Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe

United States
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Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe

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

Prepared for EPA by
Ricardo, Inc.
and
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COMPUTER SIMULATION OF LIGHT-DUTY VEHICLE TECHNOLOGIES FOR GREENHOUSE GAS EMISSION REDUCTION IN THE 2020–2025 TIMEFRAME

EXECUTIVE SUMMARY

Ricardo, Inc. was subcontracted by Systems Research and Applications Corporation (SRA), a wholly owned subsidiary of SRA International, Inc., under contract to the United States Environmental Protection Agency (EPA) to assess the effectiveness of future light duty vehicle (LDV) technologies on future vehicle performance and greenhouse gas (GHG) emissions in the 2020–2025 timeframe. GHG emissions are a globally important issue, and the EPA's Office of Transportation and Air Quality (OTAQ) has been chartered with examining the GHG emissions reduction potential of LDVs, including passenger cars and light-duty trucks. This program was performed between October 2009 and November 2011.

The scope of this project was to execute an independent and objective analytical study of LDV technologies likely to be available within the 2020–2025 timeframe, and to develop a data visualization tool to allow users to evaluate the effectiveness of LDV technology packages for their potential to reduce GHG emissions and their effect on vehicle performance. This study assessed the effectiveness of a broad range of technologies including powertrain architecture (conventional and hybrid), engine, transmission, and other vehicle attributes such as engine displacement, final drive ratio, vehicle weight, and rolling resistance on seven light-duty vehicle classes. The methodology used in this program surveyed the broad design space using robust physics-based modeling tools and then generated a computationally efficient response surface to enable extremely fast surveying of the design space within a data visualization tool. During this effort, quality assurance checks were employed to ensure that the simulation results were a valid representation of the performance of the vehicle. Through the use of the data visualization tool, the users can query the design space on a real time basis while capturing interactions between technologies that may not be identified from individual simulations.

This report documents the work done on the program "Computer Simulation of Light Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020–2025 Timeframe". This work has included identifying and selecting technologies for inclusion in the study, developing and validating baseline models, and developing the data visualization tool.

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1. INTRODUCTION

Ricardo was subcontracted by Systems Research and Applications Corporation (SRA), a wholly owned subsidiary of SRA International, Inc., under contract to the United States Environmental Protection Agency (EPA) to assess the effectiveness of future light duty vehicle (LDV) technologies on future vehicle performance and greenhouse gas (GHG) emissions in the 2020–2025 timeframe. GHG emissions are a globally important issue, and the EPA's Office of Transportation and Air Quality (OTAQ) has been chartered with examining the GHG emissions reduction potential of LDVs, including passenger cars and light-duty trucks.

SRA is a company of over 7,000 staff dedicated to solving complex problems of global significance for government organizations serving the civil government, global health, and national security markets. SRA’s Air Programs and Climate Change Account works extensively with OTAQ and other EPA offices on regulatory and voluntary programs to reduce air pollution and address climate change.

SRA and Ricardo worked closely with the EPA team on nearly every technical and contractual issue.

The team at EPA OTAQ included the following staff members:

- Matt Brusstar, Director, Advanced Powertrain Center, Testing and Advanced Technology Division
- Jeff Cherry, Staff Engineer, Light Duty Vehicles and Small Engine Center, Assessment and Standards Division
- Ann Chiu, Contract Project Officer, Data Analysis and Information Center, Compliance Division
- Ben Ellies, Staff Engineer, Climate Analysis and Strategies Center, Transportation and Climate Division
- Joe McDonald, Senior Engineer, Fuels Center, Assessment and Standards Division

In addition to the SRA–Ricardo team working for EPA, other stakeholders for the program included the International Council on Clean Transportation (ICCT) and the California Air Resources Board (ARB). ICCT contributed funding for the early portion of the study in collaboration with ARB. The Advisory Committee provided advice to EPA, and included the following representatives from ICCT and ARB:

- Steven Albu, Assistant Division Chief, ARB
- Anup Bandivedakar, Senior Researcher, ICCT
- John German, Senior Fellow and Program Director, ICCT
- Paul Hughes, Manager, ARB

Ricardo, Inc., is the US division of Ricardo plc., a global engineering consultancy with nearly 100 years of specialized engineering expertise and technical experience in engines, transmissions, and automotive vehicle research and development. This program was performed between October 2009 and November 2011.

The scope of the program was to execute an independent and objective analytical study of LDV technologies likely to be available for volume production in the 2020–2025 timeframe, and to develop a data visualization tool to allow users to evaluate the effectiveness of LDV technology packages for their potential to reduce GHG emissions. An assessment of the effect of these technologies on LDV cost was beyond the scope of this study.

This work was done in collaboration with EPA, and the approach included the following:

- Activities funded by ICCT
  - Identify a large set of future technologies that could improve LDV GHG emissions.
  - Assess these technologies for potential benefit and ability to be commercialized by the 2020–2025 timeframe.
  - Reduce this large set to the technologies selected for further study in this program.
- Activities funded by EPA:
  - Extrapolate selected technologies to their expected performance and efficiency levels in the 2020–2025 timeframe.
  - Conduct detailed simulation of the technologies over a large design space, including a range of vehicle classes, powertrain architectures, engine designs, and transmission designs, as well as parameters describing these configurations, such as engine displacement, final drive ratio, and vehicle rolling resistance.
  - Interpolate the results over the design space using a functional representation of the responses to the varied model input factors.
  - Develop a Data Visualization Tool to facilitate interrogation of the simulation results over the design space.

2. OBJECTIVES

The goal of this technical program has been to objectively evaluate the effectiveness and performance of a large LDV design space with powertrain technologies likely to be available in the 2020–2025 timeframe, and thereby assess the potential for GHG emissions reduction in these future vehicles while also understanding the effects of these technologies on vehicle performance.

3. BACKGROUND

3.1 Study Background

The EPA has an interest in improving the environmental performance and efficiency of cars, trucks, buses, and transportation systems to protect and improve public health, the environment, and quality of life. Additionally, reduction of GHG emissions—emphasizing carbon dioxide (CO_2)—is an increasing priority of national governments and other policymakers worldwide.

This program builds on the work done earlier by Perrin Quarles Associates (PQA, now part of SRA) and Ricardo in 2007–2008 to assess the potential effectiveness of GHG-reducing technologies in LDVs in the 2010–2017 timeframe (Ricardo and PQA, 2008). The earlier program was also funded by EPA and looked at a series of specific LDV configurations and from these assessed the benefits.

The purpose of this study is to define and evaluate potential technologies that may improve GHG emissions in LDVs in the 2020–2025 timeframe. These technologies represent a mixture of future mainstream technologies and some emerging technologies for the study timeframe. For this program, however, a large design space was comprehensively examined so that broader conclusions could be drawn about these technologies that could lead to benefits to GHG emissions reduction.

3.2 Ground Rules for Study

Several ground rules for the study were agreed at the beginning of the program to bound the design space considered in the study. These ground rules identified content that should be included in the study as well as content that should be excluded.

Some examples of the ground rules include the following items for the technology assessment:

- Seven vehicle classes will be included, as described below.
- LDV technologies must have the potential to be commercially deployed in 2020–2025. .
- Vehicle sizes, particularly footprint and interior space, for each class will be largely unchanged from 2010 to 2020–2025.
- Hybrid vehicles will use an advanced hybrid control strategy, focusing on battery state of charge (SOC) management, but not at the expense of drivability.
- Vehicles will use fuels that are equivalent to either 87 octane pump gasoline or 40 cetane pump diesel.
- 2020–2025 vehicles will meet future California LEV III requirements for criteria pollutants, which are assumed to be equivalent to current SULEV II (or EPA Tier 2 Bin 2) levels.
- Ricardo would be allowed to use Ricardo proprietary data and expertise to assess technologies and develop the models, as this allowed the technologies to be assessed more comprehensively than if only publicly available data were used. Ricardo confidential business information relevant to the execution of the program was shared with EPA for the purposes of allowing an external audit of the model inputs developed for the program.
- Due to the multiple designs that manufacturers may realize for any given advanced technology, the effect of technologies on overall vehicle mass is not incorporated directly in the Easy5 models. Instead, the model makes the overt simplifying assumption that all technologies are mass-neutral. The end-user has the flexibility to incorporate their own assumptions about mass reduction from advanced technologies when exploring the design space with the Data Visualization Tool.
- Similarly, other road load reductions such as aerodynamic drag and rolling resistance reduction were addressed as input variables within the complex systems modeling approach.

Likewise, EPA, along with input from the Advisory Committee agreed for this program that the technology assessment should exclude the following:

- Charge-depleting powertrains, such as plug-in hybrid electric vehicles (PHEV) or battery electric vehicles (BEV)[1].
- Fuel cell power plants for fuel cell-electric vehicles (FCEV).
- Non-reciprocating internal combustion engines (ICE) or external combustion engines.
- Manual transmissions and automated manual transmissions (AMT) with a single clutch.
- Kinetic energy recovery systems (KERS) other than battery systems.

[1] While modeling of vehicles with increased electrification would be beneficial, the highest priority was given to vehicle architectures determined most likely to be present in higher volumes during the 2020–2025 time frame. Due to resource limitations, PHEVs and BEVs were considered outside the scope of this study and left as candidates for follow-up modeling work.

- Intelligent vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) optimization technology.
- Bottoming cycles, such as organic Rankine cycles, for energy recovery.
- Vehicle safety systems or structures will not be explicitly modeled for vehicles. A full safety analysis of the technologies presented in this report is beyond the scope of this study.

