal to high overlap and normal intake valve closing.

The Package 24 engine BSFC map is shown in Figure A20, and the percent BSFC improvement map is shown in Figure A21.

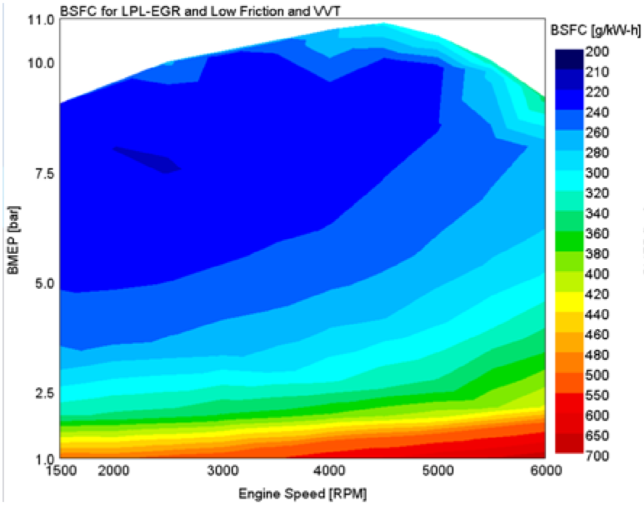


FIGURE A20 PACKAGE 7 COMBINED BSFC MAP

Gray area is less than -30%. Peak is -31%

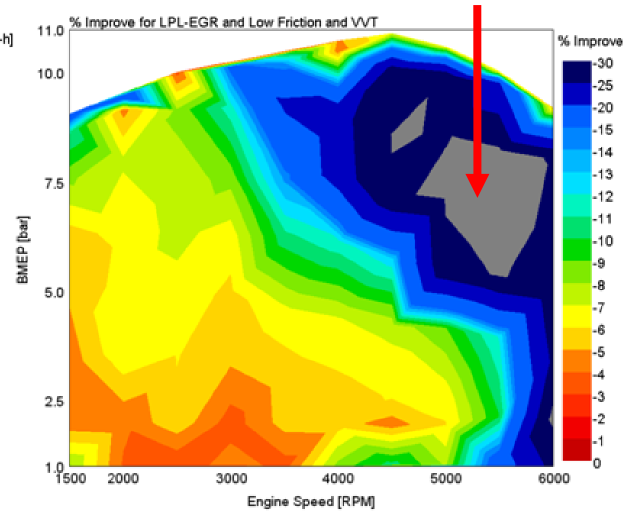


FIGURE A21 BSFC IMPROVEMENT OVER BASELINE

APPENDIX B

DIESEL ENGINE TECHNOLOGY COMBINATIONS

DIESEL ENGINE TECHNOLOGY COMBINATIONS

Objective: Simulate Future Diesel Engine Technologies to demonstrate Fuel Economy Improvement Potential in Class 2b through 7 vehicles utilizing:

- **14.6L turbocharged diesel engine**
- **6.7L VG turbocharged Medium Duty 300 bhp diesel engine**
- **6.7L VG turbocharged Pick Up 385 bhp diesel engine**

1. 15L turbocharged diesel engine combo evaluation plan:

1.1. **2019 Baseline Engine: Improved combustion**
1.2. **Combination Package 1: 2019 Baseline + engine friction reduction**
1.3. **Combination Package 2: 2019 Baseline + Downspeed, limited friction reduction**
1.4. **Combination Package 3: Package 2 + waste heat recovery systems**
1.5. **Combination Package 4: High efficiency turbo, no turbocompound, no EGR, engine friction reduction**
1.6. **Combination Package 5: Downspeed, reduced exhaust and inlet restrictions, limited friction reduction**

2. 6.7L VG turbocharged Medium Duty 300 bhp diesel engine combo evaluation plan

2.1. **2019 Baseline Engine: Improved combustion and limited reduced friction**
2.2. **Combination Package 6: 2019 Baseline + Downspeed, limited turbo efficiency increase, limited friction reduction**
2.3. **Combination Package 7: 2019 Baseline + No EGR, turbo efficiency increase, full friction reduction**
2.4. **Combination Package 8: 2019 Baseline + Downspeed, turbo efficiency increase, limited friction reduction, No EGR**
2.5. **Combination Package 9: 2019 Baseline + Limited turbo efficiency increase, full friction reduction**
2.6. **Combination Package 10: 2019 Baseline combustion + Downsized with high torque and EGR, no friction reduction**

3. 6.7L VG turbocharged Pick Up 385 bhp diesel engine combo evaluation plan

3.1. **2019 Baseline Engine: Improved combustion and limited reduced friction**

3.2. **Combination Package 11: 2019 Baseline + Downspeed, limited turbo efficiency increase, limited friction reduction**

3.3. **Combination Package 12: 2019 Baseline + No EGR, turbo efficiency increase, full friction reduction**

3.4. **Combination Package 13: 2019 Baseline + Downspeed, turbo efficiency increase, limited friction reduction, No EGR**

3.5. **Combination Package 14: 2019 Baseline + Limited turbo efficiency increase, full friction reduction**

3.6. **Combination Package 15: 2019 Baseline + Downsized, full friction reduction**

1.1 2019 DD15 Baseline Engine

The original DD15 model with an asymmetric turbo and no APT (which is approximately the build of the 2014 production DD15) was updated to represent what could reasonably be expected to be the future 2019 baseline DD15 engine performance. This was realized by improving the combustion performance, specifically reducing the combustion duration (10-90%) to achieve a 1% improvement in fuel consumption across the speed and load range. All other aspects of the engine specification and performance were kept the same as the original 2013/2014 non-turbocompound baseline DD15 model.

- **2019 Base engine specification**
  - 14.6L inline 6-cylinder diesel
  - Single fixed-geometry turbocharger
  - 4 valves per cylinder
  - 376 kW @1800 rpm
  - 2200 Nm @ 1240-1400 rpm

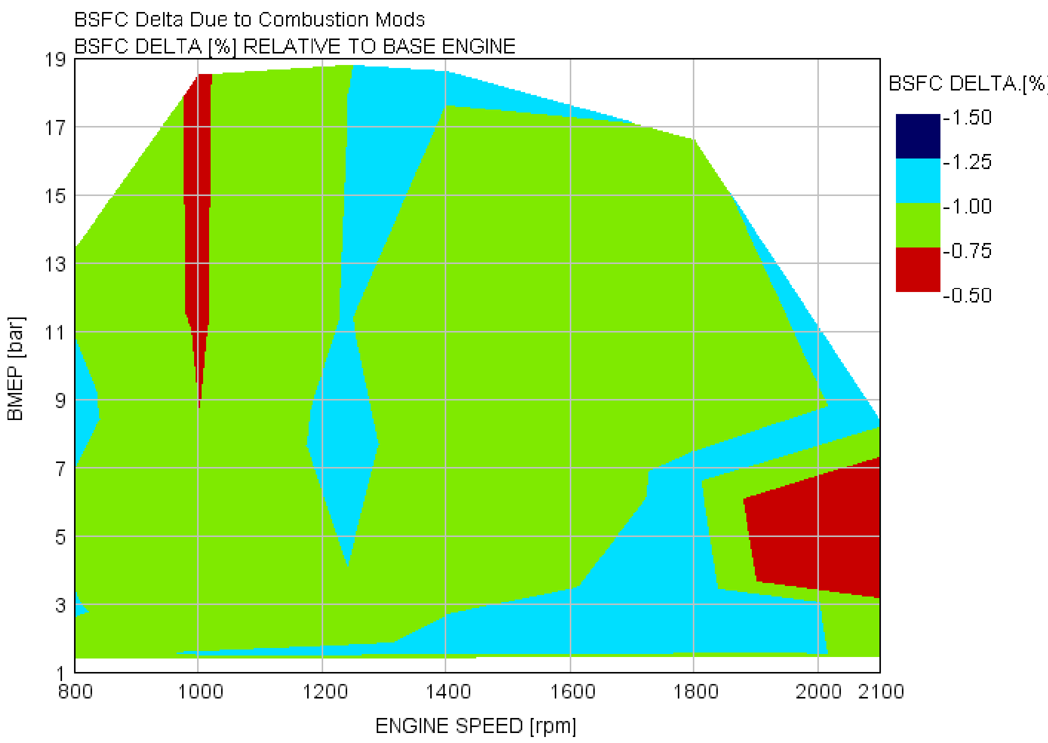


FIGURE B1.1A BSFC IMPROVEMENT DUE TO COMBUSTION MODIFICATION

Figure B1.1a shows the improvement in BSFC due to combustion changes only, for the base engine configuration. The combustion modification was then applied to the asymmetric non APT model.

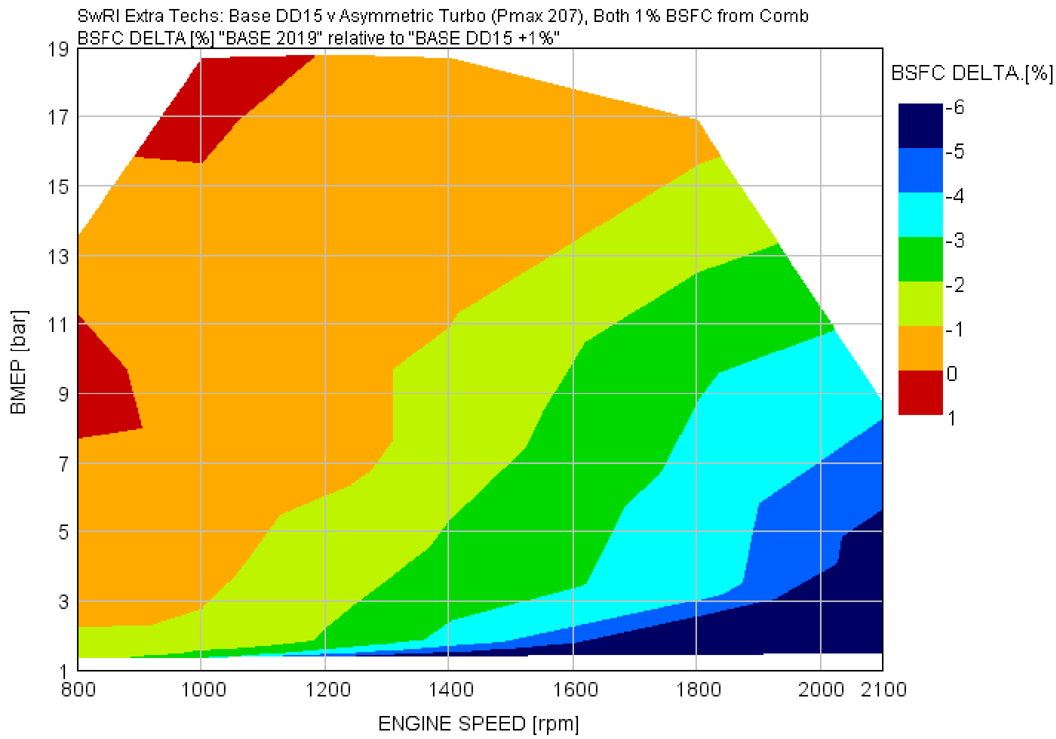


FIGURE B1.1B BSFC IMPROVEMENT OF 2019 BASE DD15 VS. ORIGINAL 2013/2014 NON-TURBOCOMPOUND DD15 (BOTH FEATURING IMPROVED COMBUSTION)

Figure B1.1b shows the improvement in BSFC between the original turbocompound DD15 configuration, including combustion improvement, compared to the 2019 base engine which has asymmetric turbo and improved combustion. The 2019 base engine is then the reference for all the following technology combination packages.

Figure B1.1c shows BSFC comparison of the original baseline DD15 and the 2019 base model. Figure B1.1d shows a summary of the full load performance comparison of the 2 engines, with the 2019 base engine cylinder pressure limit maintained at 207 bar.

Introduction of the asymmetric turbo and removal of turbocompound lead to a significant reduction in pumping work, which helps base engine efficiency, especially at high speed, light load. The 2019 baseline DD15 engine has slightly lower EGR rate at 1200 RPM full load, but the EGR rates match those of the turbocompound baseline at all other speeds and loads.

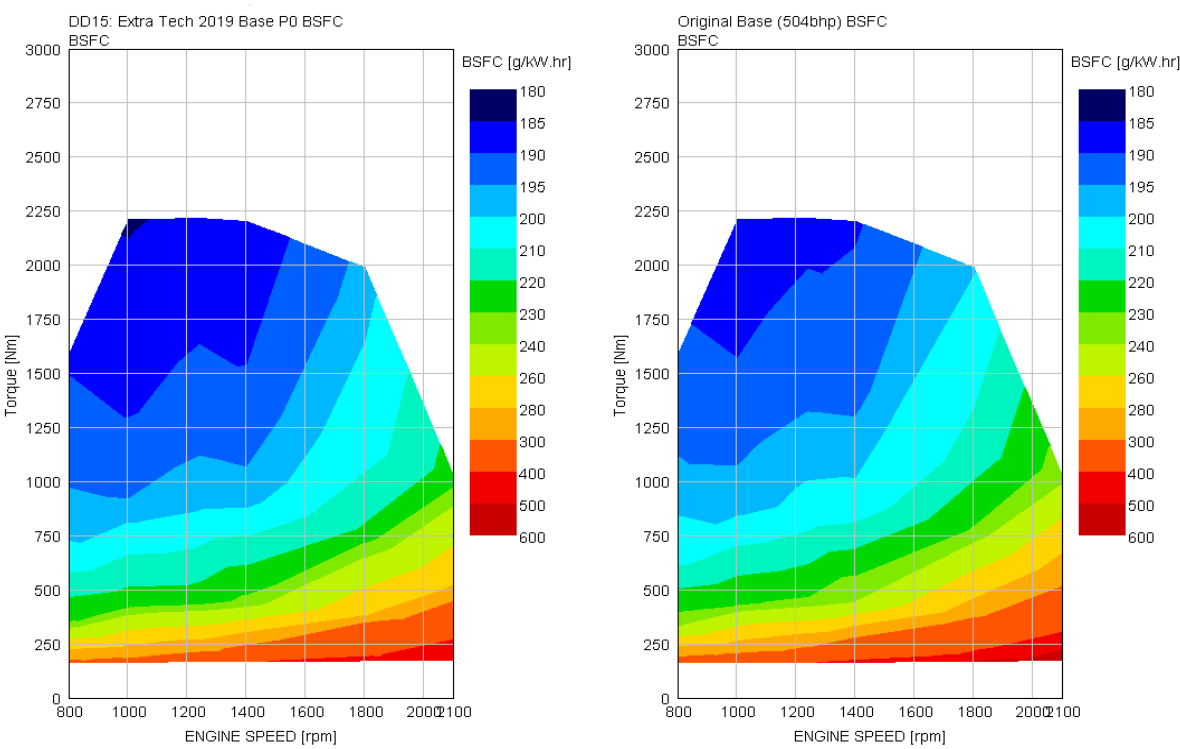


FIGURE B1.1C BSFC COMPARISON OF 2019 BASE DD15 VS. ORIGINAL DD15 (BOTH FEATURING IMPROVED COMBUSTION)

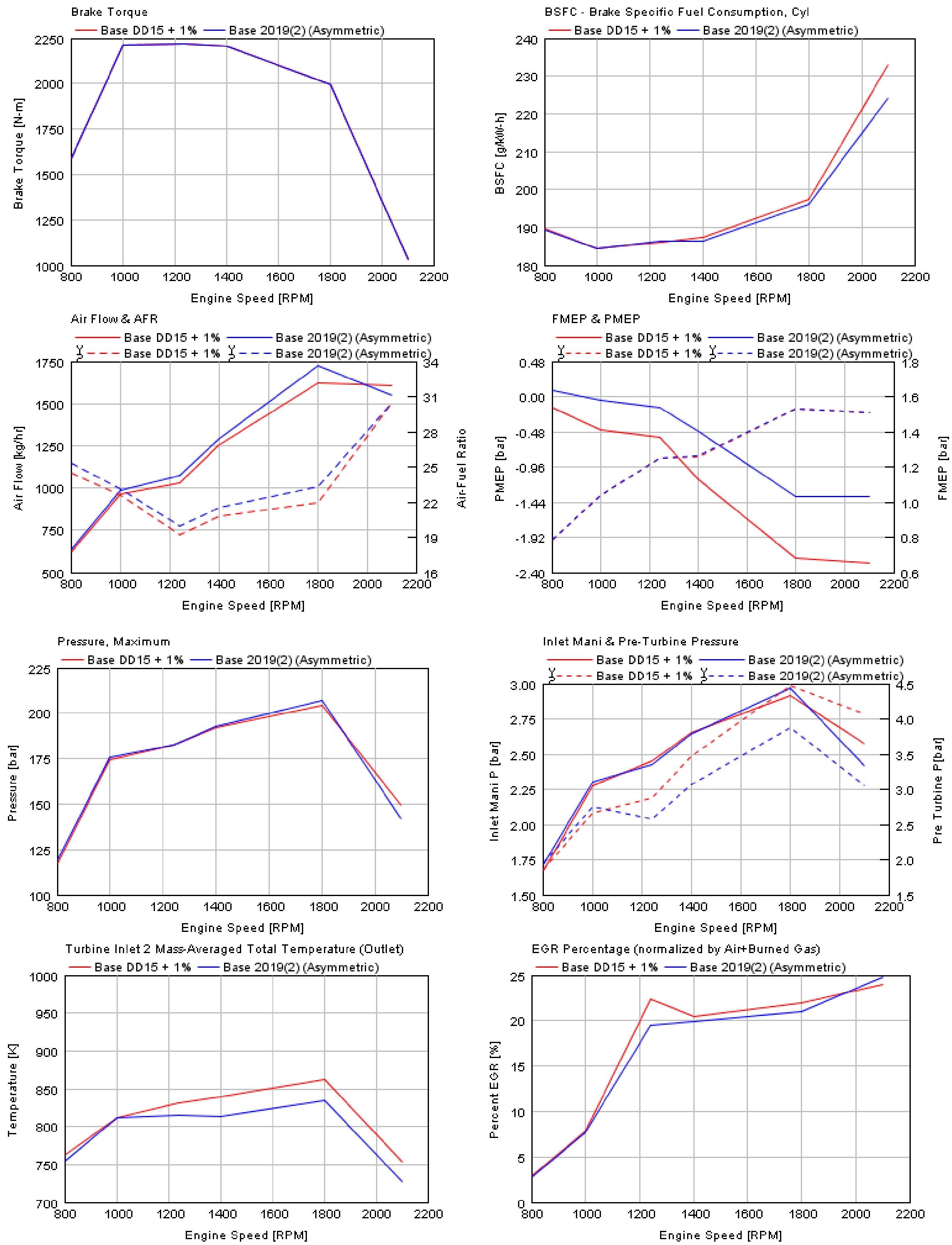


FIGURE B1.1D 2019 BASE ENGINE COMPARISON WITH ORIGINAL DD15 (BOTH FEATURING IMPROVED COMBUSTION)

1.2 DD15 Combination Package 1: Base 2019 + Engine Friction Reduction

Package one assumed that the total engine friction could be reduced significantly on a varying basis depending on the speed and load. The level of friction (FMEP) reduction used was the same as previously applied in Report #1, and the amount is shown in figure B1.2a. All other engine parameters are maintained as the 2019 base engine.

Significant BSFC gains are seen at part load conditions, particularly at lower engine speeds where the friction reduction is higher.

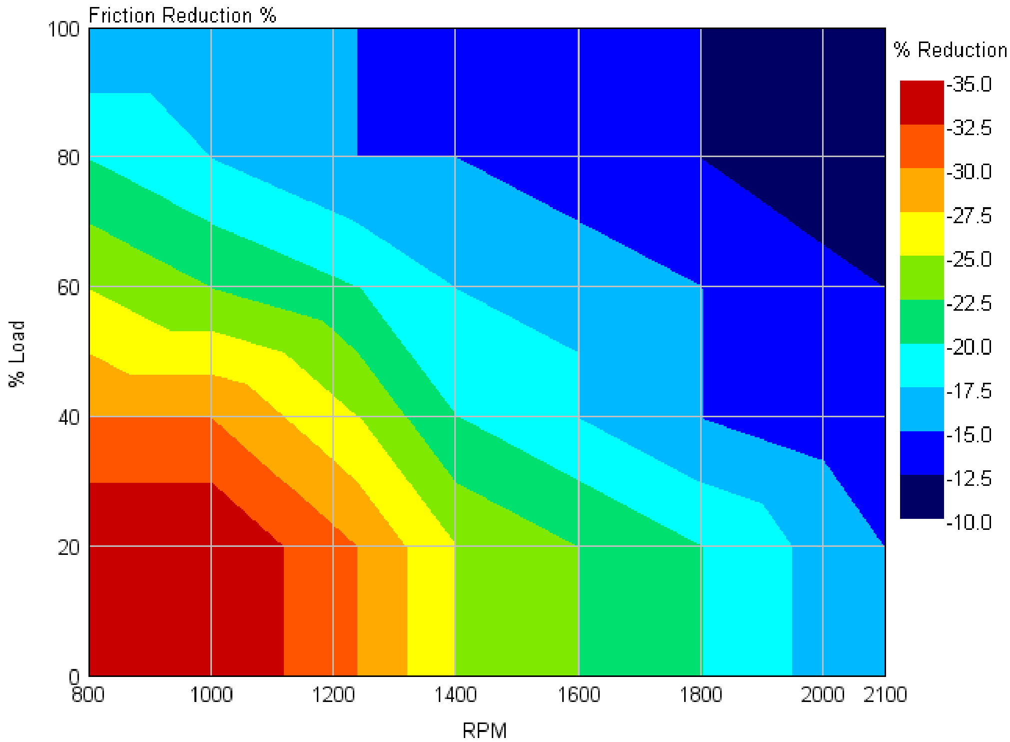


FIGURE B1.2A FRICTION REDUCTION ASSUMPTION

Figures B1.2b, B1.2c and B1.2d show the BSFC improvement and full load performance effect of the reduced engine friction compared to the 2019 Base engine.

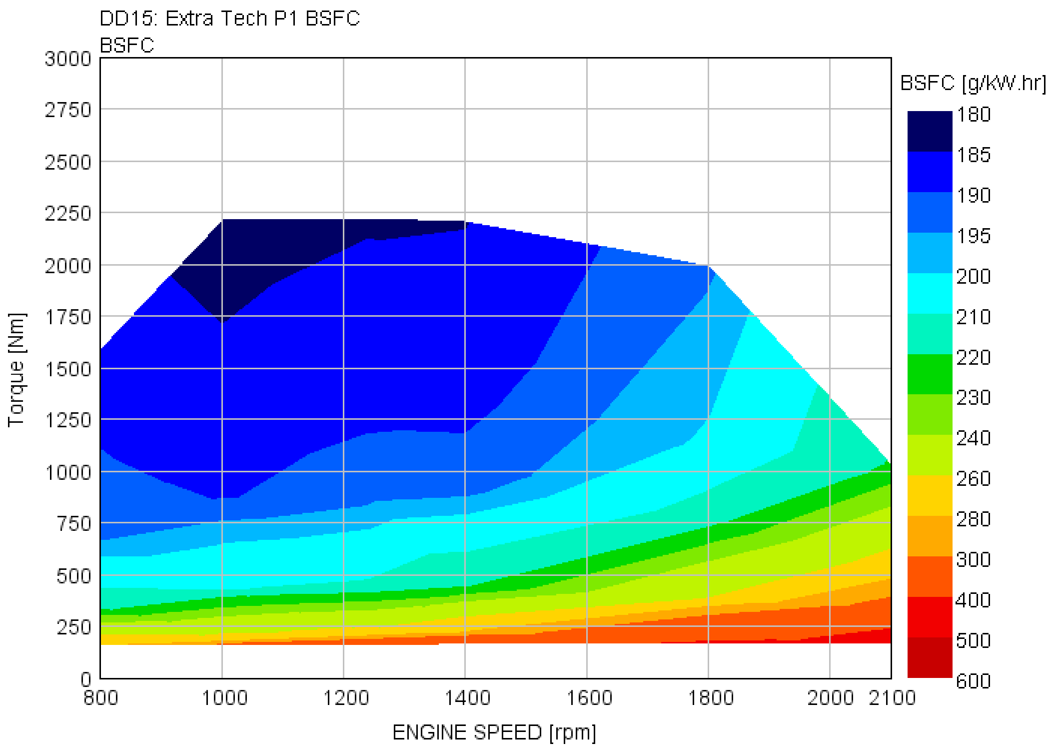


FIGURE B1.2B BSFC MAP OF PACKAGE 1 ENGINE

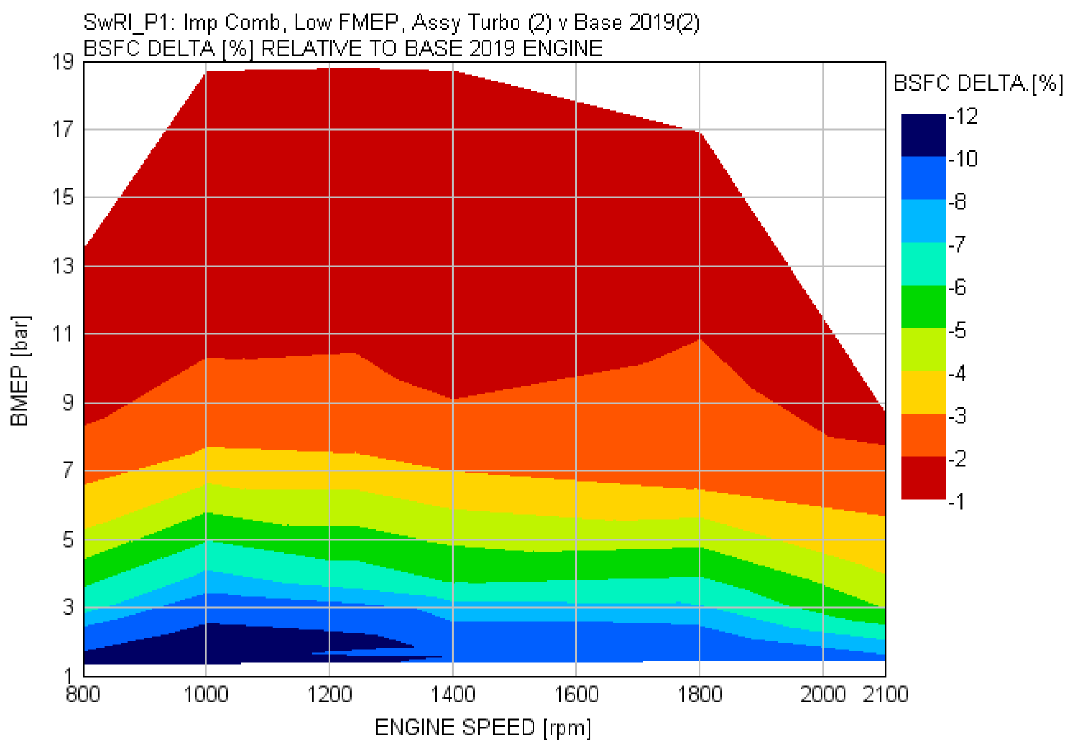


FIGURE B1.2B BSFC IMPROVEMENT MAP OF PACKAGE 1 ENGINE

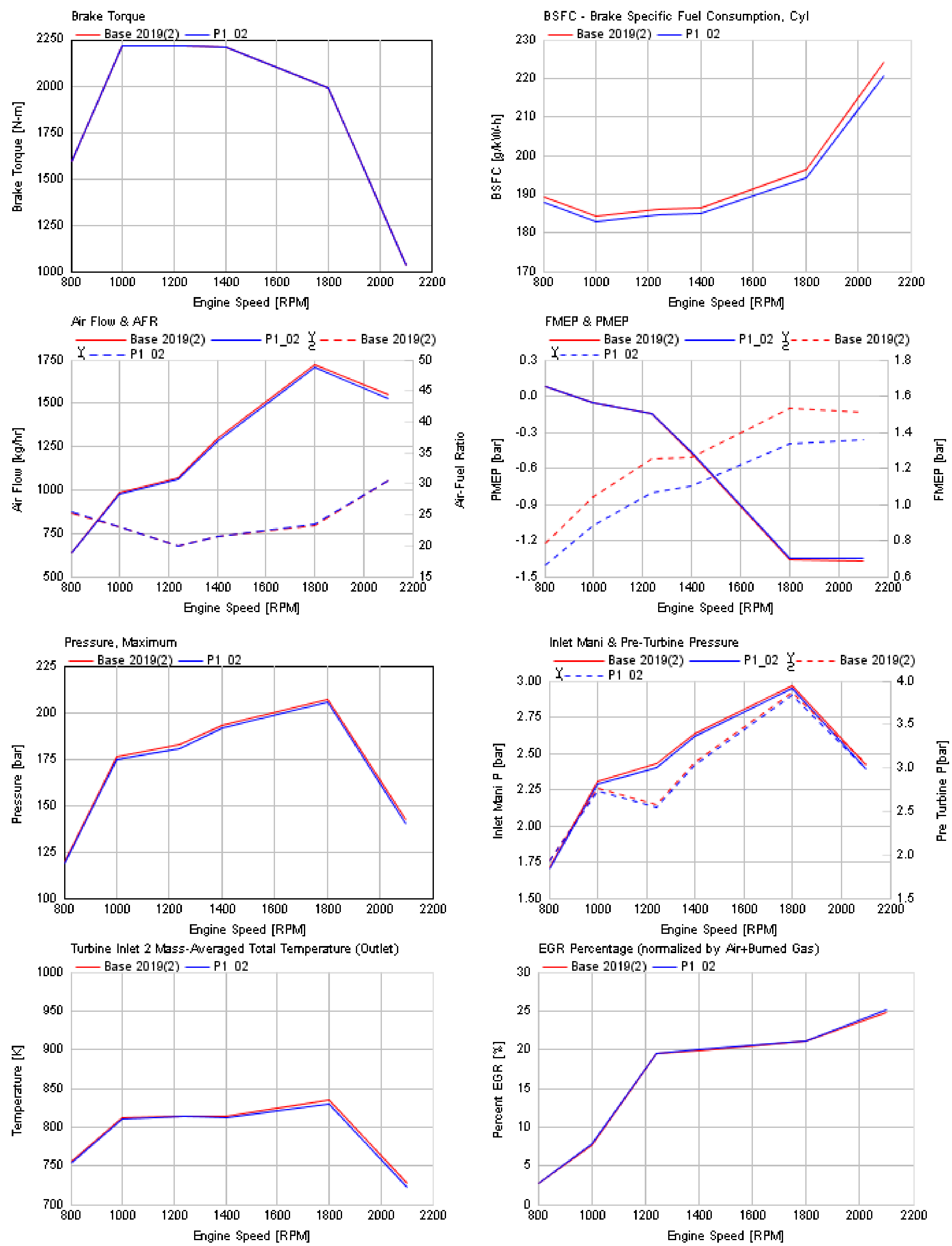


FIGURE B1.2C FULL LOAD PERFORMANCE COMPARISON – PACKAGE 1 VS. 2019 BASELINE

1.3 DD15 Combination Package 2: 2019 Baseline + Downspeed and limited friction reduction

Package two combined the 2019 engine with the previously run downspeed (B) torque curve which limited engine speed to 1600 rpm rated and 1800 rpm high idle, along with a limited engine friction reduction (half the previously used reduction) across the speed and load range. Maximum cylinder pressure was limited to 207 bar as for the baseline DD15 engine. The EGR rate was increased at low engine speed to maintain NOx performance at the new, lower test speeds. All other engine parameters where unchanged.

Figures B1.3a, B1.3b and B1.3c show the BSFC, BSFC improvement and full load performance effect of the reduced engine friction compared to the 2019 Base engine.

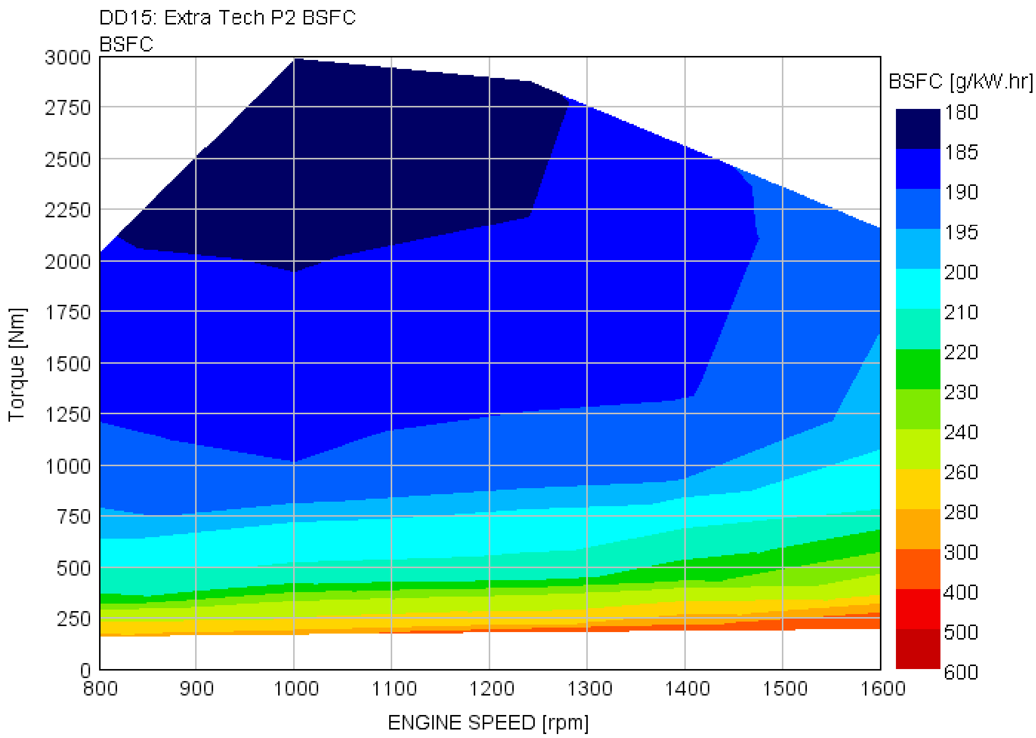


FIGURE B1.3A BSFC MAP OF PACKAGE 2 ENGINE

Significant BSFC gains are seen at part load conditions, particularly at lower engine speeds where the friction reduction is higher. At higher loads the friction reduction is limited by the higher cylinder pressures due to the increased operating load (increased torque and BMEP).

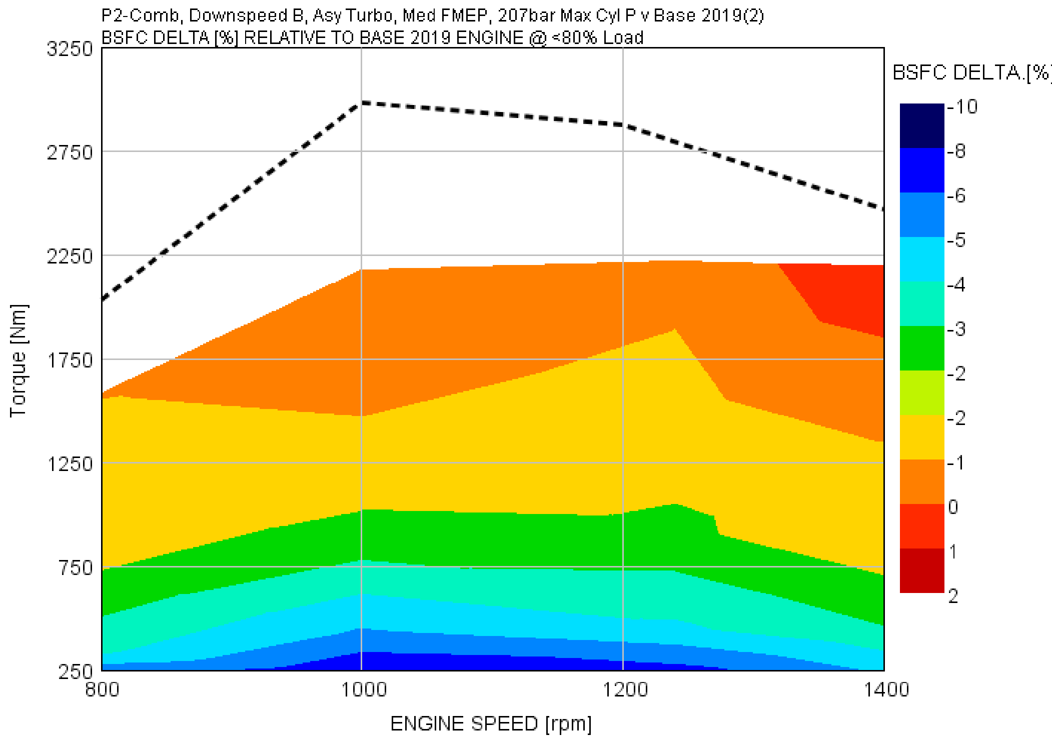


FIGURE B1.3B BSFC IMPROVEMENT MAP OF PACKAGE 2 ENGINE VS. 2019 BASELINE

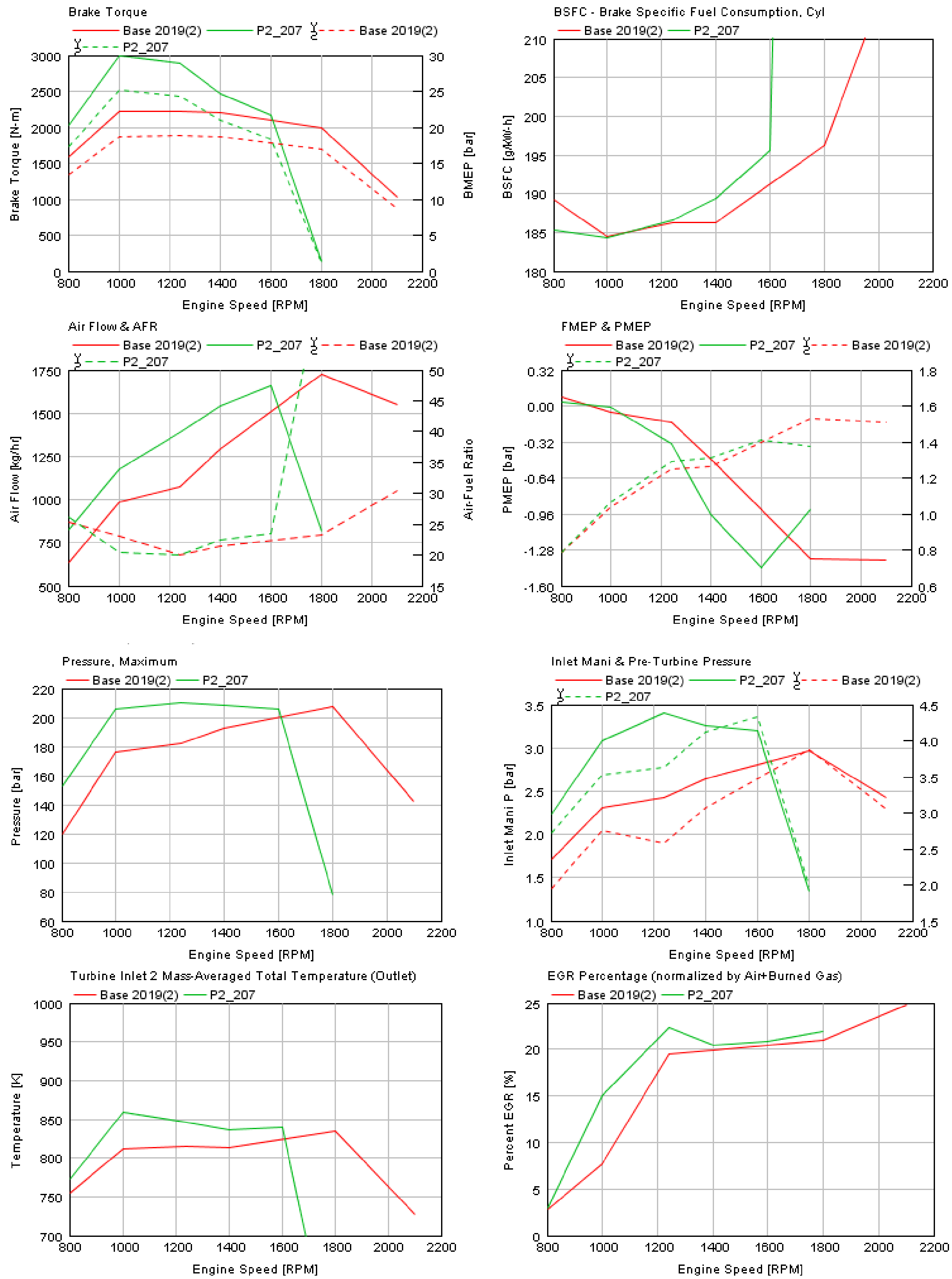


FIGURE B1.3C FULL LOAD PERFORMANCE COMPARISON

1.4 DD15 Combination Package 3: 2019 Baseline + Downspeed and limited friction reduction + Bottoming Cycle (Package 2 + Bottoming Cycle)

Package 3 added Bottoming Cycle (BC) to all the changes of Package 2. Please see Appendix D of the Final Report #1 of this project for a description of the BC theory and the model which was built for these calculations. Outputs from DD15 engine technology Package 2 GT Power simulations were utilized as input data for Excel spreadsheets created to model the bottoming cycle. The spreadsheets model fluid and gas circuits and their thermodynamic exchanges, and calculate turbine mechanical output. Conversions to electrical power (generator) and back to mechanical (motor) for engine crankshaft input were also calculated as a supplement to engine output power.

Five bottoming cycle configurations were initially modeled:

- Water as coolant – no recuperator
- R245fa as coolant – no recuperator
- Methanol as coolant – no recuperator
- R245fa as coolant plus recuperator
- Methanol as coolant plus recuperator

Later, two additional configurations were modeled, in particular to compare methanol to ethanol as coolant:

- Ethanol as coolant – no recuperator
- Ethanol as coolant plus recuperator

The BC condenser heat transfer was limited to a maximum of 80 kW to limit the impact on vehicle cooling systems and to constrain the aerodynamic impacts of accommodating larger sized bottoming cycle hardware into the truck packaging. The R245fa coolant usable temperature range was limited to ≤ 250 deg C due to thermal degradation concerns. For all working fluids, the coolant pressure was limited to 35 bar (3.5 MPa, 508 psi) absolute. Each speed/load point modeled was optimized by adjusting coolant mass flow and coolant pressure. Coolant temperature and condenser heat transfer limits were achieved by manipulation of coolant mass flows and pressures and heat exchanger temperature ranges. See Report #1, Appendix D for examples.

Figures B1.4a-1.4d show comparisons of the initial five configurations modeled. Figure B1.4a shows the Package 3 bottoming cycle gross (turbine mechanical) output power for the speed/load points modeled. Figure B1.4b shows the Package 3 bottoming cycle net output power (after electric generator and motor conversions). Figure B1.4c shows the ratio of Package 3 bottoming cycle net output power to engine output power in percent. Condenser heat rejection is shown in Figure B1.4d.

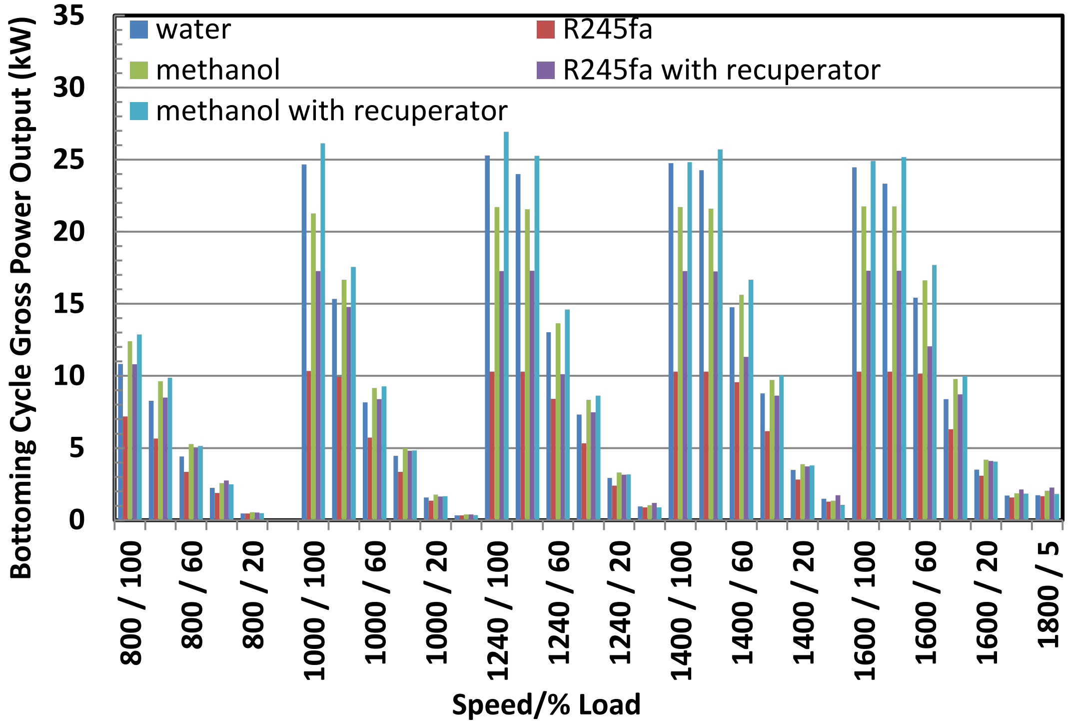


FIGURE B1.4A BOTTOMING CYCLE GROSS (TURBINE MECHANICAL) POWER OUTPUT FOR PACKAGE 3

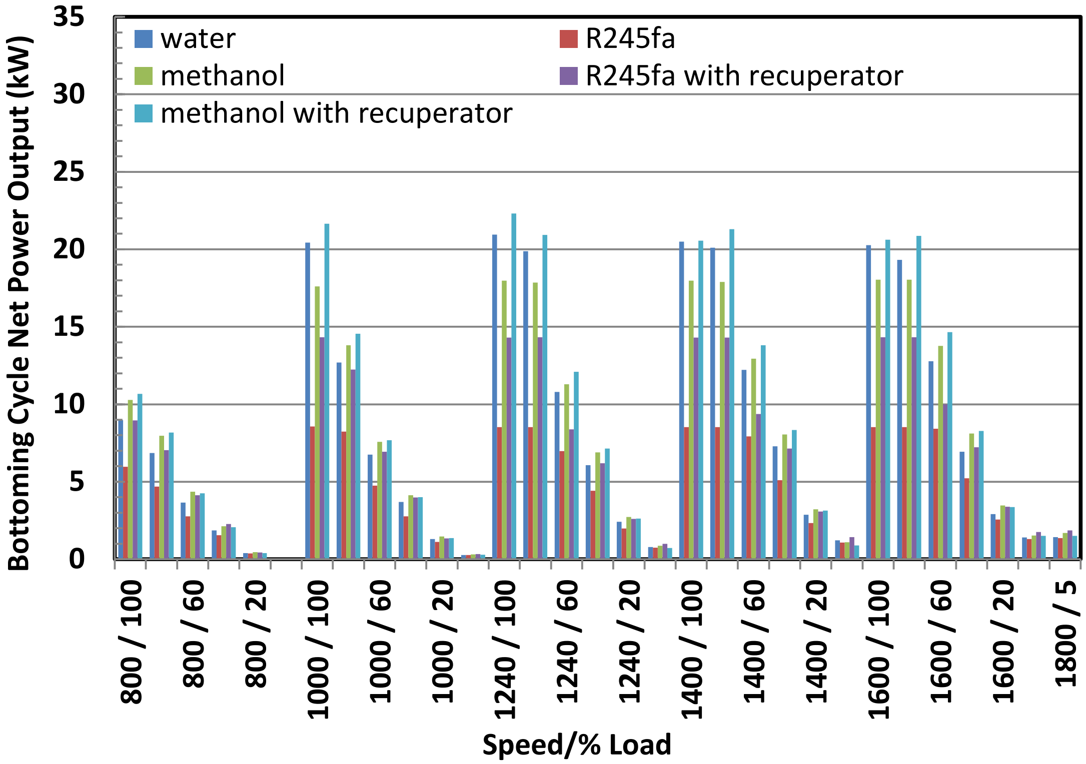


FIGURE B1.4B BOTTOMING CYCLE NET POWER OUTPUT (AFTER GENERATOR AND MOTOR CONVERSIONS) FOR PACKAGE 3

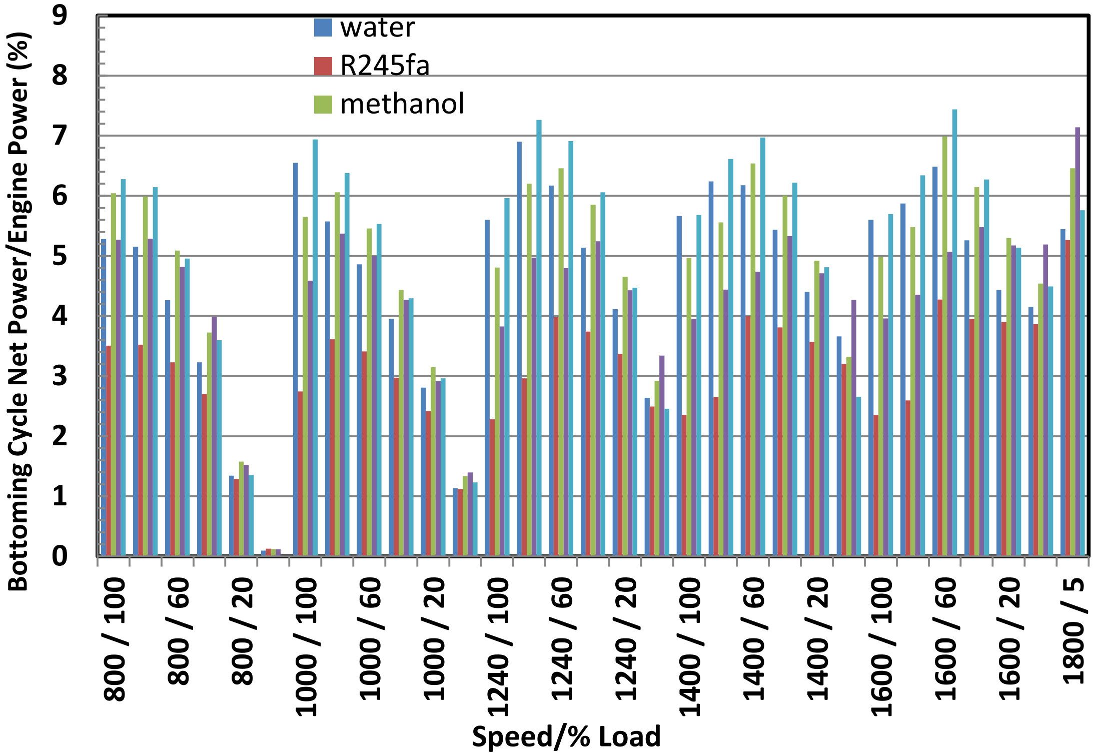


FIGURE B1.4C RATIO OF BOTTOMING CYCLE NET POWER TO ENGINE POWER OUTPUT FOR PACKAGE 3

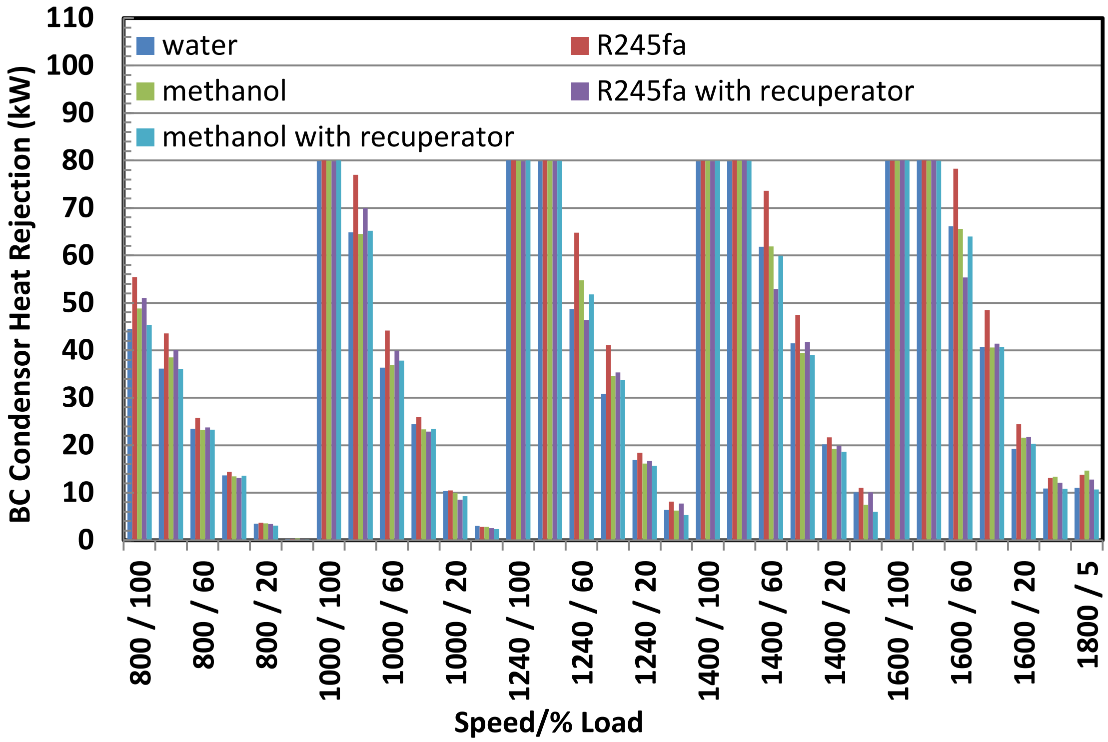


FIGURE B1.4D BOTTOMING CYCLE CONDENSER HEAT TRANSFER FOR PACKAGE 3

Significant BC output ratio percentages are seen throughout most speed/load points, with the greatest gains seen with the system using methanol as a coolant plus a recuperator. The addition of a recuperator increases the system performance for both R245fa and methanol, but R245a sees a larger benefit from the recuperator.

Figure B1.4d shows the Package 3 bottoming cycle condenser heat transfer rates, limited to 80 kW. For the speed/load points not limited to 80 kW, the highest heat transfer rates were shown with the R245fa coolant.

Figures B1.4e-1.4h show comparisons of the water, methanol and ethanol coolant combinations. For clarity of the figures, the R-245 based systems are left out of these figures. Figure B1.4e shows the Package 3 bottoming cycle gross (turbine mechanical) output power for the speed/load points modeled. Figure B1.3f shows the Package 3 bottoming cycle net output power (after electric generator and motor conversions). Figure B1.3g shows the ratio of Package 3 bottoming cycle net output power to engine output power in percent.

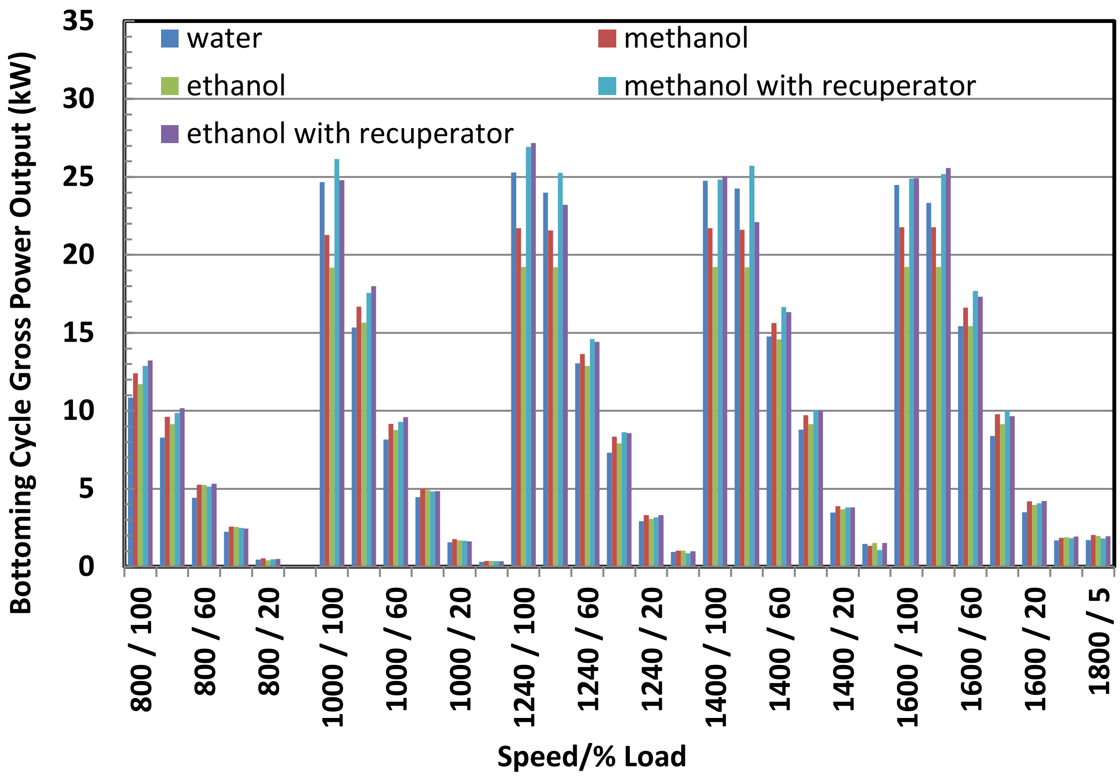


FIGURE B1.4E BC GROSS (TURBINE MECHANICAL) POWER OUTPUT FOR METHANOL AND ETHANOL

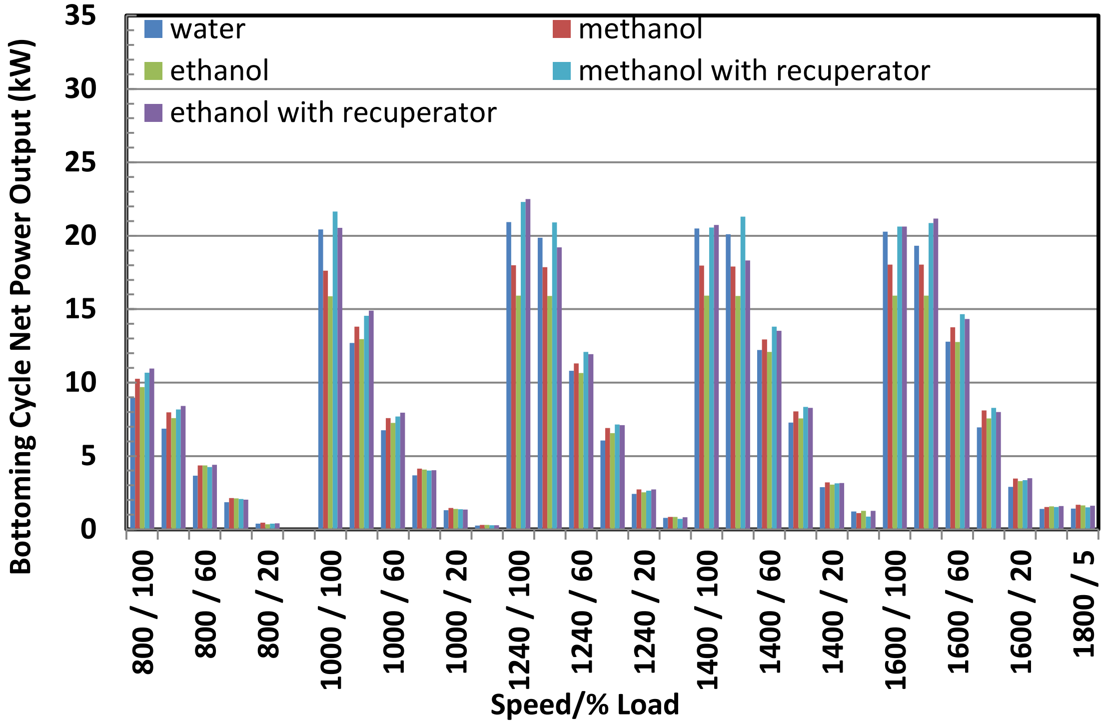


FIGURE B1.4F BC NET POWER OUTPUT FOR METHANOL AND ETHANOL

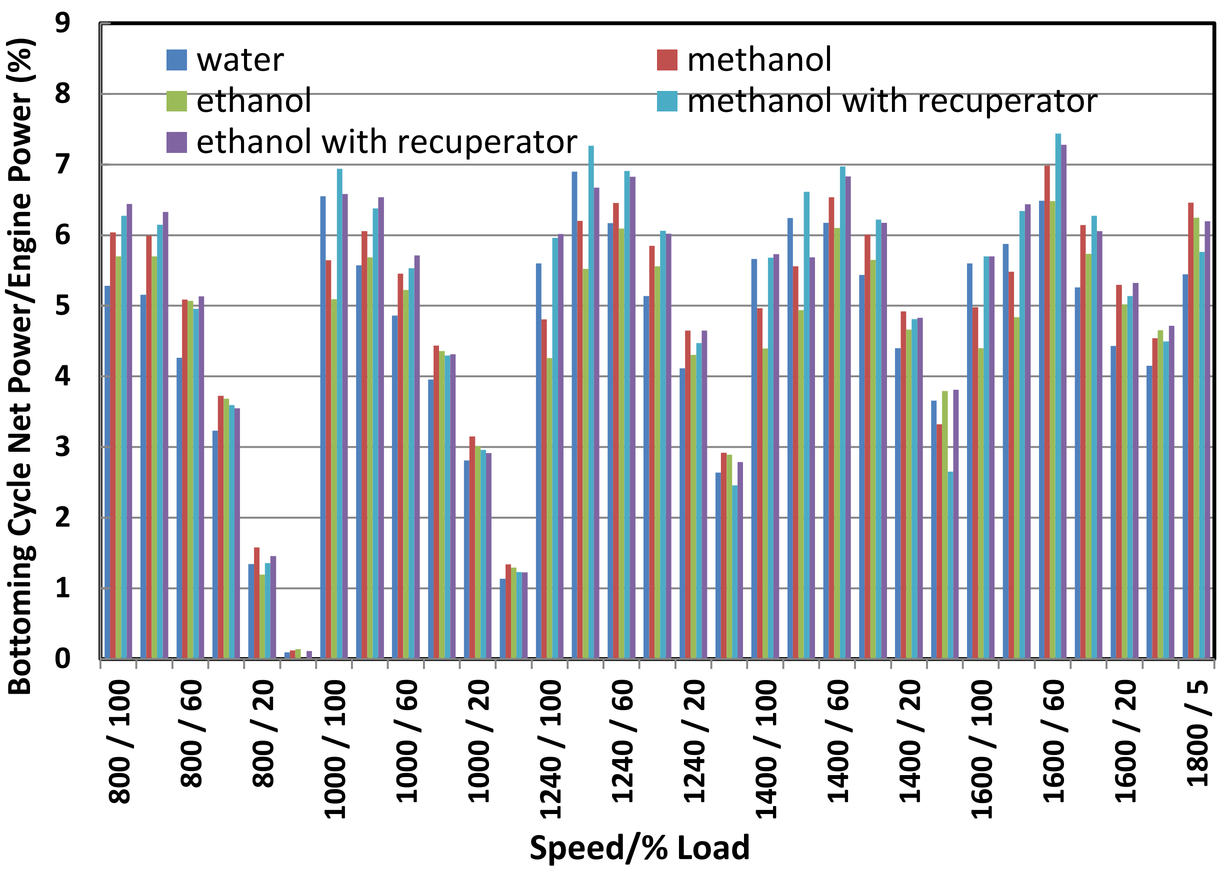


FIGURE X1.4G RATIO OF BC NET POWER TO ENGINE POWER OUTPUT FOR METHANOL AND ETHANOL

Significant BC output ratio percentages are seen throughout most speed/load points, with the greatest non-recuperator gains (other than water coolant) seen using methanol as a coolant. The addition of recuperators increases the percentages to a modest extent for both methanol and ethanol, with similar recuperator gains for ethanol compared to methanol. Figure X1.3h shows the Package 3 bottoming cycle condenser heat rejection rates, limited to 80 kW. For the speed/load points not limited, the heat rejection rates were all very similar.

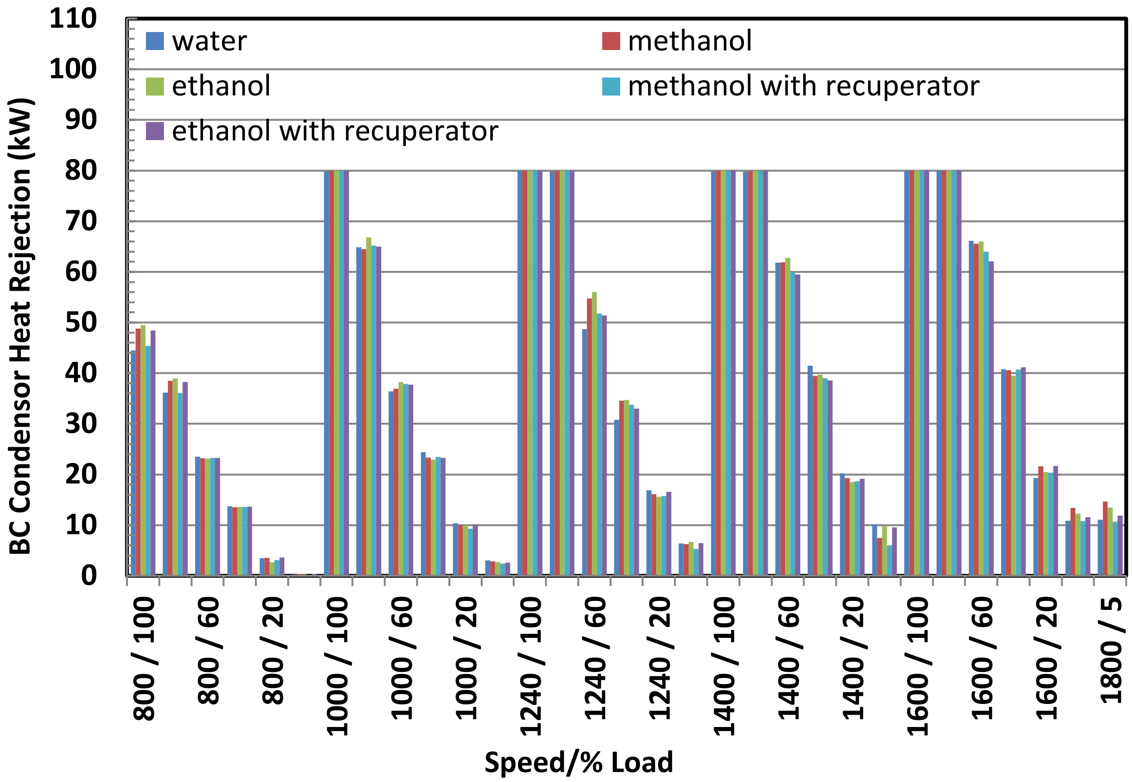


FIGURE X1.4H BC CONDENSER HEAT TRANSFER FOR METHANOL AND ETHANOL

In the bottoming cycle simulations performed here, an upper coolant temperature limit was only applied in the case of R245. Most types of expander (other than turbines) will rely on lubricant mixed with the coolant in order to provide lube to the expander. If lubricant is used in the system, the coolant temperature must be limited in order to prevent breakdown of lubricant properties. This may limit maximum system temperatures to approximately 200 degrees C, which in turn will reduce the efficiency of the bottoming cycle compared to the unlimited case shown here. If a coolant temperature limit is applied, it may make sense to put the EGR and exhaust heat exchangers in parallel, and to use mass flow rate to limit the peak coolant temperature.

Another factor limiting bottoming cycle performance is their slow transient response. Output power will be slow to increase when engine load goes up, and it will be slow to decline when engine load is reduced. The simple spreadsheet model used to predict bottoming cycle performance does not have the ability to predict transient response. Experimental data on bottoming cycle transient response is not publically available, but the values are expected to range from tens of seconds to a few minutes. To compensate for this, we have assumed that the bottoming cycle is only operational on cycles with mostly steady-state operation. The bottoming cycle is assumed active for 55 and 65 MPH cruise, and on the NESCCAF cycle. The bottoming cycle is assumed to be inactive on the CARB and WHVC cycles. This has the effect of overestimating the fuel savings on cycles where the bottoming cycle is active (because true steady-state operation in the field is actually quite rare), and underestimating the performance of the bottoming cycle on transient cycles (because we assume the performance to be zero).

1.5 DD15 Combination Package 4: High Efficiency Turbo, no Turbocompound, no EGR, Engine Friction Reduction

Combination package 4 is a high NOx option. Package 4 features a slightly different engine setup that does not include turbocompound or the asymmetric turbo layout, but it does have the combustion improvements. The technology package was based on the standard turbo layout but with a high efficiency turbo (+5% on turbine and compressor) with the APT deleted. There is no EGR supplied, and the full engine friction reduction map from Package 1 is applied.

Figures B1.4a, B1.4b and B1.4c show the BSFC, BSFC improvement and full load performance effect of the Package 4 engine, compared to the 2019 Baseline DD15 engine.

To achieve similar performance to the base engine it was necessary to re-size the turbo (a consequence of EGR removal). We took advantage of the EGR removal and increased the compression ratio to 19:1 (stock is 18:1), while maintaining the 207 bar maximum cylinder pressure limit. Higher compression ratio provides a slight efficiency benefit.

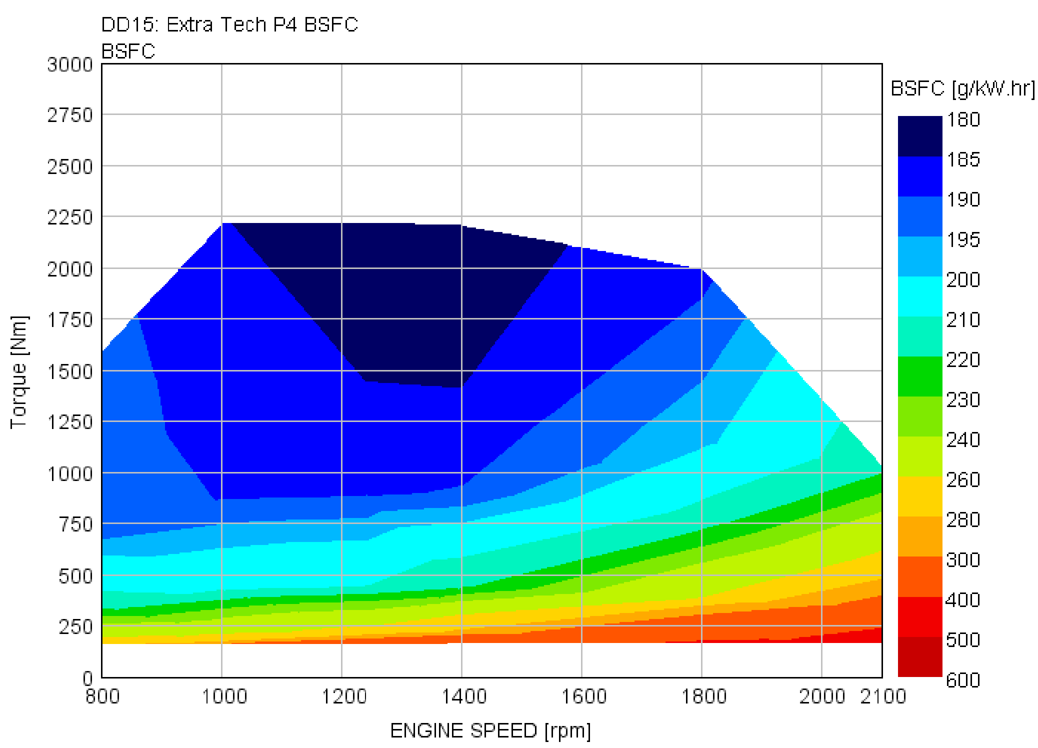


FIGURE B1.5A BSFC MAP OF COMBO PACKAGE 4 ENGINE

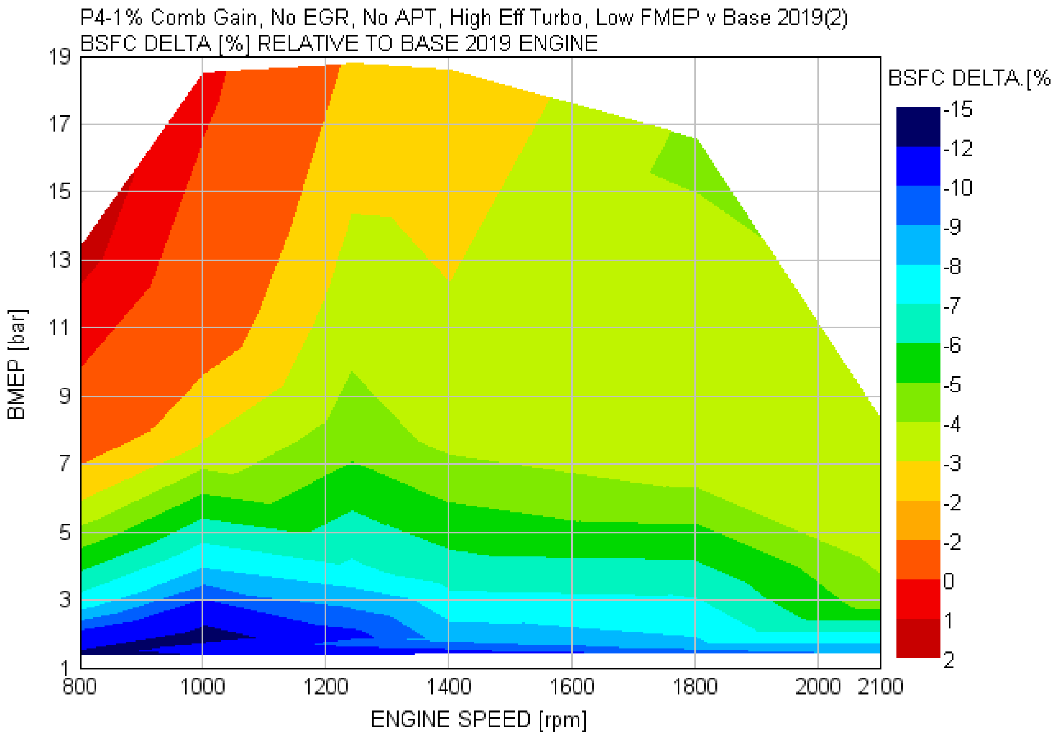


FIGURE B1.5B BSFC IMPROVEMENT MAP OF COMBO PACKAGE 4 ENGINE VS. THE 2019 BASELINE

Significant BSFC gains are seen at part load conditions, particularly at lower engine speeds where the friction reduction is higher. At low speed, high load there is a slight BSFC penalty due to the turbo resizing, which was optimized for midrange speeds and mid-lower load conditions.

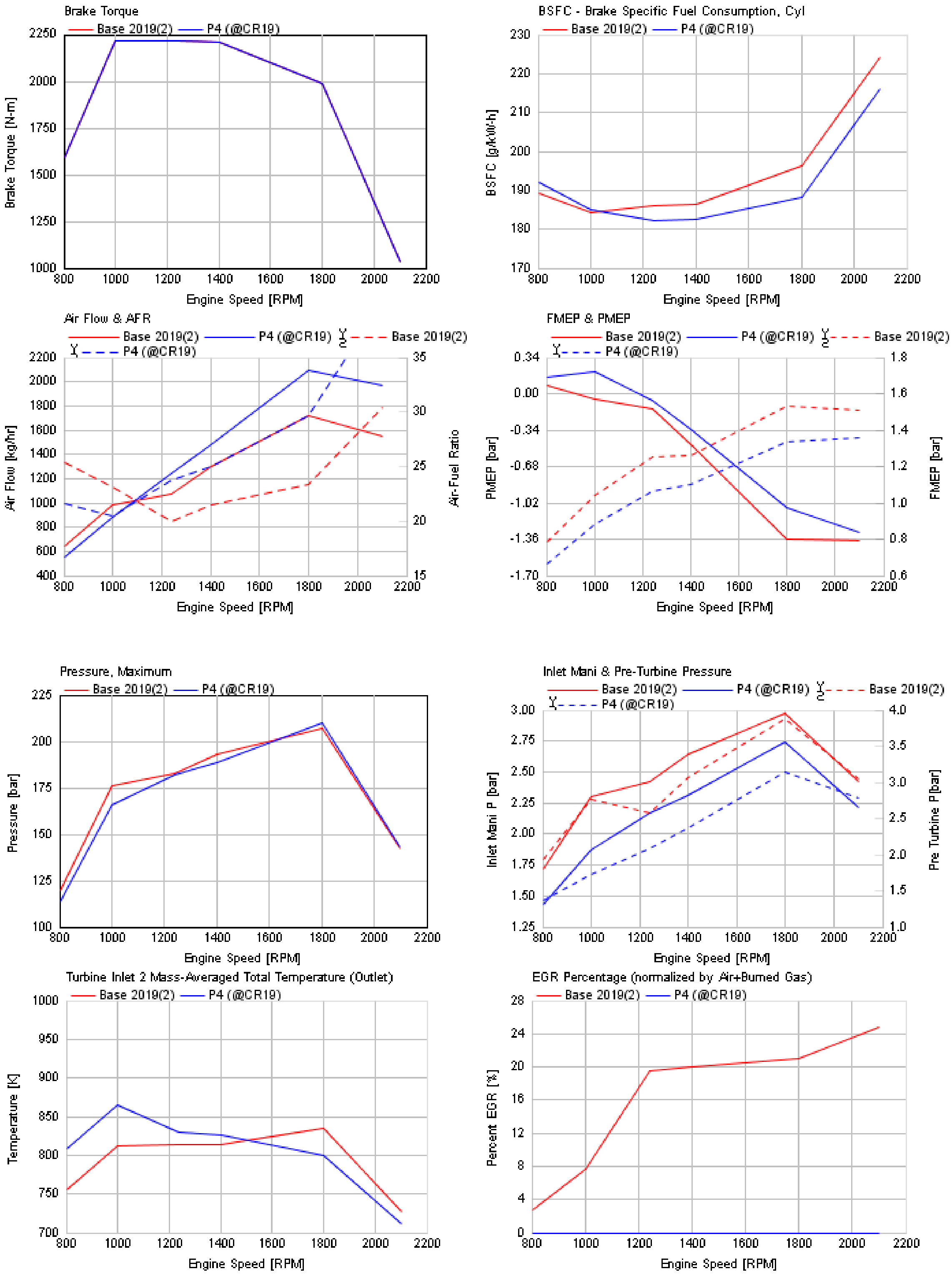


FIGURE B1.5C FULL LOAD PERFORMANCE COMPARISON

1.6 DD15 Combination Package 5: Base 2019 + Downspeed, Optimized APT, Reduced Exhaust and Inlet Restrictions, Limited Friction Reduction

Combination package 5 features a slightly different engine setup that includes turbocompound and combustion improvements, but does not include the asymmetric turbo layout. The model was run with the downspeed torque curve, and the technology package was based on the standard turbo layout with the addition of optimized APT (turbocompound turbine), engine friction reduction (limited version) and reduced exhaust system and air handling system flow restrictions. The optimized APT was achieved by re-sizing the power turbine maps and modifying the gearing of the APT-engine link so as to maximize the part load fuel consumption benefit, at the expense of full load.

Figures B1.5a, B1.5b and B1.5c show the BSFC, BSFC improvement and full load performance effect of Package 5 compared to the 2019 Base engine.

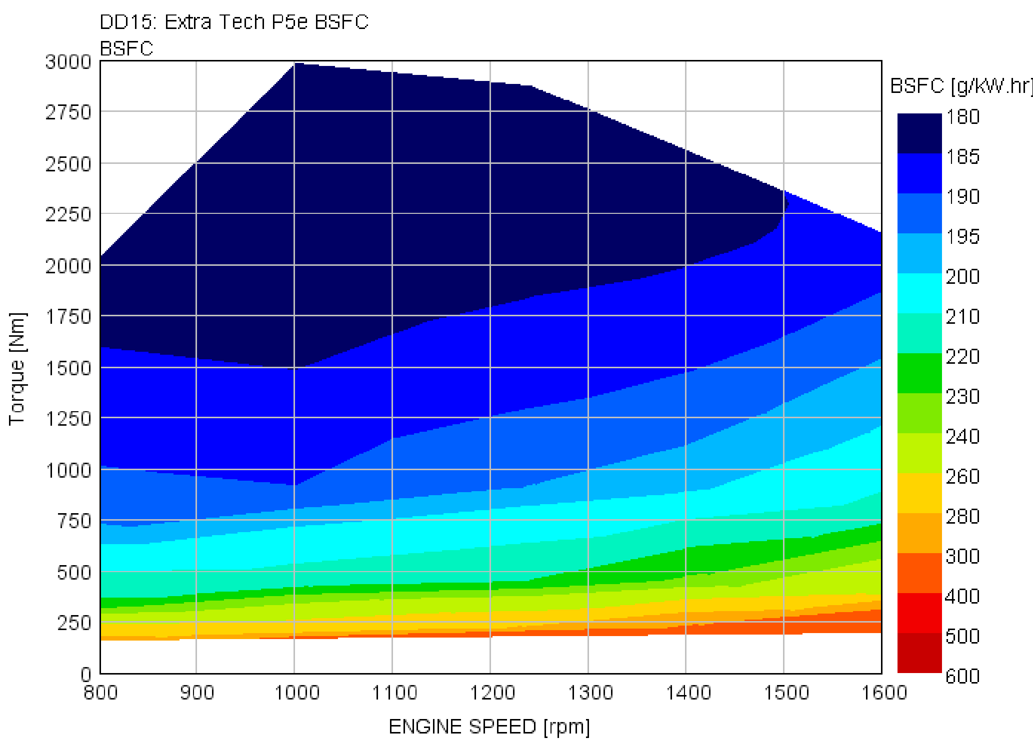


FIGURE B1.6A BSFC MAP OF PACKAGE 5 ENGINE

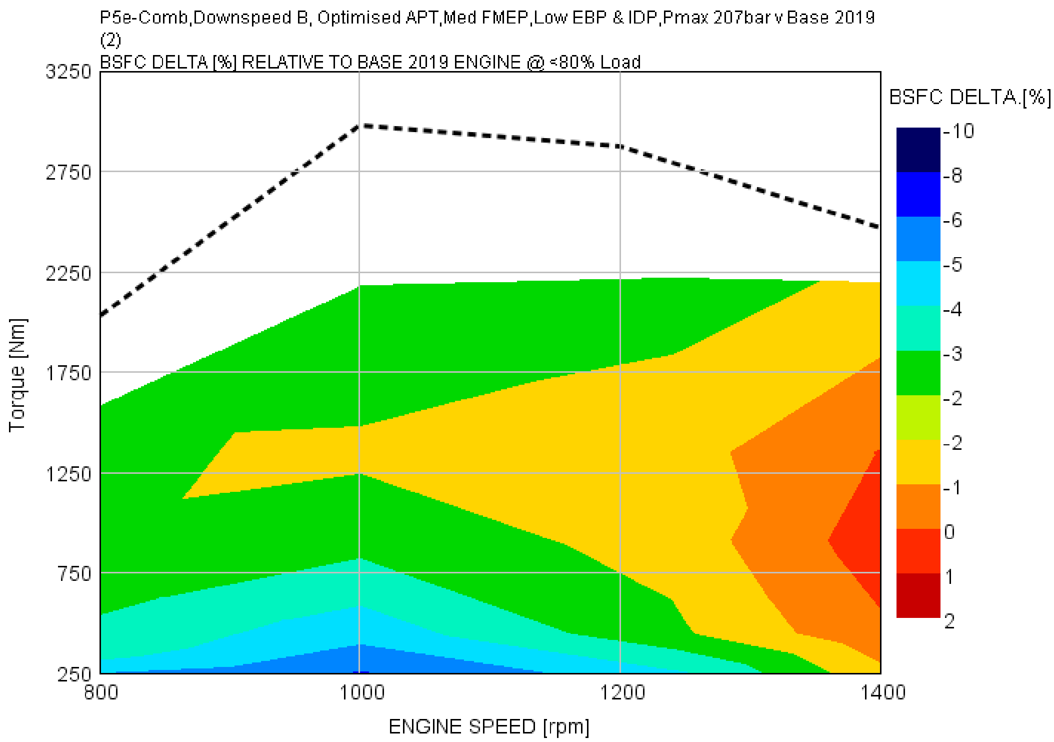


FIGURE B1.6B BSFC IMPROVEMENT MAP OF PACKAGE 5 ENGINE VS. 2019 BASELINE

Good BSFC gains are seen at part load conditions, particularly at lower engine speeds where the friction reduction is higher.