The seven vehicle classes considered in this study are the following, with a currently available example vehicle given for each class:
1. Small (B-class) Car, such as the Toyota Yaris
2. Standard (D-class) Car, such as the Toyota Camry
3. Small Multi-Purpose Vehicle (MPV), such as the Saturn Vue
4. Full Sized Car, such as the Chrysler 300
5. Large MPV, such as the Dodge Grand Caravan
6. Light-Duty Truck (LDT), such as the Ford F150
7. Light Heavy-Duty Truck (LHDT), such as the General Motors HD3500

3.3 Technology Package Selection Process

The program team used the process shown in Figure 3.1 to identify the technology options listed in Appendix 2, Assessment of Technology Options, to the set described in Chapter 4, Technology Review, and integrated into the technology bundles described in Chapter 5, Technology Bundles and Simulation Matrices.

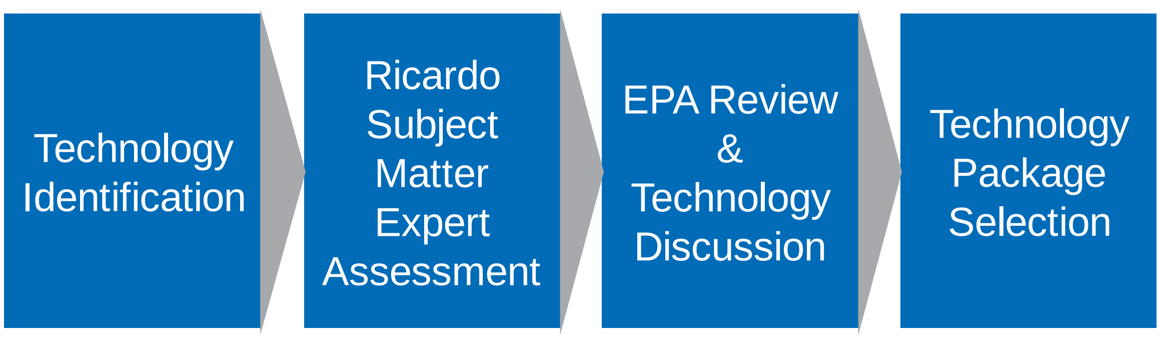

Figure 3.1: Technology package selection process.

The program team first developed a comprehensive list of potential technologies shown in Appendix 2 that could be in use on vehicles in the study timeframe, 2020–2025. These technologies were grouped by subject area, such as transmissions, engines, or vehicle, and given to Ricardo subject matter experts (SMEs) for assessment and evaluation. These SME assessments were then reviewed with EPA, who also sought input from the Advisory Committee. Together, the program team determined which technologies would be included once they were evaluated qualitatively against the following criteria for further consideration:

- Potential of the technology to improve GHG emissions on a tank to wheels basis
- State of development and commercialization of the technology in the 2020–2025 timeframe
- Current (2010) maturity of the technology

The technology options selected were then put together into technology packages for use in the vehicle performance simulations. An additional consideration was how the inclusion of the technology would affect simulation matrices presented in Section 5.2, particularly the effect on the overall number of simulations needed.

3.4 Complex Systems Modeling Approach

Complex systems modeling (CSM) is an objective, scientific approach that supports high-level decision making when there are a large number of factors to consider that influence the outcome, as with LDV development for vehicle performance and GHG emissions reduction.

A vehicle is made up of interrelated components and subsystems, which combined make up a system that by definition provides functionality greater than the sum of its parts. An automotive system like a vehicle may be defined as a "complex system" based upon the number of interrelated, interconnected, and interwoven elements and interfaces requiring a great deal of information to specify (Kinnunen, 2006). An important concept associated with complex systems is the property of "emergence". In this context it means that there may be collective behavior of the components and subsystems along with the system's response to its environment that are not predictable or linear in response to changes to the individual behavior of each part.

A number of interdisciplinary scientific efforts have led to the development of "complex systems theory", which seeks to overcome the limitations of reductionist approaches through the development of tools and models that are able to capture emergence and other behavior of complex systems (McCarthy, *et al.*, 2000). Supplementing the use of complex systems theory is the application of the system engineering process model, which dictates proceeding from the general to the detailed—a top down approach—and observes the principle of creation and selection of alternatives. These theories and principles have been developed into a methodology that utilizes physics-based modeling and simulation in order to enable quantitative analysis over a multidimensional design space along with advanced visualization techniques in order to understand the results (Biltgen, *et al.*, 2006). Ricardo has incorporated this methodology, now referred to as "complex system modeling (CSM) into its consulting practice on previous projects (Luskin, 2010).

In this program, many combinations of technologies were used to generate detailed results that were abstracted and made accessible through a Data Visualization Tool described in Section 3.5. To be objective, performance metrics were identified by EPA and the Advisory Committee; these metrics were outputs of the vehicle performance simulation effort and characterize key vehicle attributes. To be scientific, the performance simulations use a physics-based modeling approach for detailed simulation of the vehicle.

The design of experiments (DoE) approach surveys the design space in a way that extracts the maximum information using a limited budget of simulation runs. The purpose of the DoE simulation matrix was to efficiently explore a comprehensive potential design space for LDVs in the 2020–2025 timeframe. The simulation matrix was designed to generate selected performance results over the selected drive cycles, such as fuel consumption or acceleration times.

A statistical analysis was used to correlate variations in the input factors to variations in the output factors. Because of the complex nature of the LDV configurations and constituent technology packages, a neural network approach was used to quantify the relationships between input and output factors over the design space explored in the simulations. The result of this analysis was a set of response surface models (RSM) that represent in simplified form the complex relationships between the input and output factors in the design space.

3.5 Data Visualization Tool

The Data Visualization Tool allows the user to efficiently assess the effects of various combinations of future technologies on GHG emissions and other vehicle performance metrics. The tool allows the user to query the RSM and investigate options leading to equivalent GHG emissions levels. A separate User Guide for the Data Visualization Tool will be released with the tool and will provide more information on how to use the tool to access the results.

The Data Visualization Tool uses the RSM set generated by the Complex Systems approach to represent the vehicle performance simulation results over the design space. These simulations cover multiple variations of vehicle configuration, including several combinations of advanced powertrain and vehicle technologies in the seven LDV classes. Vehicle configurations with unacceptable performance, such as combined fuel economy below a certain threshold or acceleration times longer than some benchmark value, can be excluded from further study.

The tool samples vehicle configurations from a selected subset of the design space by using Monte Carlo type capabilities to pick input parameter values from a uniform distribution. Defining selected portions of the design space and plotting the results visualizes the effect of these parameters on vehicle fuel economy and performance, allowing trade off analysis via constraints setting to be performed over a wide design space representing the 2020–2025 technologies as applied.

4. TECHNOLOGY REVIEW

Following the process outlined above in Section 3.3, Technology Package Selection Process, a broad list of potential technologies was identified for consideration in the study and then narrowed to a subset for inclusion in the study. The technologies in this subset are described in this chapter.

In the study timeframe of 2020–2025, spark-ignited (SI) engines are projected to continue to be the dominant powertrain in the U.S. LDV market, especially since the efficiency of SI engines is expected to approach the efficiency of compression ignition (CI, or diesel) engines at the required 2020–2025 emissions levels. Diesel engines are also included as they are still expected to be present in the study timeframe, especially in the heavier vehicle classes.

The first two sections of this chapter therefore describe the technologies expected to appear in future engines generally and in the specific engine configurations considered in the study, respectively. The other sections in this chapter describe the transmission and driveline, vehicle, and hybrid system technologies that were included in the overall design space of the study. The implementation of these technologies in the vehicle performance models is described in Chapter 6, Vehicle Model.

4.1 Advanced Engine Technologies

The primary challenge for advanced engines in the 2020–2025 timeframe is to reduce GHG emissions and maintain performance while meeting increasingly stringent criteria pollutant standards. This challenge is expected to be met through a range of improvements, from the application of highly-efficient downsized engines through to detailed optimization of components and systems. This section describes specific technologies or systems that are expected to be included in future engines, each of which supports the overall goal of reduced GHG emissions in future vehicles. Section 4.2, Engine Configurations, describes the complete engine technology packages that synthesize the effects of the technologies described here to develop the model inputs used.

4.1.1 Advanced Valvetrains

Several advances in valvetrain technology are expected to be available in the study timeframe. These technologies are expected to apply to engines across the whole set of vehicle classes examined in the study.

Advanced valvetrain systems improve fuel consumption and GHG emissions mainly by reducing pumping losses in the engine. The pumping loss mitigation provides larger benefits at part-load operation, such as during urban driving. Advanced valvetrains also support engine downsizing, which provides fuel consumption benefits across the complete engine operating map. Lastly, they can be used to support faster aftertreatment warm-up through varied timing, leading to additional, synergistic gains if the faster aftertreatment warm-up creates a benefit to tailpipe-out NO_x emissions that can be traded off to improve GHG emissions.

Two advanced valvetrain options, cam-profile switching and digital valve actuation, were included in the study and are discussed below. The effects of these valvetrains were integrated into the model inputs developed for the complete engine technology packages described in Section 4.2.

4.1.1.1 Cam-Profile Switching Valvetrain

Cam-profile switching (CPS) systems use a hydraulically-actuated mechanical system to select between two or three cam profiles. CPS systems, such as the Honda VTEC, Mitsubishi MIVEC, Porsche VarioCam, and Audi Valvelift, have been developed by a number of Japanese and European manufacturers. Figure 4.1 shows a diagram of Honda's VTEC CPS system (Honda, 2011). CPS systems can be designed to improve low-speed torque or to improve fuel economy by reducing pumping losses at light load. CPS systems are applicable in all LDV classes. The benefit to fuel consumption is expected to range up to 7% at specific part-load operating points, as shown in Figure 4.2, and will therefore provide a larger benefit in city driving than in highway driving.

4.1.1.2 Digital Valve Actuation Valvetrain

Digital valve actuation (DVA) uses a mechanical, hydraulic, or electrical system to actuate the valves independently of a camshaft. The full realization of DVA in the study timeframe will be a camless DVA system, where there is no mechanical linkage between the engine crank and the valves. The engine fueling maps with DVA were assumed to use camless DVA systems, such as electrohydraulic or electromagnetic systems. Electropneumatic systems are less mature currently, but may yet be available late in the timeframe. An example DVA system in current production is the Fiat MultiAir system, which is an electro-hydraulic system (Fiat, 2009), although it still uses a camshaft to provide the primary timing for the valve open and valve close events. The Schaeffler Group's INA UniAir DVA system is shown in Figure 4.3. The DVA system could be implemented to provide flexibility with valve event timing, valve lift profiles, or both. As with the CPS systems, the main benefit in GHG emissions is a result of reducing pumping losses at part-load operation and lower engine speeds, although the benefits at specific operating points can range up to 12% as shown in Figure 4.4.

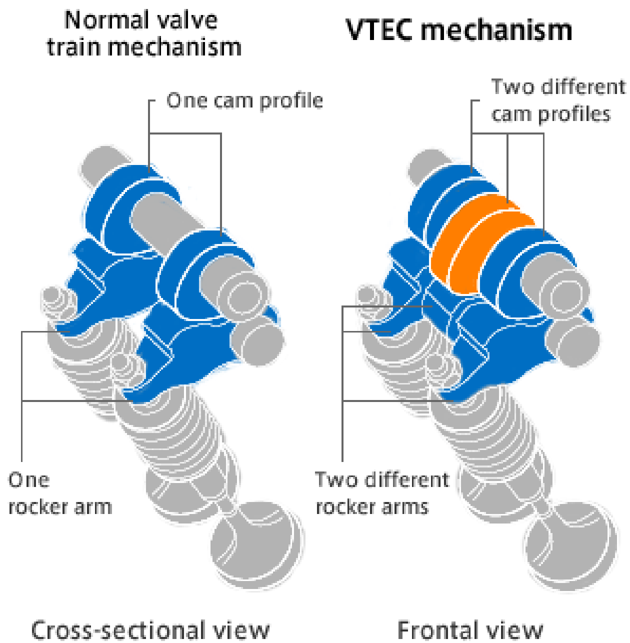

Figure 4.1: Honda's VTEC cam profile switching system. (Honda, 2011)

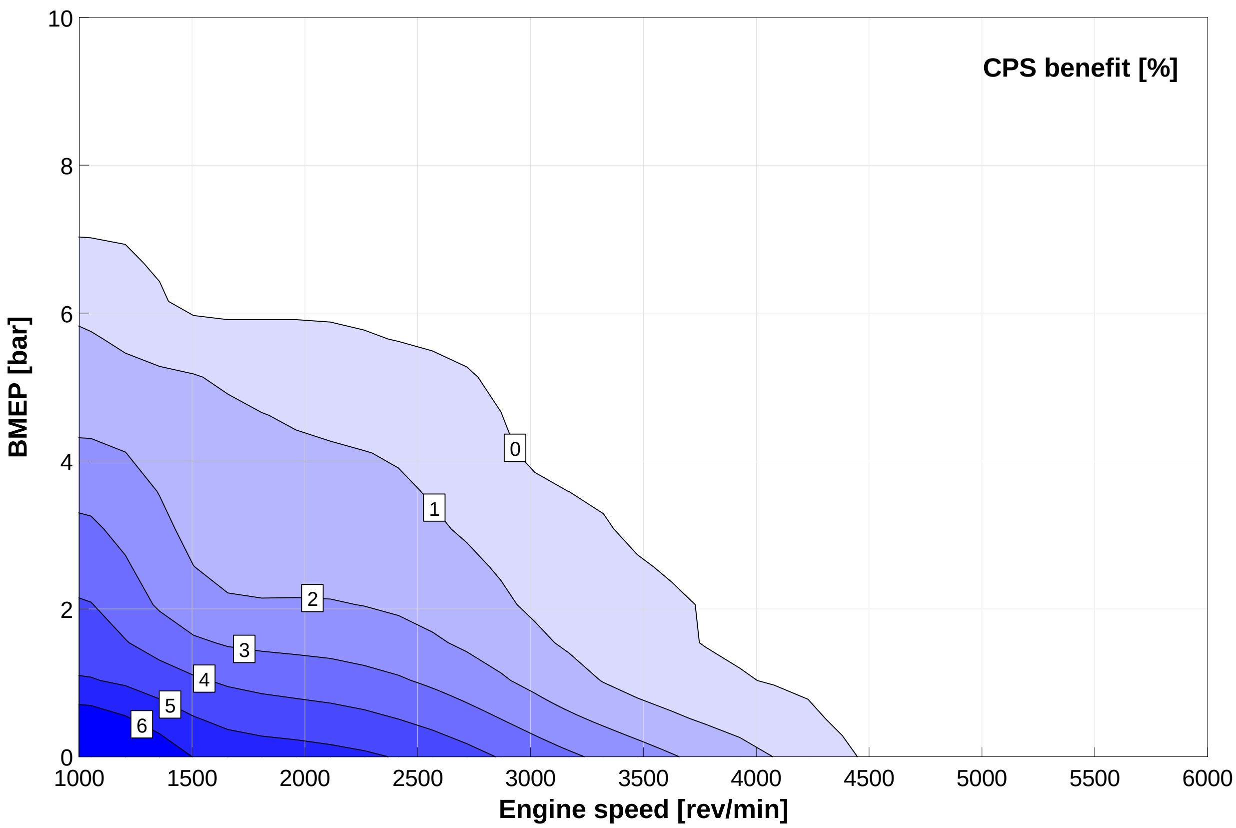

Figure 4.2: Expected BSFC benefit from CPS system over typical engine operating map.

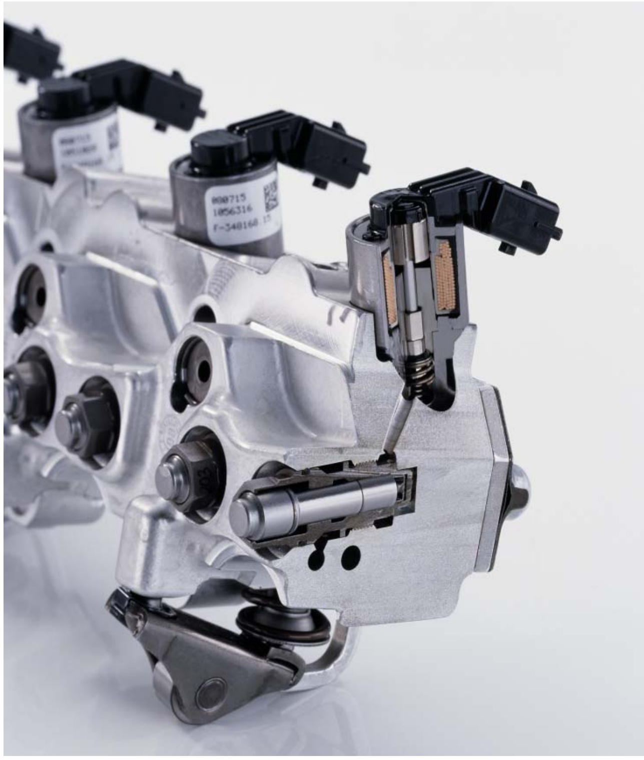

Figure 4.3: INA UniAir digital valve actuation system. (Schaeffler Group, 2010)