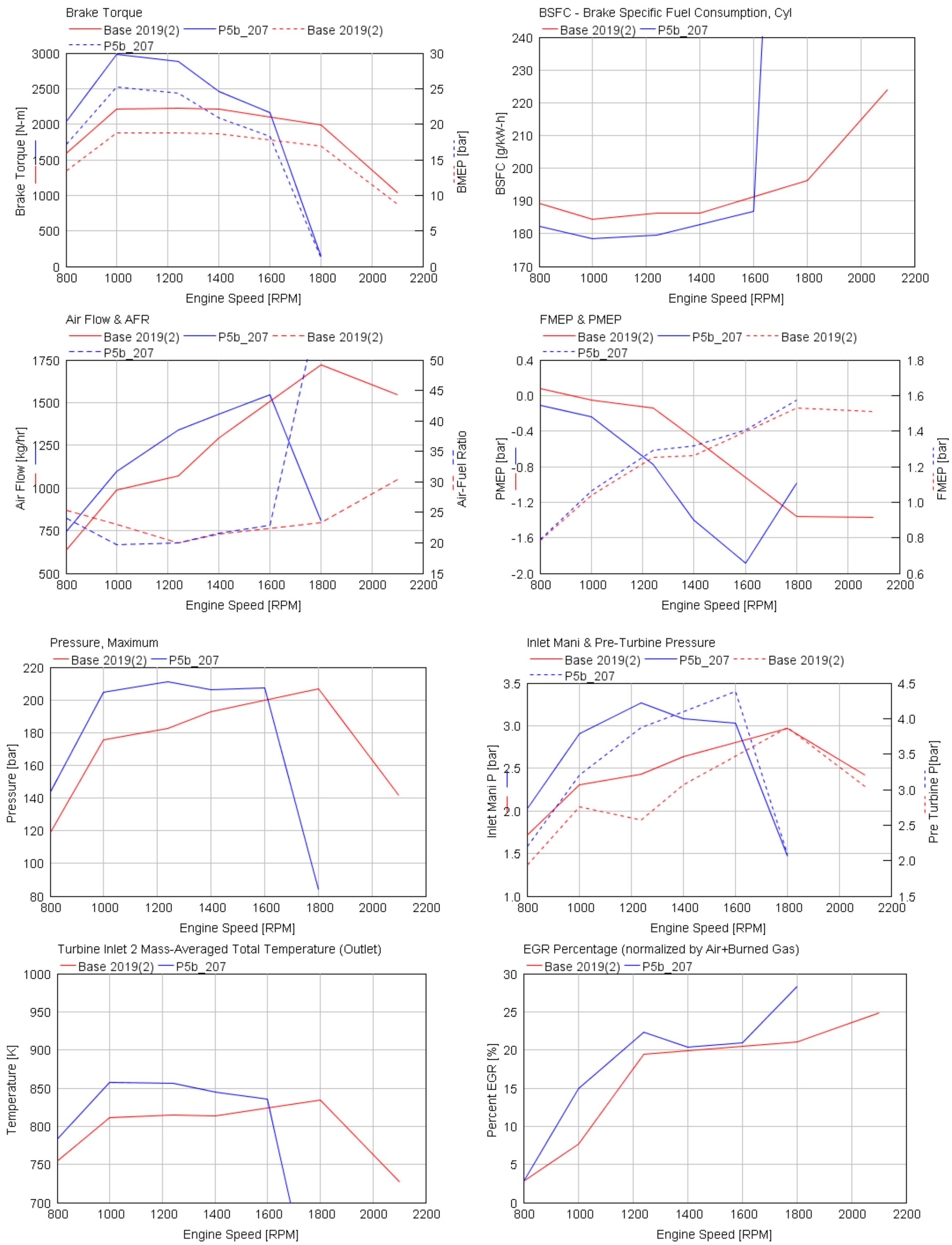


FIGURE B1.6C FULL LOAD PERFORMANCE COMPARISON

2.1 2019 Baseline ISB Medium Duty 300bhp Engine

The original ISB medium duty model was updated to represent what could reasonably be expected to be the future 2019 baseline ISB engine performance. This was achieved by improving the combustion performance, specifically the combustion duration (10-90%) to achieve a 1% improvement in fuel consumption across the speed and load range. Additionally the model was run with a limited reduced friction setup (50% of the reduction used in the initial technologies study for the ISB). All other aspects of the engine specification and performance were kept the same as the original baseline ISB model, including EGR and AFR levels.

- **Basic engine specification**
  - 6.7L inline 6-cylinder diesel
  - Single variable-geometry turbo
  - 4 valves per cylinder
  - 225 kW @ 2500 rpm
  - 900+ Nm @ 1300-2200 rpm

Figure B2.1a shows the comparison of the full and limited friction reduction.
Figure B2.1b shows the improvement in BSFC between the original medium duty ISB configuration, with combustion improvement and reduced friction. This setup is then the reference for all the following technology combination packages. Figure B2.1c shows the BSFC comparison of the original base engine and the 2019 baseline ISB model. Figure B2.1d shows a summary of the full load performance comparison between the 2 engines.

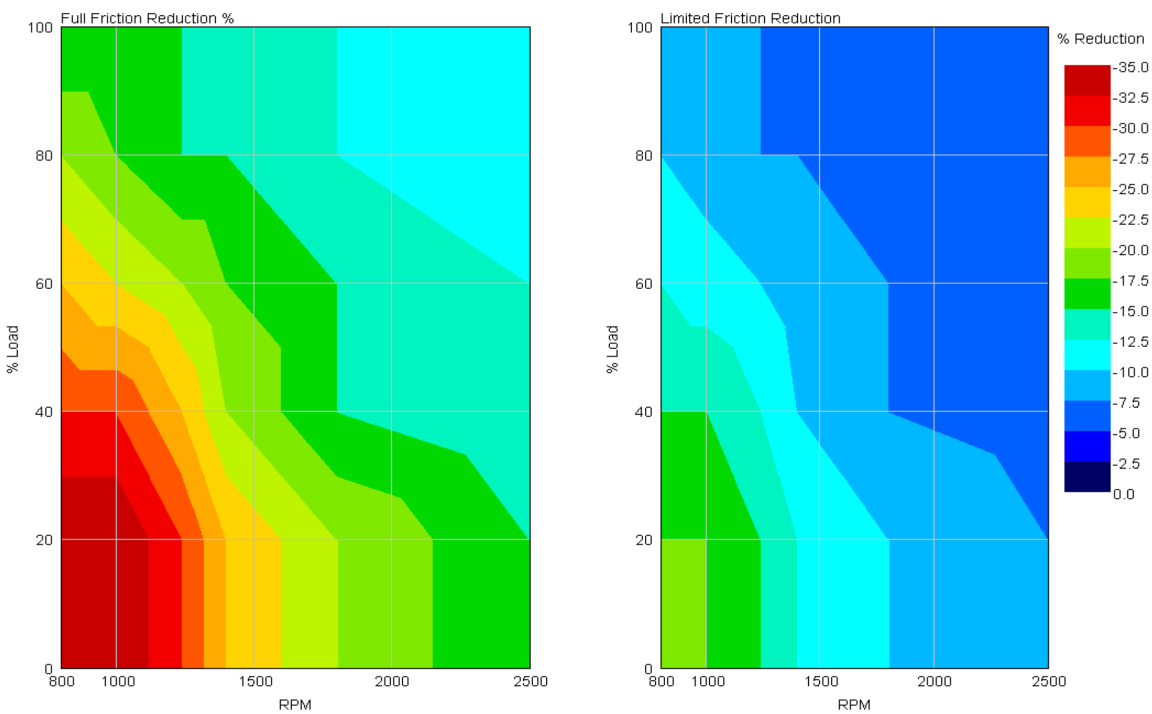


FIGURE B2.1A FRICTION REDUCTION COMPARISON

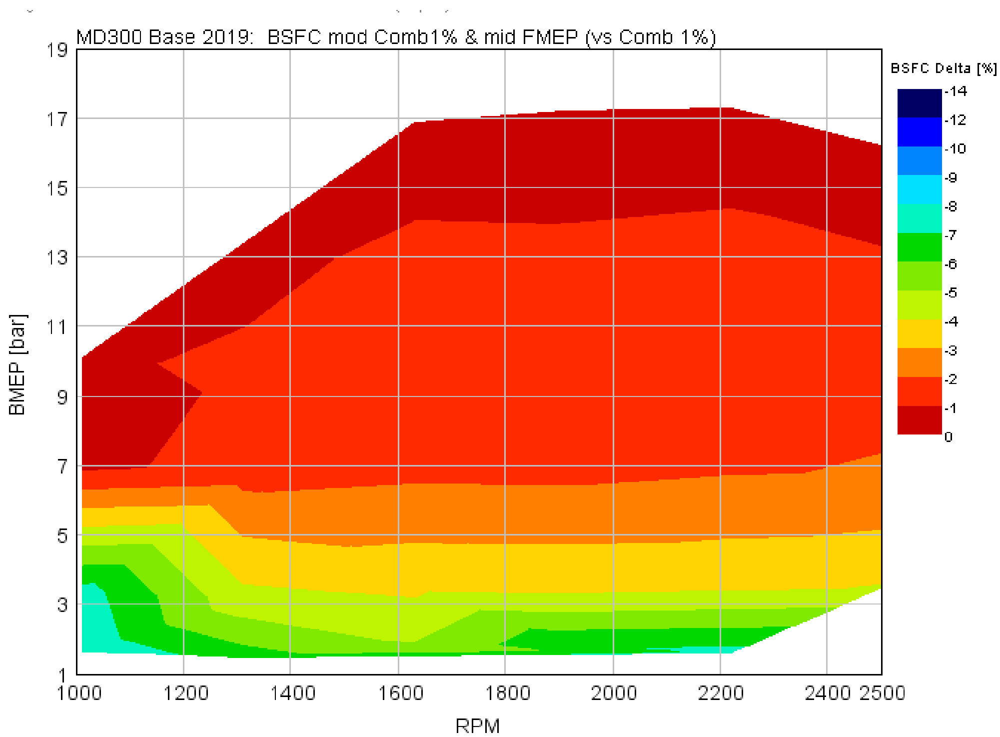


FIGURE B2.1B BSFC IMPROVEMENT MAP OF 2019 BASE ENGINE VS. ORIGINAL MEDIUM DUTY ISB

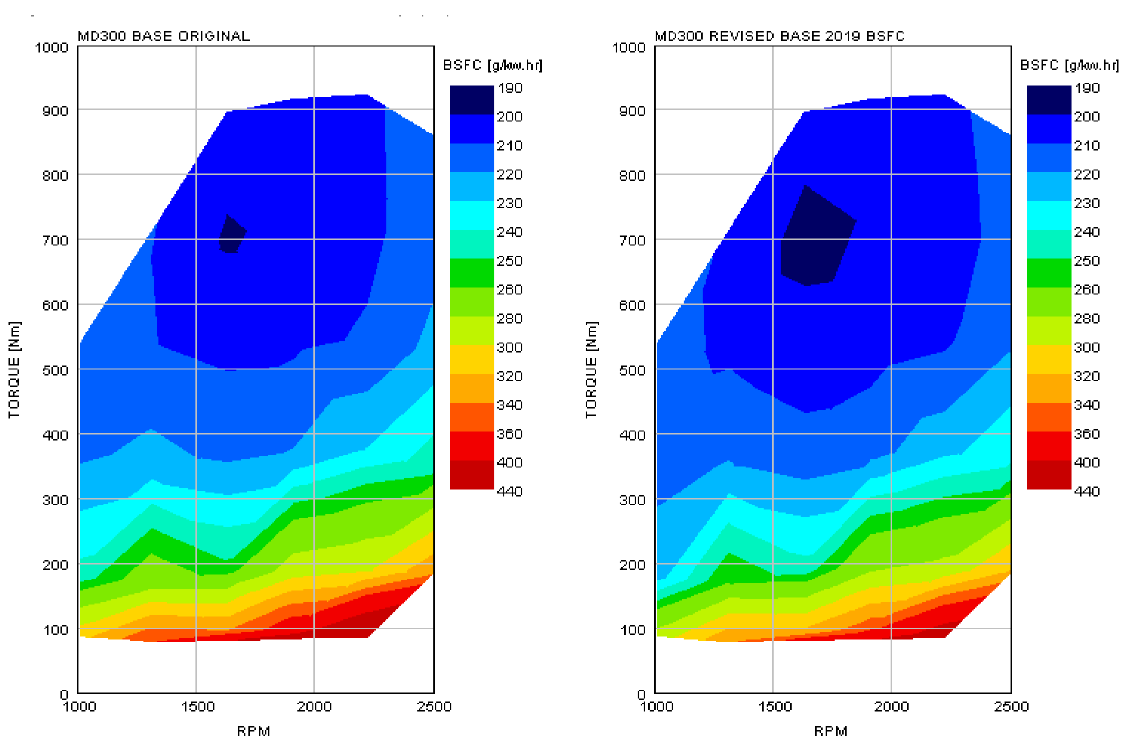
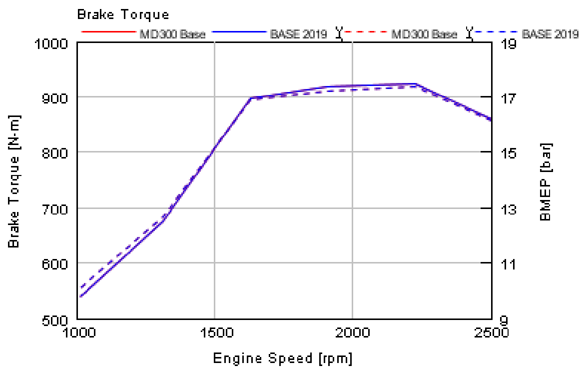
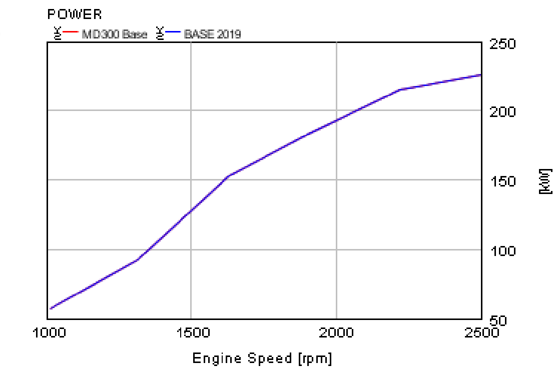
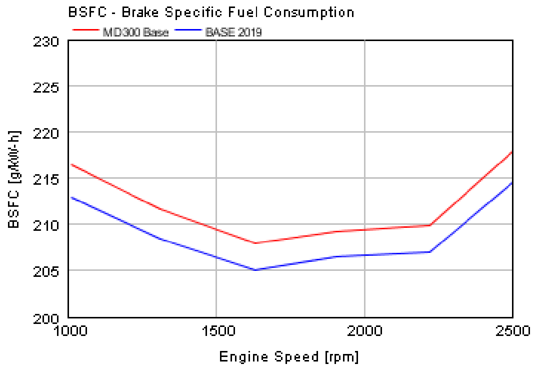
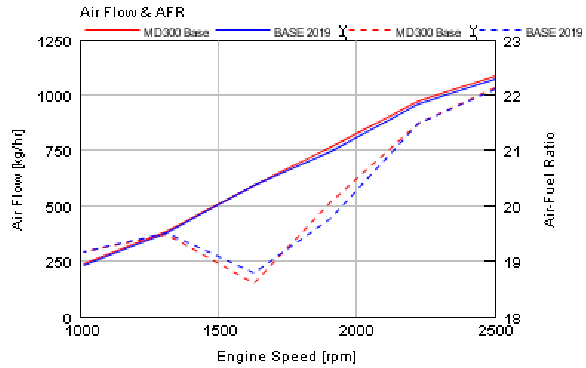


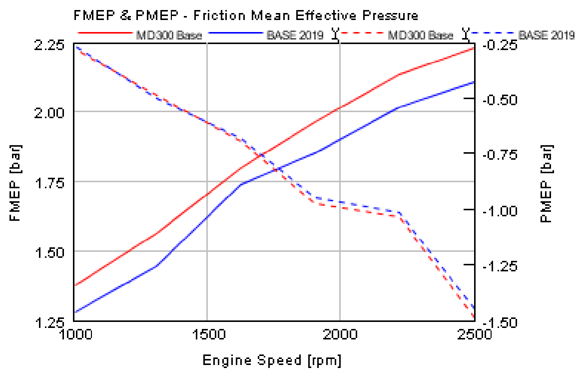
FIGURE B2.1C BSFC MAPS OF 2019 BASE ENGINE (RIGHT) VS. 2012 MEDIUM DUTY ISB

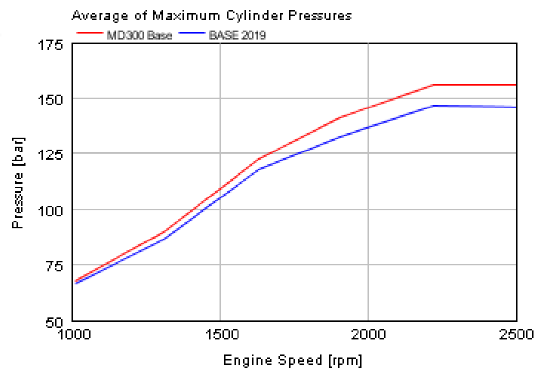

Brake Torque
MD300 Base
BASE 2019
MD300 Base
BASE 2019
Brake Torque [N-m]
BMEP [bar]
Engine Speed [rpm]

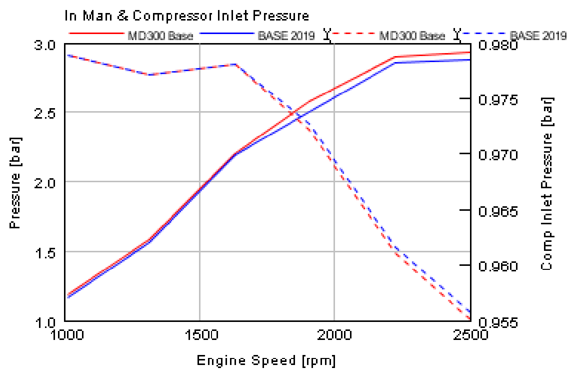

POWER
MD300 Base
BASE 2019
[kW]
Engine Speed [rpm]

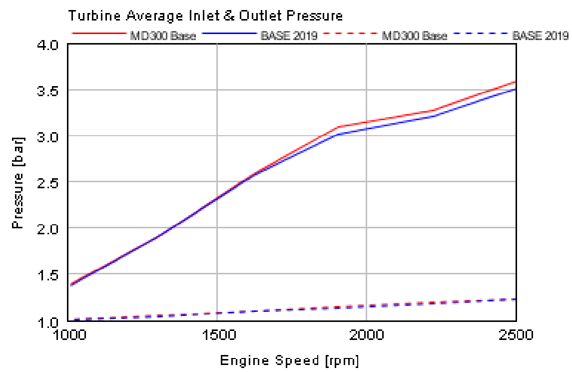

BSFC - Brake Specific Fuel Consumption
MD300 Base
BASE 2019
BSFC [g/kW-h]
Engine Speed [rpm]

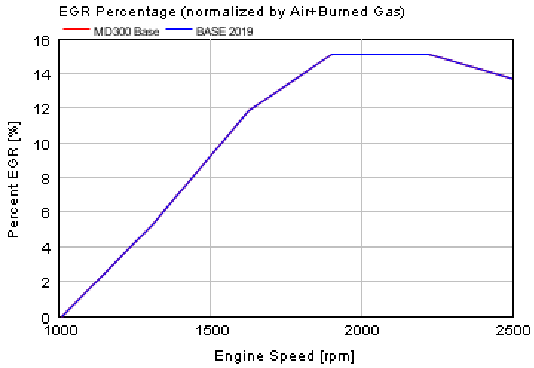

Air Flow & AFR
MD300 Base
BASE 2019
MD300 Base
BASE 2019
Air Flow [kg/hr]
Air-Fuel Ratio
Engine Speed [rpm]

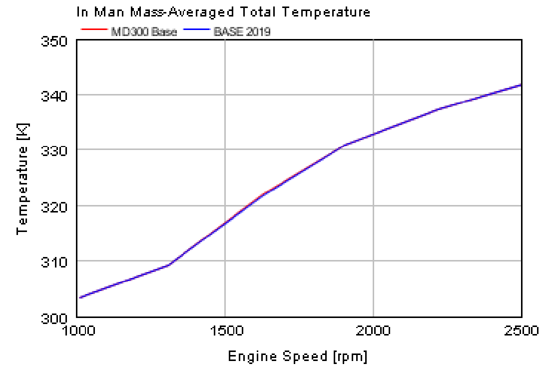

FMEP & PMEP - Friction Mean Effective Pressure
MD300 Base
BASE 2019
MD300 Base
BASE 2019
FMEP [bar]
PMEP [bar]
Engine Speed [rpm]

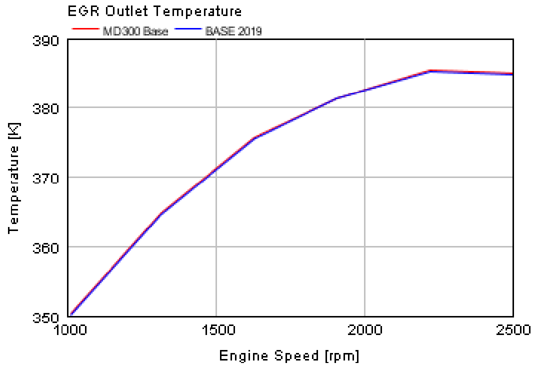

Average of Maximum Cylinder Pressures
MD300 Base
BASE 2019
Pressure [bar]
Engine Speed [rpm]

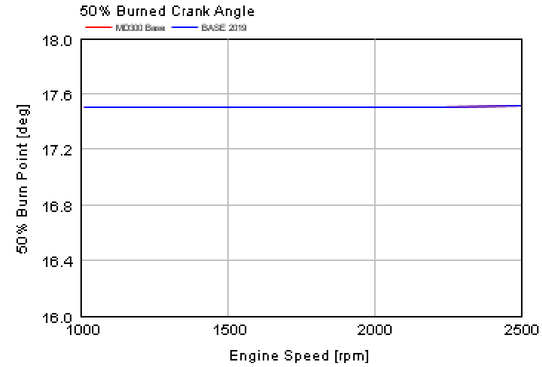

In Man & Compressor Inlet Pressure
MD300 Base
BASE 2019
MD300 Base
BASE 2019
Pressure [bar]
Comp Inlet Pressure [bar]
Engine Speed [rpm]

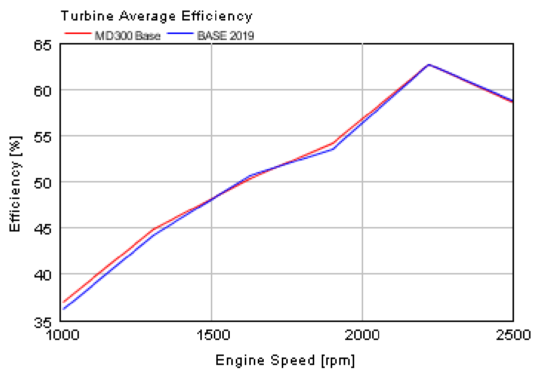

Turbine Average Inlet & Outlet Pressure
MD300 Base
BASE 2019
MD300 Base
BASE 2019
Pressure [bar]
Engine Speed [rpm]

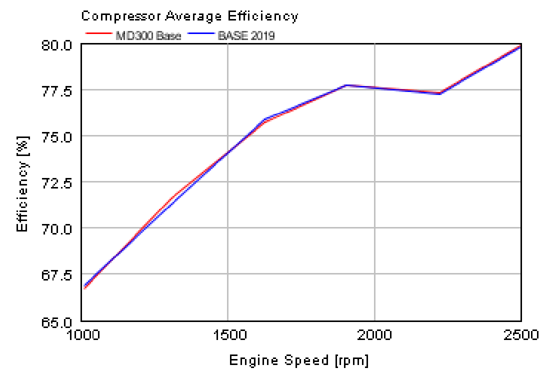

EGR Percentage (normalized by Air+Burned Gas)
MD300 Base
BASE 2019
Percent EGR [%]
0
2
4
6
8
10
12
14
16
1000
1500
2000
2500
Engine Speed [rpm]

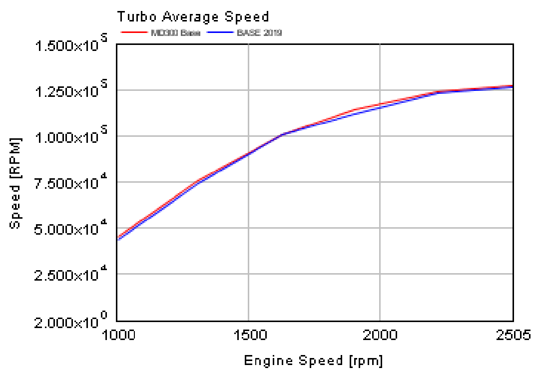

In Man Mass-Averaged Total Temperature
MD300 Base
BASE 2019
Temperature [K]
300
310
320
330
340
350
1000
1500
2000
2500
Engine Speed [rpm]

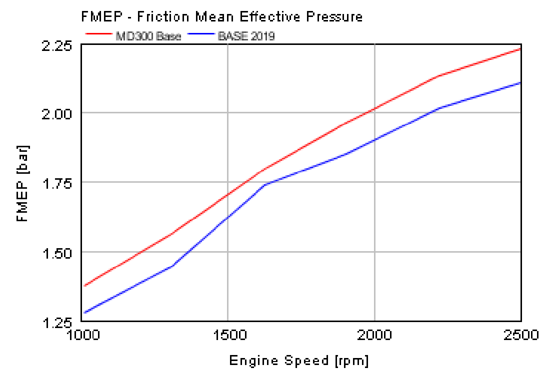

EGR Outlet Temperature
MD300 Base
BASE 2019
Temperature [K]
350
360
370
380
390
1000
1500
2000
2500
Engine Speed [rpm]


50% Burned Crank Angle
MD300 Base
BASE 2019
50% Burn Point [deg]
16.0
16.4
16.8
17.2
17.6
18.0
1000
1500
2000
2500
Engine Speed [rpm]


Turbine Average Efficiency
MD300 Base
BASE 2019
Efficiency [%]
35
40
45
50
55
60
65
1000
1500
2000
2500
Engine Speed [rpm]


Compressor Average Efficiency
MD300 Base
BASE 2019
Efficiency [%]
65.0
67.5
70.0
72.5
75.0
77.5
80.0
1000
1500
2000
2500
Engine Speed [rpm]


Turbo Average Speed
MD300 Base
BASE 2019
Speed [RPM]
2.000x10^0
2.500x10^4
5.000x10^4
7.500x10^4
1.000x10^5
1.250x10^5
1.500x10^5
1000
1500
2000
2505
Engine Speed [rpm]


FMEP - Friction Mean Effective Pressure
MD300 Base
BASE 2019
FMEP [bar]
1.25
1.50
1.75
2.00
2.25
1000
1500
2000
2500
Engine Speed [rpm]

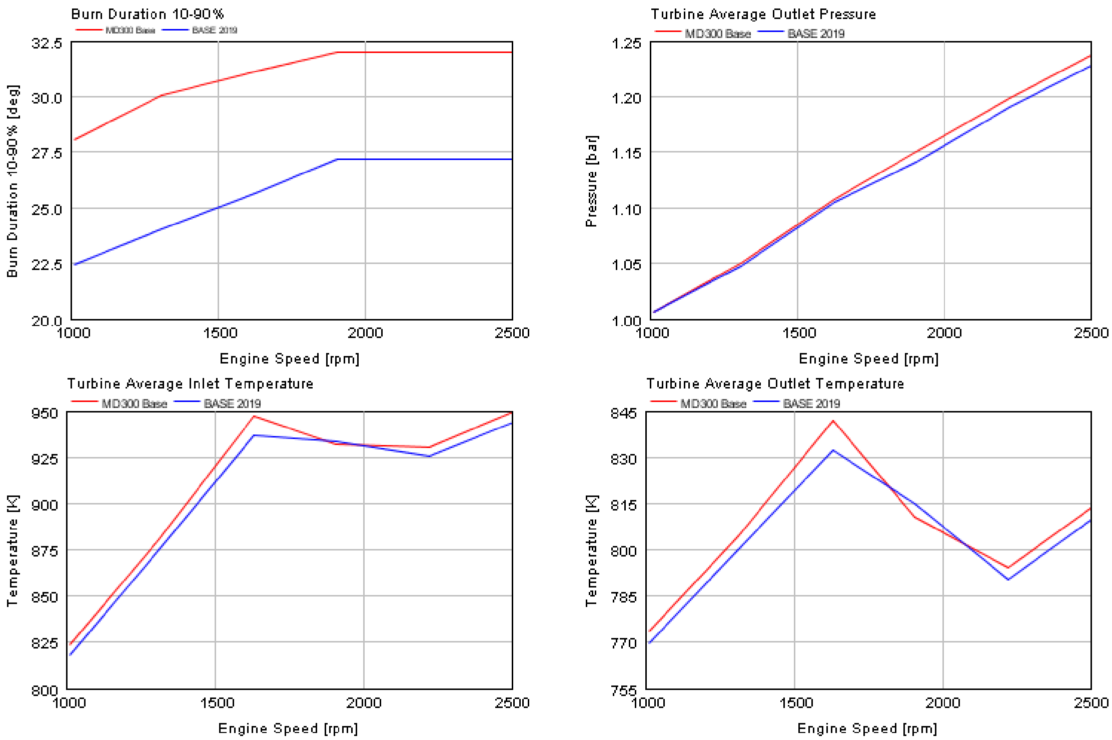


FIGURE B2.1D 2019 BASE ENGINE FULL LOAD COMPARISON

2.2 ISB MD Combination Package 6: Base 2019 + Downspeed, limited turbo efficiency increase, limited friction reduction

Combination package 6 took the 2019 base engine and ran it at a downspeed condition with maximum speed reduced from 2500 rpm to 2200 rpm, and maximum torque increased to 1100Nm. In addition, the turbo efficiency was increased 2.5% for both the turbine and the compressor. To maintain emissions (NOx) control at low speed the EGR levels were increased at 1300 and 1600 rpm to compensate for the increased engine performance and at the same time AFR levels were maintained at a minimum of ~19:1. Note that running a downspeed engine at higher torque would require a significant upgrade to the truck's transmission, driveline, and rear axle. The downspeed engine also runs significantly higher peak cylinder pressure, which would require upgrades to the engine structure.

Figures B2.2a, B2.2b and B2.2c show the BSFC, BSFC improvement and full load performance effect of package 6 compared to the 2019 Base engine.

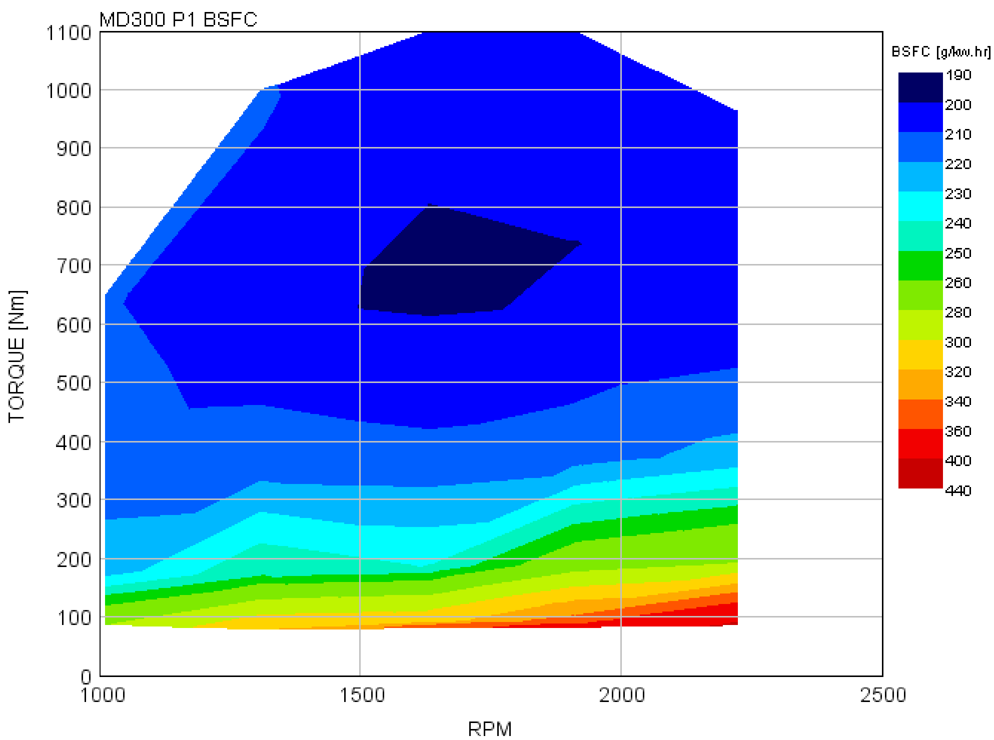


FIGURE B2.2A BSFC MAP FOR COMBO PACKAGE 6

The results for this technology combination show that the benefits of the downspeed and turbo efficiency improvements are at the low load conditions, with limited gains at the higher loads.

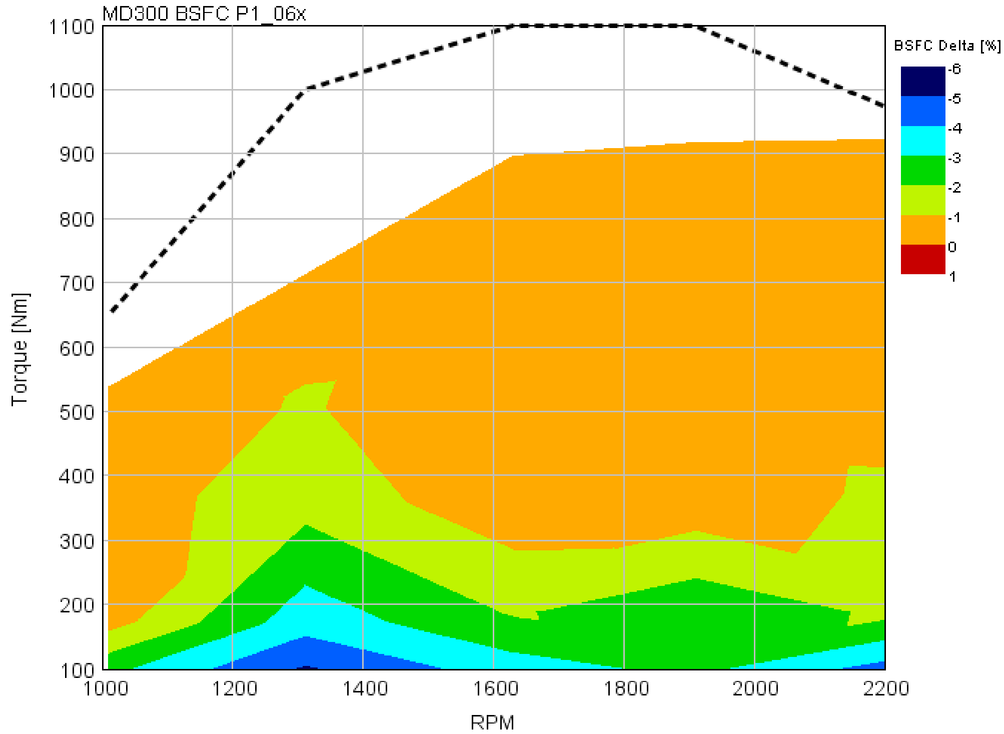


FIGURE B2.2B BSFC IMPROVEMENT MAP FOR COMBO PACKAGE 6 VS. 2019 BASELINE

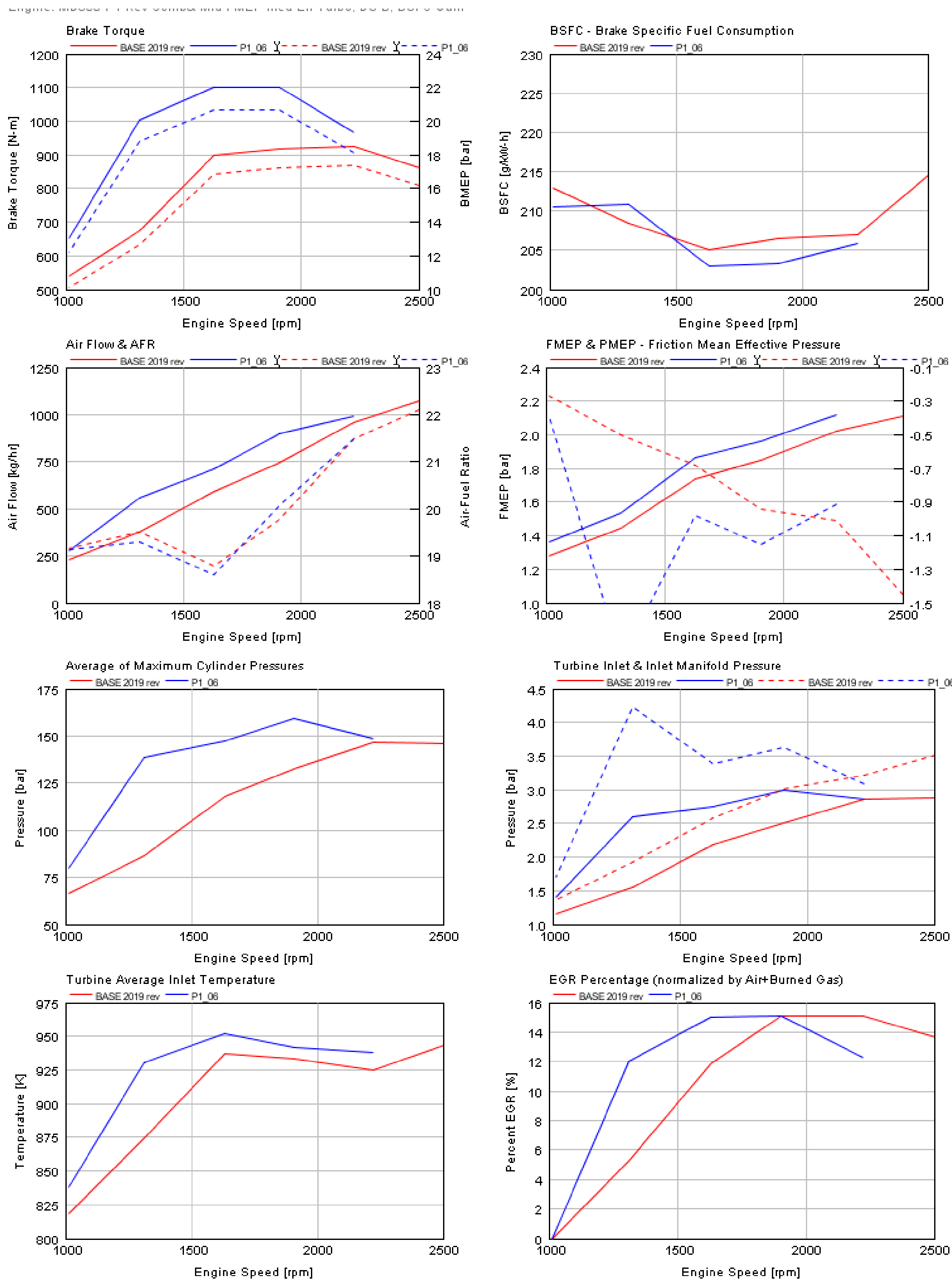


FIGURE B2.2C PACKAGE 6 FULL LOAD PERFORMANCE COMPARISON

2.3 ISB MD Combination Package 7: 2019 Base Engine + No EGR, Turbo Efficiency Increase and Full Friction Reduction

Combination package 7 takes the 2019 base engine plus the full friction reduction and ran it with no EGR and a 5% efficiency improvement for both the turbine and the compressor. This combination package provides high engine-out NOx, and would thus require an extremely efficient aftertreatment system and high urea consumption. To achieve the required performance (AFR), the turbo was rescaled, since removing the EGR the system tends to deliver excess air.

Figures B2.3a, B2.3b and B2.3c show the BSFC, BSFC improvement and full load performance effect of package 7 compared to the 2019 Base engine.