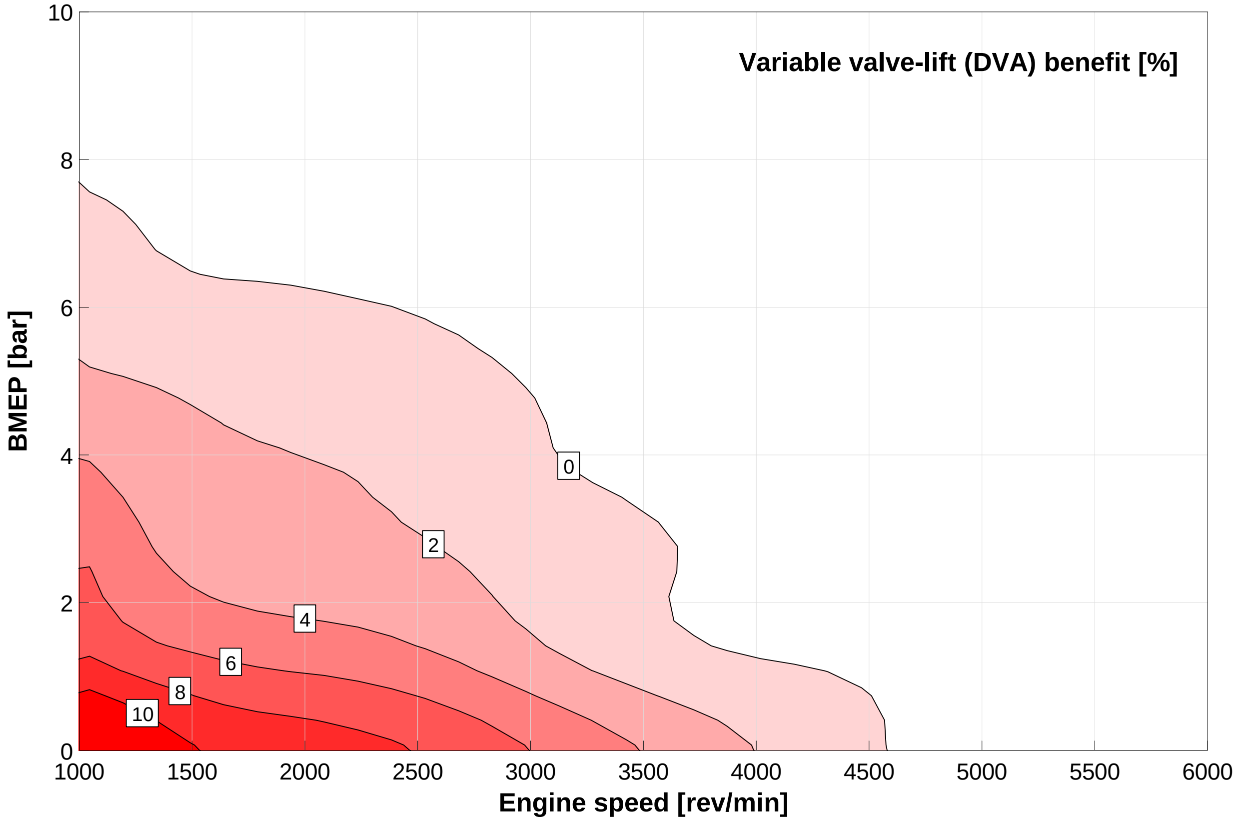

Figure 4.4: Expected BSFC benefit from DVA system over typical engine operating map.

4.1.2 Direct Injection Fuel Systems

Direct injection (DI) fuel systems are the standard fuel injection system in use on current diesel engines. One of the significant changes expected by the 2020–2025 timeframe is a continued transition from port fuel injection (PFI) to DI in SI engines as well. For SI engines with DI, the fuel is injected directly into the combustion cylinder before being ignited. DI fuel systems inject the fuel at a higher pressure than PFI injectors do, and allow the use of multiple injection events to support advanced combustion control. SI engines with DI were first introduced in Japan in 1996, and an increasing number of new SI engines now feature DI.

Using DI improves fuel consumption across the full range of engine operation, including at part-load and high-load conditions, with an expected benefit of 2–4%. DI improves fuel economy by facilitating a higher compression ratio in the engine, which improves the engine's volumetric and thermal efficiency. Although detailed injection control strategies were not specifically modeled, the effects of DI fuel systems were integrated into the model inputs developed for the complete engine technology packages described in Section 4.2. The program team used their experience with research engines and with developing and benchmarking production engines to project that spray-guided DI will be the mainstream DI technology in use in the 2020–2025 timeframe, supplanting wall guided DI. Spray-guided DI offers the capability to deliver a stratified charge—where the fuel concentration decreases away from the spark plug—that will facilitate lower GHG emissions through unthrottled lean-burn operation.

For diesel engines, emissions requirements will cause the injection pressures to continue to increase to the 2000–2400 bar injection pressure range. These very high injection pressures support better combustion and reduced engine-out emissions. In addition, multiple injection events will be used to better control the onset and progress of the combustion event in the cylinder.

4.1.3 Boosting System

Using devices to boost the engine's intake air pressure will increase the torque and power available from a given engine displacement. By increasing the boost pressure while decreasing engine displacement, the power level is maintained while reducing pumping work in the engine by shifting engine operation to higher-load operating points.

The advanced engines in the 2020–2025 timeframe are expected to have advanced boosting systems to increase the pressure of the intake charge up to 3 bar. Various boosting approaches are possible, such as superchargers, turbochargers, and electric motor-driven compressors and turbines. The appropriate technology for 2020–2025 will need to provide cost-effective improvement in performance and efficiency while mitigating turbo lag. Matching a boosting system to a particular engine is very important to realize the maximum benefits of this technology. For this study, the effects of the boosting system are already incorporated in the engine map to produce a reasonably optimized system performance over a wide range of input variables.

Turbocharged engines in the 2020–2025 timeframe are expected to have an advanced boost strategy that provides a smooth acceleration feel. The advanced engines with boost systems were assumed to have two-stage series sequential turbocharger systems. Turbocharging means that there is some risk of the vehicle performance being affected by turbo lag, a delay in the torque rise that results from the dynamics of the gas flow through the engine. This effect is illustrated in Figure 4.5, which shows the benefits of the two-stage turbo system described by

Schmuck-Soldan, *et al.* (2011), that General Motors had tested against twin-scroll turbochargers. Figure 4.5 shows the torque response using net mean effective pressure (NMEP), which equals both the difference between the indicated and pumping mean effective pressures (IMEP and PMEP, respectively), and the sum of the brake and friction mean effective pressures (BMEP and FMEP, respectively). Turbo lag is most significant during hard acceleration events, especially when the engine starts at or near its idle speed and load. Mitigating turbo lag means carefully choosing the capacities of the high pressure and low pressure compressors and turbines and connecting pipes to provide acceptable steady-state torque across the engine speed range and an acceptable transient rate of torque rise, often expressed as the time required to reach 85% of maximum torque at a given engine speed. Modeling turbo lag effects is described later in Section 6.3, Engine Models.

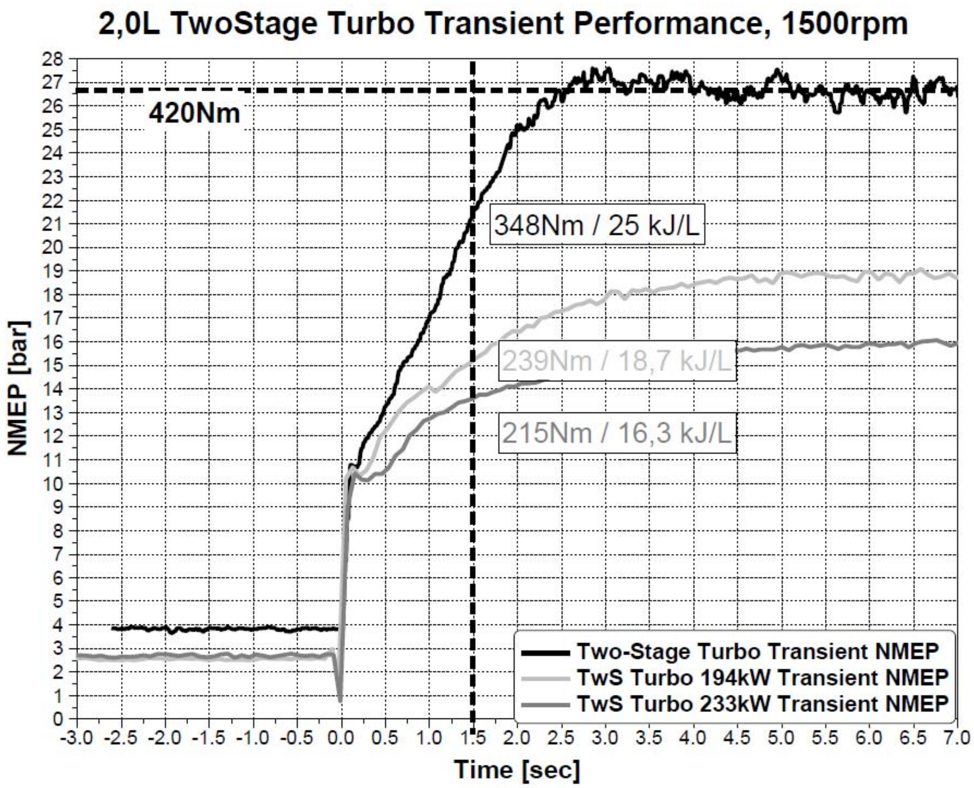

Figure 4.5: General Motors two-stage turbo transient performance. (Schmuck-Soldan, *et al.*, 2011)

4.1.4 Other Engine Technologies

Other engine technologies incorporated into the future engines were further improvements in engine friction leading to a global reduction in engine fuel consumption. This friction reduction is expected to result from a combination of technology advances, including piston ringpack, bore finish, lower-viscosity crankcase lubricants, low-friction coatings, valvetrain components, and bearing technology. The details of these improvements in engine friction were not explicitly itemized in this study, and were instead treated as a global engine friction reduction.

Another approach is to optimize the overall engine design, for example, by combining engine components to reduce mass and thermal inertia, giving an improved package and faster warm-up. Ancillary systems may also be electrified to remove the front engine accessory drive (FEAD) and allow variable accessory performance independent of engine speed. (See, for example, Section 4.5.2, Electric Power Assisted Steering.) The combination of components, such as the exhaust manifold and cylinder head design, will improve the response time for turbocharging and aftertreatment warm-up. Electrification of FEAD components, such as the electrical coolant pump, oil pump, or AC compressor, reduces parasitic losses on the engine and allows accessory operation to be optimized for the operating point independently of the engine.

4.2 Engine Configurations

Several engine configurations were defined using combinations of the advanced engine technologies described in Section 4.1 based on an assessment of what would be in mainstream use in the 2020–2025 timeframe. Five main types of engines were used in the study, and are described in this section.

The engines considered for the 2020–2025 timeframe were developed using two main methods. The first method, used with the boosted SI engines, was to review the reported performance of current research engines, and assume that these current research engines would closely resemble the production engines of the 2020–2025 timeframe. This method takes current research engines and refines them to meet production standards, including manufacturability, cost, and durability. The second method, used with the Atkinson cycle SI and the diesel engines, was to start from current production engines and then determine a pathway of technology improvements over the next 10–15 years that would lead to an appropriate engine configuration for the 2020–2025 timeframe. With both methods, current trends in engine design and development were extrapolated to obtain an advanced concept performance for the 2020–2025 timeframe that should be achievable in production volumes. All of the engine fueling maps developed accounted for the effects of future criteria pollutant standards, assumed to be equivalent to California ARB's SULEV II or to EPA Tier 2 Bin 2. These fueling maps were reviewed by EPA and the Advisory Committee to ensure that they were suitable for the study.