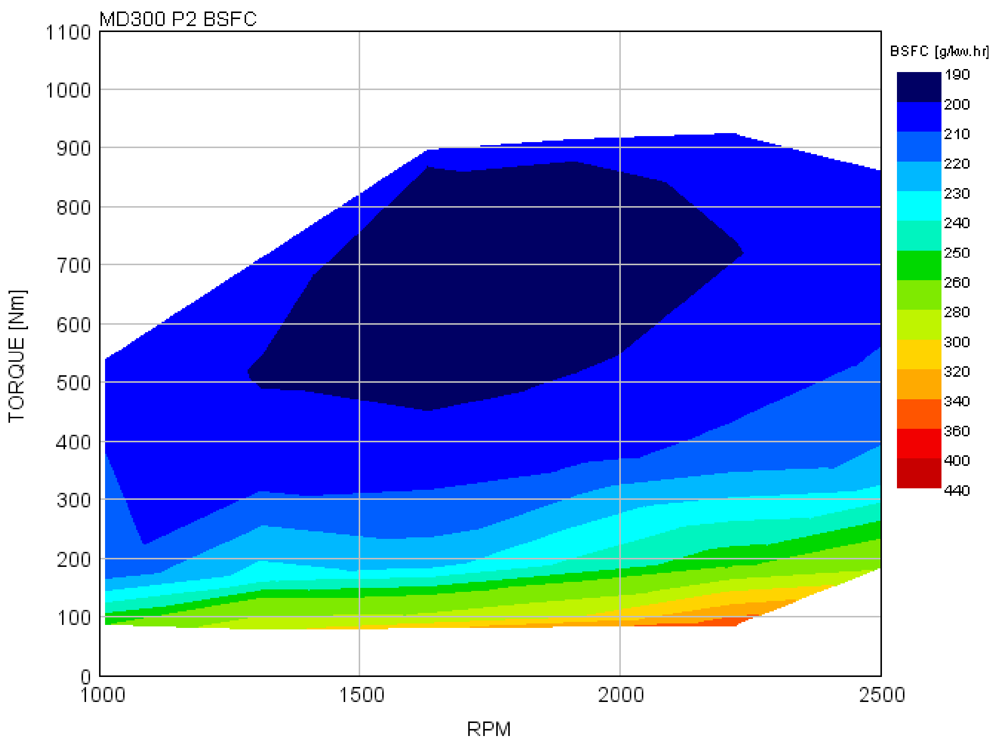


FIGURE B2.3A BSFC MAP OF COMBO PACKAGE 7

The results for this technology package show benefits across the speed/load range. One contributor to the improved fuel consumption is reduced engine friction, which is a result of lower cylinder pressure. The elimination of EGR flow caused lower peak cylinder pressure values. In addition, the elimination of EGR and resizing of the turbo resulted in reduced pumping work. The final contributor to reduced fuel consumption is the increased turbo efficiency.

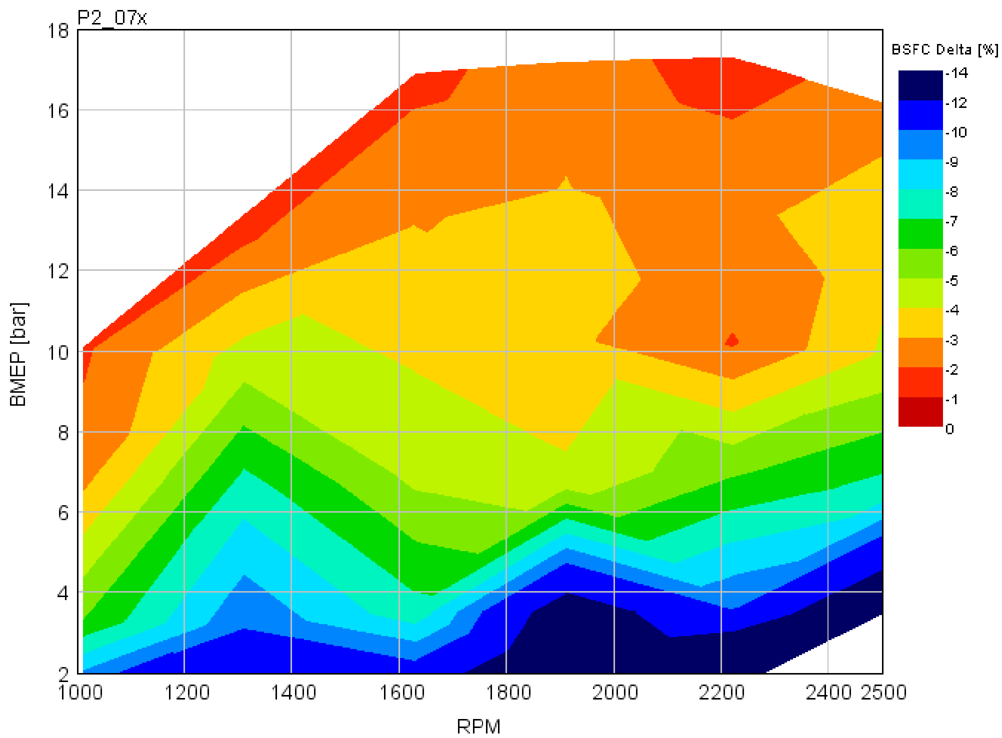


FIGURE B2.3B BSFC IMPROVEMENT MAP OF COMBO PACKAGE 7 VS. 2019 BASELINE

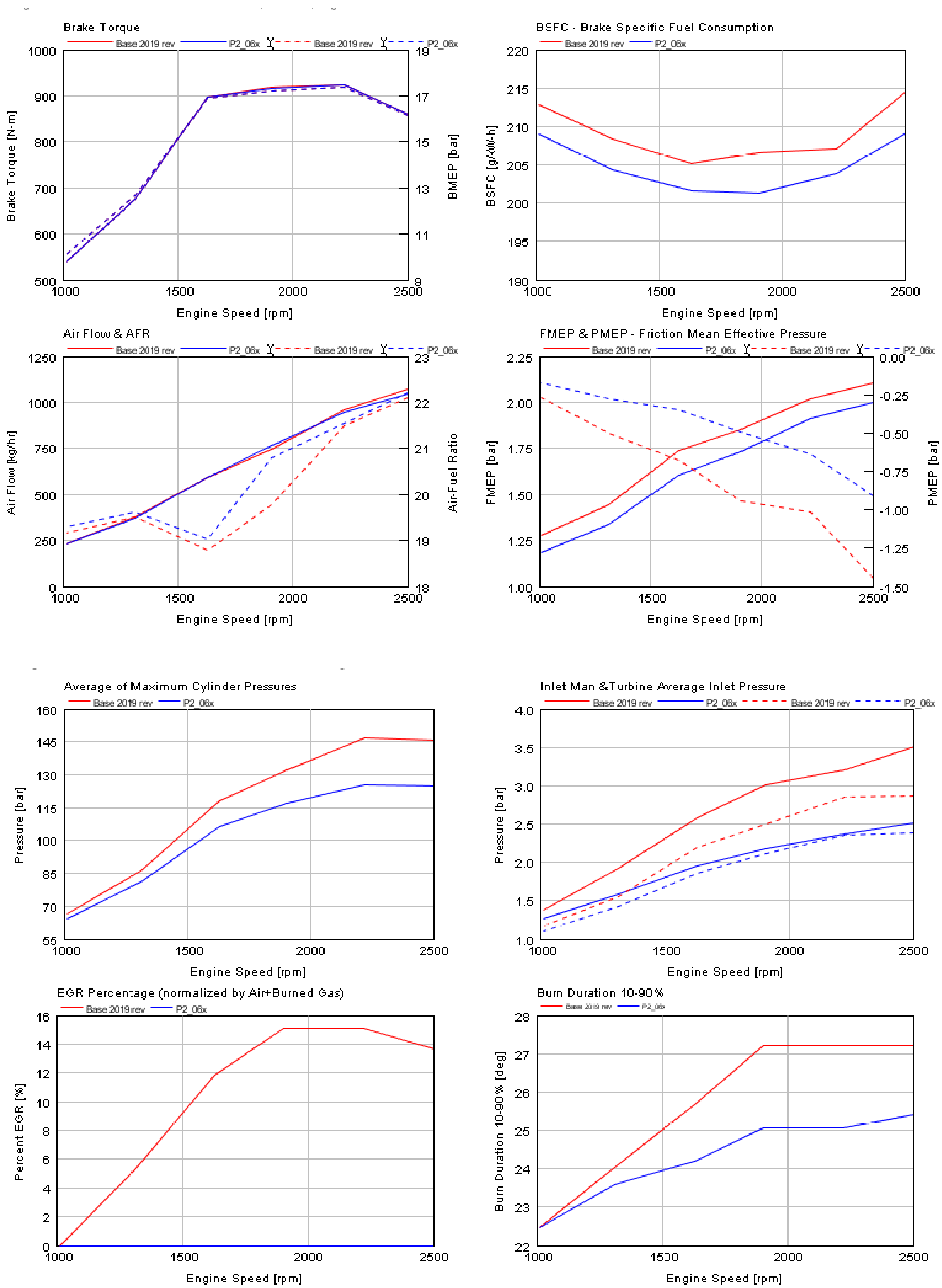


FIGURE B2.3C PACKAGE 7 FULL LOAD PERFORMANCE COMPARISON

2.4 ISB MD Combination Package 8: Base 2019 + Downspeed, Turbo Efficiency Increase, Limited Friction Reduction, No EGR

Combination Package 8 took the Package 7 engine and ran it at a downspeed condition with maximum speed reduced from 2500 rpm to 2200 rpm, and maximum torque increased to 1100Nm. To accommodate the higher BMEP, only a partial friction reduction was assumed (5% at high speed and load, increasing to 17.5% at low speed, light load). The turbo was rescaled to achieve the required performance. Like Package 7, Package 8 is a high engine-out NOx alternative which would require very high efficiency aftertreatment. Note that running a downspeed engine at higher torque would require a significant upgrade to the truck's transmission, driveline, and rear axle.

Figures B2.4a, B2.4b and B2.4c show the BSFC, BSFC improvement and full load performance effect of package 8 compared to the 2019 Base engine.

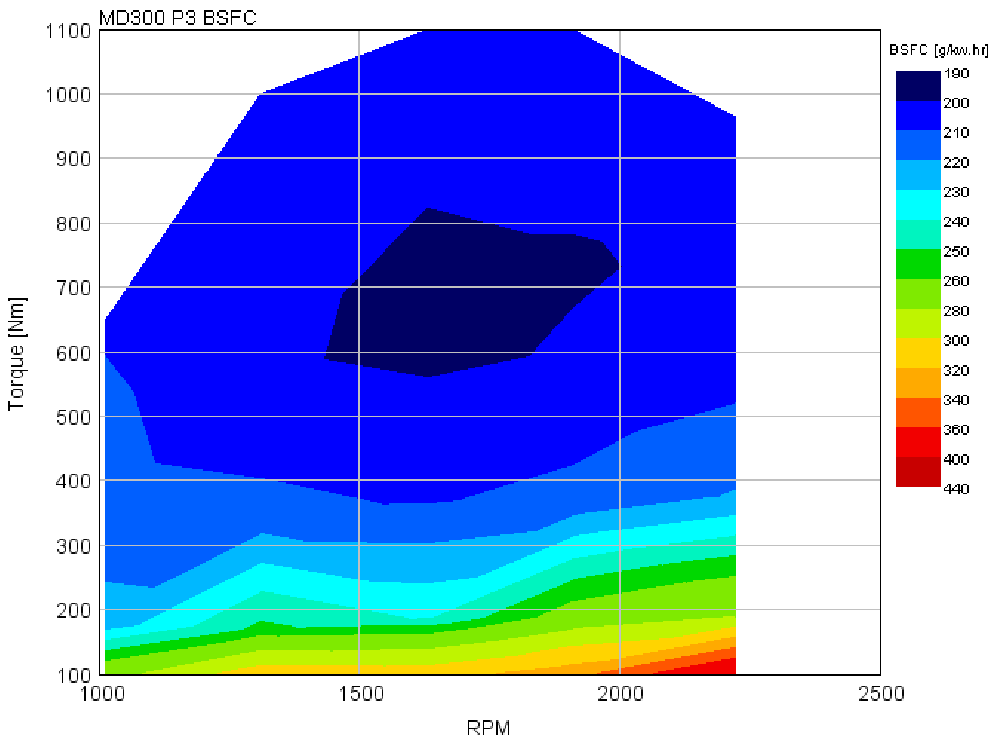


FIGURE B2.4A BSFC MAP OF PACKAGE 8

The results for this technology combination show benefits from the downspeed, EGR removal and turbo efficiency improvements are seen across the rest of the speed/load range. The improvements at light load are not as dramatic as those for Package 7, because only a partial friction reduction is employed. However, Package 8 will benefit in the vehicle by running any given vehicle power demand at a lower RPM and thus a higher BMEP. At light and medium loads, this will move the engine operating point into a more efficient part of the BSFC map.

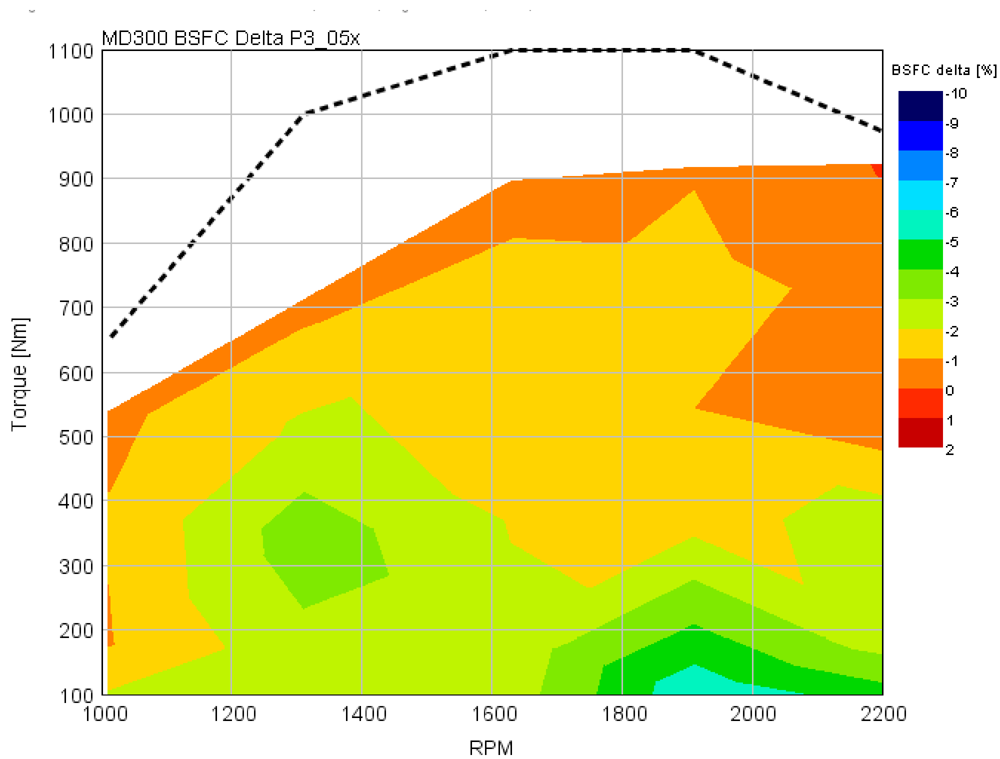


FIGURE B2.4B BSFC IMPROVEMENT MAP OF PACKAGE 8 VS. 2019 BASELINE

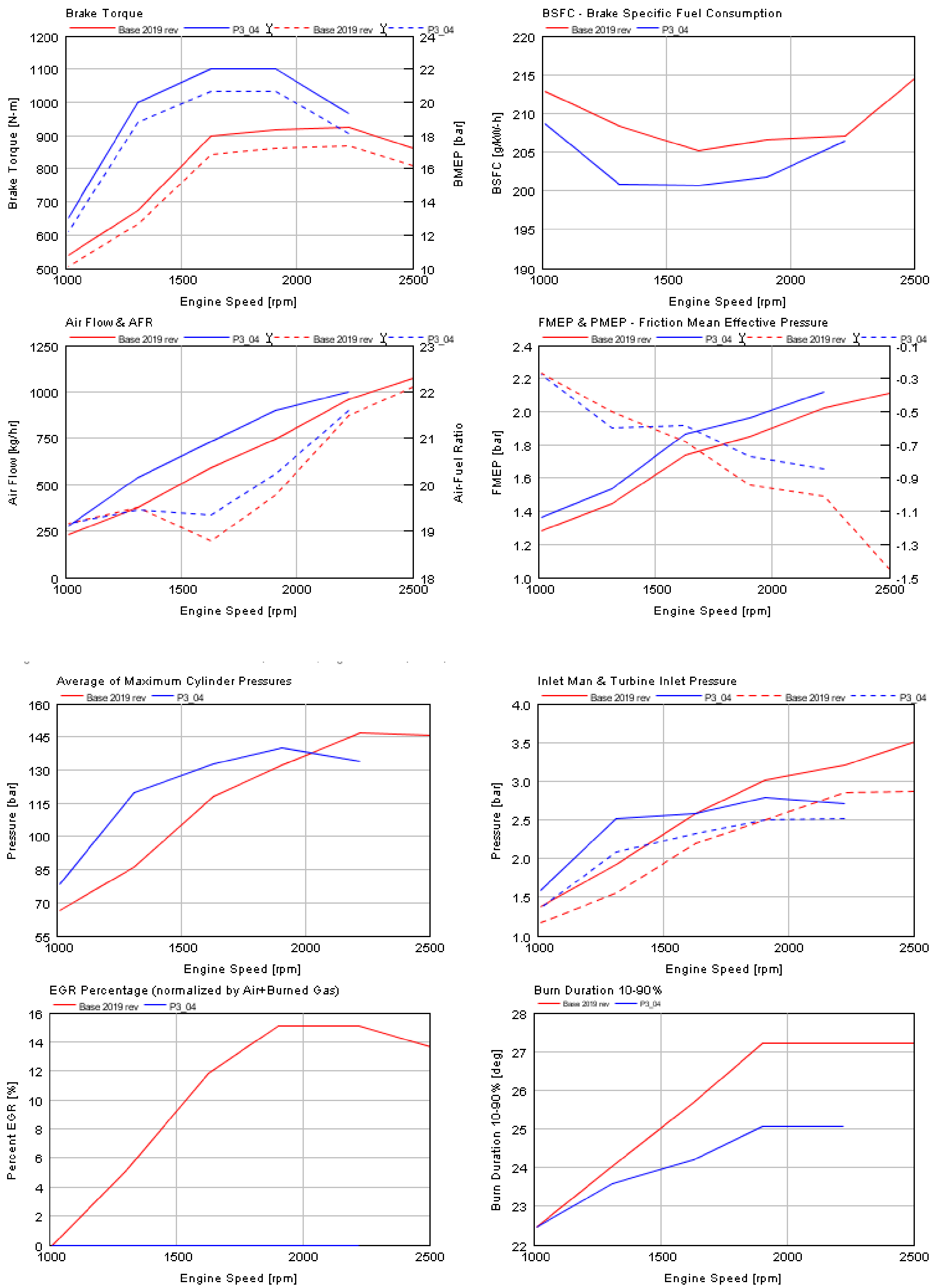


FIGURE B2.4C PACKAGE 8 FULL LOAD PERFORMANCE COMPARISON

2.5 ISB MD Combination Package 9: Base 2019 + Full Friction Reduction and Limited turbo efficiency increase

Combination package 9 took the 2019 base engine plus the full friction reduction and ran it with a 2.5% efficiency improvement for both the turbine and the compressor. No other changes were made, and no turbo rescaling was required

Figures B2.5a, B2.5b and B2.5c show the BSFC, BSFC improvement and full load performance effect of package 9 compared to the 2019 Base engine.

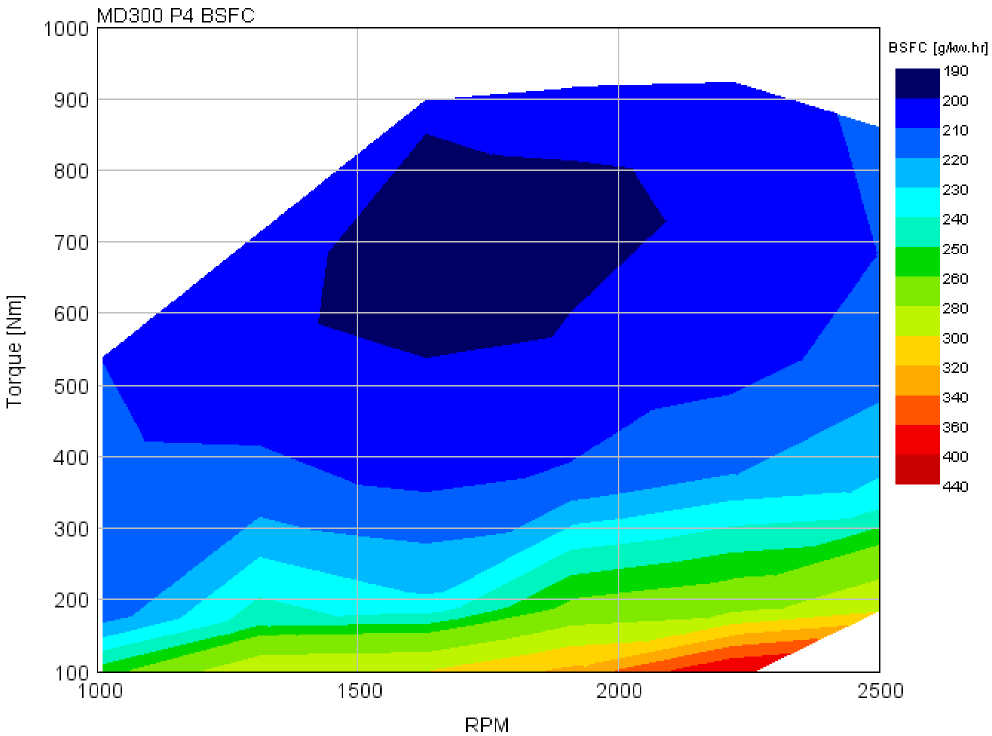


FIGURE B2.5A BSFC MAP OF PACKAGE 9

The combination of lower friction and increased turbine and compressor efficiency gives a reasonable BSFC improvement across the speed/load range.

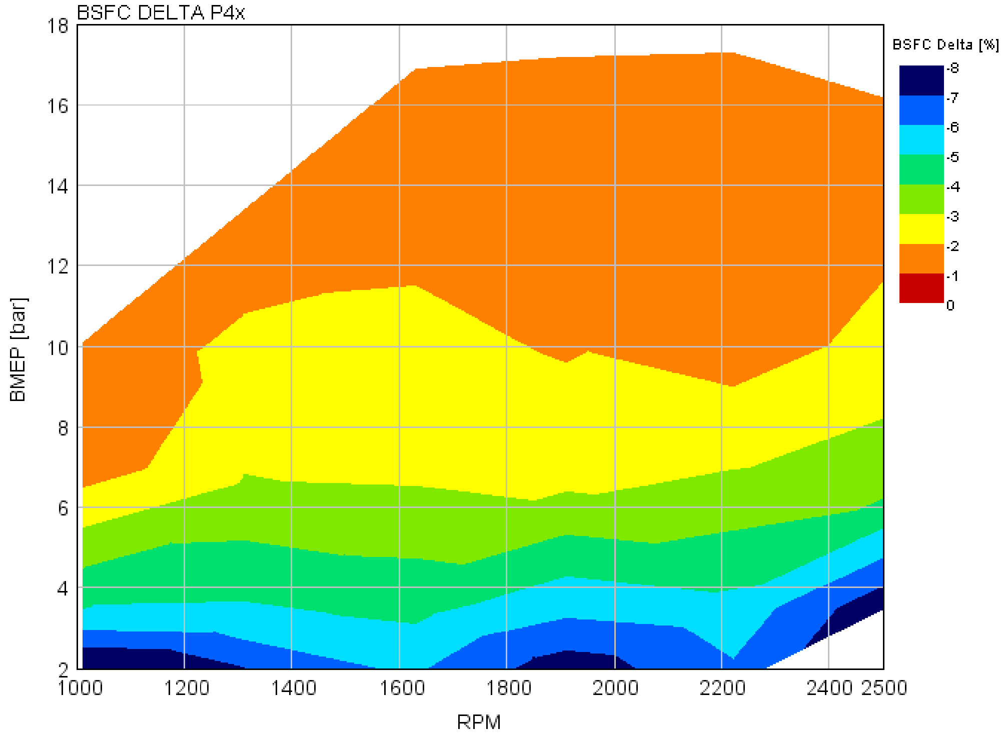


FIGURE B2.5B BSFC IMPROVEMENT MAP OF PACKAGE 9 VS. 2019 BASELINE

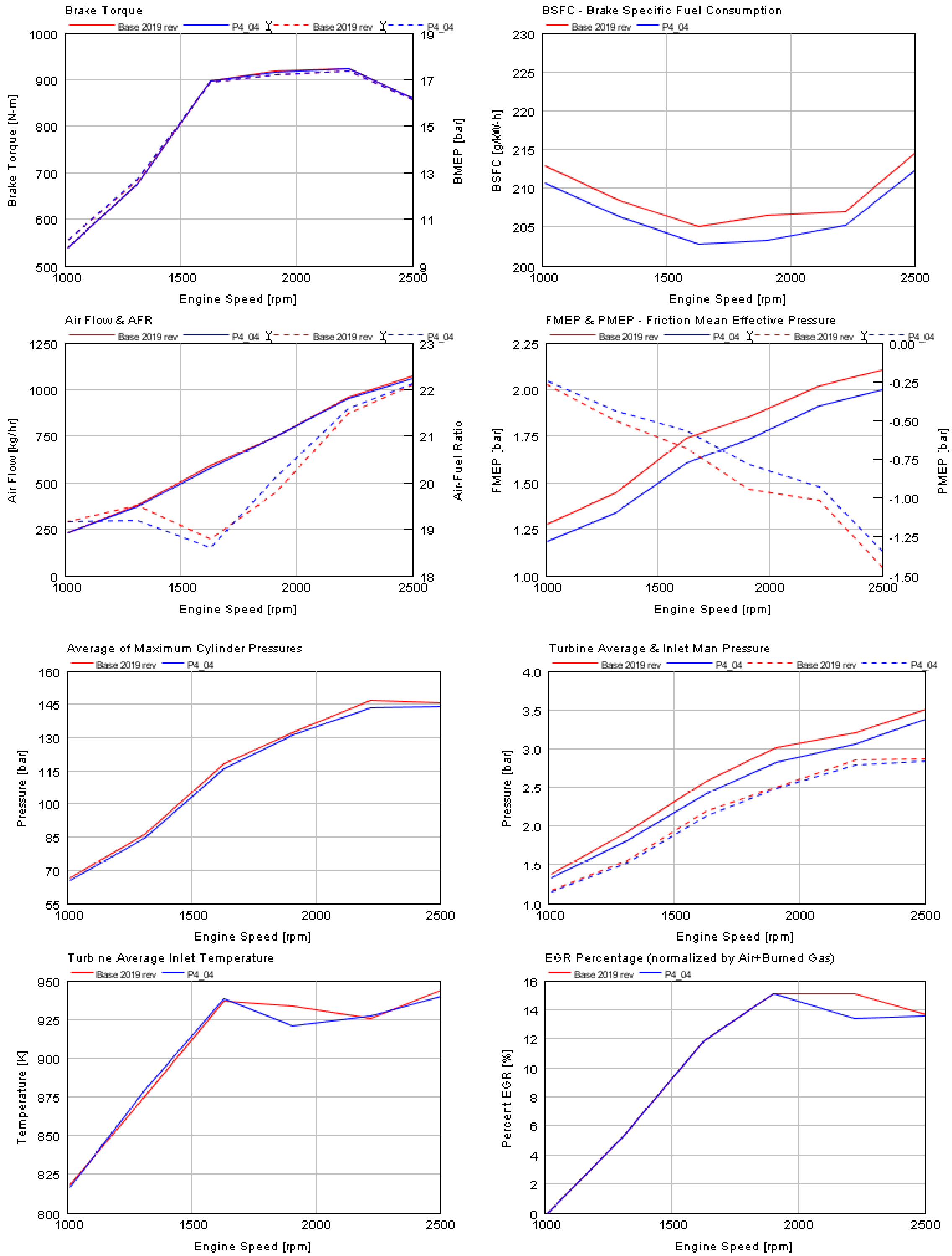


FIGURE B2.5C PACKAGE 9 FULL LOAD PERFORMANCE COMPARISON

2.6 ISB MD Combination Package 10: 4-Cylinder Version with Base 2019 Combustion + High BMEP and EGR, no friction reduction

Combination Package 10 is a downsized 4-cylinder version of the engine. To partially compensate for the smaller engine size, the engine was run at the higher BMEP levels used in the pickup truck version of the ISB engine. Package 10 includes the combustion improvements of the 2019 baseline ISB engine. The EGR rates of the medium duty engine are carried over to maintain engine-out NOx performance. This represents an increase in EGR rate from the pickup truck version, which does not use EGR at high load. As a result of the high BMEP and EGR rates, cylinder pressures are higher than for any other package considered in this study. To account for the high cylinder pressure, the original ISB friction rates are used. This represents a step back to higher friction from the 2019 baseline ISB. These changes required the turbo system to be rescaled to maintain performance and a minimum AFR of 19:1. Peak power for Package 10 is reduced from 300 HP to 252 HP as a result of the downsizing and increased BMEP. To compensate for the lower power rating, the Package 10 engine has a higher maximum speed rating of 3,000 RPM, like the pickup truck version.

Figures B2.6a and B2.6b show the BSFC, BSFC comparison, both on a BMEP and Torque basis, and Figures B2.6c shows full load performance effect of package 10 (P5_O4) compared to the 2019 Base engine and the original PU385 4 cylinder engine from Report #1 (PU 385 I4 (P5_O2). Note that the original pickup 4 cylinder engine did not require EGR at high load.

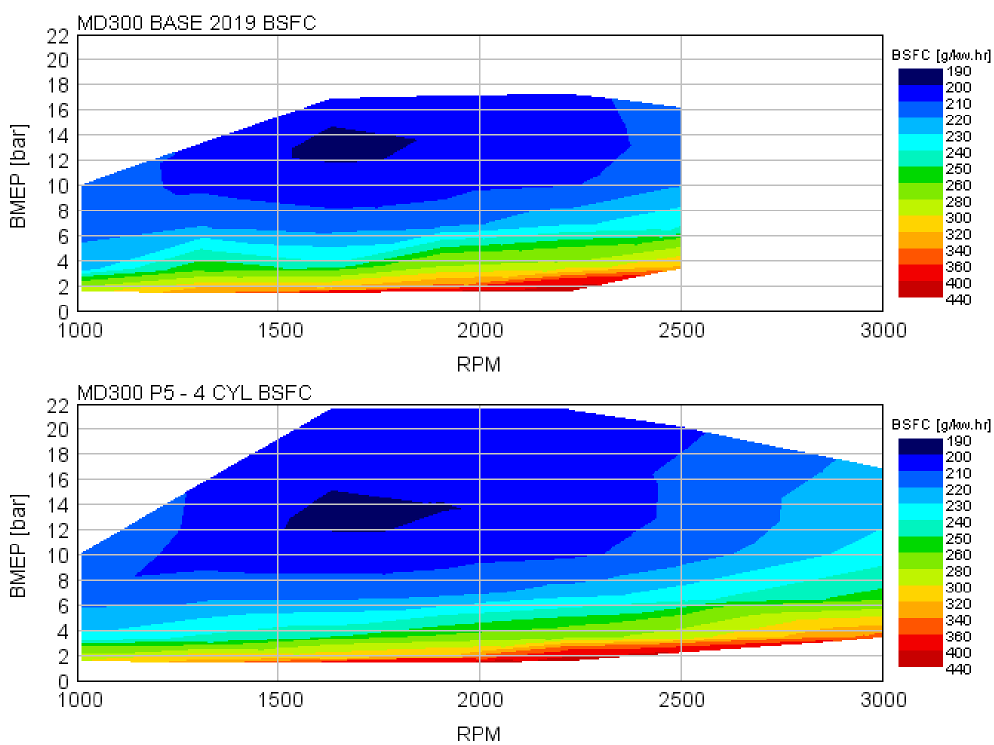


FIGURE B2.6A BSFC MAPS OF BASE 2019 ENGINE AND PACKAGE 10

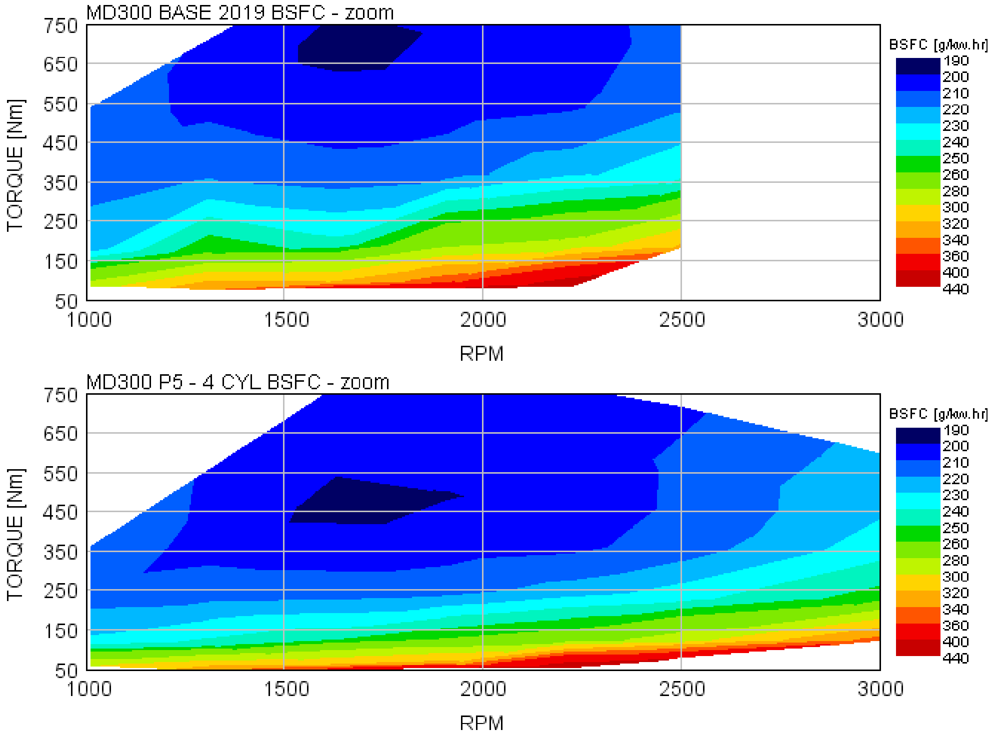


FIGURE B2.6B BSFC MAPS OF BASE 2019 ENGINE AND PACKAGE 10 – ZOOMED TORQUE

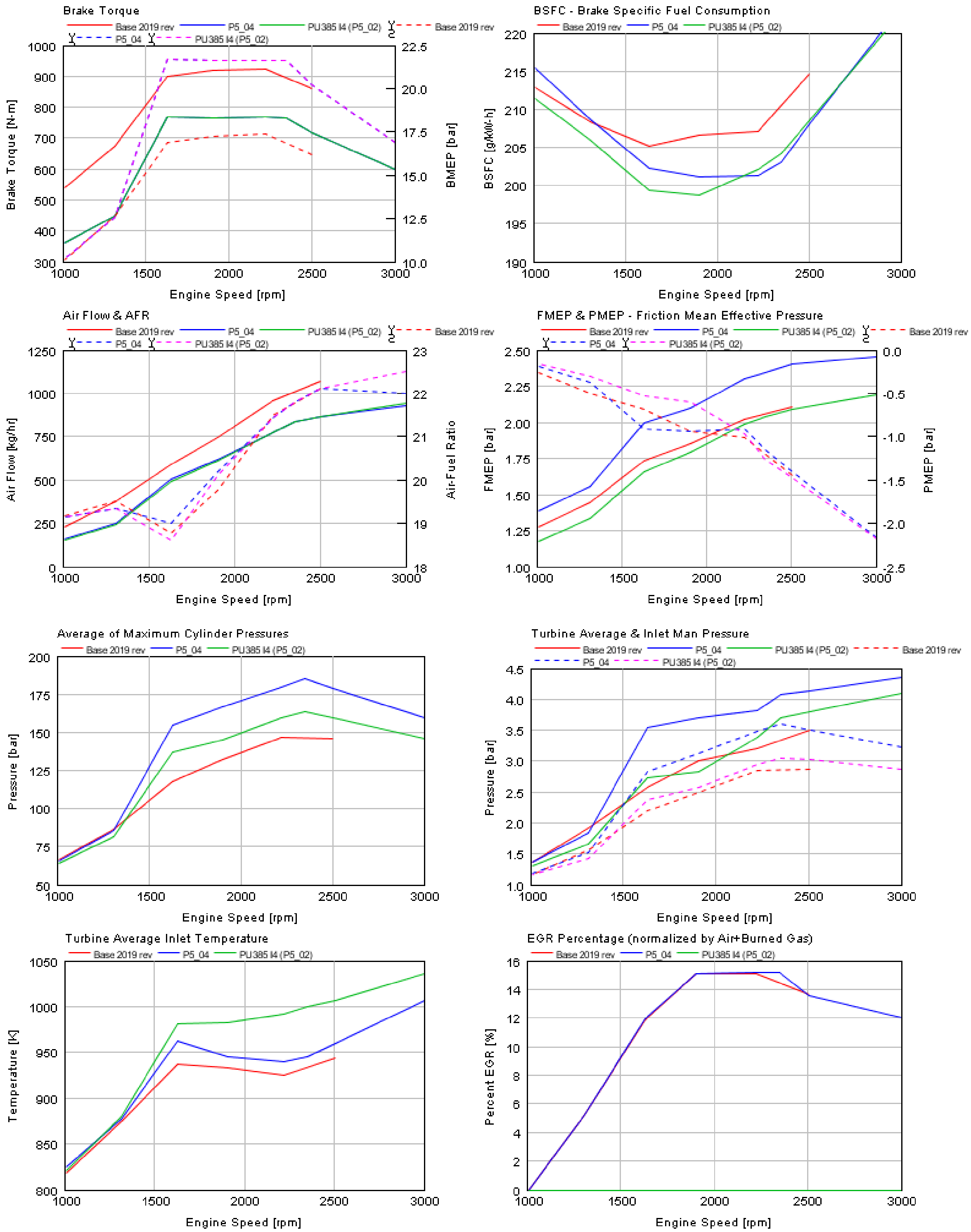


FIGURE B2.6C PACKAGE 10 FULL LOAD PERFORMANCE COMPARISON. NOTE THAT THE BLUE CURVES REPRESENT PACKAGE 10, WHILE GREEN REPRESENTS THE 4-CYLINDER PICKUP VERSION.

3.1 2019 Baseline ISB Pickup 385 bhp Engine

The original ISB Pickup (385 bhp) model was updated to represent what could reasonably be expected to be the future 2019 baseline ISB engine performance. This was achieved by improving the combustion performance, specifically the combustion duration (10-90%) to achieve a 1% improvement in fuel consumption across the speed and load range. Additionally, the model was run with a limited reduced friction setup (half the improvement as used in the initial technologies study for the ISB). All other aspects of the engine specification and performance were kept the same as the original baseline ISB model, including EGR and AFR levels. Because pickup engines are generally chassis certified, they do not need to control NOx at full load. As a result, EGR is not used at full load. This allows pickup engines to run at a higher BMEP than the same engine can achieve in an engine dyno certified version, such as is used for medium-duty trucks.

- **Basic engine specification**
  - 6.7L inline 6-cylinder diesel
  - Single variable-geometry turbo
  - 4 valves per cylinder
  - 285 kW @ 2350 rpm
  - 1150 Nm @ 1600-2350 rpm

Figure B3.1a and B3.1b show the BSFC and the improvement in BSFC between the original pickup ISB configuration and the 2019 baseline ISB with combustion improvement and limited reduced friction. This setup is then the reference for all the following technology combination packages.