The combinations of technologies encompassed in each advanced engine concept provide benefits to the fueling map, or values of brake-specific fuel consumption (BSFC) over the operating speed and load ranges of each engine. For these future engines, the BSFC is improved by up to 10% from current levels. Many of the future engine concepts have low BSFC values over large zones of the engine operating map, with the best BSFC point often at lower speeds and part-load conditions. The implementation of these technology packages into the vehicle performance models is described in Section 6.3.

4.2.1 Stoichiometric DI Turbo

The basic advanced engine configuration is the Stoichiometric DI Turbo SI engine. This advanced engine assumes continued use of a stoichiometric air-fuel ratio for simplified aftertreatment using a three-way catalyst. The engine modeled has a peak brake mean effective pressure (BMEP) of 25–30 bar, which supports significant downsizing compared to current 2010 engines. This high BMEP level is reached through a combination of engine technologies, including advanced valve actuation, such as CPS; spray-guided DI; and advanced boost systems, such as series-sequential turbochargers (see Sections 4.1.1, 4.1.2, and 4.1.3, respectively). The compression ratio of the engines was set at 10.5:1, which provides a balance between fuel consumption and performance.

Current research engines of this configuration have been developed by several groups. One example is the Sabre engine described by Coltman, *et al*. (2008) and by Turner, *et al*. (2009).

The Sabre engine uses CPS to reduce pumping losses at part-load operation (Turner, *et al*., 2009), but only uses single-stage turbocharging with DI in a 1.5 ℓ three-cylinder engine to reach 20 bar peak BMEP. Lumsden, *et al*. (2009) at MAHLE Powertrain have also developed a 1.2 ℓ, three-cylinder research engine similar to the Stoichiometric DI Turbo SI engine with a peak BMEP of 28 bar to support up to 50% downsizing.

The Stoichiometric DI Turbo engine was assumed to operate with a stoichiometric air-fuel ratio, without enrichment, over the complete operating map, even at high-speed, high-load operating conditions, which significantly improves the fuel consumption in this part of the operating map as shown in Figure 4.6. This change in operation requires design changes to support the higher exhaust gas temperatures to ensure protecting the valves, pistons, and exhaust system components. For example, the future engine configuration uses a cooled exhaust manifold to keep the turbine inlet temperatures below 950°C over the full operating range of the engine to mitigate the need for upgraded materials in the exhaust manifold and turbine. This change also provides benefits to criteria pollutant emissions, especially over the US06 cycle.

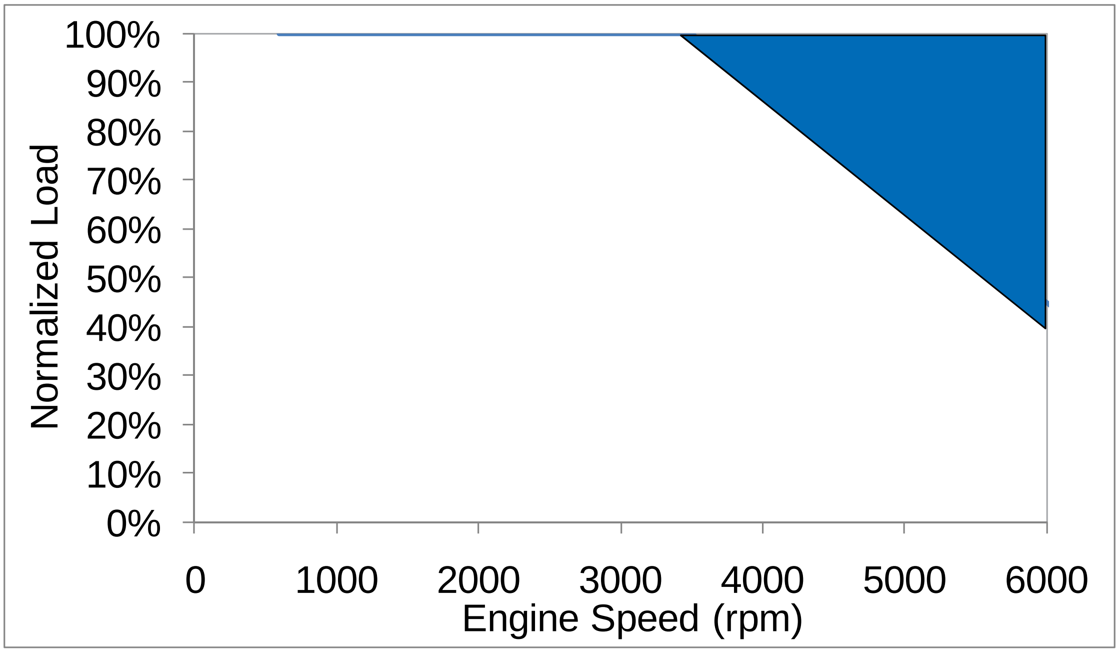

Figure 4.6: Typical region of fuel enrichment in stoichiometric DI engines (shown in blue), eliminated through use of a water-cooled exhaust manifold.

Since the initial conception of the 2020 Stoichiometric DI Turbo, several companies have engineered new versions of direct injected turbo engines with fueling maps that closely resemble the maps that were synthesized and used in this study. One example is the research engine executed by General Motors described by Schmuck-Soldan, *et al.* (2011), that uses a two-stage series sequential boosting system like that envisioned for the Stoichiometric DI Turbo engine in a 2.0-ℓ variant of the Ecotec SIDI engine. Presented at the Internationales Wiener Motorensymposium, General Motors' engine achieves a maximum BMEP of 26.4 bar. The best BSFC island shown in Figure 4.7 is rather large and the zone of best BSFC (up to 105% of the minimum BSFC) marked on the map encompasses almost half of the useable engine operating range. All of the features described by General Motors are similar to those integrated into the Stoichiometric DI Turbo engine concept modeled for this program, and consequently the two engines have very comparable fueling maps.

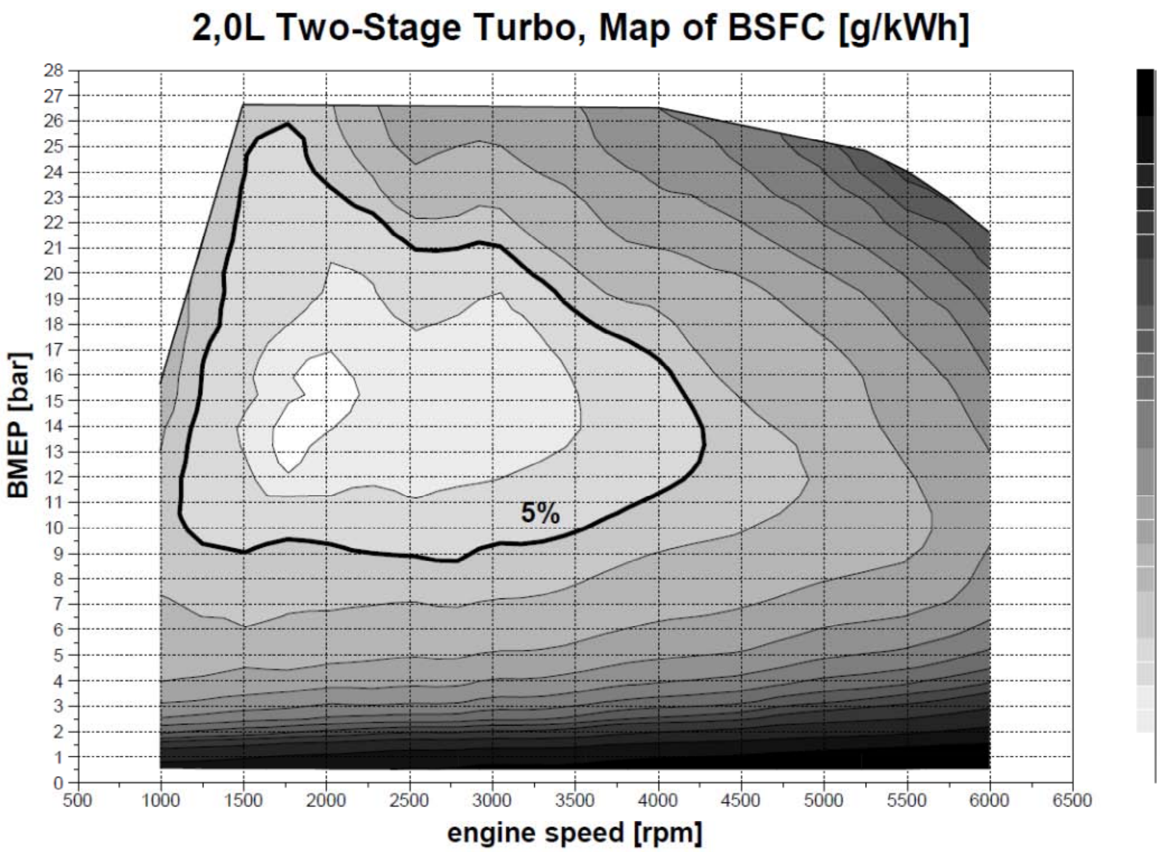

Figure 4.7: 2.0-ℓ General Motors SIDI two-stage boosted engine BSFC map. (Schmuck-Soldan, et al., 2011)

4.2.2 Lean-Stoichiometric Switching

The Lean-Stoichiometric DI Turbo SI engine configuration is similar in all respects to the Stoichiometric DI Turbo engine described above in Section 4.2.1, except that it uses a fuel-lean air-fuel ratio with $\lambda \approx 1.5$ at moderate speeds and loads, such as those seen on the FTP75 cycle. Elsewhere, such as on the US06 cycle, the engine switches to stoichiometric operation with a three-way catalyst, to avoid exceeding the expected temperature and space velocity limits of the lean aftertreatment system. This mixed-mode operation allows the engine to take advantage of the efficiency benefits of lean operation while mitigating the technical challenges associated with lean-burn emissions control. Figure 4.8 illustrates the zones of lean and stoichiometric operation over the engine operating map.