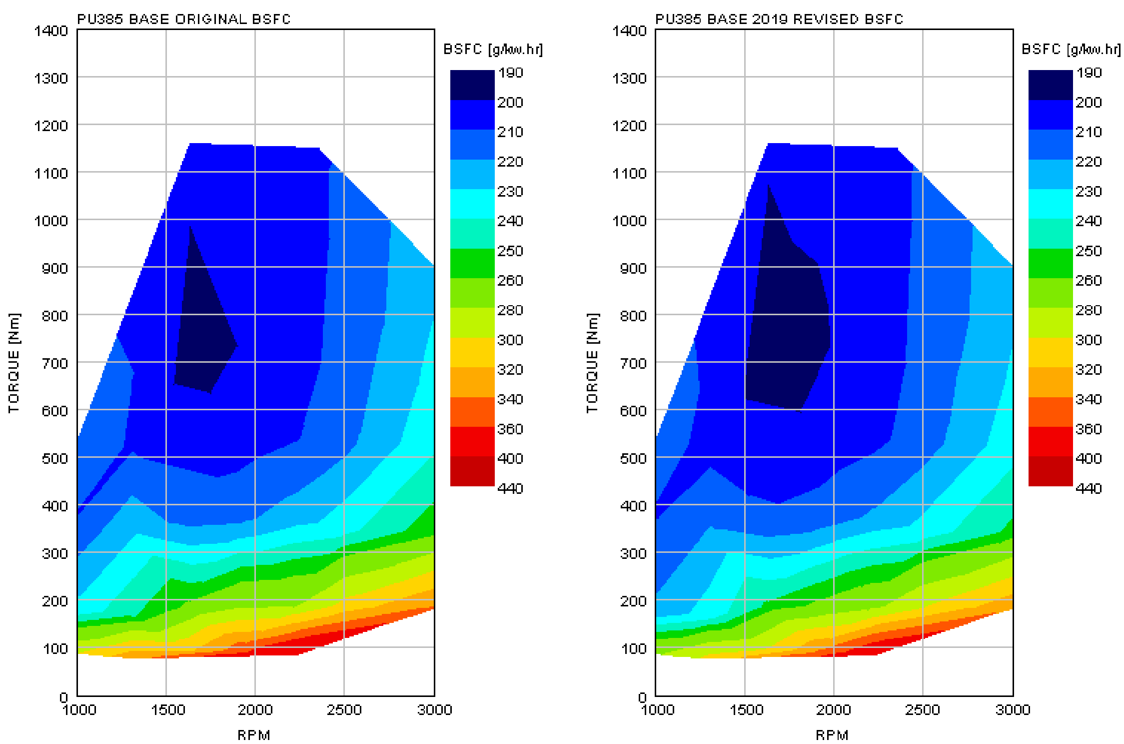


FIGURE B3.1A BSFC MAPS OF 2013 BASE ENGINE AND 2019 BASE ENGINE

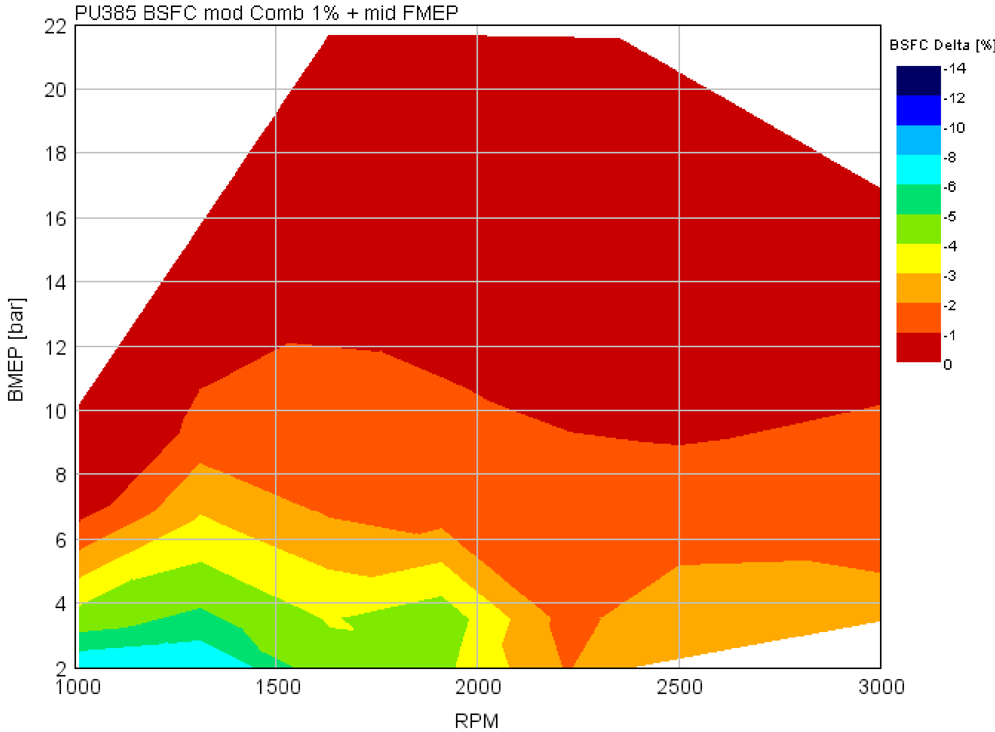
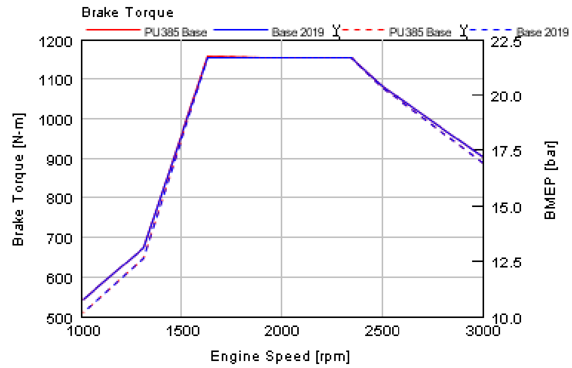
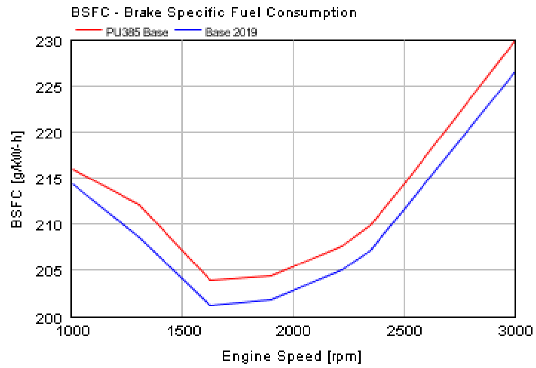
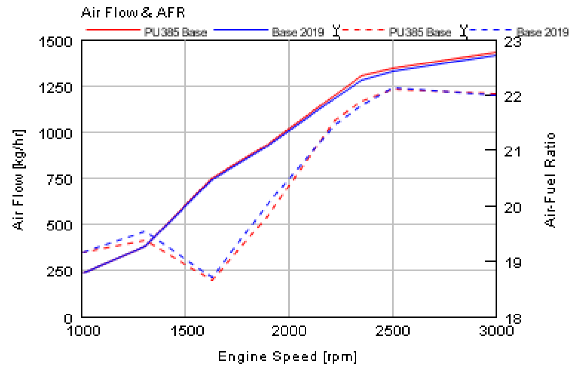


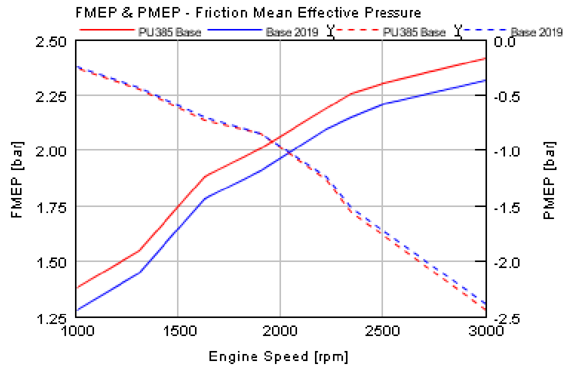
FIGURE B3.1B BSFC IMPROVEMENT OF 2019 BASE ENGINE VS. ORIGINAL BASE ENGINE

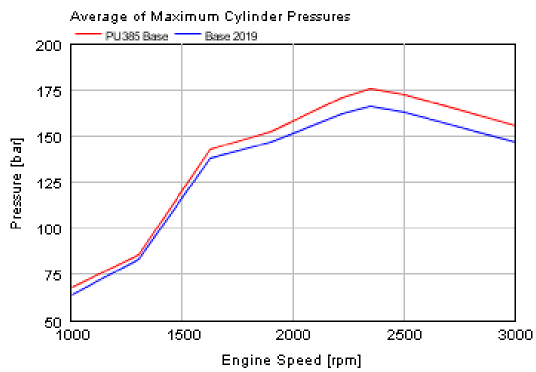
Figure B3.1c shows a summary of the full load performance comparison between the 2 engines.

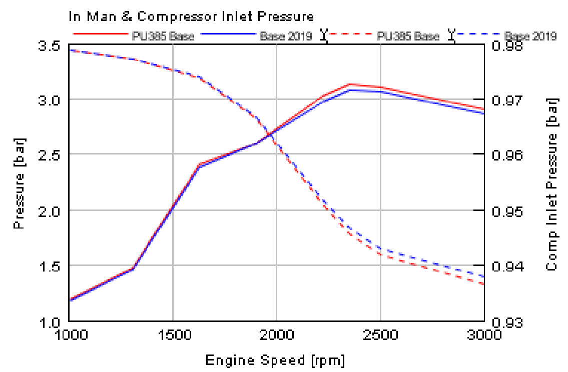

Brake Torque
PU385 Base
Base 2019
Brake Torque [N-m]
BMEP [bar]
Engine Speed [rpm]
1200
1100
1000
900
800
700
600
500
22.5
20.0
17.5
15.0
12.5
10.0
1000
1500
2000
2500
3000

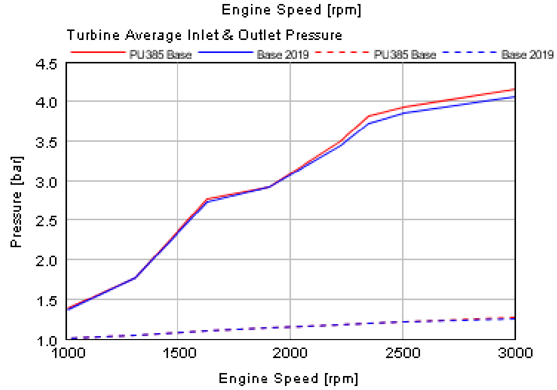

BSFC - Brake Specific Fuel Consumption
PU385 Base
Base 2019
BSFC [g/kW-h]
Engine Speed [rpm]
230
225
220
215
210
205
200
1000
1500
2000
2500
3000

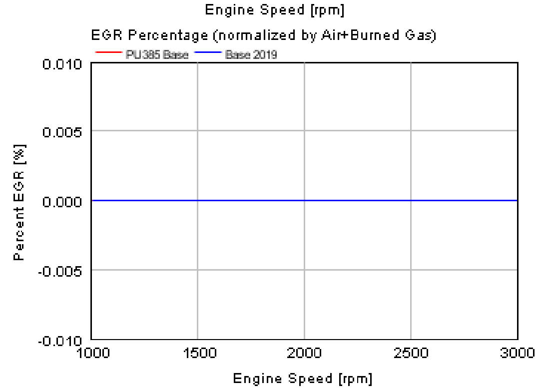

Air Flow & AFR
PU385 Base
Base 2019
Air Flow [kg/hr]
Air-Fuel Ratio
Engine Speed [rpm]
1500
1250
1000
750
500
250
0
23
22
21
20
19
18
1000
1500
2000
2500
3000


FMEP & PMEP - Friction Mean Effective Pressure
PU385 Base
Base 2019
FMEP [bar]
PMEP [bar]
Engine Speed [rpm]
2.50
2.25
2.00
1.75
1.50
1.25
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
1000
1500
2000
2500
3000


Average of Maximum Cylinder Pressures
PU385 Base
Base 2019
Pressure [bar]
Engine Speed [rpm]
200
175
150
125
100
75
50
1000
1500
2000
2500
3000


In Man & Compressor Inlet Pressure
PU385 Base
Base 2019
Pressure [bar]
Comp Inlet Pressure [bar]
Engine Speed [rpm]
3.5
3.0
2.5
2.0
1.5
1.0
0.98
0.97
0.96
0.95
0.94
0.93
1000
1500
2000
2500
3000


Turbine Average Inlet & Outlet Pressure
PU385 Base
Base 2019
Pressure [bar]
Engine Speed [rpm]
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
1000
1500
2000
2500
3000


EGR Percentage (normalized by Air+Burned Gas)
PU385 Base
Base 2019
Percent EGR [%]
Engine Speed [rpm]
0.010
0.005
0.000
-0.005
-0.010
1000
1500
2000
2500
3000

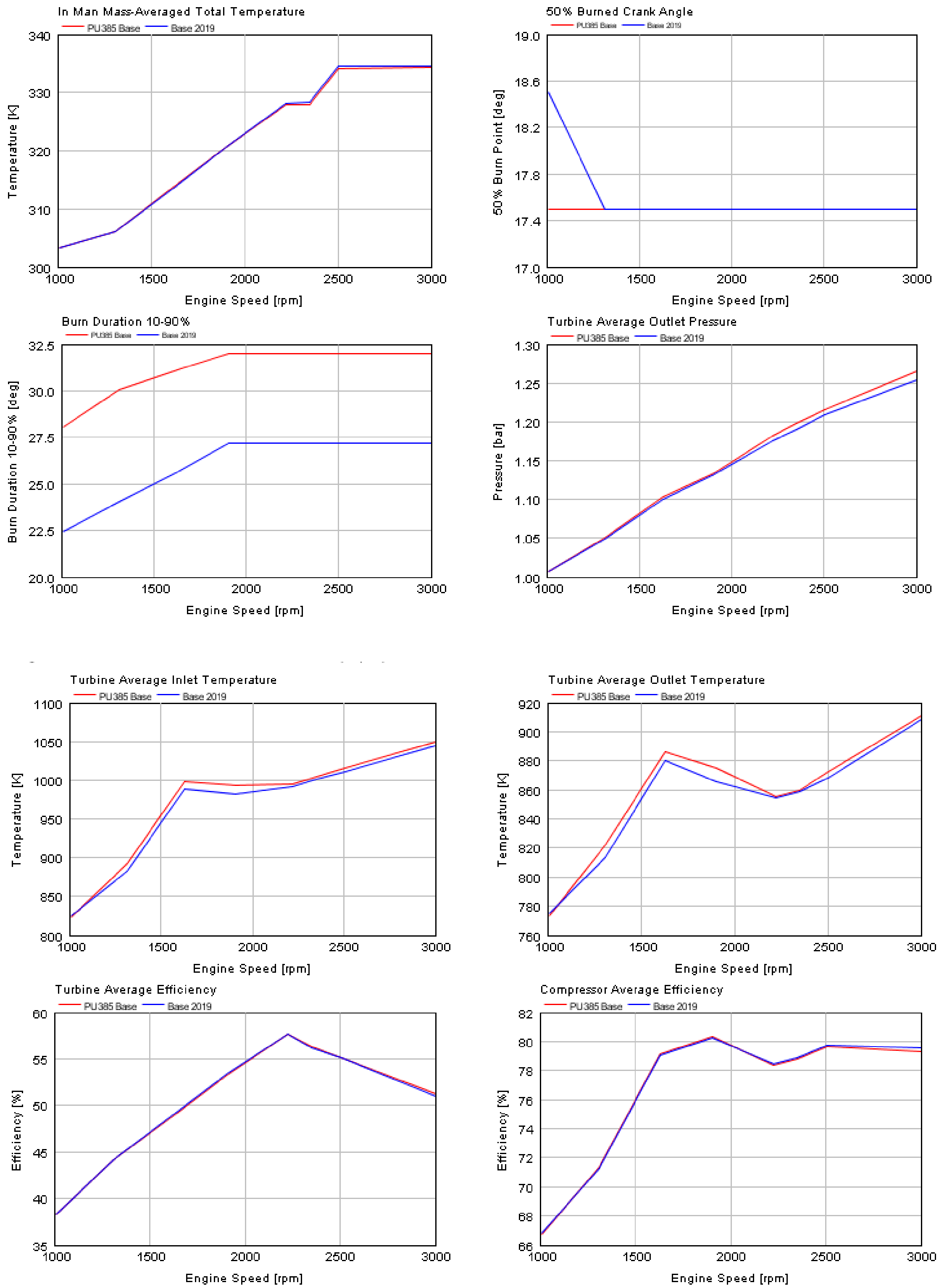


FIGURE B3.1C 2019 BASE ENGINE FULL LOAD COMPARISON

3.2 ISB Pickup Combination Package 11: Base 2019 + Downspeed and limited turbo efficiency increase and Limited Friction Reduction

Combination package 11 took the 2019 base engine and ran it at a downspeed condition with maximum speed reduced to 2500 rpm and maximum torque increased to 1360Nm. Additionally the turbo efficiency was increased 2.5% for both the turbine and the compressor. No EGR was demanded at the Full load conditions, and AFR levels were maintained at a minimum of ~19:1. The baseline ISB 2019 friction levels were maintained. Note that running a downspeed engine at higher torque would require a significant upgrade to the truck's transmission, driveline, and rear axle. The peak cylinder pressure capability of the engine must also be upgraded.

Figures B3.2a, B3.2b and B3.2c show the BSFC, BSFC improvement and full load performance effect of package 11 compared to the 2019 Base engine. The results for this technology combination show benefits for the downspeed and turbo efficiency improvements across the speed/load range. In addition, vehicle fuel economy will benefit because for a given vehicle power demand, the engine will run at a lower speed and higher BMEP. At light and medium loads, this will cause the engine to operate at a more efficient part of the fuel map.

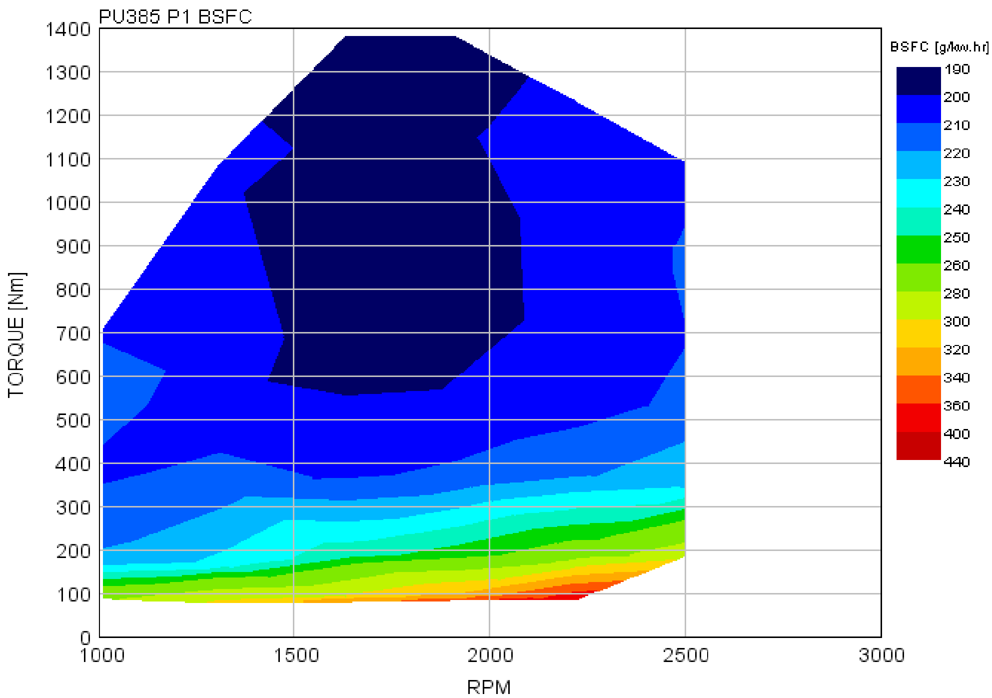


FIGURE B3.2A BSFC MAP OF COMBO PACKAGE 11

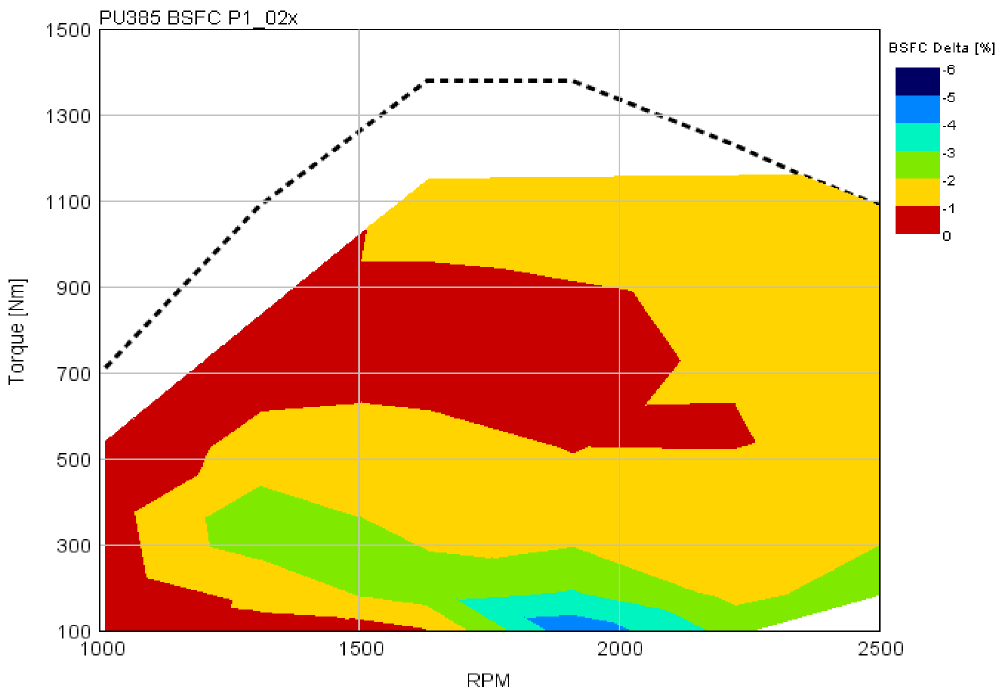
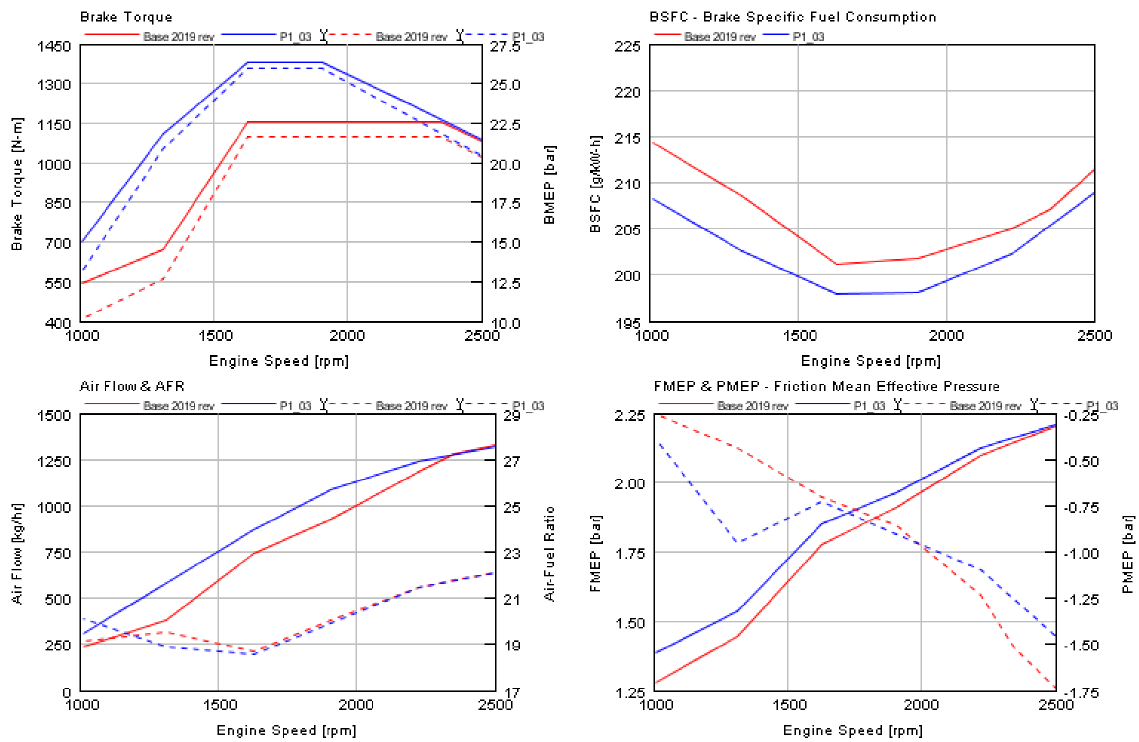


FIGURE B3.2B BSFC IMPROVEMENT MAP OF COMBO PACKAGE 11 VS. THE 2019 BASELINE



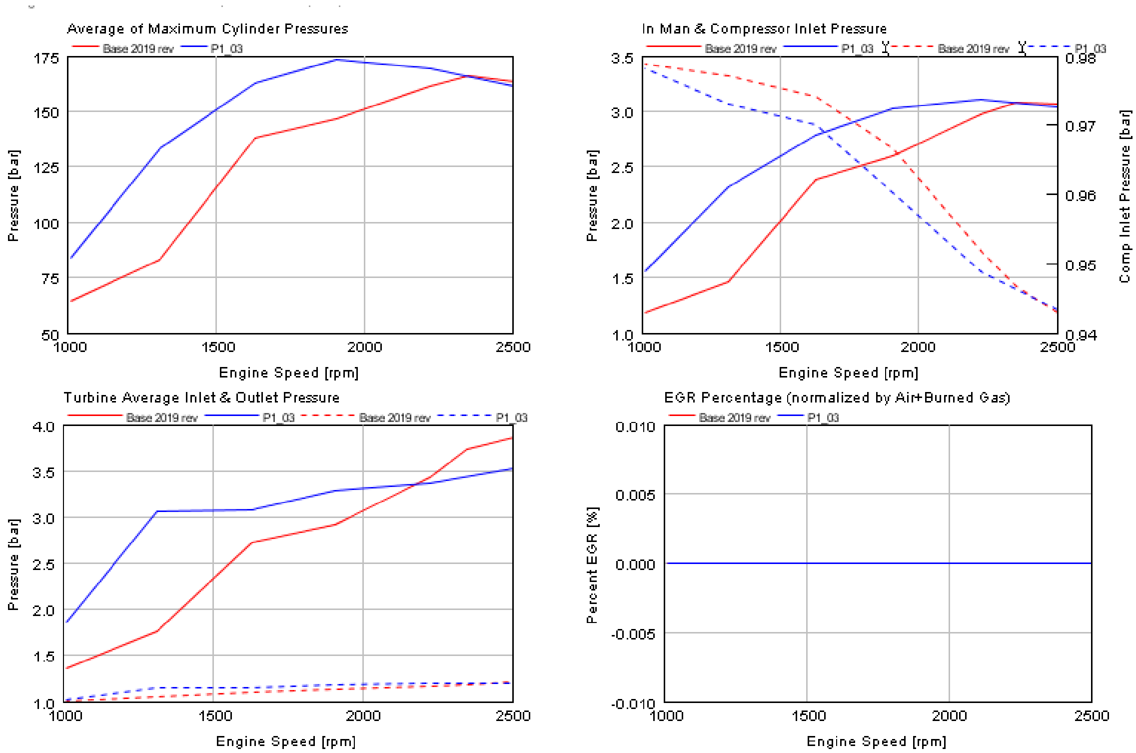


FIGURE B3.2C PACKAGE 11 FULL LOAD PERFORMANCE COMPARISON

3.3 ISB Pickup Combination Package 12: 2019 Base Engine + No EGR, Turbo Efficiency Increase and Full Friction Reduction

Combination package 12 takes the 2019 base engine plus the full friction reduction and ran it with no EGR and a 5% efficiency improvement for both the turbine and the compressor. To achieve the required performance (AFR) the turbo was rescaled, since removing the EGR the system tends to deliver excess air. This is a high engine-out NOx package, which would require an extremely efficient aftertreatment system and high urea consumption.

Figures B3.3a, B3.3b and B3.3c show the BSFC, BSFC improvement and full load performance effect of package 12 compared to the 2019 Base engine.

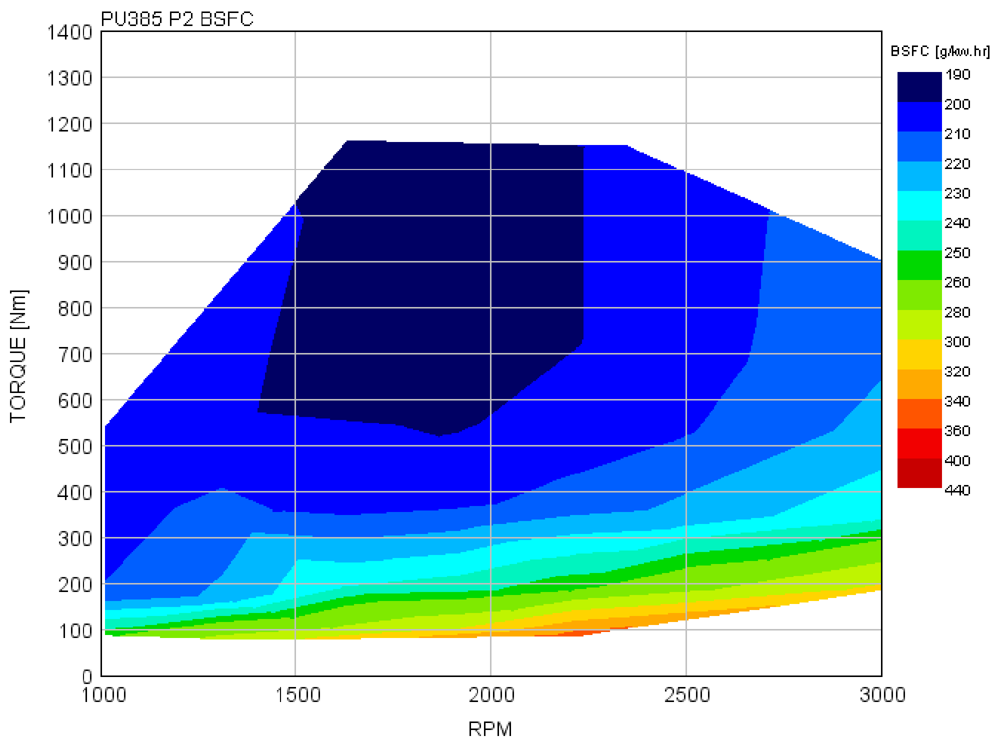


FIGURE B3.3A BSFC MAP OF PACKAGE 12

The results for this technology package show benefits across the speed/load range. This is achieved from a combination of reduced friction, the reduced pumping work from the resized turbo (due to no EGR), and the increased turbo efficiency.

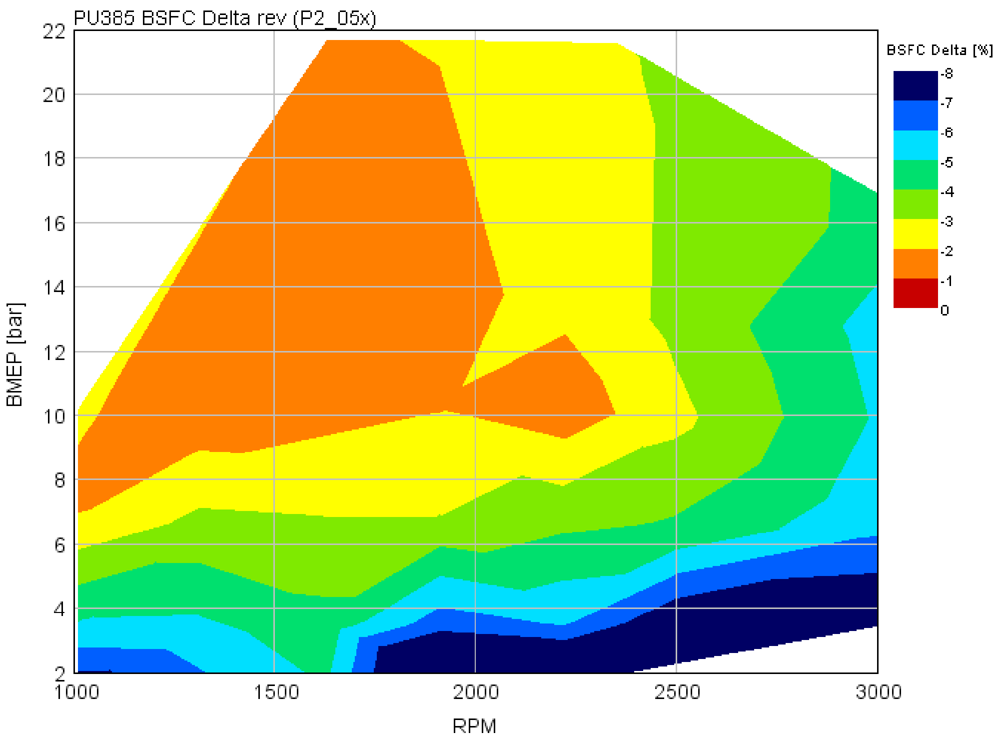


FIGURE B3.3B BSFC IMPROVEMENT MAP OF PACKAGE 12 VS. 2019 BASELINE

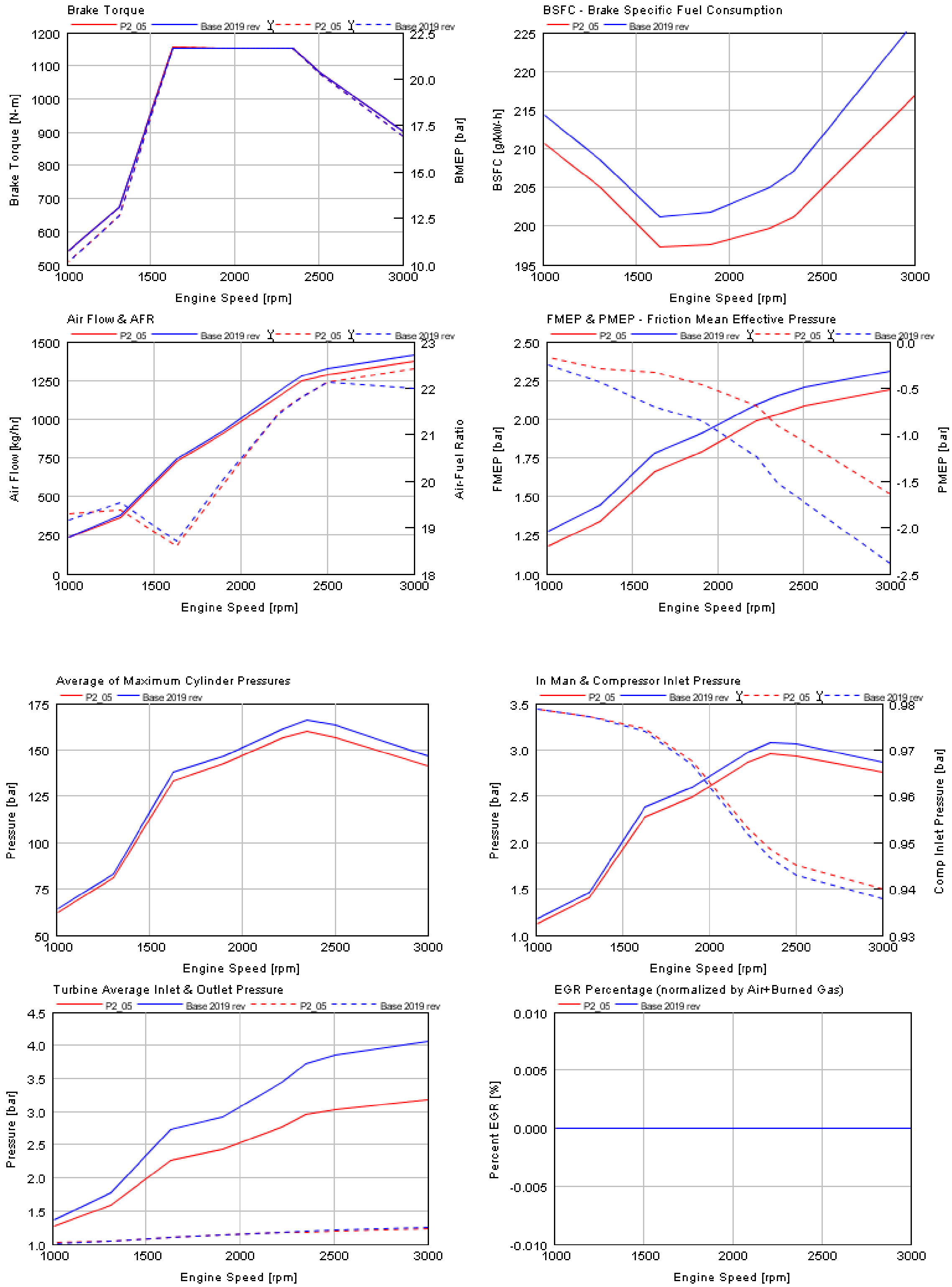


FIGURE B3.3C PACKAGE 12 FULL LOAD PERFORMANCE COMPARISON

3.4 ISB Pickup Combination Package 13: Base 2019 + Downspeed, Turbo Efficiency Increase, Limited Friction Reduction, No EGR

Combination package 13 took the 2019 base engine and ran it at a downspeed condition with maximum speed reduced to 2200 rpm and maximum torque increased to 1100Nm. Additionally it was run with no EGR and a 5% efficiency improvement for both the turbine and the compressor. The turbo was rescaled to achieve the required performance. Package 13 is a high engine-out NOx alternative which would require very high efficiency aftertreatment and high urea consumption. Note that running a downspeed engine at higher torque would require a significant upgrade to the truck's transmission, driveline, and rear axle. The peak cylinder pressure capability of the engine must also be upgraded.

Figures B3.4a, B3.4b and B3.4c show the BSFC, BSFC improvement and full load performance effect of package 13 compared to the 2019 Base engine.

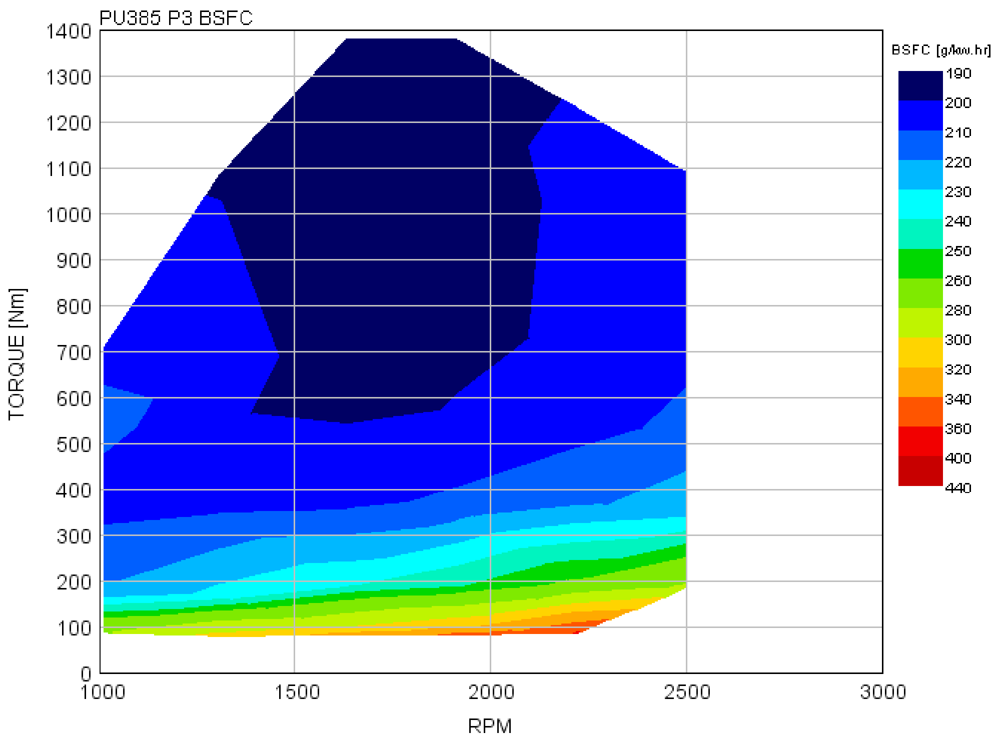


FIGURE B3.4A BSFC MAP OF COMBO PACKAGE 13

The results for this technology combination show that benefits from the downspeed, EGR removal and turbo efficiency improvements are seen across the speed/load range. In addition, vehicle fuel economy will benefit because for a given vehicle power demand, the engine will run at lower speed and higher BMEP. At light and medium load, this will push the engine into a more efficient part of the fuel map.

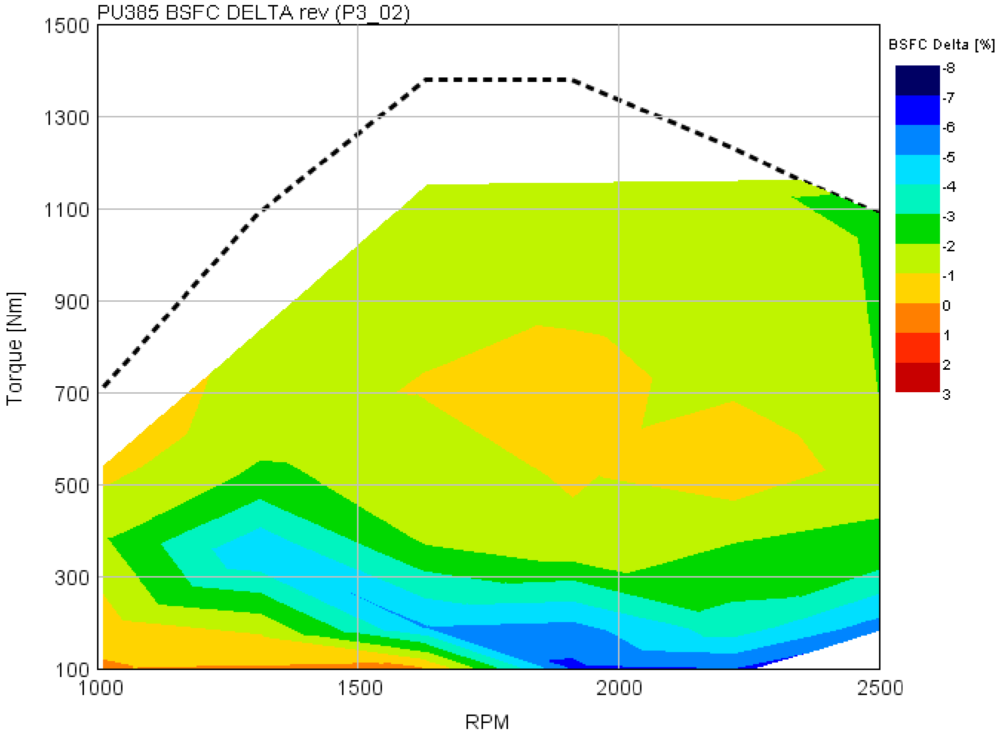


FIGURE B3.4B BSFC IMPROVEMENT OF P13 DOWNSPEED, NO EGR, TURBO EFFICIENCY INCREASE and LIMITED FRICTION REDUCTION

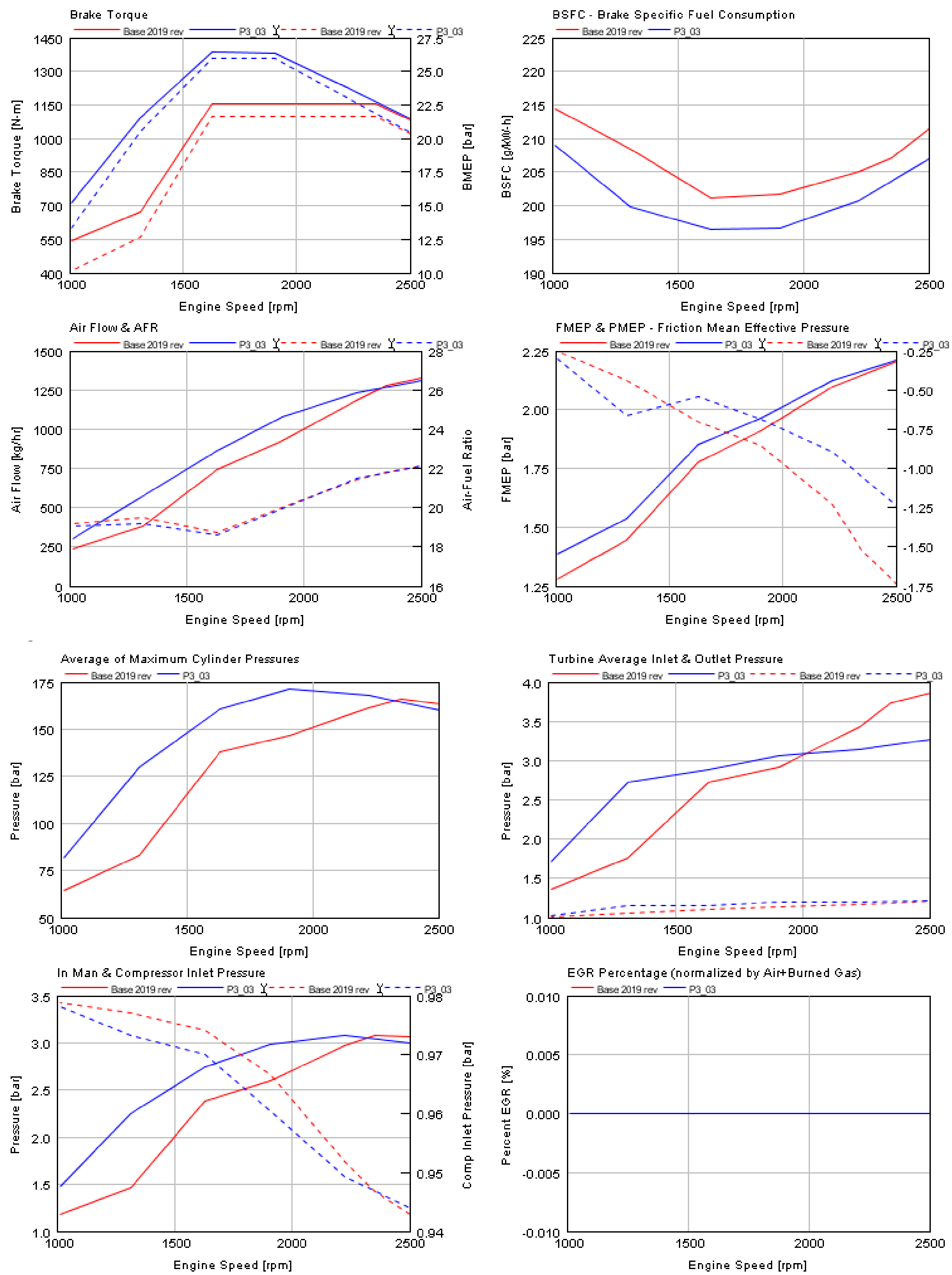


FIGURE B3.4C FULL LOAD PERFORMANCE COMPARISON FOR P13

3.5 ISB Pickup Combination Package 14: Base 2019 + Limited turbo efficiency increase and Full Friction Reduction

Combination package 14 took the 2019 base engine plus the full friction reduction and ran it with a 2.5% efficiency improvement for both the turbine and the compressor. No other changes were made and no turbo rescaling was required

Figures B3.5a, B3.5b and B3.5c show the BSFC, BSFC improvement and full load performance effect of package 14 compared to the 2019 Base engine.

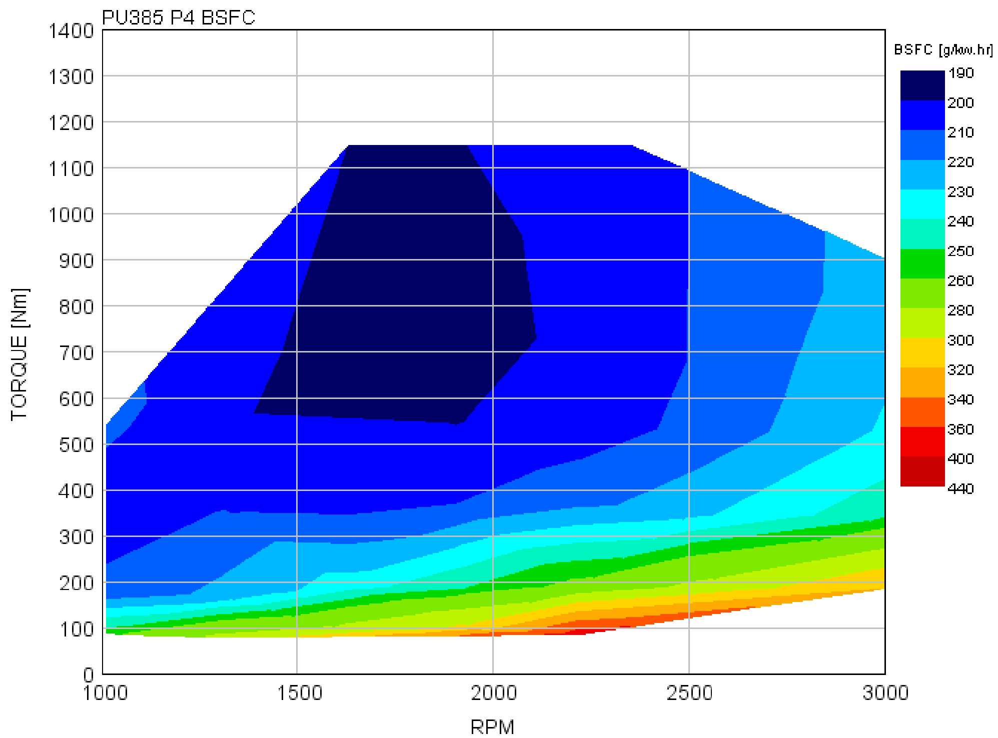


FIGURE B3.5A BSFC OF 2.5% TURBINE and COMPRESSOR EFFICIENCY INCREASE (P14)

The results for this technology combination seem to show significant part load gains, but the major part of this is due to the full friction reduction of this setup, compared to the limited reduction for the baseline ISB model. If run in isolation the increased turbine and compressor efficiency would result in limited BSFC improvements across the speed/load range.

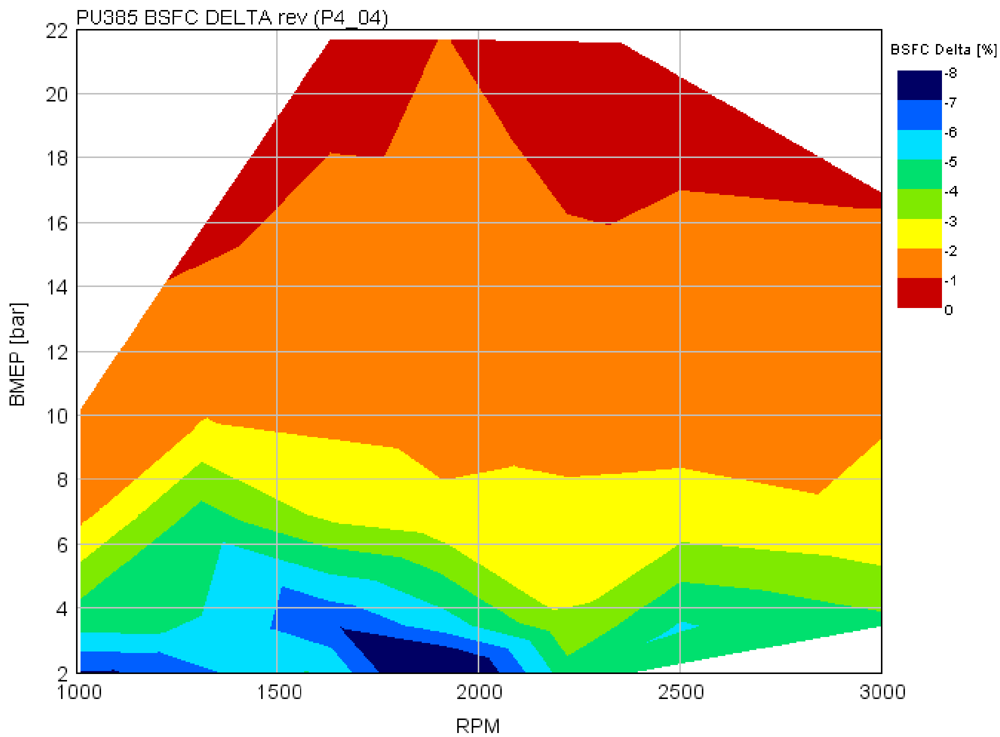


FIGURE B3.5B BSFC IMPROVEMENT 2.5% TURBINE AND COMPRESSOR EFFICIENCY INCREASE (P14)

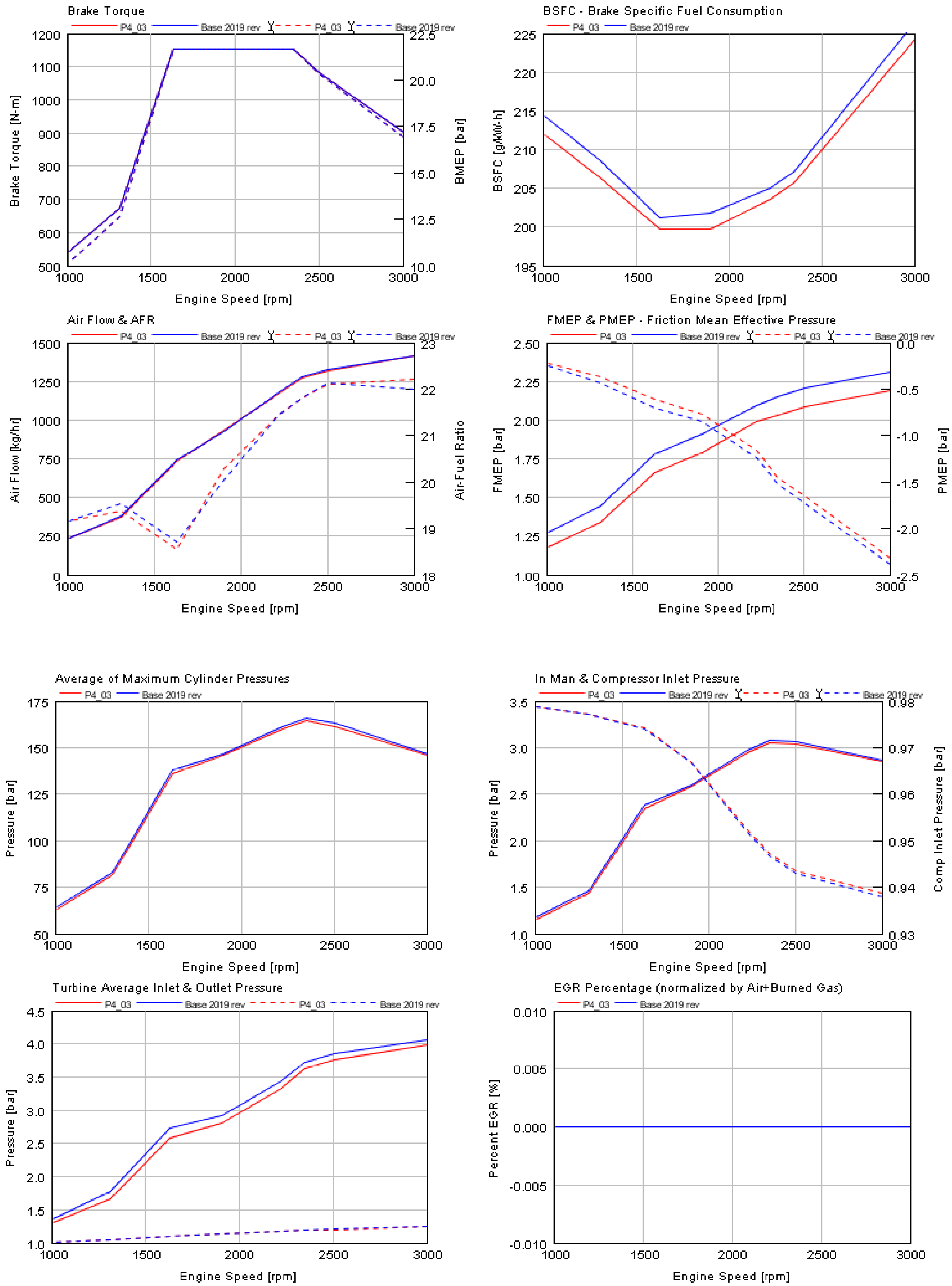


FIGURE B3.5C FULL LOAD PERFORMANCE COMPARISON (P14)

3.6 ISB Pickup Combination Package 15: Base 2019 + Downsized 4 Cylinder and Full Friction Reduction

Combination package 15 took the combustion improvements of the 2019 base engine plus the full friction reduction and applied them to the downsized I4 version run in the original study. These changes required the turbo system to be rescaled to maintain performance and a minimum AFR of 19:1

Figures B3.6a and B3.6b show the BSFC comparison, both on a BMEP and Torque basis, and Figures B3.6c shows full load performance effect of package 15 (P5_O2) compared to the 2019 Base engine and the original PU385 4 cylinder engine from the original study (PU 385 I4).

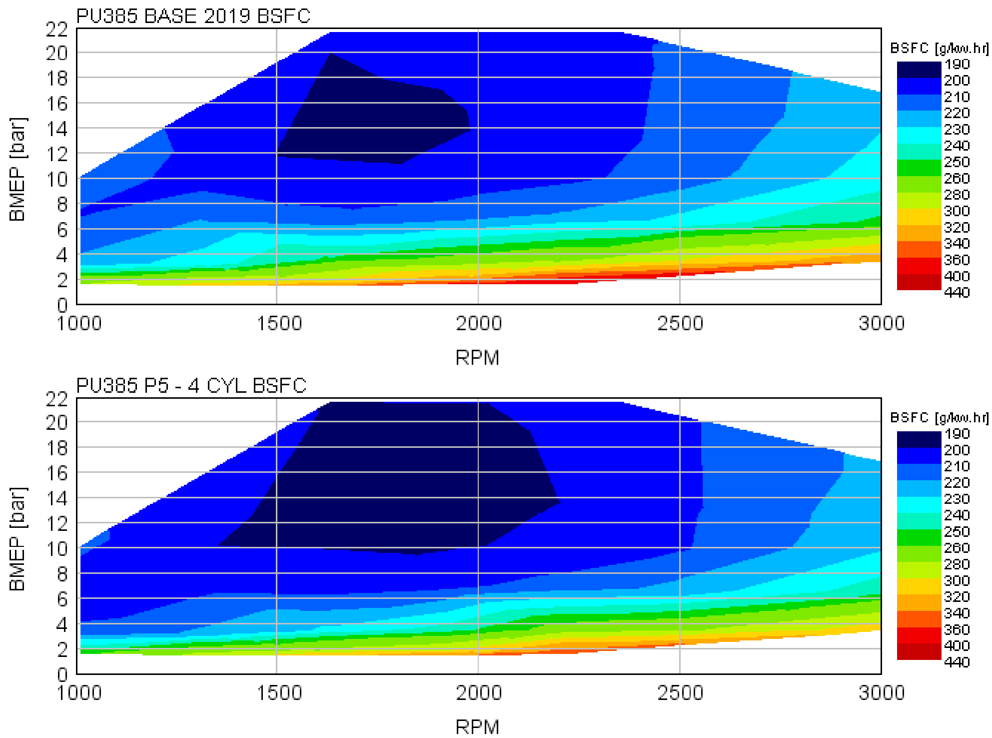
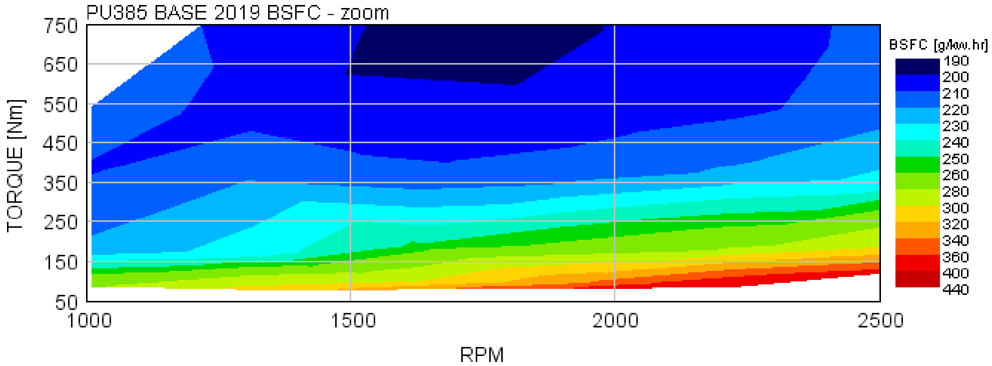


FIGURE B3.6B BSFC COMPARISON OF P15 I4 – BMEP



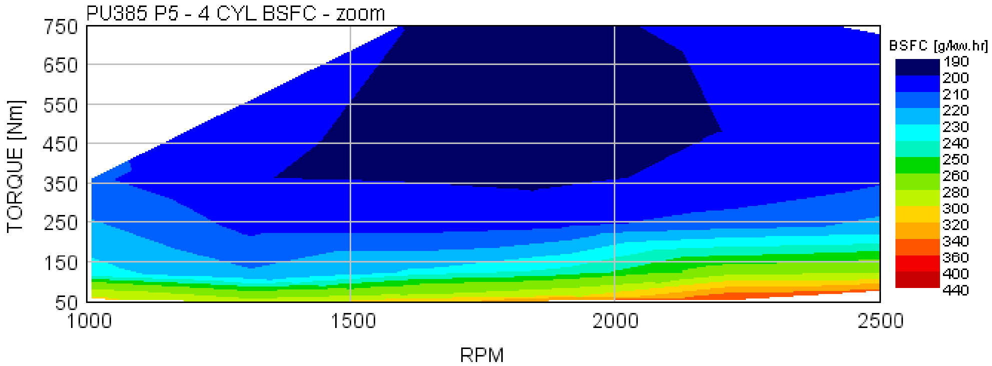


FIGURE B3.6B BSFC COMPARISON P15 I4 – ZOOMED TORQUE

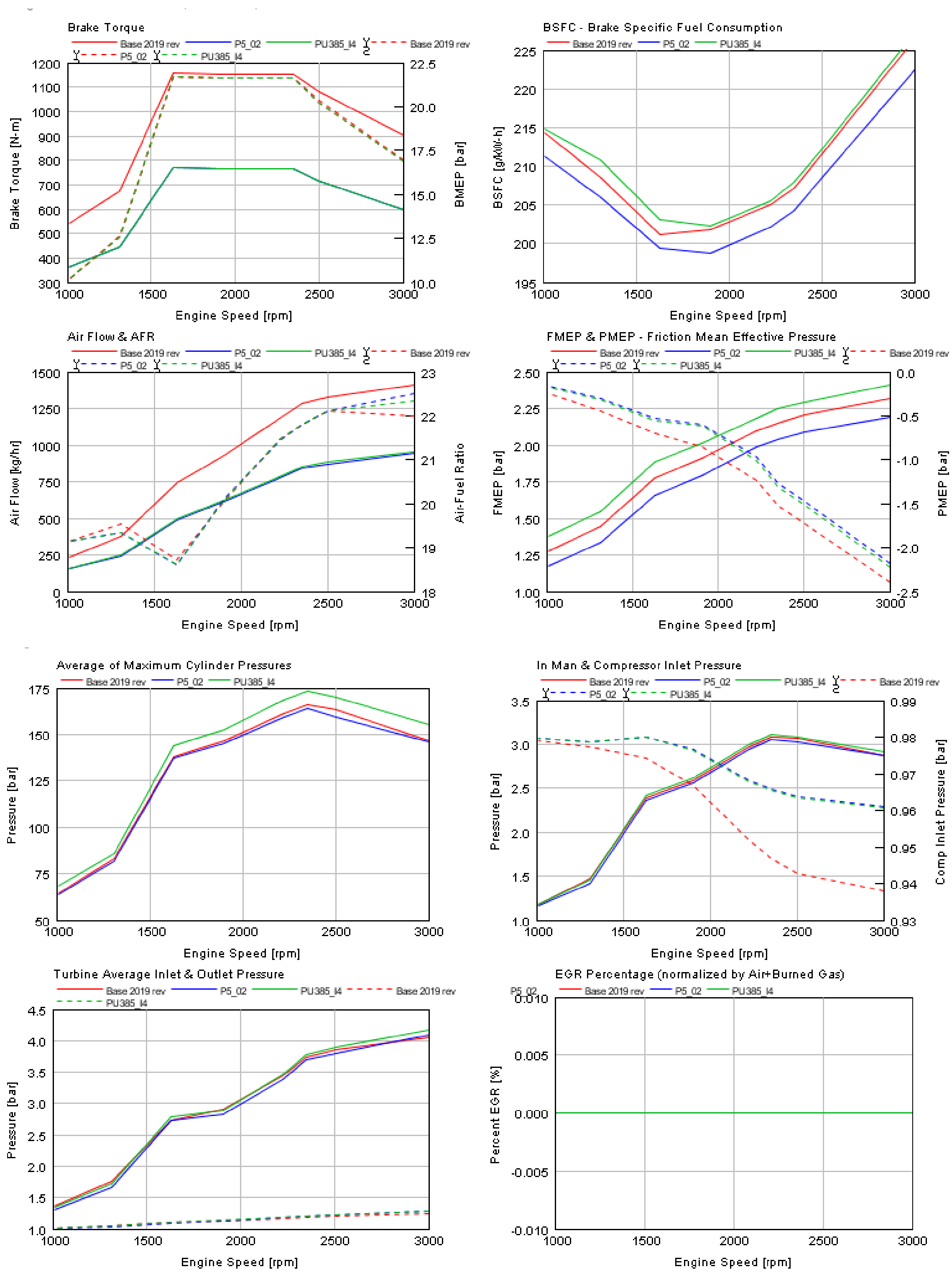


FIGURE B3.6C FULL LOAD PERFORMANCE COMPARISON OF P15

APPENDIX C

VEHICLE SIMULATION AND VEHICLE TECHNOLOGIES

VEHICLE SIMULATION AND VEHICLE TECHNOLOGIES

Objective: Simulate Future Vehicle and Engine Technologies to Demonstrate Fuel Economy Improvement Potential in Class 2b through 7 vehicles utilizing:

- **A range of engines and engine technologies**
- **A range of vehicle technologies**

1. Vehicle Modeling Approach:

1.1. Simulation Tool

1.2. Description of Baseline Vehicle Models

1.2.1. Ram Pickup Truck
1.2.2. Ford F-650 Roll-On Tow Truck
1.2.3. Kenworth T270 Box Delivery Truck
1.2.4. Kenworth T-700 Tractor-Trailer Truck

2. Vehicle Efficiency Technologies

2.1. Reduced Air Conditioner Power Demand

2.2. Reduced Aerodynamic Drag (Cd)

2.3. Reduced Tire Rolling Resistance (Crr)

2.4. Weight Reduction

2.5. Chassis Friction Reduction

2.6. 6X2 Axle Configuration

2.7. Road Speed Governor (Reduced Vmax)

2.8. Transmission Alternatives

2.8.1. 6-Speed, 10-Speed, and 18-Speed AMT Transmissions
2.8.2. 10-Speed Manual Transmission
2.8.3. 5-Speed, 6-Speed, and 8-Speed Torque Converter Automatic Transmissions

2.9. Engine Alternatives

2.9.1. 4.5 and 6.7 Liter Diesel (Pickup Only)
2.9.2. 6.7 and 8.9 Liter Diesel (Classes 4 – 8)
2.9.3. 3.5 V-6 and 6.2 V-8 Gasoline Engines (Classes 2b – 7)
2.9.4. 12.5 Liter and 14.8 Liter Diesel (Class 8 Only)

C1 Vehicle Modeling Approach

C1.1 Simulation Tool

The simulation tool utilized in Phase II of this research was SwRI's Vehicle Simulation Tool (VST) described in Appendix C of Final Report #1. No customized modifications were required to conduct Phase II simulations and analyses. The drive cycles are also described in Appendix C of Final Report #1.

C1.2 Drive Cycles

A total of eleven vehicle drive cycles were used in the study. Each cycle is described in this section. The NESCCAF cycle was developed to represent a typical line haul type of operation. There are brief urban/suburban sections at the beginning and end of the cycle, to represent getting out to the highway. The main portion of the cycle consists of five cruise segments at speeds of 65 to 70 MPH. One of the cruise segments has an alternating +/- 1% grade, and a second cruise segment has an alternating +/- 3% grade. The NESCCAF cycle is the only cycle that includes grades. Because tractor-trailer trucks cannot normally maintain cruise speed on a 3% grade, the cycle was given a feature that extended the drive time to force the vehicle to complete the required distance. Figure C6 shows the speed vs. time trace, and Figure C7 shows the grade vs. time trace. This cycle was only used for tractor-trailer trucks.

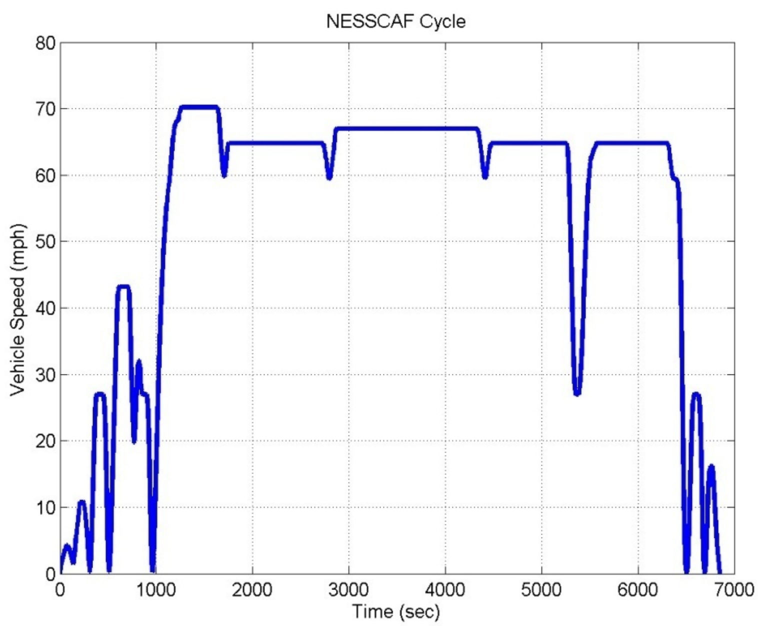


FIGURE C6 SPEED VS. TIME TRACE FOR THE NESCCAF CYCLE

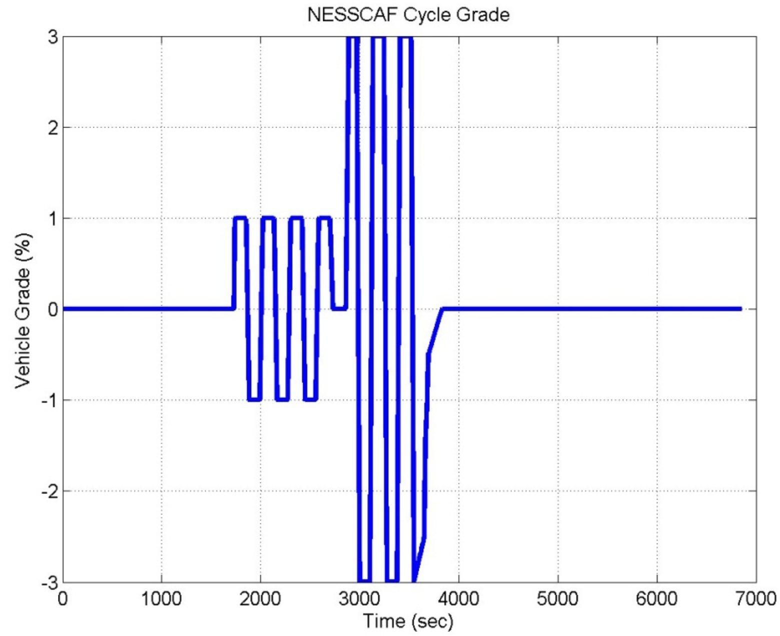


FIGURE C7 GRADE VS. TIME TRACE FOR THE NESCCAF CYCLE

Figure C8 shows the World Harmonized Vehicle Cycle. This cycle is intended for medium and heavy-duty trucks, and includes urban, suburban, and highway segments. The cycle assumes that a road speed governor is used to limit speed to about 53 MPH, which is required in Europe. The WHVC was used for all vehicles, to provide a way to compare results across different vehicle types.

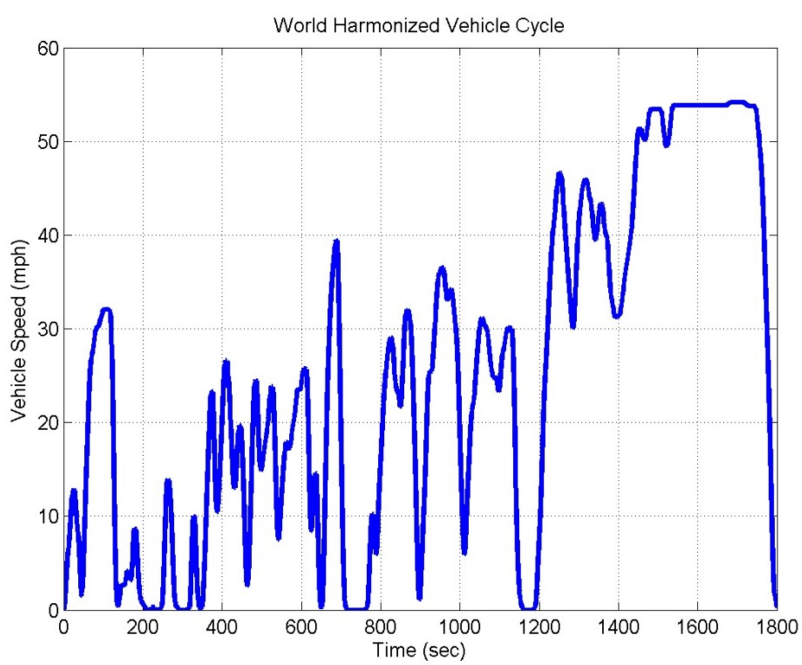


FIGURE C8 WORLD HARMONIZED VEHICLE CYCLE (WHVC)

The FTP-Highway cycle shown in Figure C9 has been used for many years to evaluate light duty vehicle fuel economy. This cycle was developed in the time of the 55 MPH speed limit, so speeds are low compared to typical modern highway driving, and accelerations are gentle. This cycle was only used for the pickup truck.

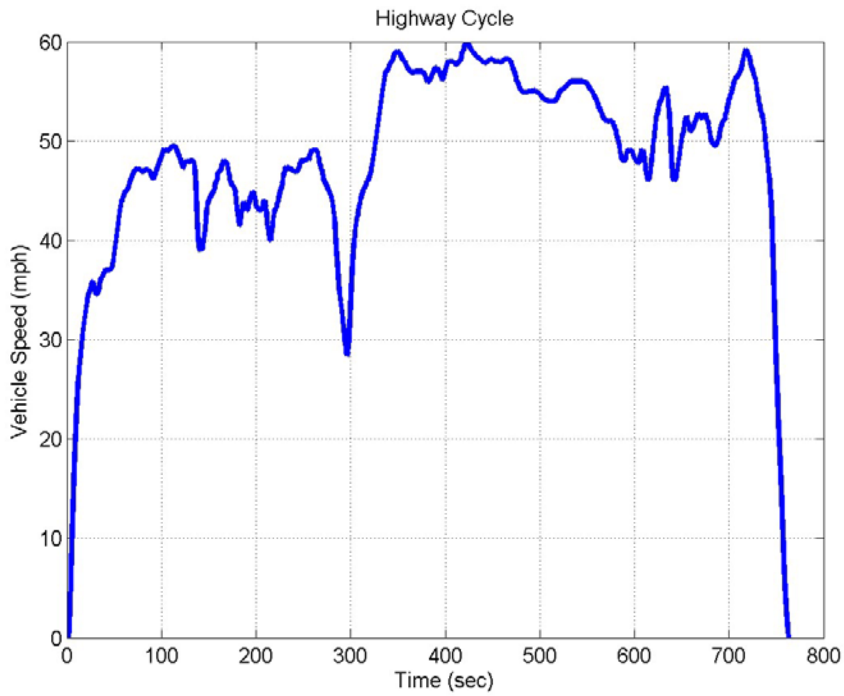


FIGURE C9 FTP-HIGHWAY DRIVE CYCLE

The FTP-City cycle shown in Figure C10 has been used for many years to evaluate light duty vehicle fuel economy. The cycle uses relatively gentle accelerations compared to what is found in typical city driving. This cycle was only used for the pickup truck.

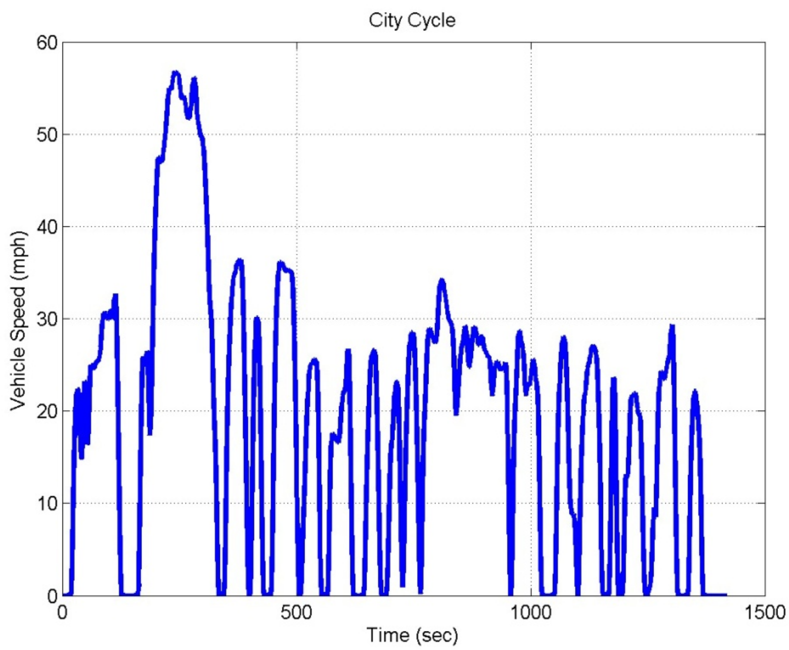


FIGURE C10 FTP-CITY DRIVE CYCLE

The CARB urban cycle shown in Figure C11 is used in the GEM regulatory model for medium and heavy-duty vehicles. This cycle simulates urban driving for trucks. The CARB cycle was used for all vehicles simulated, except the pickup truck.

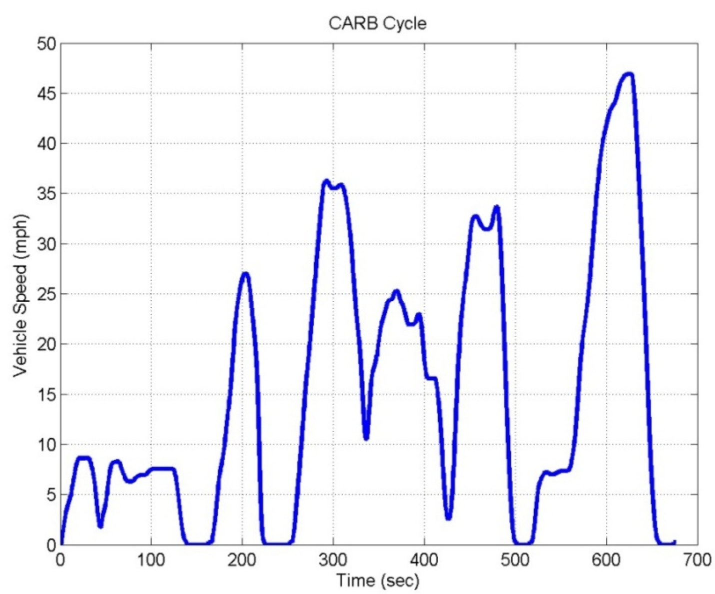


FIGURE C11 CARB URBAN TRUCK DRIVING CYCLE

The US06 cycle shown in Figure C12 is an aggressive drive cycle for light duty vehicles. It was introduced to help compensate for the overly optimistic fuel economy values generated by the older FTP city and highway cycles. This cycle was only used for the pickup truck.

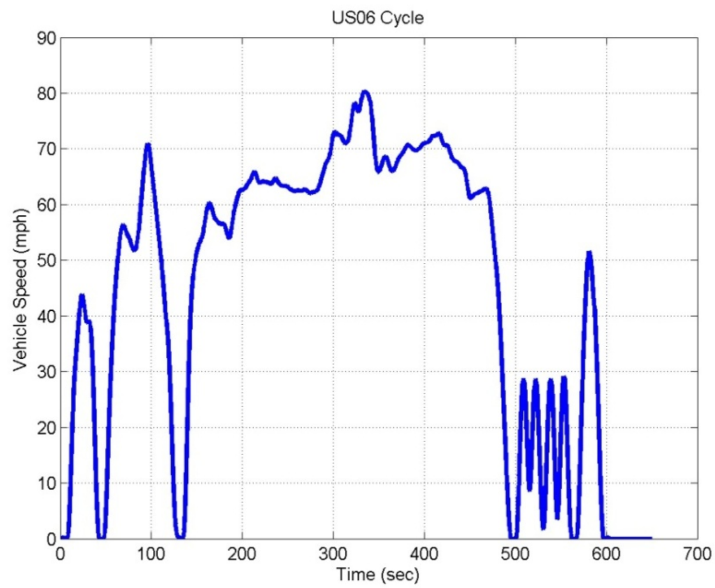


FIGURE C12 US06 AGGRESSIVE LIGHT DUTY DRIVE CYCLE

The SC03 cycle shown in Figure C13 was developed to evaluate the effect of air conditioner use in hot conditions on fuel economy. In this study, the air conditioner was run on all drive cycles, which is not the standard approach. This cycle was used only with the pickup truck.

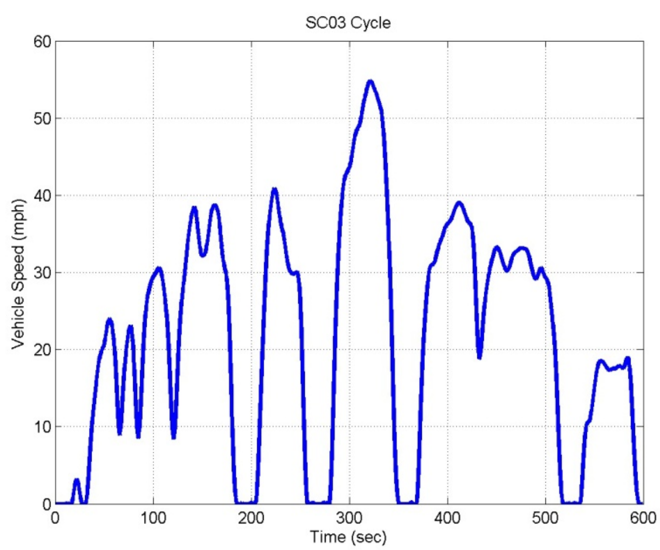


FIGURE C13 SC03 AIR CONDITIONER DRIVE CYCLE

The Parcel cycle shown in Figure C14 was developed to model the drive cycle of a parcel delivery truck. About 50% of the drive cycle time is at idle. This causes fuel consumption at idle to be significant, especially with an automatic, where the torque converter load is significant. The Parcel cycle was only used for the T270 and F-650 medium trucks.

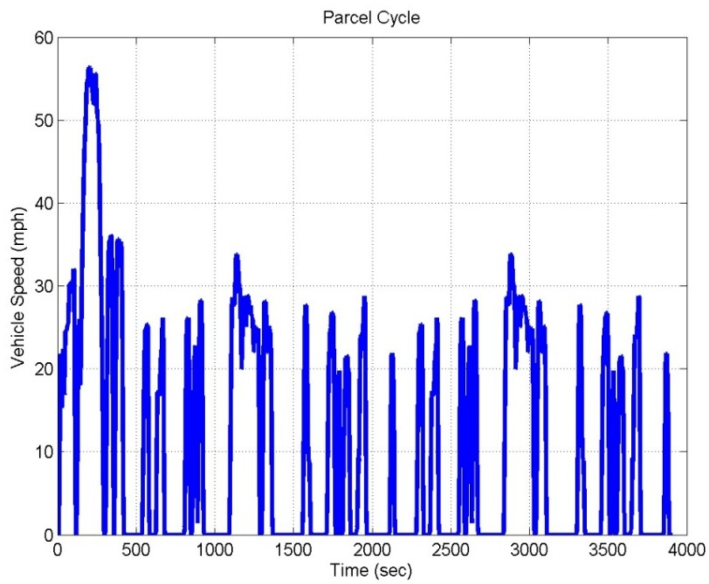


FIGURE C14 PARCEL DELIVERY DRIVE CYCLE

The Combined International Local and Commuter Cycle (CILCC) shown in Figure C15 was developed to simulate urban driving. The general approach, with steady, very gentle accelerations, steady speed operation, and then gradual deceleration, is similar to the European NEDC cycle. This cycle results in very light loads on the engine. The CILCC cycle was only used for the T270 and F-650 medium trucks.

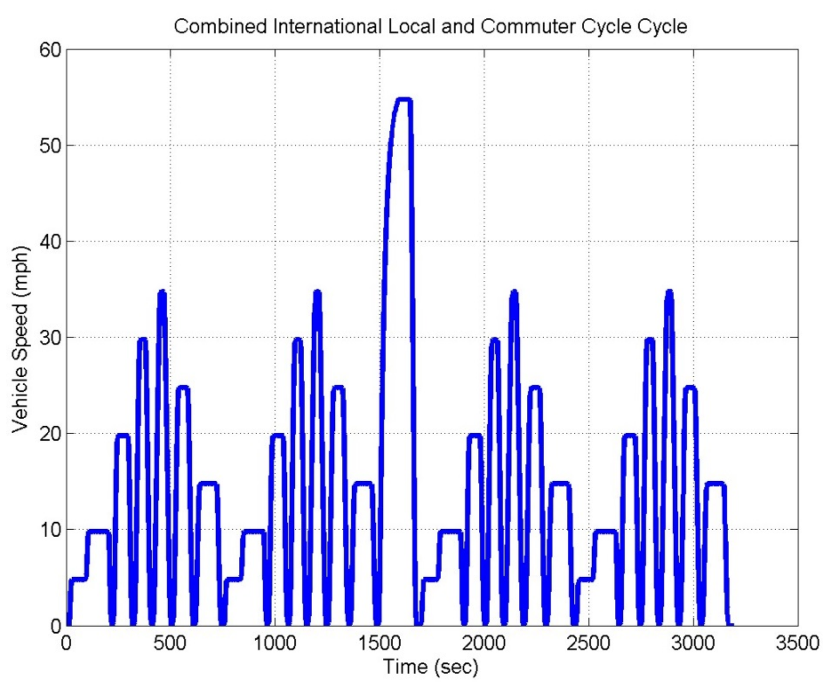


FIGURE C15 COMBINED INTERNATIONAL LOCAL AND COMMUTER DRIVE CYCLE (CILCC)

There are two remaining drive cycles that were used: the 55 MPH and 65 MPH cruise cycles. These cycles are strictly steady state, with no grades or other changes in load, so they effectively only operate the engine at one speed/load point. These two cycles are part of the GEM vehicle certification model. The 65 MPH cruise was used for all vehicles in the study, while the 55 MPH cycle was used for all vehicles except the pickup truck.