Fuel lean operation improves fuel consumption by increasing the relative charge volume per unit of fuel burned, enabling a higher compression ratio, improved charge mixing and less intake throttling. Nevertheless, while lean operation leads to efficient oxidation of unburned hydrocarbon and carbon monoxide pollutants in the engine exhaust stream, the presence of excess oxygen makes reduction of nitrogen oxides (NO_x) more challenging. Therefore, an additional emissions control device, such as a lean NO_x trap (LNT) or a urea-based selective catalytic reduction (SCR) system, would be required to remove NO_x from the net oxidizing exhaust gas. The program team raised concerns about the effectiveness of these NO_x removal systems at the high temperatures and exhaust gas flow rates, or space velocities, easily reached by SI engines at high engine speed or load, and also about catalyst durability under hot and oxidizing conditions over the vehicle life. These concerns suggest that meeting criteria pollutant levels over a drive cycle such as the US06 could be challenging to the expected end of life, but advances would be made over the intervening years to make such systems production feasible.

Therefore, the engine switches to stoichiometric operation when the exhaust temperature crosses a threshold above which the NO_x removal system catalysts would suffer accelerated degradation. This transition zone between lean and stoichiometric operation is shown in Figure 4.8. At high load conditions, then, the exhaust emissions are treated using typical three-way catalysts. The engine therefore performs exactly like the Stoichiometric DI Turbo engine at higher load, but has improved BSFC at lower load because it switches to lean operation. A modest fuel consumption penalty is applied over each drive cycle to account for the use of fuel or other reducing agent to remove NO_x during lean operation.

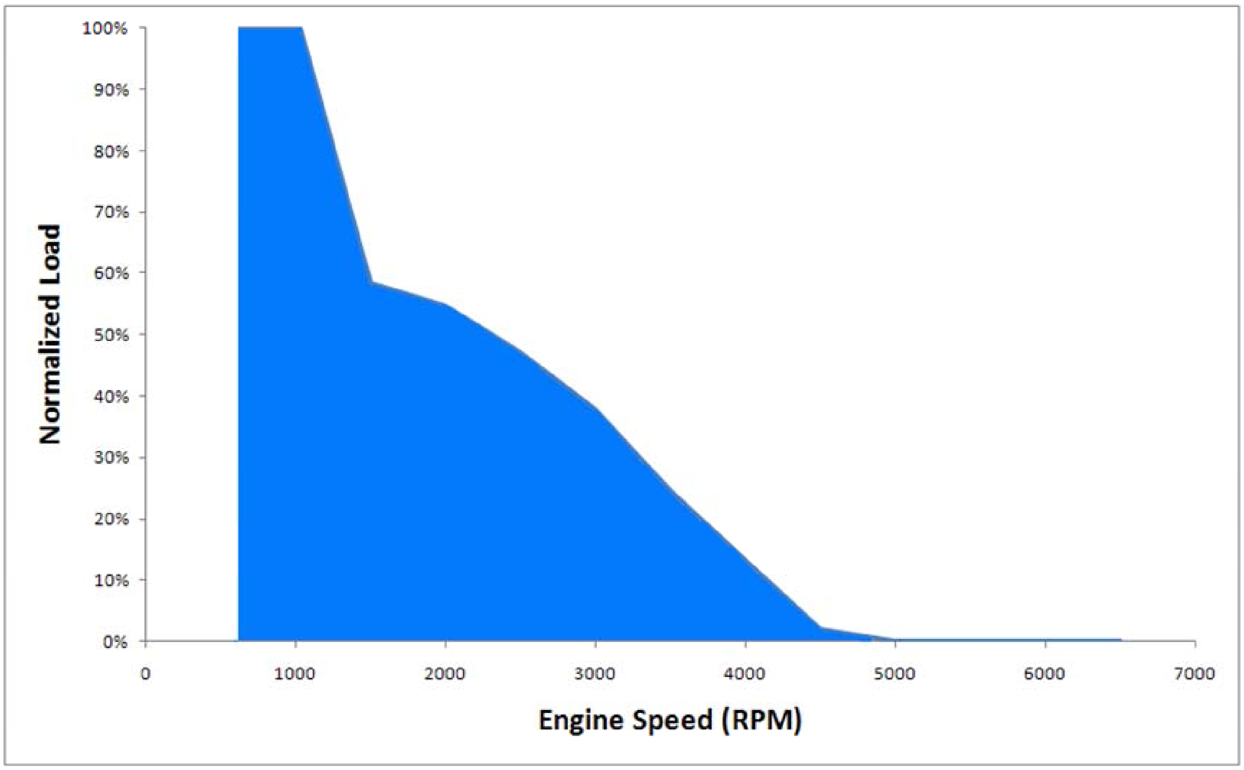

Figure 4.8: Zone of lean operation for Lean-Stoichiometric DI Turbo engine.

4.2.3 EGR DI Turbo

The EGR DI Turbo engine is also similar to the Stoichiometric DI Turbo Engine described in Section 4.2.1, except that it uses cooled external exhaust gas recirculation (EGR) to reduce intake throttling and to manage combustion knock and exhaust temperatures. The recirculated exhaust gas dilutes the air and fuel charge in the cylinder, thereby moderating the temperature during combustion and allowing operation without enrichment over a higher range of load and speed. Additionally, the EGR mitigates the tendency for engine knock, potentially enabling a higher compression ratio, and reduces the need for throttling at low-load operation, thereby reducing engine pumping losses.

Dual high-pressure and low-pressure EGR loops were assumed for this engine configuration, which will require additional components such as EGR valves and a heat exchanger (EGR cooler) to manage the EGR flow and temperature. EGR rates of up to 20–25% are feasible with this air system (Cruff, *et al*., 2010; Beazley, 2010). EGR use allows a modest overall improvement in fuel consumption across the complete operating map compared to the Stoichiometric DI Turbo engine.

4.2.4 Atkinson Cycle

The Atkinson cycle is characterized by leaving the intake valves open during the start of the compression stroke, which lowers the effective compression ratio of the engine back to that of the normal SI engine, but allows for a larger effective expansion ratio. This change in engine operation improves fuel consumption, but penalizes torque availability at lower engine speeds. For this reason, Atkinson cycle engines are typically used only in hybrid vehicle applications, where the electric machine can be used to provide extra torque during launch or other hard acceleration events.

Separate Atkinson cycle engine fueling maps were developed for the 2020–2025 timeframe with both CPS and DVA valvetrains. These fueling maps reflect the differing net benefits of the valvetrains, including actuation losses. These engines are only used with the P2 parallel and Input Powersplit hybrid powertrains described in Section 4.3, Hybrid Technologies. The torque curve and fueling map thus generated also reflect the benefits of so-called downspeeding, or a lower overall operating speed range, which yields further fuel consumption benefits by reducing frictional losses in the engine (Hohenner, 2010).

4.2.5 Advanced Diesel

The advanced diesel engines for the 2020–2025 timeframe were developed by starting with existing production engines and identifying technology advances that would lead to further improvements in fuel consumption. Several of the technologies discussed in Section 4.1, Advanced Engine Technologies, are applicable to advanced diesels, including series-sequential, two-stage turbocharging, enhanced EGR and charge air cooling, and CPS. The composite effects of these technologies were reflected in the improvements made to existing engine fueling maps to derive the advanced diesel engine fueling maps.

This approach led to different maps being developed for each of the vehicle classes that had diesel engines available: the Small Car, Full Size Car, Large MPV, LDT, and LHDT. For example, the LHDT engine torque curve and fueling maps were generated by starting with a 6.6 ℓ diesel engine typical for this class and applying the benefits of improvements in pumping losses or friction to the fueling map. Engine displacements for the advanced diesels were chosen based on the current torque and power levels available from these engines, the expected future requirements, and the effects of applying advanced technologies to support further downsizing. Current diesel engines for LDVs already use advanced variable-geometry boost systems and high-pressure common-rail direct injection for better torque response and specific power. Improvements in these areas are therefore expected to be incremental, by contrast with the more extensive changes to SI engine architectures described above. For example, the peak BMEP of the advanced diesels is in the 17–23 bar range, which is noticeably lower than that expected for the advanced SI engines.

This difference is, however, consistent with Ricardo's expectation of the pace and direction of technology development for diesel engines that comply with the expected emissions requirements defined in the study's ground rules defined in Section 3.2, that is, emissions standards consistent with today's California SULEV II or EPA Tier 2 Bin 2 standards. A modest fuel consumption penalty was applied to account for the additional fuel required for particulate filter regeneration and lean NOx aftertreatment.

4.2.6 Fueling Map Development Examples

Examples of each method of developing the advanced engine fueling maps are presented below. The first example shows how the EGR DI Turbo engine described in Section 4.2.3 was developed, and the second, how the Atkinson engine described in Section 4.2.4 was developed.