C1.3 Vehicle Models

This section provides the input parameters that are used for each of the four vehicle models that are covered in this report.

C1.3.1 Ram Pickup

Table C.1 through Table C.4 show all of the vehicle configurations and vehicle simulation input parameters of the Ram Pickup model. This model is used to represent Class 2b and 3 vehicles.

TABLE C.1 INPUT PARAMETERS FOR THE DODGE RAM PICKUP TRUCK MODEL IN THE DIESEL ENGINE-PACKAGE STUDY

Component	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6
Vehicle Name	Dodge RAM	Dodge RAM	Dodge RAM	Dodge RAM	Dodge RAM	Dodge RAM
Vehicle Type	Class 2b/3 Truck	CL 2b/3 Truck	CL 2b/3 Truck	CL 2b/3 Truck	CL 2b/3 Truck	CL 2b/3 Truck
Engine	Baseline 2019 ISB	ISB Engine Package 11	ISB Engine Package 12	ISB Engine Package 13	ISB Engine Package 14	ISB Engine Package 15 – Inline 4
Transmission	6-Speed Auto	6-Speed Auto	6-Speed Auto	6-Speed Auto	6-Speed Auto	6-Speed Auto
Transmission Controller	6-Speed Auto Diesel Schedule	6-Speed Auto Downspeed Diesel Schedule	6-Speed Auto Diesel Schedule	6-Speed Auto Downspeed Diesel Schedule	6-Speed Auto Diesel Schedule	6-Speed Auto Diesel Schedule
Engine/ Transmission Coupling	Torque Converter (stall speed of 2,791 rpm)	Torque Converter (stall speed of 2,500 rpm)	Torque Converter (stall speed of 2,791 rpm)	Torque Converter (stall speed of 2,500 rpm)	Torque Converter (stall speed of 2,791 rpm)	Torque Converter (stall speed of 2,431 rpm)
Engine RPM (Top Gear at 65 mph)	1,592 rpm	1,368 rpm	1,592 rpm	1,368 rpm	1,592 rpm	1,820 rpm
Final Drive	3.42:1	2.94:1	3.42:1	2.94:1	3.42:1	3.91:1
Wheel Radius	0.3726	0.3726	0.3726	0.3726	0.3726	0.3726

TABLE C.2 INPUT PARAMETERS FOR THE DODGE RAM PICKUP TRUCK MODEL IN THE 3.5L V6 GASOLINE ENGINE-PACKAGE STUDY

Component	Vehicle 7	Vehicle 8	Vehicle 9
Vehicle Name	Dodge RAM	Dodge RAM	Dodge RAM
Vehicle Type	Class 2b/3 Truck	CL 2b/3 Truck	CL 2b/3 Truck
Engine	3.5L V6 Gas - P16	3.5L V6 Gas - P17, P19	3.5L V6 Gas - P18
Transmission	6-Speed Auto	6-Speed Auto	6-Speed Auto
Transmission Controller	6-Speed Auto Gas Schedule	6-Speed Auto Downspeed Gas Schedule	6-Speed Auto Gas Schedule
Engine/ Transmission Coupling	Torque Converter (stall speed of 2,331 rpm)	Torque Converter (stall speed of 2,090 rpm)	Torque Converter (stall speed of 2,330 rpm)
Engine RPM (Top Gear at 65 mph)	2,500	1,987	2,500
Final Drive	5.37:1	4.27:1	5.37:1
Wheel Radius	0.3726	0.3726	0.3726

TABLE C.3 INPUT PARAMETERS FOR THE DODGE RAM PICKUP TRUCK MODEL IN THE 6.2L V8 GASOLINE ENGINE-PACKAGE STUDY

Component	Vehicle 10	Vehicle 11	Vehicle 12	Vehicle 13	Vehicle 14
Vehicle Name	Dodge RAM	Dodge RAM	Dodge RAM	Dodge RAM	Dodge RAM
Vehicle Type	Class 2b/3 Truck	Class 2b/3 Truck	Class 2b/3 Truck	Class 2b/3 Truck	Class 2b/3 Truck
Engine	6.2L V8 Gas – P20	6.2L V8 Gas – P21	6.2L V8 Gas – P22	6.2L V8 Gas – P23	6.2L V8 Gas – P24
Transmission	6-Speed Auto	6-Speed Auto	6-Speed Auto	6-Speed Auto	6-Speed Auto
Transmission Controller	6-Speed Auto Gas Schedule	6-Speed Auto Gas Schedule	6-Speed Auto Gas Schedule	6-Speed Auto Gas Schedule	6-Speed Auto Gas Schedule
Engine/ Transmission Coupling	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)
Engine RPM (Top Gear at 65 mph)	2,500	2,500	2,500	2,500	2,500
Final Drive	5.37:1	5.37:1	5.37:1	5.37:1	5.37:1
Wheel Radius	0.3726	0.3726	0.3726	0.3726	0.3726

TABLE C.4 INPUT PARAMETERS FOR THE DODGE RAM PICKUP TRUCK MODEL IN THE VEHICLE- PACKAGE STUDY

Component	Vehicle 15	Vehicle 16	Vehicle 17	Vehicle 18	Vehicle 19	Vehicle 20
Vehicle Name	Dodge RAM	Dodge RAM	Dodge RAM	Dodge RAM	Dodge RAM	Dodge RAM
Vehicle Type	Class 2b/3 Truck	Class 2b/3 Truck	Class 2b/3 Truck	Class 2b/3 Truck	Class 2b/3 Truck	Class 2b/3 Truck
Vehicle Package Number	P17, P20	P17, P20	P17, P20	P18	P18	P18
Engine	Baseline 2019 ISB	Baseline 2019 3.5L V6	Baseline 2019 6.2L V8	Baseline 2019 ISB	Baseline 2019 3.5L V6	Baseline 2019 6.2L V8
Transmission	8-Speed Auto	8-Speed Auto	8-Speed Auto	8-Speed Auto	8-Speed Auto	8-Speed Auto
Transmission Controller	8-Speed Auto Diesel Schedule	8-Speed Auto Gas Schedule	8-Speed Auto Gas Schedule	8-Speed Auto Diesel Schedule - Idle Neutral	8-Speed Auto Gas Schedule - Idle Neutral	8-Speed Auto Gas Schedule - Idle Neutral
Engine/ Transmission Coupling	Torque Converter (stall speed of 2,790 rpm)	Torque Converter (stall speed of 2,330 rpm)	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,790 rpm)	Torque Converter (stall speed of 2,330 rpm)	Torque Converter (stall speed of 2,445 rpm)
Engine RPM (Top Gear at 65 mph)	1,600	2,500	2,500	1,600	2,500	2,500
Final Drive	3.21:1	5.03:1	5.03:1	3.21:1	5.03:1	5.03:1
Wheel Radius	0.3726	0.3726	0.3726	0.3726	0.3726	0.3726

C1.3.2 Ford F-650 Tow Truck

Table C.5 through Table C.8 show all of the vehicle configurations and vehicle simulation input parameters of the Ford F-650 roll-on tow truck. This Class 5 model is one of two trucks used to represent medium-duty vocational vehicles.

TABLE C.5 INPUT PARAMETERS FOR THE F-650 TOW TRUCK MODEL FOR DIESEL ENGINE-PACKAGE STUDY

Component	Vehicle 21	Vehicle 22	Vehicle 23	Vehicle 24	Vehicle 25	Vehicle 26
Vehicle Name	F650	F650	F650	F650	F650	F650
Vehicle Type	Class 5 Truck	Class 5 Truck	Class 5 Truck	Class 5 Truck	Class 5 Truck	Class 5 Truck
Engine	Baseline 2019 ISB	ISB Engine Package 6	ISB Engine Package 7	ISB Engine Package 8	ISB Engine Package 9	ISB Engine Package 10 – Inline 4
Transmission	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto
Transmission Controller	5-Speed Auto Diesel Schedule	5-Speed Auto Downsped Diesel Schedule	5-Speed Auto Diesel Schedule	5-Speed Auto Downsped Diesel Schedule	5-Speed Auto Diesel Schedule	5-Speed Auto Diesel Schedule
Engine/ Transmission Coupling	Torque Converter (stall speed of 2,554 rpm)	Torque Converter (stall speed of 2,290 rpm)	Torque Converter (stall speed of 2,554 rpm)	Torque Converter (stall speed of 2,290 rpm)	Torque Converter (stall speed of 2,554 rpm)	Torque Converter (stall speed of 2,586 rpm)
Engine RPM (Top Gear at 65 mph)	2,073	1,785	2,073	1,785	2,073	2,408
Final Drive	4.33:1	3.73:1	4.33:1	3.73:1	4.33:1	5.03:1
Wheel Radius	0.4125	0.4125	0.4125	0.4125	0.4125	0.4125

TABLE C.6 INPUT PARAMETERS FOR THE F-650 TOW TRUCK MODEL FOR 3.5L V6 STUDY

Component	Vehicle 27	Vehicle 28	Vehicle 29	Vehicle 30
Vehicle Name	F650	F650	F650	F650
Vehicle Type	Class 5 Truck	Class 5 Truck	Class 5 Truck	Class 5 Truck
Engine	Baseline 2019 3.5L V6	3.5 V6 Engine Package 16	3.5 V6 Engine Package 17,19	3.5 V6 Engine Package 18
Transmission	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto
Transmission Controller	5-Speed Auto Gas Schedule	5-Speed Auto Gas Schedule	5-Speed Auto Downsped Gas Schedule	5-Speed Auto Gas Schedule
Engine/ Transmission Coupling	Torque Converter (stall speed of 2,330 rpm)	Torque Converter (stall speed of 2,330 rpm)	Torque Converter (stall speed of 2,090 rpm)	Torque Converter (stall speed of 2,330 rpm)
Engine RPM (Top Gear at 65 mph)	3,299	3,299	2,576	3,299
Final Drive	6.89:1	6.89:1	5.38:1	6.89:1
Wheel Radius	0.4125	0.4125	0.4125	0.4125

TABLE C.7 INPUT PARAMETERS FOR THE F-650 TOW TRUCK MODEL FOR 6.2L V8 STUDY

Component	Vehicle 31	Vehicle 32	Vehicle 33	Vehicle 34	Vehicle 35	Vehicle 36
Vehicle Name	F650	F650	F650	F650	F650	F650
Vehicle Type	Class 5 Truck	Class 5 Truck	Class 5 Truck	Class 5 Truck	Class 5 Truck	Class 5 Truck
Engine	Baseline 2019 6.2L V8	V8 Engine Package 20	V8 Engine Package 21	V8 Engine Package 22	V8 Engine Package 23	V8 Engine Package 24
Transmission	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto
Transmission Controller	5-Speed Auto Gas Schedule	5-Speed Auto Gas Schedule	5-Speed Auto Gas Schedule	5-Speed Auto Gas Schedule	5-Speed Auto Gas Schedule	5-Speed Auto Gas Schedule
Engine/ Transmission Coupling	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)
Engine RPM (Top Gear at 65 mph)	3,299	3,299	3,299	3,299	3,299	3,299
Final Drive	6.89:1	6.89:1	6.89:1	6.89:1	6.89:1	6.89:1
Wheel Radius	0.4125	0.4125	0.4125	0.4125	0.4125	0.4125

TABLE C.8 INPUT PARAMETERS FOR THE F-650 TOW TRUCK MODEL FOR VEHICLE-PACKAGE STUDY

Component	Vehicle 37	Vehicle 38	Vehicle 39	Vehicle 40	Vehicle 41	Vehicle 42
Vehicle Name	F650	F650	F650	F650	F650	F650
Vehicle Type	Class 5 Truck	Class 5 Truck	Class 5 Truck	Class 5 Truck	Class 5 Truck	Class 5 Truck
Vehicle Package Number	P12, P13, P15	P12, P13, P15	P12, P13, P15	P14	P14	P14
Engine	Baseline 2019 ISB	Baseline 2019 3.5L V6	Baseline 2019 6.2L V8	Baseline 2019 ISB	Baseline 2019 3.5L V6	Baseline 2019 6.2L V8
Transmission	8-Speed Auto	8-Speed Auto	8-Speed Auto	6-Speed AMT	6-Speed AMT	6-Speed AMT
Transmission Controller	8-Speed Auto Diesel Schedule	8-Speed Auto Gas Schedule	8-Speed Auto Gas Schedule	6-Speed AMT Diesel Schedule	6-Speed AMT Gasoline Schedule	6-Speed AMT Gasoline Schedule
Engine/ Transmission Coupling	Torque Converter (stall speed of 2,555 rpm)	Torque Converter (stall speed of 2,330 rpm)	Torque Converter (stall speed of 2,440 rpm)	Clutch	Clutch	Clutch
Engine RPM (Top Gear at 65 mph)	2,073	3,235	3,235	2,072	3,290	3,290
Final Drive	4.62:1	7.21:1	7.21:1	3.08:1	4.89:1	4.89:1
Wheel Radius	0.4125	0.4125	0.4125	0.4125	0.4125	0.4125

C1.3.3 Kenworth T270 Box Delivery Truck

Table C.9 through Table C.12 show all of the vehicle configurations and vehicle simulation input parameters of the Kenworth T270 box delivery truck. This Class 6 model is one of two trucks used to represent the medium-duty vocational vehicle segment.

TABLE C.9 INPUT PARAMETERS FOR THE T270 BOX TRUCK MODEL FOR THE DIESEL ENGINE-PACKAGE STUDY

Component	Vehicle 43	Vehicle 44	Vehicle 45	Vehicle 46	Vehicle 47	Vehicle 48
Vehicle Name	T270	T270	T270	T270	T270	T270
Vehicle Type	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck
Engine	Baseline 2019 ISB	ISB Engine Package 6	ISB Engine Package 7	ISB Engine Package 8	ISB Engine Package 9	ISB Engine Package 10 – Inline 4
Transmission	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto
Transmission Controller	5-Speed Auto Diesel Schedule	5-Speed Auto Downsped Diesel Schedule	5-Speed Auto Diesel Schedule	5-Speed Auto Downsped Diesel Schedule	5-Speed Auto Diesel Schedule	5-Speed Auto Diesel Schedule
Engine/ Transmission Coupling	Torque Converter (stall speed of 2,554 rpm)	Torque Converter (stall speed of 2,288 rpm)	Torque Converter (stall speed of 2,554 rpm)	Torque Converter (stall speed of 2,283 rpm)	Torque Converter (stall speed of 2,554 rpm)	Torque Converter (stall speed of 2,586 rpm)
Engine RPM (Top Gear at 65 mph)	2,071	1,785	2,071	1,785	2,071	2,416
Final Drive	5.29:1	4.56:1	5.29:1	4.56:1	5.29:1	6.17:1
Wheel Radius	0.4125	0.4125	0.4125	0.4125	0.4125	0.4125

TABLE C.10 INPUT PARAMETERS FOR THE T270 BOX TRUCK MODEL FOR THE 3.5L V6 ENGINE-PACKAGE STUDY

Component	Vehicle 49	Vehicle 50	Vehicle 51	Vehicle 52
Vehicle Name	T270	T270	T270	T270
Vehicle Type	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck
Engine	Baseline 2019 3.5L V6	3.5 V6 Engine Package 16	3.5 V6 Engine Package 17,19	3.5 V6 Engine Package 18
Transmission	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto
Transmission Controller	5-Speed Auto Gas Schedule	5-Speed Auto Gas Schedule	5-Speed Auto Downsped Gas Schedule	5-Speed Auto Gas Schedule
Engine/ Transmission Coupling	Torque Converter (stall speed of 2,330 rpm)	Torque Converter (stall speed of 2,330 rpm)	Torque Converter (stall speed of 2,090 rpm)	Torque Converter (stall speed of 2,330 rpm)
Engine RPM (Top Gear at 65 mph)	3,297	3,297	2,475	3,297
Final Drive	8.42:1	8.42:1	6.32:1	8.42:1
Wheel Radius	0.4125	0.4125	0.4125	0.4125

TABLE C.11 INPUT PARAMETERS FOR THE T270 BOX TRUCK MODEL FOR THE 6.2L V8 ENGINE-PACKAGE STUDY

Component	Vehicle 53	Vehicle 54	Vehicle 55	Vehicle 56	Vehicle 56	Vehicle 58
Vehicle Name	T270	T270	T270	T270	T270	T270
Vehicle Type	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck
Engine	Baseline 2019 6.2L V8	V8 Engine Package 20	V8 Engine Package 21	V8 Engine Package 22	V8 Engine Package 23	V8 Engine Package 24
Transmission	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto
Transmission Controller	5-Speed Auto Gas Schedule	5-Speed Auto Gas Schedule	5-Speed Auto Gas Schedule	5-Speed Auto Gas Schedule	5-Speed Auto Gas Schedule	5-Speed Auto Gas Schedule
Engine/ Transmission Coupling	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)	Torque Converter (stall speed of 2,445 rpm)
Engine RPM (Top Gear at 65 mph)	3,297	3,297	3,297	3,297	3,297	3,297
Final Drive	8.42:1	8.42:1	8.42:1	8.42:1	8.42:1	8.42:1
Wheel Rad.	0.4125	0.4125	0.4125	0.4125	0.4125	0.4125

TABLE C.12 INPUT PARAMETERS FOR THE T270 BOX TRUCK MODEL FOR THE VEHICLE-PACKAGE STUDY

Component	Vehicle 59	Vehicle 60	Vehicle 61	Vehicle 62	Vehicle 63	Vehicle 64
Vehicle Name	T270	T270	T270	T270	T270	T270
Vehicle Type	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck
Vehicle Package Number	P12, P13, P15	P12, P13, P15	P12, P13, P15	P14	P14	P14
Engine	Baseline 2019 ISB	Baseline 2019 3.5L V6	Baseline 2019 6.2L V8	Baseline 2019 ISB	Baseline 2019 3.5L V6	Baseline 2019 6.2L V8
Transmission	8-Speed Auto	8-Speed Auto	8-Speed Auto	6-Speed AMT	6-Speed AMT	6-Speed AMT
Transmission Controller	8-Speed Auto Diesel Schedule	8-Speed Auto Gas Schedule	8-Speed Auto Gas Schedule	6-Speed AMT Diesel Schedule	6-Speed AMT Gasoline Schedule	6-Speed AMT Gasoline Schedule
Engine/ Transmission Coupling	Torque Converter (stall speed of 2,554 rpm)	Torque Converter (stall speed of 2,330 rpm)	Torque Converter (stall speed of 2,330 rpm)	Clutch	Clutch	Clutch
Engine RPM (Top Gear at 65 mph)	2,070	3,295	3,295	2,052	3,295	3,295
Final Drive	5.64:1	8.98:1	8.98:1	3.73:1	5.99:1	5.99:1
Wheel Radius	0.4125	0.4125	0.4125	0.4125	0.4125	0.4125

C1.3.4 Kenworth T-700 Tractor-Trailer Truck

The Kenworth T-700 is used to represent long-haul high-roof sleeper tractor-trailer combination trucks. The vehicle configurations and simulation input parameters are provided in Table C.13 below.

TABLE C.13 INPUT PARAMETERS FOR THE T-700 TRACTOR-TRAILER MODEL

Component	Vehicle 65	Vehicle 66	Vehicle 67	Vehicle 68	Vehicle 69	Vehicle 70
Vehicle Name	T700	T700	T700	T700	T700	T700
Vehicle Type	Class 8 Tractor-Trailer	Class 8 Tractor-Trailer	Class 8 Tractor-Trailer	Class 8 Tractor-Trailer	Class 8 Tractor-Trailer	Class 8 Tractor-Trailer
Engine	DD15 P0, P1, P4	DD15 P2, P3(a,b, c,d,e,f), P5	DD15 P0	DD15 P3	DD15 P5	DD15 P2
Transmission and Driveline	10-Speed AMT, 6X4	10-Speed AMT, 6X4	18-Speed AMT Chassis Reduction 6X2	18-Speed AMT Chassis Reduction 6X2	10-Speed AMT Chassis Reduction 6X2	18-Speed AMT Chassis Reduction 6X2
Transmission Controller	10-Speed AMT Shift Schedule	10-Speed AMT Downsped Shift Sched	18-Speed AMT Shift Schedule	18-Speed AMT Downsped Shift Sched	10-Speed AMT Sched	18-Speed AMT Downsped Shift Sched
Engine/ Transmission Coupling	Clutch	Clutch	Clutch	Clutch	Clutch	Clutch
Engine RPM (Top Gear at 65 mph)	1,368	1,050	1,368	1,050	1,368	1,050
Final Drive	3.36:1	2.58:1	3.36:1	2.58:1	2.58:1	2.58:1
Wheel Radius	0.4975	0.4975	0.4975	0.4975	0.4975	0.4975

C2. Vehicle Technologies

C2.1 Reduced Air Conditioner Power Demand

Accessory power demand is one of the contributors to overall vehicle power demand. Accessories can be defined as power absorbing devices that are not necessary to run the engine. These include the alternator, power steering pump, air conditioner, air compressor, and engine cooling fan. In this report, devices that are required in order to run the engine, such as the water pump, oil pump, and fuel pump, are treated as part of the engine friction. As a representative accessory power demand reduction, the air conditioner system was evaluated. The air conditioner is operating on all vehicles during all drive cycles that are covered in this report. The power demand of the air conditioner system (including compressor, evaporator fan, and condenser fan) was modeled as a continuous load of 1,500 watts. This is a typical power demand for steady-state operation in a hot (90 to 95F) environment.

An improved air conditioner system can incorporate features such as a more efficient compressor (such as a scroll design), the use of less reheat, or the use of additional cab insulation. For this project, a reduction in air conditioner demand of 40% was simulated, from a baseline of 1,500 watts to 900 watts. No specific technology approaches were considered, so the only effect on the vehicle is the reduction in power demand. This 600 watt reduction in air conditioner power demand could represent the fuel economy impact of a reduction in power demand from any engine accessory. The values utilized in this Phase II study are identical to the ones used in Phase I, and are listed below for reference purposes.

TABLE C.14 RAM PICKUP ACCESSORY POWER DEMANDS

Dodge RAM	air cond pwr	other mech_pwr	acc_mech_pwr
base	1500	2950	**4450**
scale factor	60%	100%	**60%**
Variant 1	900	2950	**3850**
Variant 2	1500	-	**4450**
Units	**W**	**W**	**W**

TABLE C.15 F-650 AND T270 MEDIUM TRUCK ACCESSORY POWER DEMANDS

Ford F650/KW T270	air cond pwr	other mech_pwr	acc_mech_pwr
base	1500	4250	**5750**
scale factor	60%	100%	**60%**
Variant 1	900	4250	**5150**
Variant 2	1500	4250	**5750**
Units	**W**	**W**	**W**

TABLE C.16 T-700 TRACTOR-TRAILER ACCESSORY POWER DEMANDS

KW T700	air cond pwr	other mech_pwr	acc_mech_pwr
base	1500	5150	**6650**
scale factor	60%	100%	**60%**
Variant 1	900	5150	**6050**
Variant 2	1500	4250	**6650**
Units	**W**	**W**	**W**

C2.2 Reduced Aerodynamic Drag (Cd)

Aerodynamic drag can be a substantial contributor to overall vehicle power demand, particularly at higher road speeds. Depending on the vehicle type, there is a range of potential for improvement in Cd. In this Phase II study, Cd reductions were assumed as shown below. Table C.17 below shows the baseline Cd values and potential Cd improvements for each vehicle type. No specific set of hardware features is being simulated here. The assumption is that the OEM will put together a package that meets the Cd change targets shown in the table.

TABLE C.17 AERODYNAMIC DRAG BASELINE VALUES AND REDUCTIONS FOR EACH VEHICLE TYPE

<table>
<tr><th rowspan="2">Vehicle</th><th colspan="7">Drag Coefficient Information</th></tr>
<tr><th>Baseline Cd</th><th>Baseline CdA</th><th>Reduction</th><th>Reduced Cd</th><th>Reduced CdA</th><th>Cd w/ Trailer</th><th>Cd Reduced w/ Trailer</th></tr>
<tr><td rowspan="2">Dodge RAM</td><td rowspan="2">0.4</td><td rowspan="2">1.505</td><td>5%</td><td>0.380</td><td>1.430</td><td rowspan="2">0.600</td><td>0.570</td></tr>
<tr><td>10%</td><td>0.360</td><td>1.355</td><td>0.540</td></tr>
<tr><td rowspan="3">Ford F650</td><td rowspan="3">0.619</td><td rowspan="3">3.151</td><td>5%</td><td>0.588</td><td>2.993</td><td rowspan="3">--</td><td rowspan="3">--</td></tr>
<tr><td>10%</td><td>0.557</td><td>2.836</td></tr>
<tr><td>15%</td><td>0.526</td><td>2.678</td></tr>
<tr><td rowspan="3">KW T270</td><td rowspan="3">0.514</td><td rowspan="3">5.033</td><td>5%</td><td>0.488</td><td>4.785</td><td rowspan="3">--</td><td rowspan="3">--</td></tr>
<tr><td>10%</td><td>0.463</td><td>4.530</td></tr>
<tr><td>15%</td><td>0.437</td><td>4.278</td></tr>
<tr><td rowspan="2">KW T700</td><td rowspan="2">No value for tractor only</td><td rowspan="2">6.262</td><td>15%</td><td rowspan="2">--</td><td>5.323</td><td rowspan="2">0.639</td><td>0.543</td></tr>
<tr><td>25%</td><td>4.697</td><td>0.479</td></tr>
</table>

C2.3 Reduced Tire Rolling Resistance (Crr)

Tire rolling resistance is a major contributor to overall vehicle power demand. The following Crr reductions were simulated in Phase II. For 3 out of 4 vehicles involved in this study, three levels of reduction (10%, 20%, and 30%) in tire rolling resistance were assumed. Note that no specific tire technologies are being simulated. It is assumed that the tire manufacturer would put together a package of features to achieve the assumed Crr values. There was no effort to take any side effects of these features into account (reduced traction and braking performance, durability, etc.). As shown in Section 5.3.2.3 of Report #1, the fuel consumption benefit of a reduction in Crr is very linear.

The tire rolling resistance data used for all vehicle simulations comes from coastdown testing. In coastdown tests, there is no way to separate tire rolling resistance from driveline friction (transmission output shaft, driveshaft and axle). Axle efficiency test data was used to quantify the contribution from axle friction, while engineering judgment was used to split the remaining rolling resistance between tires (96%) and the transmission output and driveshaft (4%). The coastdown testing was run on tires that were broken in but near the full tread depth. Lab data on the tires used in the coastdown testing is not available.

For the tractor-trailer vehicle, separate Crr values were used for the steer tires, drive tires, and trailer tires. For the medium-duty trucks, a single Crr value was used for the steer and drive tires. When the simulation models were run, only the average Crr value was used, so the effect of weight distribution at different payloads was not taken into account. These Crr values came from truck coastdown test runs and were divided between steer, drive, and trailer values using engineering judgment, so they will not match with values required by any particular standard, such as SmartWay or the 2014 GHG standards. Table C.18 provides the baseline Crr values and the improvement assumptions for each vehicle type. The Crr values for each vehicle were obtained from coast-down test results.

TABLE C.18 TIRE ROLLING RESISTANCE BASELINE VALUES AND REDUCTIONS FOR EACH VEHICLE TYPE

Vehicle	Rolling Resistance	
	Baseline	% Reduction
Dodge RAM	0.0078	10%, 20%, 30%
Ford F650	0.010068	10%, 20%, 30%
KW T270	0.010967	10%, 20%, 30%
KW T700	0.005608	10%, 30%

C2.4 Weight Reduction

Vehicle mass (weight) has two effects. First, it takes energy to accelerate the vehicle mass up to a desired speed. The energy put into accelerating the vehicle is largely lost as brake heat when the vehicle slows down. The second consequence of vehicle mass is that rolling resistance is proportional to mass. If vehicle mass can be reduced, less power is required to accelerate the mass, and less power is required to overcome rolling resistance. Mass reduction can be achieved in a number of ways, including:

- Material substitution, such as replacing steel with aluminum or a composite
- Design changes to eliminate mass that is not required to achieve the target capability and durability

Unfortunately, many fuel saving, emissions, and safety technologies add mass. Maintaining a given truck empty weight takes a consistent weight reduction effort to offset new features that are added for both regulatory and vehicle performance reasons.

The effect of vehicle mass on light duty vehicle fuel efficiency is huge. Large fuel economy benefits can be obtained by reducing light duty vehicle mass. Considered from the point of view of freight efficiency, light duty vehicles are extremely inefficient. A 4,000 pound light duty vehicle transporting a 200 pound person has a “cargo” constituting less than 5% of the total vehicle mass. If the empty weight of our example light duty vehicle is reduced 10% (400 pounds), the total mass of vehicle plus cargo is reduced by 9.5%. Heavy duty trucks, on the other hand, may have a cargo mass greater than that of the vehicle. Consider the example of a tractor-trailer with an empty weight of 34,000 pounds and a loaded weight of 80,000 pounds. If the empty weight is reduced by 10%, the total mass of truck + cargo is reduced by only 4.25%, half as much as in the light duty example.

Table C.19 shows the empty weights and payload weights for each vehicle in the project. The following weight reductions were applied to each vehicle to evaluate the effect of a reduction in empty weight:

Vehicle	Weight Reductions
Ram Pickup	300, 600, 900 Pounds
F-650 Tow Truck	400, 700, 1000 Pounds
T270 Box Truck	400, 800, 1200 Pounds
T-700 Tractor-Trailer	2200 Pounds, 4400 Pounds

These weight reductions were applied to the tare weights (empty weights) shown in Table C.19 below. When changes in empty weight were applied, the payloads were kept unchanged.

TABLE C.19 VEHICLE EMPTY WEIGHTS AND PAYLOADS USED IN SIMULATIONS. "TARE" WEIGHT IS EQUIVALENT TO "CURB WEIGHT" OR "EMPTY WEIGHT"

Weights in Pounds	RAM diesel			RAM gasoline		
	Tare	**Payload**	**Total**	**Tare**	**Payload**	**Total**
0% payload	6876	0	6876	6376	0	6376
ALVW	6876	1562	8438	6376	1562	7938
100% GCW	6876	18124	25000	6376	18124	24500

Weights in Pounds	F650 diesel			F650 gasoline		
	Tare	**Payload**	**Total**	**Tare**	**Payload**	**Total**
0% payload	15640	0	15640	15139	0	15139
50% payload	15640	3180	18820	15139	3180	18319
100% payload	15640	6360	21999	15139	6360	21499

Weights in Pounds	T270 diesel			T270 gasoline		
	Tare	**Payload**	**Total**	**Tare**	**Payload**	**Total**
0% payload	17141	0	17141	16640	0	16640
50% payload	17141	4430	21571	16640	4430	21070
100% payload	17141	8860	26001	16640	8860	25500

Weights in Pounds	T700 diesel		
	Tare	Payload	Total
0% payload	33960	0	33960
50% payload	33960	23020	56980
100% payload	33960	46039	79999

The percentage of fuel consumption reduction that is provided by a given percent weight reduction is a function of several parameters:

- Drive cycle
- Coefficient of rolling resistance
- Vehicle payload

A given percent weight reduction will provide a larger percent fuel savings on a drive cycle with frequent stops and starts. This is because inertia loads represent a higher portion of the total power demand on a highly transient cycle. If the coefficient of rolling resistance is high, there will be a larger benefit from a weight reduction, since rolling resistance will be a larger portion of overall power demand. As the payload increases, a given percentage weight reduction on the empty vehicle becomes a smaller percentage of the test weight, so the percent fuel savings decreases.

C2.5 Chassis Friction Reduction

Chassis friction includes losses in the axle, U-joints, and wheel bearings. An improvement in axle efficiency, for example, can lead to a reduction in overall chassis friction power demand. In this study, no effort was made to evaluate individual chassis friction technologies, except for the use of a 6X2 drive axle configuration in the tractor-trailer truck (See Section C2.6 below). Table C.20 shows the percentage of vehicle power demand accounted for by chassis friction at a steady speed of 65 MPH, along with the level of improvement that has been simulated for each vehicle type.

TABLE C.20 CHASSIS FRICTION LEVELS AT 65 MPH, AND FRICTION REDUCTION ASSUMPTIONS

Chassis Friction	Dodge RAM	Ford F650	KW T270	KW T700
Driveline Spin Losses (N/N)	0.000899	0.000488	0.000606	0.000230
Axle Loaded Torque Efficiency (%)	97.5	97.5	97.5	97.5
Driveline Spin Losses Reduction (%)	30%	30%	30%	20%

C2.6 6X2 Axle Configuration

One way to reduce chassis friction on a tractor-trailer truck is to reduce the number of drive axles from the standard value of two, down to one. A two drive axle configuration is referred to as a 6X4 or tandem drive axle set, while a single drive axle configuration is referred to as a 6X2, where there is a drive axle and a tag axle (non-driven axle). When two drive axles are used, there are two sets of spin losses that need to be overcome, rather than only one. Note that the single axle needs to have a higher torque capacity than the tandems, so it will typically have a higher spin loss than the rear axle in a tandem pair. Another source of losses in the tandem is that the front axle in a tandem needs to split the power between the two axles. This involves additional gear sets and oil seals, which are losses that do not occur with a single drive axle.

The single drive axle has a downside: reduced traction. For a fully loaded tractor trailer at 80,000 pounds, there is only 17,000 pounds, or 21.25% of the total vehicle weight, on the drive axle of a 6X2 configuration. This can lead to problems in low friction environment surfaces, such as snow, ice, sand, or even wet pavement. Trucks that need to go off-road, or which frequently operate in snow and ice, are not good candidates for a 6X2 configuration. One way to deal with the traction issue is to use the air suspension to temporarily lift the non-driven axle in situations where traction becomes a problem. Some 6X2 systems incorporate a “smart” control of the tag axle, in which the loads on the drive axle and tag axle are continuously adjusted to provide both the required traction and the lowest possible overall rolling resistance. This feature was not simulated in this study.

In this project, the 6X2 configuration is compared to the standard 6X4 configuration on the Kenworth T-700 tractor-trailer truck.

C2.7 Road Speed Governor (Reduced Vmax)

Road speed governors are widely used by large truck fleets as a fuel saving technology. The governor limits the road speed to a value set by the owner. Road speed governors can also be used to gain credits under the GEM model, but in this case the governor has to be set at the factory either permanently or for a defined number of miles, and cannot be changed by the owner.

C2.8 Transmission Alternatives

A wide range of transmissions have been evaluated in this program. Section C1.2 shows which transmissions were evaluated in each vehicle model. This section describes the individual transmissions in detail.

TABLE C.12 TRANSMISSION PARAMETER TABLES FOR ALL VEHICLE CONFIGURATIONS

Dodge RAM – Diesel Eng Study	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6
Num of Gears	6	6	8	6	6	6
Vehicle 1	3.231	3.231	4.696	3.231	3.231	3.231
2	1.837	1.837	3.13	1.837	1.837	1.837
3	1.41	1.41	2.104	1.41	1.41	1.41
4	1	1	1.667	1	1	1
5	0.816	0.816	1.285	0.816	0.816	0.816
6	0.625	0.625	1	0.625	0.625	0.625
7	-	-	0.839	-	-	-
8	-	-	0.667	-	-	-
TC Stall K Factor	9.38	8.18	9.38	8.18	9.38	11.55
TC Stall Torque Ratio	1.74	1.74	1.74	1.74	1.74	2.16

Dodge RAM 3.5L V6 Engine Study	Vehicle 7	Vehicle 8	Vehicle 9
Num of Gears	6	6	6
1	3.231	3.231	3.231
2	1.837	1.837	1.837
3	1.41	1.41	1.41
4	1	1	1
5	0.816	0.816	0.816
6	0.625	0.625	0.625
7	-	-	-
8	-	-	-
TC Stall K Factor	11.55	8.74	11.55
TC Stall Torque Ratio	2.16	1.7	2.16

Dodge RAM – 6.2L V8 Engine Study	Vehicle 10	Vehicle 11	Vehicle 12	Vehicle 13	Vehicle 14
Num of Gears	6	6	6	6	6
1	3.231	3.231	3.231	3.231	3.231
2	1.837	1.837	1.837	1.837	1.837
3	1.41	1.41	1.41	1.41	1.41
4	1	1	1	1	1
5	0.816	0.816	0.816	0.816	0.816
6	0.625	0.625	0.625	0.625	0.625
7	-	-	-	-	-
8	-	-	-	-	-
TC Stall K Factor	11.55	11.55	11.55	11.55	11.55
TC Stall Torque Ratio	2.16	2.16	2.16	2.16	2.16

Dodge RAM – Vehicle Study	Vehicle 15	Vehicle 16	Vehicle 17	Vehicle 18	Vehicle 19	Vehicle 20
Num of Gears	8	8	8	8	8	8
1	4.696	4.696	4.696	4.696	4.696	4.696
2	3.13	3.13	3.13	3.13	3.13	3.13
3	2.104	2.104	2.104	2.104	2.104	2.104
4	1.667	1.667	1.667	1.667	1.667	1.667
5	1.285	1.285	1.285	1.285	1.285	1.285
6	1	1	1	1	1	1
7	0.839	0.839	0.839	0.839	0.839	0.839
8	0.667	0.667	0.667	0.667	0.667	0.667
TC Stall K Factor	9.38	11.55	11.55	9.38	11.55	11.55
TC Stall Torque Ratio	1.74	2.16	2.16	1.74	2.16	2.16

F650 - Diesel Engine Study	Vehicle 21	Vehicle 22	Vehicle 23	Vehicle 24	Vehicle 25	Vehicle 26
Num of Gears	5	5	5	5	5	5
1	3.102	3.102	3.102	3.102	3.102	3.102
2	1.8107	1.8107	1.8107	1.8107	1.8107	1.8107
3	1.406	1.406	1.406	1.406	1.406	1.406
4	1	1	1	1	1	1
5	0.7117	0.7117	0.7117	0.7117	0.7117	0.7117
6					-	-
7	-	-	-	-	-	-
8	-	-	-	-	-	-
TC Stall K Factor	10.26	8.74	10.26	8.74	10.26	10.26
TC Stall Torque Ratio	2.71	1.7	2.71	1.7	2.71	2.71

F650 3.5L V6 Engine Study	Vehicle 27	Vehicle 28	Vehicle 29	Vehicle 30
Num of Gears	5	5	5	5
1	3.102	3.102	3.102	3.102
2	1.8107	1.8107	1.8107	1.8107
3	1.406	1.406	1.406	1.406
4	1	1	1	1
5	0.7117	0.7117	0.7117	0.7117
6	-			
7	-	-	-	-
8	-	-	-	-
TC Stall K Factor	11.55	11.55	8.74	11.55
TC Stall Torque Ratio	2.16	2.16	1.7	2.16

F650 6.2L V8 Engine Study	Vehicle 31	Vehicle 32	Vehicle 33	Vehicle 34	Vehicle 35	Vehicle 36
Num of Gears	5	5	5	5	5	5
1	3.102	3.102	3.102	3.102	3.102	3.102
2	1.8107	1.8107	1.8107	1.8107	1.8107	1.8107
3	1.406	1.406	1.406	1.406	1.406	1.406
4	1	1	1	1	1	1
5	0.7117	0.7117	0.7117	0.7117	0.7117	0.7117
6					-	-
7	-	-	-	-	-	-
8	-	-	-	-	-	-
TC Stall K Factor	11.55	11.55	11.55	11.55	11.55	11.55
TC Stall Torque Ratio	2.16	2.16	2.16	2.16	2.16	2.16

F650 Vehicle Tech Study	Vehicle 37	Vehicle 38	Vehicle 39	Vehicle 40	Vehicle 41	Vehicle 42
Num of Gears	8	8	8	6	6	6
1	4.696	4.696	4.696	9.01	9.01	9.01
2	3.13	3.13	3.13	5.27	5.27	5.27
3	2.104	2.104	2.104	3.22	3.22	3.22
4	1.667	1.667	1.667	2.04	2.04	2.04
5	1.285	1.285	1.285	1.36	1.36	1.36
6	1	1	1	1	1	1
7	0.839	0.839	0.839	-	-	-
8	0.667	0.667	0.667	-	-	-
TC Stall K Factor	10.26	11.55	11.55	-	-	-
TC Stall Torque Ratio	2.71	2.16	2.16	-	-	-

T270 - Diesel Engine Study	Vehicle 43	Vehicle 44	Vehicle 45	Vehicle 46	Vehicle 47	Vehicle 48
Num of Gears	5	5	5	5	5	5
1	3.102	3.102	3.102	3.102	3.102	3.102
2	1.8107	1.8107	1.8107	1.8107	1.8107	1.8107
3	1.406	1.406	1.406	1.406	1.406	1.406
4	1	1	1	1	1	1
5	0.7117	0.7117	0.7117	0.7117	0.7117	0.7117
6					-	-
7	-	-	-	-	-	-
8	-	-	-	-	-	-
TC Stall K Factor	10.26	8.74	10.26	8.74	10.26	10.26
TC Stall Torque Ratio	2.71	1.7	2.71	1.7	2.71	2.71

T270 3.5L V6 Engine Study	Vehicle 49	Vehicle 50	Vehicle 51	Vehicle 52
Num of Gears	5	5	5	5
1	3.102	3.102	3.102	3.102
2	1.8107	1.8107	1.8107	1.8107
3	1.406	1.406	1.406	1.406
4	1	1	1	1
5	0.7117	0.7117	0.7117	0.7117
6	-			
7	-	-	-	-
8	-	-	-	-
TC Stall K Factor	11.55	11.55	8.74	11.55
TC Stall Torque Ratio	2.16	2.16	1.7	2.16

T270 6.2L V8 Engine Study	Vehicle 53	Vehicle 54	Vehicle 55	Vehicle 56	Vehicle 57	Vehicle 58
Num of Gears	5	5	5	5	5	5
1	3.102	3.102	3.102	3.102	3.102	3.102
2	1.8107	1.8107	1.8107	1.8107	1.8107	1.8107
3	1.406	1.406	1.406	1.406	1.406	1.406
4	1	1	1	1	1	1
5	0.7117	0.7117	0.7117	0.7117	0.7117	0.7117
6					-	-
7	-	-	-	-	-	-
8	-	-	-	-	-	-
TC Stall K Factor	11.55	11.55	11.55	11.55	11.55	11.55
TC Stall Torque Ratio	2.16	2.16	2.16	2.16	2.16	2.16

T270 Vehicle Tech Study	Vehicle 59	Vehicle 60	Vehicle 61	Vehicle 62	Vehicle 63	Vehicle 64
Num of Gears	8	8	8	6	6	6
1	4.696	4.696	4.696	9.01	9.01	9.01
2	3.13	3.13	3.13	5.27	5.27	5.27
3	2.104	2.104	2.104	3.22	3.22	3.22
4	1.667	1.667	1.667	2.04	2.04	2.04
5	1.285	1.285	1.285	1.36	1.36	1.36
6	1	1	1	1	1	1
7	0.839	0.839	0.839	-	-	-
8	0.667	0.667	0.667	-	-	-
TC Stall K Factor	10.26	11.55	11.55	-	-	-
TC Stall Torque Ratio	2.71	2.16	2.16	-	-	-

T700	Vehicle 65	Vehicle 66	Vehicle 67	Vehicle 68	Vehicle 69	Vehicle 70
Num of Gears	10	10	18	18	10	10
1	12.796	12.796	14.4	14.4	12.796	12.796
2	9.251	9.251	12.29	12.29	9.251	9.251
3	6.761	6.761	8.56	8.56	6.761	6.761
4	4.901	4.901	7.3	7.3	4.901	4.901
5	3.579	3.579	6.05	6.05	3.579	3.579
6	2.611	2.611	5.16	5.16	2.611	2.611
7	1.888	1.888	4.38	4.38	1.888	1.888
8	1.38	1.38	3.74	3.74	1.38	1.38
9	1	1	3.2	3.2	1	1
10	0.73	0.73	2.73	2.73	0.73	0.73
11	-	-	2.29	2.29	-	-
12	-	-	1.95	1.95	-	-
13	-	-	1.62	1.62	-	-
14	-	-	1.38	1.38	-	-
15	-	-	1.17	1.17	-	-
16	-	-	1	1	-	-
17	-	-	0.86	0.86	-	-
18	-	-	0.73	0.73	-	-

C2.8.1 6-Speed, 10-Speed, and 18-Speed AMT Transmissions

The 6-speed and 10-speed AMT transmissions were evaluated as alternative transmissions in the medium duty applications (Kenworth T270 and Ford F-650). The 10-speed AMT was the standard transmission in the long haul Kenworth T700 tractor trailer truck. The 18-speed AMT was used as an alternative in the T700. Proprietary SwRI test data was used to quantify the efficiency of each gear as a function of input torque. Eaton provided proprietary shift schedules for the 6- and 10-speed AMT transmissions. SwRI modified these schedules slightly to achieve smooth transitions during the drive cycles – in other words, to avoid situations of excessive gear hunting. SwRI developed a shift schedule for the 18-speed transmission, based on the 10-speed schedule. Tables C9, C10, and C11 detail the gear ratios and other characteristics of these transmissions.

Table C12 above shows the transmission ratios for the 6-speed AMT transmission. The data can be found in the Vehicle 40-42 and 62-64 columns for both the T270 and F-650 portions of the table. Table C12 above also shows the transmission ratios for the 10-speed AMT transmission (Vehicles 65, 66, 69 and 70) and for the 18-speed AMT transmission (Vehicles 67 and 68).

C2.8.2 Automatic Transmissions

A variety of torque converter automatic transmissions were used for the Ram pickup and the medium duty trucks (T270 and F-650). The standard transmission for the pickup truck simulation model was the Aisin 6-speed automatic. This is the transmission used in the 2014 Ram with the 385 HP rating of the Cummins ISB engine. SwRI does not have access to factory efficiency data, torque converter match, and shift schedules, so SwRI used existing data and engineering judgment to develop the required parameters. Alternative torque converter matches were developed for the 3.5 liter V-6 and 6.2 liter V-8 gasoline engines. Table C12 provides data on the 6-speed Aisin transmission (Vehicles 1, 2, and 4 – 14).

For the T270 and F-650 medium-duty trucks, the standard transmission is a 5-speed Allison 2000 Series. This is actually a 6-speed box, but for many applications, 6th gear is not used. The explanation for this is that 6th gear is a tall overdrive ratio, which causes the driveshaft speed to be well above engine speed. High driveshaft speeds lead to two potential problems. One issue is that the driveshaft length must be limited, in order to avoid driveshaft whirl. The fix for this issue is to use a multi-piece driveshaft with carrier bearings, so that each driveshaft segment is short enough to avoid whirl.

The second issue with a tall overdrive ratio is that it increases the frequency of any imbalance forces that may occur in a driveshaft. Unbalance forces in the driveshaft excite the powertrain bending resonances of the engine/transmission assembly. If the frequency of driveshaft rotation matches the lowest powertrain bending resonance somewhere in the operating range of the engine, mechanical failures of the flywheel housing are likely. Fixing this issue requires an increase in powertrain bending frequency. This is normally obtained by optimization of the flywheel housing structure. Occasionally, the transmission housing may also need to be stiffened. In some cases, it is not possible to achieve the target powertrain bending resonance frequency with conventional stiffening measures. In these cases, external brackets which tie the engine block directly to the transmission housing may be required. Some example values:

Maximum engine speed: 2,800 RPM
Overdrive ratio: 0.62:1
Maximum driveshaft speed: 2,200/0.62 = 4,516 RPM = 75.3 Hz
Target powertrain bending frequency with 15% margin: 86.6 Hz

Powertrain bending excitation normally becomes a problem when the vehicle is going downhill and the driver is using the engine for braking. Under these conditions, the engine can be motored above its normal maximum speed. This causes high driveshaft speed, and thus high rotating imbalance force frequency. Shaft whirl is also more likely to be a problem in downhill operation with engine overspeed.

The 2012 model T270 and F-650 trucks that were modeled in this project both lock out 6th gear. As of 2014, Ford has modified their truck to make use of 6th gear. Kenworth now offers both 5 and 6-speed versions of the Allison transmission, depending on the vehicle specification. The trend appears to be moving towards drivelines that can accommodate taller overdrive ratios.

Different torque converter matches were selected for the ISB diesel and the two gasoline engines. Allison provided proprietary efficiency data, which was input to the vehicle simulation model. Details of the 5-speed Allison are in Table C13 below.

Table C12 above shows the transmission ratios for the 5-speed torque converter automatic transmission in the T270 and F-650 sections in columns Vehicle 21 – 36 and 43 - 58.

As an upgrade to the 5 and 6-speed automatics, an 8-speed unit was evaluated. The advantages of an 8-speed over the baseline 5 and 6-speed units include closer ratios and a wider ratio range. The biggest advantage of the 8-speed is that it has a higher mechanical efficiency than the baseline transmission. SwRI used proprietary efficiency test data from the most efficient 8-speed light truck transmission now available, and scaled it to match the requirements of this project.

By scaling, we mean the following. Assume that the transmission subjected to physical testing has a torque limit of 500 Nm, but our engine provides 1000 Nm. Thus, the transmission's performance needs to be scaled up by a factor of 2. If the tested transmission has an efficiency of 97% at 300 Nm, we would then input an efficiency of 97% at 600 Nm for the simulation.

There are three primary sources of benefit for the 8-speed in vehicle operation:

1. The wider ratio range allows for a taller top gear for cruise
2. The closer gear spacing should allow the engine to be kept in a more efficient part of its operating map
3. The improved mechanical efficiency should reduce fuel consumption during all types of operation

In our simulations, we did not take advantage of advantage 1. We geared the trucks to obtain the same cruise RPM at 65 MPH in top gear regardless of the number of transmission ratios available. In practice, advantage 2 proved to be a very minor factor. The 5 and 6-speed transmissions actually do a very good job of keeping the engine in an efficient part of the operating map. Advantage 3 proved most significant, since the 8-speed is about 2% more efficient across much of the operating range, with a larger advantage at light load.

Table C12 above shows the transmission ratios for the 8-speed torque converter automatic transmission in the Dodge Ram section in columns Vehicle 3 and Vehicles 15 - 20. The same data is also shown in the T270 and F-650 sections in columns Vehicle 37 – 39 and 59 - 61.

C2.9 Engine Alternatives

C2.9.1 4.5 and 6.7 Liter Diesel for Pickup (Class 2b/3)

The baseline engine for the pickup was a 385 HP 6.7 liter diesel. Several engine technology packages were explored on this engine, and a 4.5 liter 4-cylinder variant was developed to explore downsizing. Details are provided in Appendix B.

C2.9.2 6.7 Liter Diesel for Classes 4 – 7

The baseline engine for the T270 and F-650 medium-duty trucks was a 300 HP rating of the 6.7 liter diesel. Several engine technology packages were explored on this engine. Details of the medium-duty diesel engines are provided in Appendix B.

C2.9.3 3.5 V-6 and 6.2 V-8 Gasoline Engines for Class 2b – 7 Vehicles

Gasoline engines were explored as alternatives to the diesel on the Ram pickup and also in the T270 and F-650 vocational trucks. The smaller V-6 represents a downsized, turbocharged, direct injection alternative. The 6.2 V-8 is a more traditional naturally aspirated, port injected engine. Several technologies were explored on each engine type. Details of the gasoline engines and their technology packages are provided in Appendix A.

C2.9.4 15 Liter Diesel Engines for Class 8

The baseline engine for the Kenworth T-700 long-haul tractor-trailer truck is a 485 HP rating of the 15 liter diesel. A wide range of technology packages have been applied to this engine. Details on these engines and technologies are provided in Appendix B.

APPENDIX D

HYBRIDIZATION OF CLASS 2B PICKUP TRUCK

HYBRIDIZATION OF CLASS 2B PICKUP TRUCK

Objective: Simulate Potential Hybridization Technologies to Demonstrate Fuel Economy Improvement Potential in Class 2b, over:

- **A range of engines**
- **A range of hybridization technologies**

1. Hybrid System Modeling Approach:

1.1. **Baseline Engines and Vehicle**
1.2. **Hybrid Systems Modeled for this Project**
1.3. **Vehicle Parameter Assumptions**

2. Hybrid System Results:

2.1. **Baseline Vehicle Fuel Economy**
2.2. **Hybrid System Results**

3. Conclusions

D1. Hybrid System Modeling Approach

D1.1 Baseline Engines and Vehicle

Argonne National Laboratory performed the hybrid system modeling under a separate NHTSA contract. Their results are included in this report to provide completeness. SwRI provided Argonne with the engine fuel maps and Ram Pickup vehicle parameters used in the rest of this study. Argonne modified certain parameters for their hybrid system evaluation. These changes will be documented in this Appendix, along with the results of the hybrid system simulation.

Argonne used the 2011/2012 baseline engine fuel maps for the ISB diesel, the 3.5 liter turbocharged V-6 gasoline engine, and the 6.2 liter naturally aspirated V-8 gasoline engine. The baseline vehicle parameters were also carried over, with exceptions noted below.

D1.2 Hybrid Systems Modeled for this Project

Three different hybrid systems were simulated: a belt-drive integrated starter-generator (BISG), and crankshaft drive integrated starter-generator (CISG), and a parallel hybrid. The two ISG systems both feed power to the engine, either through the accessory drive belt (BISG) or directly to the crankshaft (CISG). The parallel hybrid feeds power into the transmission input.
All three systems are configured to perform regenerative braking as well as to assist with acceleration. Table D.1 below shows some details of the three hybrid systems.

TABLE D.1 HYBRID SYSTEM PARAMETERS

	Parameter	BISG	CISG	Parallel Hybrid
Basic Parameters	Peak Motor Power	7 kW	15 kW	50 kW
	Power Density	1500 W/kg	1500 W/kg	1500 W/kg
	# of Battery Cells	30	68	Sized to Meet Requirements
	Battery Power @ 65% SOC	8 kW	18 kW	Sized to Meet Requirements
	Vehicle Accessories	Engine Driven	Engine Driven	Electrically Driven
	Vehicle Mass	Adjusted to Account for Hybrid Components	Adjusted to Account for Hybrid Components	Adjusted to Account for Hybrid Components

D1.3 Vehicle Parameter Assumptions

The diesel powered pickup retained the same transmission ratios and rear axle ratio as was used in the rest of the project. However, Argonne substituted the GM 6L80 6-speed transmission for the scaled diesel transmission used by SwRI. The 6L80 has a top gear ratio of 0.67:1, which is 9% shorter than the 0.625 ratio of the diesel transmission. The 6L80 also has wider spacing between the gears, so that first gear is shorter by 20%. Argonne chose a 3.73 rear axle ratio for the gasoline engines, compared to the 5.37 ratio used in the SwRI study. A portion of this difference can be explained by the shorter transmission gearing of the 6L80, but the majority of the difference is explained by the fact that SwRI used a non-standard axle ratio in order to achieve the high towing capacity (25,000 pounds GCW) of the diesel. The overall effect of these changes will be that with Argonne's assumptions:

- The gasoline powered trucks will get better MPG than in the SwRI study
- The gasoline powered trucks will have worse trailer towing performance than in the SwRI study

Argonne chose to reduce the accessory power demand from the value of 4,450 Watts used in the main study to 350 Watts for the mild ISG hybrids and 400 Watts for the parallel hybrid. This assumption eliminates the use of the air conditioning, which is the standard approach for light duty vehicle testing on the UDDS and HWFET cycles. The assumption also includes reduction of power demand from other accessories, such as power steering and the cooling fan. Argonne selected these accessory power demand values because they are typical of light duty vehicles being tested on the UDDS and HWFET cycles. As a result of the reduced accessory power demand, the baseline engines will achieve lower fuel consumption and higher MPG in the Argonne study than was obtained in the SwRI work.

Argonne uses a tire rolling resistance value of 0.008, compared to the SwRI value of 0.0078. This minor change will have little effect on the results.

D2. Hybrid System Results

D2.1 Baseline Vehicle Fuel Economy

Figure D.1 below shows the results of fuel economy simulations for the baseline Ram pickup truck with all three baseline engines. The vehicle is operated at three payloads: zero payload, ALVW (approximately 50% payload, with no trailer), and full GCW (25,000 pounds for the diesel and 24,500 pounds for the gasoline engines, with a loaded trailer).

Table D.1 provides the same data in tabular form. Fuel consumption values in gallons per 100 miles are also provided. The diesel engine consistently provides the highest MPG and lowest fuel consumption. The 3.5 V-6 is consistently in second place, although its advantage over the V-8 is quite small when the vehicle is operated at full load. The reduction in accessory load and modifications to other vehicle parameters results in MPG values that are significantly higher than those reported by SwRI in Final Report #1.

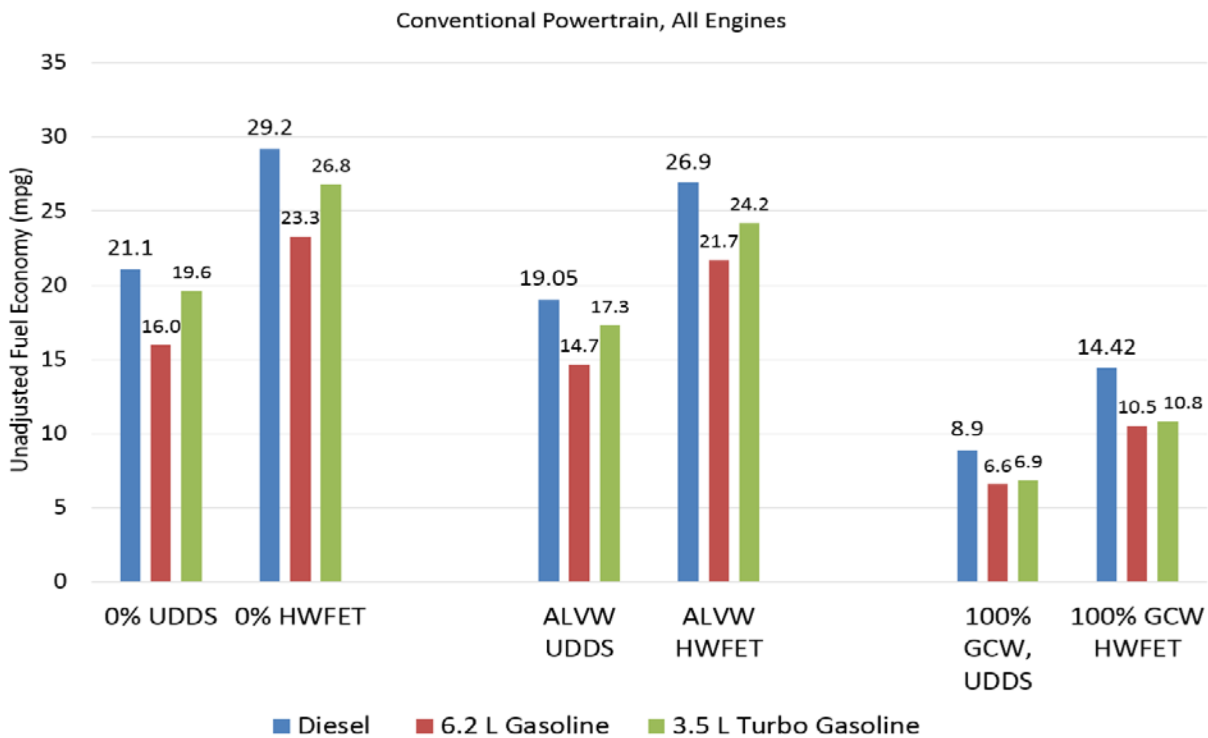


FIGURE D.1 FUEL ECONOMY COMPARISON OF 3 ENGINES IN THE BASELINE RAM PICKUP

TABLE D.1 FUEL ECONOMY AND FUEL CONSUMPTION OF 3 ENGINES IN THE BASELINE RAM PICKUP

Engine	Drive Cycle	Payload	Base FE, MPG	Base FC, gal/100
Diesel	HWFET	0%	29.2	3.42
Diesel	UDDS	0%	21.1	4.73
3.5 V-6	HWFET	0%	26.8	3.73
3.5 V-6	UDDS	0%	19.7	5.08
6.2 V-8	HWFET	0%	23.4	4.28
6.2 V-8	UDDS	0%	16.0	6.24
Diesel	HWFET	ALVW	27.0	3.71
Diesel	UDDS	ALVW	19.1	5.25
3.5 V-6	HWFET	ALVW	24.2	4.13
3.5 V-6	UDDS	ALVW	17.3	5.77
6.2 V-8	HWFET	ALVW	21.7	4.60
6.2 V-8	UDDS	ALVW	14.7	6.81
Diesel	HWFET	GCW	14.4	6.93
Diesel	UDDS	GCW	8.9	11.3
3.5 V-6	HWFET	GCW	10.8	9.22
3.5 V-6	UDDS	GCW	6.9	14.6
6.2 V-8	HWFET	GCW	10.5	9.50
6.2 V-8	UDDS	GCW	6.6	15.2

D2.2 Hybrid System Results

The two different integrated starter/generator systems and the parallel hybrid system were applied to all three engines and run on the two drive cycles. A summary of the results is provided in Table D.2. Fuel consumption rates are provided for all four configurations (the baseline non-hybrid and the three hybrid system options). The final three columns in Table D.2 provide the benefit of the hybrid systems in terms of percent reduction in fuel consumption. At ALVW payload on the UDDS cycle, the belt driven BISG provides a 5.6% to 7.7% reduction in fuel consumption, while the more powerful crank driven CISG provides 7.0% to 8.3% fuel consumption benefit. The full hybrid system provides a 25.2% to 29.5% fuel savings at ALVW payload. Results on the higher speed HWFET cycle are much smaller for all hybrid systems.

The results can also be displayed in graphical form. Figure D.2 shows the performance of the three hybrid systems with the diesel engine, while Figure D.3 provides turbocharged V-6 gasoline engine results, and Figure D.4 shows V-8 results. The general trends are quite similar between all three engines. The BISG system has the lowest performance (and cost/complexity), the CISG performs somewhat better, and the larger, more complex parallel hybrid system provides the largest benefits. As expected, all hybrid systems provide a much larger benefit on the urban UDDS cycle than on the rural HWFET cycle. There is much more opportunity for

TABLE D.2 FUEL CONSUMPTION COMPARISON BETWEEN BASELINE AND HYBRID SYSTEMS

Engine	Drive Cycle	Payload	Base FC, gal/100	FC w/ BISG, gal/100	FC w/ CISG, gal/100	FC w/ Parallel Gal/100	BISG % Benefit	CISG % Benefit	Parallel % Benefit
Diesel	HWFET	0%	3.42	3.41	3.41	3.23	0.30	0.23	5.75
Diesel	UDDS	0%	4.73	4.46	4.33	3.35	5.75	8.56	29.2
3.5 V-6	HWFET	0%	3.73	3.70	3.63	3.54	0.80	2.66	5.03
3.5 V-6	UDDS	0%	5.08	4.68	4.57	3.82	7.76	10.0	24.8
6.2 V-8	HWFET	0%	4.28	4.28	4.25	4.00	0.08	0.72	6.45
6.2 V-8	UDDS	0%	6.24	5.80	5.59	4.35	6.99	10.3	30.2
Diesel	HWFET	ALVW	3.71	3.70	3.68	3.48	0.28	0.85	6.21
Diesel	UDDS	ALVW	5.25	4.95	4.81	3.74	5.62	8.29	28.8
3.5 V-6	HWFET	ALVW	4.13	4.10	4.02	3.87	0.86	2.76	6.27
3.5 V-6	UDDS	ALVW	5.77	5.33	5.33	4.32	7.66	7.58	25.2
6.2 V-8	HWFET	ALVW	4.60	4.56	4.57	4.28	0.99	0.76	6.95
6.2 V-8	UDDS	ALVW	6.81	6.40	6.34	4.80	6.14	6.99	29.5
Diesel	HWFET	GCW	6.93	6.91	6.83	6.50	0.40	1.48	6.25
Diesel	UDDS	GCW	11.3	10.9	10.7	9.15	3.05	5.13	18.7
3.5 V-6	HWFET	GCW	9.22	9.18	9.14	8.68	0.46	0.92	5.92
3.5 V-6	UDDS	GCW	14.6	13.9	13.5	12.2	4.65	7.11	16.4
6.2 V-8	HWFET	GCW	9.50	9.43	9.38	8.76	0.73	1.31	7.79
6.2 V-8	UDDS	GCW	15.2	14.5	14.4	12.0	4.67	5.03	20.8

regenerative braking on the urban cycle. The V-6 gains the most benefit from the simple BISG system, but results are similar for all 3 engines with the CISG system. With the full parallel hybrid system, the V-8 gets the largest benefit, and the V-6 gets the smallest benefit. Note that the performance of the hybrid system on each engine is compared to that specific engine's baseline, not to a common baseline.

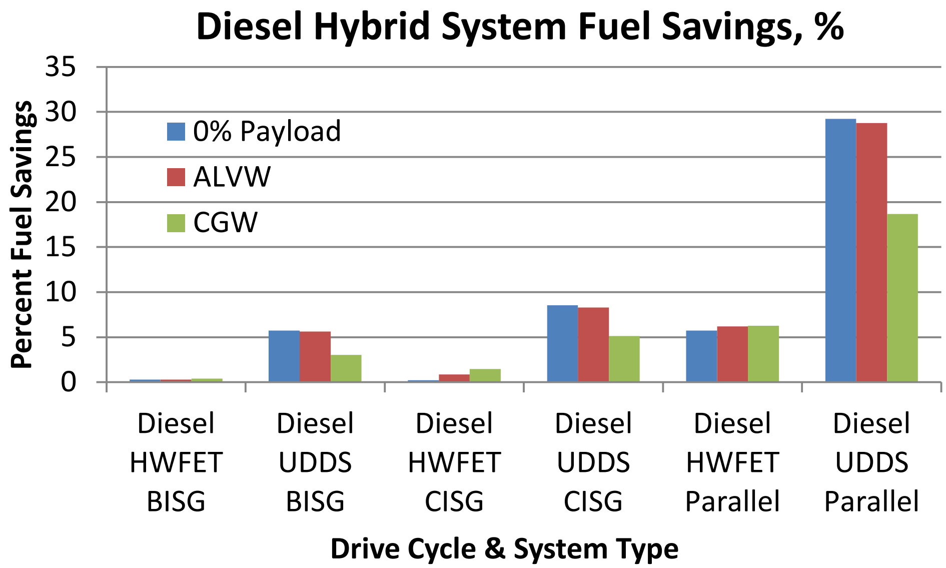


FIGURE D.2 DIESEL HYBRID SYSTEM FUEL CONSUMPTION REDUCTION IN PERCENT

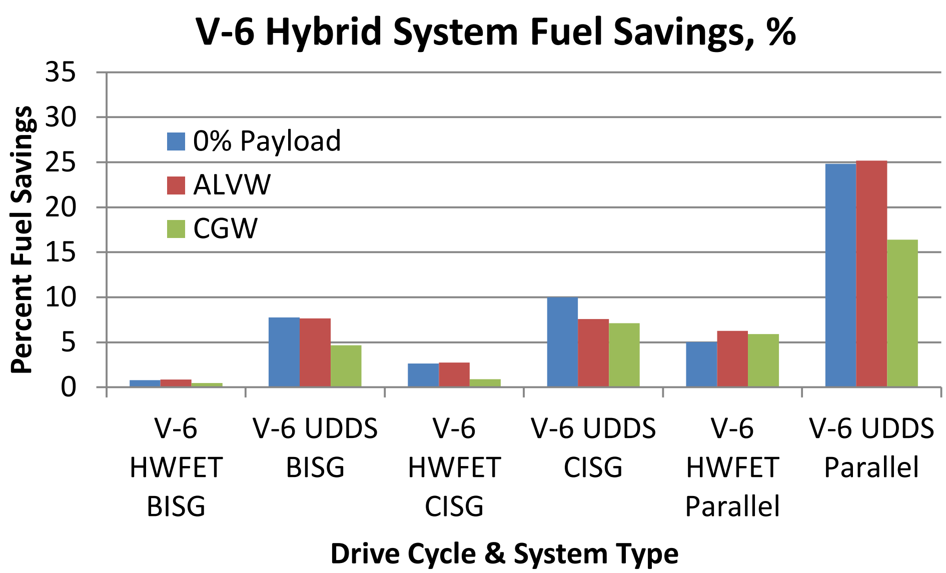


FIGURE D.3 V-6 GASOLINE HYBRID SYSTEM FUEL CONSUMPTION REDUCTION IN PERCENT

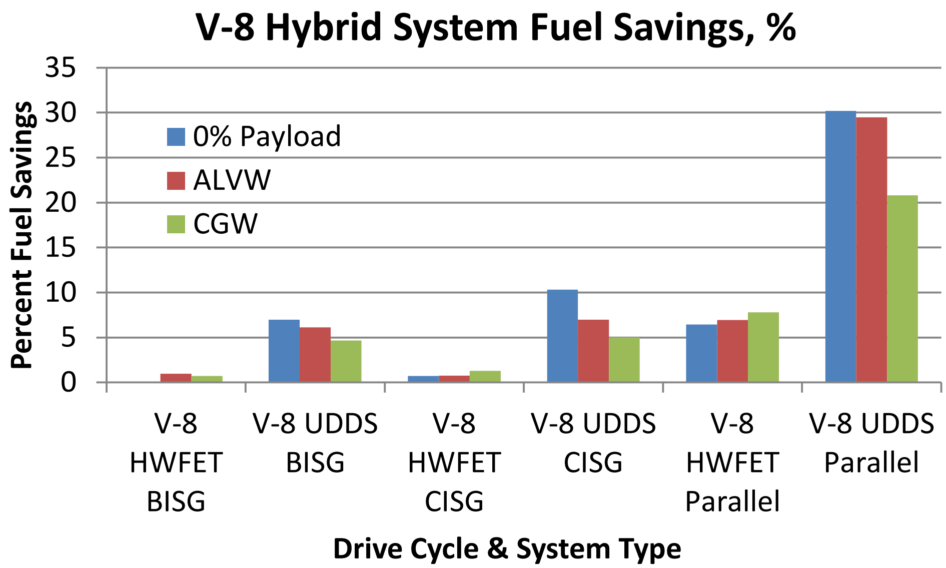


FIGURE D.4 V-8 GASOLINE HYBRID SYSTEM FUEL CONSUMPTION REDUCTION IN PERCENT

Since the diesel has the lowest fuel consumption without a hybrid system, it also has the lowest fuel consumption with a hybrid system. However, diesels are a very expensive option in heavy-duty pickups, and a diesel hybrid would be even more expensive.

D3 Conclusions

1. On the UDDS city driving cycle at ALVW:
   a) Mild hybrid systems (BISG and CISG) applied to a Class 2b pickup truck can reduce vehicle fuel consumption by 5.6% to 8.5% compared to conventional powertrains
   b) A 50 kW parallel hybrid system can reduce fuel consumption by 25% to 30%
2. On the HWFET highway driving cycle at ALVW:
   a) Mild hybrid systems (BISG and CISG) applied to a Class 2b pickup truck can reduce vehicle fuel consumption by 0.3% to 2.8% compared to conventional powertrains
   b) A 50 kW parallel hybrid system can reduce fuel consumption by 6.2% to 7%
3. Hybridization benefits at higher payloads are reduced relative to the unloaded truck.

APPENDIX E

ERRATA

A pre-peer review draft version of this report was released in June of 2015 with the following note on its cover:

> **Pre-Peer Review Draft Report**
>
> Note: This pre-peer review draft report is currently being subjected to external peer review per OMB guidelines for a Highly Influential Scientific Assessment (HISA). A final report and the accompanying materials from the peer review process will be made publicly available at a later date.

As described in Section 2.3.2, the subsequent independent peer review and public release of the draft report identified some errors in the analysis that affected the fuel consumption benefits ascribed to the DD15 engine with all technology packages. Since the draft version of the report was widely disseminated, it is important to understand how the final version differs from the initial draft. This appendix will describe the issues in more detail, and show how the results changed once the errors were found and corrected.

Three errors were discovered during the independent peer review and public release of the draft report that have been corrected in this final version. The first error was the use of the wrong fuel map to represent the model year 2019 DD15 engine baseline. The fuel map inadvertently used was a model year 2011 baseline turbocompound engine with a 1% benefit from combustion duration, but otherwise unchanged. The analysis for this section should have used a variation of the 2011 engine map (adjusted to represent the more efficient 2013 DD15 engine without turbocompound and with an asymmetric turbocharger) as the baseline to allow exploration of improvements beyond the Phase 1 standards. The second error was an Excel lookup reference which pointed to the wrong vehicle frontal area. The frontal area for the T700 truck used in the draft version of this report was about 5% low. This had the effect of making all technology combination fuel consumption results look slightly better than they should have. This error had the largest effect (up to 2%) on the high speed cruise cycles, where aerodynamic load plays the largest role. The final error was that several of the technology packages were run by mistake with preliminary rather than final fuel maps.

In addition to correcting the errors described above, one other change was made in the interest of providing the most accurate possible comparison. The original 2011 DD15 GT model was revised to include a fueling controller (which defines the torque curve) and an exhaust backpressure controller (which defines an orifice in the exhaust to achieve a target backpressure).

These controllers were used in all subsequent technology simulations, so they were applied to the baseline engine model in an effort to guarantee consistency in the modeling approach.

The revised results included in this version of the report show the following effects:

- There is now a larger difference between the 2011 and 2019 DD15 baseline engine results, particularly on the CARB and WHVC cycles
- The fuel savings benefits of all the DD15 technology combination packages are reduced by up to 3.3%, depending on the technology package and driving cycles compared to the original draft, primarily because the 2019 DD15 baseline now has lower fuel consumption
- The relative benefit of waste heat recovery is essentially unchanged

The results that changed are shown in Table 2.11 in the main body of this report. In this appendix, we will compare the original values in Table 2.11 to the current values. The new and old draft versions of Table 2.11 are listed below:

TABLE E.1 CURRENT VERSION OF TABLE 2.11. FUEL SAVINGS RESULTS OF DD15 ENGINE TECHNOLOGY COMBINATIONS VS. 2019 BASELINE

Engine Technology Combos	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload														
	CARB			55 MPH			65 MPH			WHVC			NESCCAF		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
1. 2011 Base DD15	-3.0	-2.7	-2.5	-2.5	-2.4	-2.3	-2.8	-2.7	-2.5	-2.8	-2.6	-2.4	-2.8	-2.6	-2.5
2. DD15 Combo 1	5.5	3.9	3.0	2.9	2.2	1.7	1.6	1.2	1.0	4.6	3.1	2.2	2.0	1.4	1.1
3. DD15 Combo 2	8.1	5.6	4.1	2.2	2.4	2.3	4.0	3.3	2.9	6.3	4.4	3.2	4.8	3.2	2.6
4. DD15 Combo 3	8.1	5.6	4.1	6.8	7.2	7.3	8.6	8.1	7.9	6.3	4.4	3.2	9.5	8.1	7.7
5. DD15 Combo 3a	8.1	5.6	4.1	5.7	5.9	5.9	7.3	6.7	6.3	6.3	4.4	3.2	7.9	6.4	5.7
6. DD15 Combo 3b	8.1	5.6	4.1	6.7	6.9	6.9	8.7	8.0	7.7	6.3	4.4	3.2	9.3	8	7.1
7. DD15 Combo 3c	8.1	5.6	4.1	7.4	7.7	7.8	9.2	8.6	8.4	6.3	4.4	3.2	10	8.4	7.9
8. DD15 Combo 3d	8.1	5.6	4.1	7.4	7.8	8.0	9.3	8.8	8.6	6.3	4.4	3.2	10	8.7	8.3
9. DD15 Combo 3e	8.1	5.6	4.1	7.1	7.5	7.5	9.0	8.4	8.1	6.3	4.4	3.2	10	8.1	7.5
10. DD15 Combo 3f	8.1	5.6	4.1	7.4	7.8	7.9	9.4	8.8	8.7	6.3	4.4	3.2	10	8.7	8.3
11. DD15 Combo 4	6.4	4.9	4.1	5.9	5.0	4.2	5.2	4.7	4.3	6.0	4.6	3.7	5.2	4.4	3.9
12. DD15 Combo 5	7.6	5.4	6.5	1.3	1.6	1.8	4.3	3.4	2.7	5.6	4.1	3.3	5.0	3.6	3.2

TABLE E.2 DRAFT VERSION OF TABLE 2.11. FUEL SAVINGS RESULTS OF DD15 ENGINE TECHNOLOGY COMBINATIONS Vs. 2019 BASELINE

Engine Technology Combos	Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload														
	CARB			55 MPH			65 MPH			WHVC			NESCCAF		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
1. 2011 Base DD15	-1.2	-0.9	-0.7	-3.3	-2.5	-1.9	-3.5	-2.8	-2.2	-1.9	-1.4	-1.0	-3.1	-2.4	-1.8
2. DD15 Combo 1	7.7	5.8	4.7	4.8	4.0	3.4	3.8	3.4	3.0	6.7	5.0	3.9	4.1	3.4	2.9
3. DD15 Combo 2	11	8.4	6.6	4.8	4.6	4.4	6.6	5.6	4.9	9.3	7.0	5.5	7.4	5.5	4.8
4. DD15 Combo 3	11	8.4	6.6	9.3	9.4	9.4	11	10	9.9	9.3	7.0	5.5	12	10	10
5. DD15 Combo 3a	11	8.4	6.6	8.2	8.2	8.0	9.9	9.0	8.4	9.3	7.0	5.5	11	8.7	8.0
6. DD15 Combo 3b	11	8.4	6.6	9.2	9.2	9.0	11	10	9.7	9.3	7.0	5.5	12	10	9.4
7. DD15 Combo 3c	11	8.4	6.6	9.9	10	9.9	12	11	10	9.3	7.0	5.5	13	11	10
8. DD15 Combo 3d	11	8.4	6.6	9.9	10	10	12	11	11	9.3	7.0	5.5	13	11	11
9. DD15 Combo 3e	11	8.4	6.6	9.7	9.7	9.6	12	11	10	9.3	7.0	5.5	12	10	10
10. DD15 Combo 3f	11	8.4	6.6	9.9	10	10	12	11	11	9.3	7.0	5.5	13	11	11
11. DD15 Combo 4	6.1	4.7	3.9	3.9	3.3	2.7	3.0	2.7	2.5	5.2	3.9	3.2	3.3	2.8	2.5
12. DD15 Combo 5	11	8.5	7.9	3.7	3.9	3.8	7.0	6.2	5.8	8.7	6.9	5.9	8.0	6.5	6.1

Table E.3 below shows how the fuel savings benefits have changed, as a result of correcting the errors. A negative number indicates that the final fuel savings were smaller than the original draft results indicated.

TABLE E.3 DIFFERENCE BETWEEN VERSIONS OF TABLE 2.11. NEGATIVE VALUES INDICATE THAT THE FINAL FUEL SAVINGS ARE SMALLER THAN WAS SHOWN IN THE DRAFT REPORT

Engine Technology Combos	Difference Between Final and Draft Fuel Consumption Reduction In Percent On Drive Cycle and Percent of Maximum Payload														
	CARB			55 MPH			65 MPH			WHVC			NESCCAF		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
1. 2011 Base DD15	-1.8	-1.8	-1.8	0.9	0.2	-0.4	0.7	0.1	-0.3	-0.9	-1.2	-1.4	0.3	-0.2	-0.7
2. DD15 Combo 1	-2.2	-2.0	-1.7	-1.9	-1.8	-1.7	-2.2	-2.2	-2.1	-2.1	-1.9	-1.7	-2.2	-1.9	-1.8
3. DD15 Combo 2	-3.3	-2.8	-2.5	-2.6	-2.3	-2.1	-2.6	-2.3	-2.0	-3.1	-2.6	-2.3	-2.7	-2.3	-2.3
4. DD15 Combo 3	-3.3	-2.8	-2.5	-2.5	-2.3	-2.1	-2.5	-2.3	-2.0	-3.1	-2.6	-2.3	-2.6	-2.3	-2.3
5. DD15 Combo 3a	-3.3	-2.8	-2.5	-2.5	-2.3	-2.1	-2.6	-2.3	-2.0	-3.1	-2.6	-2.3	-2.7	-2.3	-2.3
6. DD15 Combo 3b	-3.3	-2.8	-2.5	-2.5	-2.3	-2.1	-2.6	-2.3	-2.0	-3.1	-2.6	-2.3	-2.7	-2	-2.3
7. DD15 Combo 3c	-3.3	-2.8	-2.5	-2.5	-2.3	-2.1	-2.5	-2.3	-2.0	-3.1	-2.6	-2.3	-3	-2.3	-2.3
8. DD15 Combo 3d	-3.3	-2.8	-2.5	-2.5	-2.3	-2.1	-2.5	-2.3	-2.0	-3.1	-2.6	-2.3	-3	-2.3	-2.3
9. DD15 Combo 3e	-3.3	-2.8	-2.5	-2.5	-2.3	-2.1	-2.5	-2.3	-2.0	-3.1	-2.6	-2.3	-3	-2.3	-2.3
10. DD15 Combo 3f	-3.3	-2.8	-2.5	-2.5	-2.3	-2.1	-2.5	-2.3	-2.0	-3.1	-2.6	-2.3	-3	-2.3	-2.3
11. DD15 Combo 4	-2.2	-1.9	-1.7	-1.7	-1.6	-1.5	-2.1	-2.0	-1.8	-2.1	-1.8	-1.6	-2.1	-1.8	-1.7
12. DD15 Combo 5	-3.3	-3.0	-1.2	-2.5	-2.2	-2.0	-2.6	-2.8	-3.1	-3.1	-2.8	-2.6	-3.0	-2.9	-2.9

The final version of the 2019 baseline DD15 fuel map provided lower fuel consumption results then the draft 2019 DD15 map. As a result, there is now a larger difference between the original 2011 DD15 baseline and the 2019 DD15 baseline on the CARB and WHVC cycles. Results on the higher speed cycles were skewed, because the draft 2019 DD15 baseline was accidentally run with a smaller frontal area than the 2011 baseline. For these cycles, the two errors effectively canceled each other, and there is not much difference between the two baseline engines when comparing the draft and final results.

Technology Combo 1 shows the effect of engine friction reduction, compared to the 2019 baseline. This benefit is about 2% smaller in the final version of the report than it was in the draft report. The fuel savings attributed to a FMEP reduction in draft Report #2 was larger than the values provided in Report #1. After correcting for the issues described above, the fuel savings found for a friction reduction is now slightly (0.6% to 1.0%) smaller than the fuel savings reported in Report #1. Given the evolution of the GT-POWER models used over the project time frame, this sort of difference lies within the bounds of variability to be expected.

Technology Combo 2 includes downspeeding and a partial friction reduction (50% of the friction reduction simulated in Combo 1). Largely due to the lower fuel consumption of the final 2019 DD15 baseline, this combination provides fuel savings 2.0% to 3.3% smaller than those given in the draft report. All of the Combo 3 variants add different waste heat recovery systems to Combo 2. The projected benefits are reduced by the same amount as was observed for Combo 2. Combo 4 saw a benefit reduction of about 2% across the board compared to the draft report. Combo 5 experienced a 1.2% to 3.3% benefit reduction from the initial draft report.

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