4.2.6.1 EBDI® to EGR DI Turbo

The EBDI® engine (Cruff, *et al*., 2010; Beazley, 2010) is a recently-developed research engine that incorporates many of the technologies expected in the EGR DI Turbo engine and was therefore the starting point for the advanced engine. Adjustments were then made to the EBDI® engine fueling map to make it representative of a production engine expected in the 2020–2025 timeframe.

The current research engine has the fueling map shown in Figure 4.9, where the contours show BSFC (in g/kW·h) as a function of engine speed and BMEP and the best BSFC point marked is 230 g/kW·h at 2000 rpm and 12 bar BMEP. This engine is designed to reach 30 bar BMEP running on gasoline and up to 35 bar BMEP on E85. To this end, the EBDI® engine uses a 10:1 compression ratio and the single-stage turbocharger is sized to reach 2.88 bar boost pressure. EGR rates vary from 0% up to 23% during operation. The research engine uses direct injection and has variable intake and exhaust cam phasing.

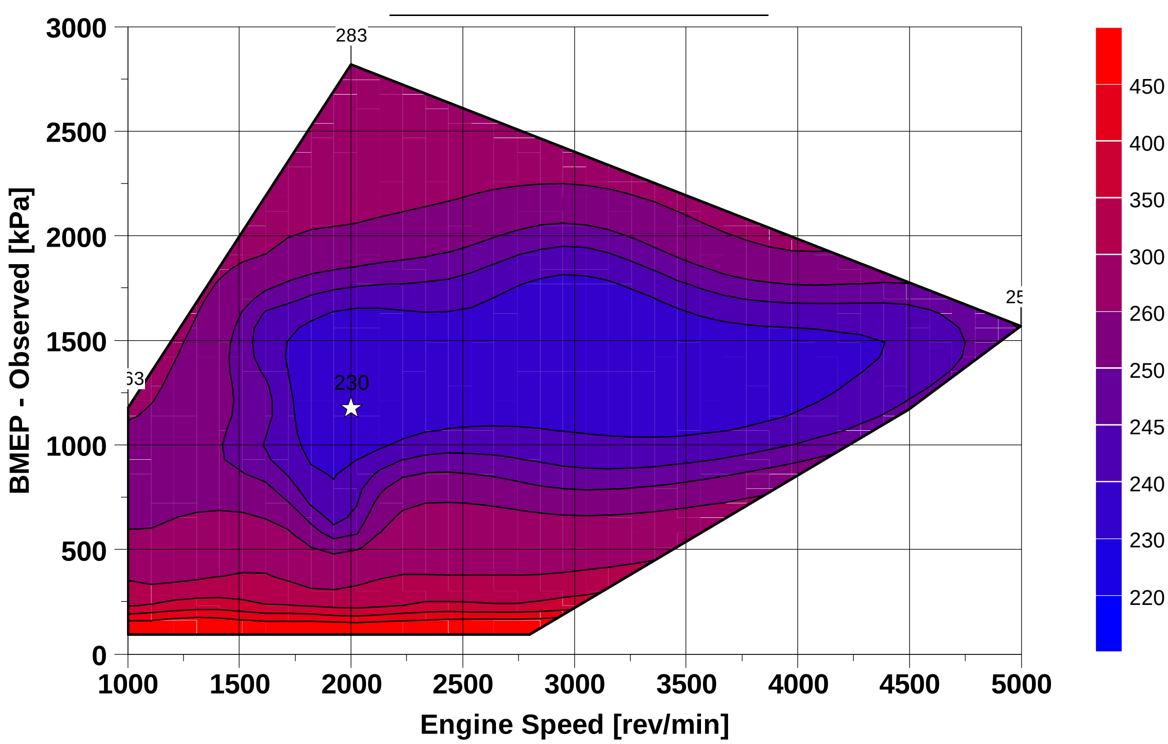

Figure 4.9: BSFC map (in g/kW•h) for EBDI® engine with EGR. (Beazley, 2010)

To translate this to the 2020–2025 timeframe's EGR DI Turbo engine, the compression ratio was increased to 10.5:1, which improves the fuel consumption by approximately 1% across the map. The EGR DI Turbo engine also assumes use of an advanced boost system as described in Section 4.1.3 instead of a single-stage system. Switching from the current valvetrain to the CPS system described in Section 4.1.1.1 will provide up to 7% improvements in the steady-state fueling map, with the best benefits coming at moderate load and low speed as shown in Figure 4.2. Lastly, a fuel consumption improvement of 3.5% was applied to account for continued application of friction reduction technologies. The final fueling map used in the study for the EGR DI Turbo engine is the result of synthesizing these technology improvements into a cohesive whole.

4.2.6.2 Contemporary to Future Atkinson

In the case of the Atkinson cycle engines, the program team started with a contemporary example of the class of engine and translated it into the future by applying technology improvements to an existing fueling map. These technology improvements include those described in Section 4.1.1, Advanced Valvetrains, and Section 4.1.4, Other Engine Technologies.

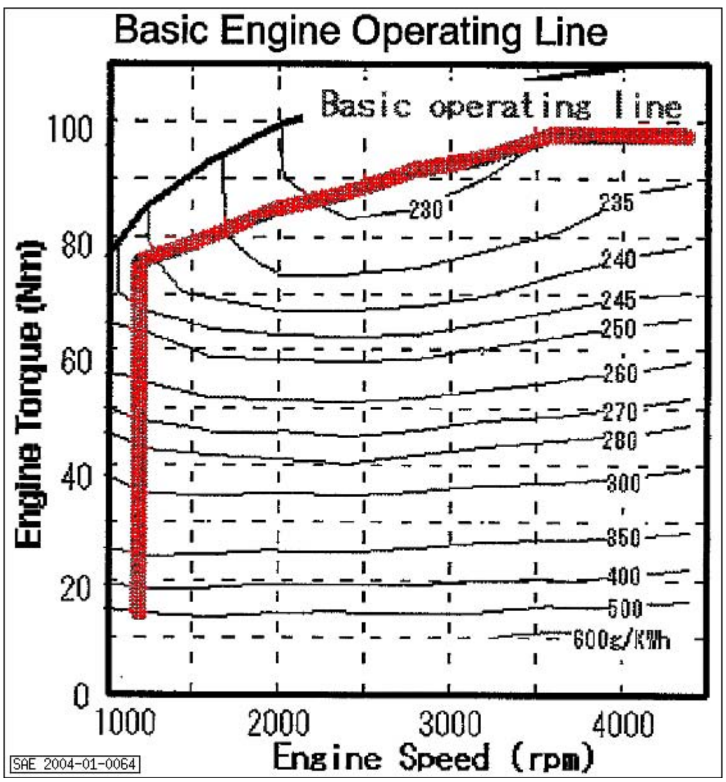

Figure 4.10: BSFC map (in g/kW•h) for Toyota Prius engine. (Muta, *et al*., 2004)

An example of a contemporary Atkinson cycle engine is the Toyota Prius engine as presented by Muta, *et al*. (2004), which uses the fueling map shown in Figure 4.10. To translate the current map to the study timeframe, several adjustments were made to the fueling map. First, the engine speed range was modified so that the engine would tend to operate at lower speeds, which reduces frictional losses in the engine. Additional friction reduction improvements, such as those described in Section 4.1.4, Other Engine Technologies, were also applied to the map. Furthermore, the Atkinson engines in the design space can use either of the advanced valvetrains, the CPS or DVA, which provides additional benefits to fuel consumption at part-load conditions, especially at lower engine speeds as described in Section 4.1.1 and shown in Figures 4.2 and 4.4.

These technologies together have the net effect of improving the best BSFC by about 5%, but more importantly, of substantially improving fuel consumption across the map, especially at lower-speed and moderate load operating conditions.

4.3 Hybrid Technologies

The selection of hybrid technology for a vehicle is complex, comprising a series of engineering trade-offs between fuel consumption benefit and system complexity and cost. As the market share of hybrid vehicles continues to grow, consumers will have a range of choices.

A wide range of hybrid configurations were considered in the initial part of the program, with the program studying three main approaches: micro hybrid (stop-start), P2 parallel, and Input Powersplit. For this study, it was assumed that the hybrid powertrain configurations will be studied in all but the LHDT vehicle class as shown in Table 5.2. The implementation of these hybrid systems into the vehicle models is described in Section 6.8.

4.3.1 Micro Hybrid: Stop-Start

The most basic hybridization method shuts off the engine during idle periods, and typically uses an enhanced starter motor and limited use of driver comfort features during engine off, such as the radio and some heat but not air conditioning. This approach reduces fuel use over city drive cycles by minimizing idling, but provides no benefit for highway driving or when air conditioning is requested.

The stop-start, micro hybrid approach is the lowest-cost hybrid system, and can be implemented relatively quickly on most vehicles on the market today. Stop-start systems are already in production and the technology is maturing. Further development will lead to increased user acceptance, for example, through transparent integration with low impact on vehicle performance or noise, vibration, and harshness (NVH) and by implementing new technologies to mitigate the effects on cabin cooling (Weissier, 2011).

The program team has assumed that by the 2020–2025 timeframe, all vehicles with an otherwise conventional powertrain will have stop-start functionality implemented. For the vehicle models in this study, the starter motor does not provide motive power, but is capable of recovering enough energy to offset accessory loads.

4.3.2 P2 Parallel Hybrid

The P2 Parallel Hybrid powertrain places an electric machine on the transmission input, downstream of the engine clutch. This system allows stop-start, electrical launch, launch assist, and regenerative braking functionality. The clutch also allows the engine to be decoupled from the rear of the driveline, allowing pure electric propulsion, or electric vehicle (EV) mode operation. This wide application of electrical power in a variety of vehicle operating conditions facilitates downsizing the engine from that in the comparable conventional vehicle.

This hybrid powertrain is expected to significantly reduce GHG emissions, especially during city driving. Highway driving fuel consumption is expected to improve because the electric machine in the P2 hybrid allows a smaller, more efficient internal combustion engine to be used. This smaller engine, however, may limit vehicle performance in situations requiring continuous engine power, such as a sustained hill climb.

P2 Parallel hybrids are in limited production currently, including such vehicles as the Hyundai Sonata, the Porsche Cayenne, and the Volkswagen Touareg. Prototypes have also been built by various companies using existing off-the-shelf components.

A P2 Parallel Hybrid system can be used with an automatic transmission, automated manual transmission (AMT), continuously variable transmission (CVT), or dual clutch transmission (DCT). Hellenbroich and Rosenburg (2009) describe a P2 variant with AMT, for example. For this program, the P2 Parallel Hybrid powertrain was modeled using the DCT, which has fixed gear ratios and no torque converter, as described in Section 4.4.2.

4.3.3 Input Powersplit

The simplest Powersplit hybrid configuration replaces the vehicle’s transmission with a single planetary gearset and two electrical machines connected to the planetary gearset. The planetary gearset splits engine power between the mechanical path and the electrical path to achieve a continuously variable transmission. In some Input Powersplit configurations, a second planetary gearset is used to speed up one of the electrical machines while retaining the CVT functionality. The Toyota Prius and the Ford Hybrid Escape are two examples of Input Powersplit hybrid vehicles currently sold in the US.

With the appropriate electric accessories, the Input Powersplit system allows for EV mode operation, as well as stop-start operation, electric launch, launch assist, and regenerative braking. In addition, the system allows for engine downsizing to help reduce fuel consumption, although the smaller engine may limit vehicle performance in situations requiring continuous engine power, such as a sustained hill climb. The Powersplit system provides significant improvements in fuel consumption in city driving. During highway cycles, the benefits of regenerative braking and engine start-stop are reduced, although the CVT feature of the engine helps during the highway cycle as the engine is kept at an efficient operating point.

4.4 Transmission Technologies

The U.S. vehicle market is currently dominated by automatic transmissions, with a development emphasis on increasing the launch-assist device efficiency and on increasing the number of gear ratios to keep the engine operating in regions of high efficiency. Nevertheless, dual clutch transmissions (DCT) are expected to be adopted over the next 10 to 15 years because of their potential to further improve fuel economy and maintain drivability. CVTs tend to have higher friction than DCTs and provide a different driving experience than stepped transmissions. Although CVTs are a current production technology, CVTs were not included in the scope of this study. The baseline 6-speed transmissions used the same gear ratios as the previous fuel economy study by Ricardo and PQA, (2008) to maintain continuity between improvement projections. The 6-speed ratios have a total ratio span of 6.05 which is typical of current 6-speed transmissions that were designed for fuel economy and performance improvements over their 4-speed or 5-speed predecessors. The 8-speed ratios offer a first gear ratio that has improved launch torque multiplication over the 6-speed and two overdrive ratios that provide lower engine rpm than the 6-speed ratios. The gear step progression of the 8-speed transmission is similar to current production and provides acceptable drivability, and is shown in Table 6.3.

The development of DCT technology is expected to be implemented in the U.S. based on experience with European and Japanese applications. Some vehicles with DCTs are entering volume production, such as the Ford Fiesta, Ford Focus, and VW Passat. Automatic transmissions too are still being developed and refined, with new technologies being implemented in luxury vehicles, and then cascaded down to other vehicle classes. Given that 94% of current U.S. transmissions are automatics, efficiency improvements that mitigate GHG emissions are expected to come from the following:

- Increased gear count from 4–6 currently to 7 or 8 by 2020–2025
- Improved kinematic design
- Component efficiency improvement or alternative technologies
- Launch devices
- Dry sump technology

The various base transmission technologies are described, followed by launch device options, and, finally, other technologies expected to improve transmission efficiency. The effects of these various technologies on transmission efficiency were incorporated into the models as described in Section 6.4, Transmission Models.

4.4.1 Automatic Transmission

The automatic transmission is hydraulically operated, and uses a fluid coupling or torque converter and a set of gearsets to provide a range of gear ratios. Viscous losses in the torque converter decrease the efficiency of the automatic transmission. For the study timeframe, it was assumed that eight-speed automatic transmissions will be in common use, as this supports more efficient operation. The Small Car is an exception, and was assumed to only have enough package space to support a six-speed transmission. For the 2020–2025 timeframe, losses in advanced automatic transmissions are expected to be about 20–33% lower than the losses in current automatic transmissions from the application of the specific technologies described in Section 4.4. The overall benefits are compiled from Ricardo's confidential business information on transmission systems. Additional benefits will be realized by having more gear ratios available to help maintain the engine near its best operating condition.

4.4.2 Dual Clutch Transmission (DCT)

The DCT has two separate gearsets operating in tandem, one with even gears and the other, odd. As the gear changes, one clutch engages as the other disengages, thereby reducing torque interrupt and improving shift quality, making it more like an automatic transmission. The DCT, however, does not require a torque converter which improves its efficiency compared to an automatic transmission, and may use either wet or dry type launch clutches. For the study timeframe, energy losses in both wet clutch and dry clutch DCTs are expected to be 40–50% lower than in current automatic transmissions. Additional benefits will be realized by having more gear ratios available to help keep the engine near its best operating condition. As with the automatic transmission, the Small Car was assumed to only have package space for a six-speed transmission. An overall comparison of the efficiency of the stepped-gear transmissions is shown in Figure 4.11.

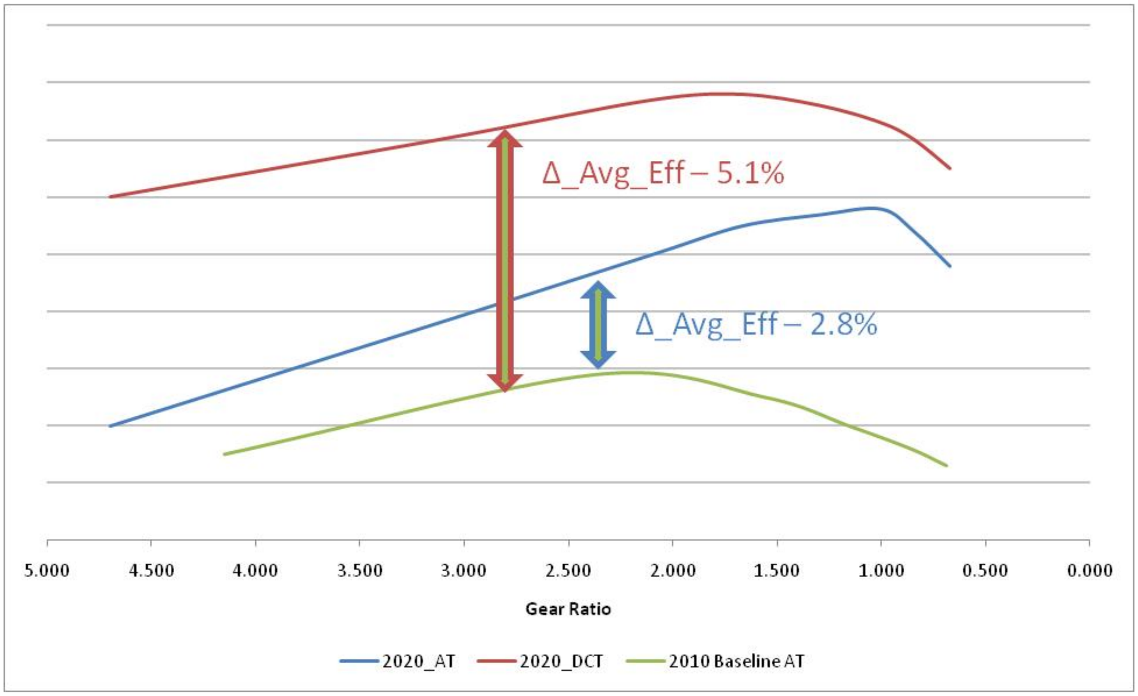

Figure 4.11: Comparison of Automatic and DCT Transmission Efficiencies

4.4.3 Launch Device: Wet Clutch

A wet clutch provides torque transmission during operation by means of friction action between surfaces wetted by a lubricant. The lubricant is required for cooling during gear shifts when the clutch is slipping in larger LDV classes. Wet clutch DCTs provide added durability for the higher torque requirements of larger LDVs, although a secondary lubrication system is needed for the actuation requirements. As a result, wet clutch systems are expected to be heavier, cost more, and be less efficient than dry clutch systems. An example of a wet clutch DCT system is shown in Figure 4.12.

By the 2020–2025 timeframe, wet clutch DCTs are expected to develop into so-called damp clutch DCTs, which approach the efficiency of a dry clutch with the longevity and higher torque capacity of a wet clutch. In damp clutch DCTs, a limited spray is applied to cool the clutch materials. A damp clutch requires a lubrication system but is more efficient due to improved control, leading to reduced windage and churning losses.

4.4.4 Launch Device: Dry Clutch Advancements

The standard dry clutch requires advanced materials to dissipate heat and prevent slipping. The thermal load resulting from engagement prevents dry clutches from being used in high torque and heavy duty cycle applications, even though they are more efficient since they significantly reduce parasitic shear fluid losses and do not require an additional lubrication system. The GHG emissions benefit of a dry clutch over a wet clutch should be realized at launch and during transient driving, thus primarily for city driving. Advancements in materials or electric assist could enable this technology to be used in larger LDVs and more severe duty cycles by the study timeframe, but is generally assumed to be prevalent in the smaller vehicle classes.

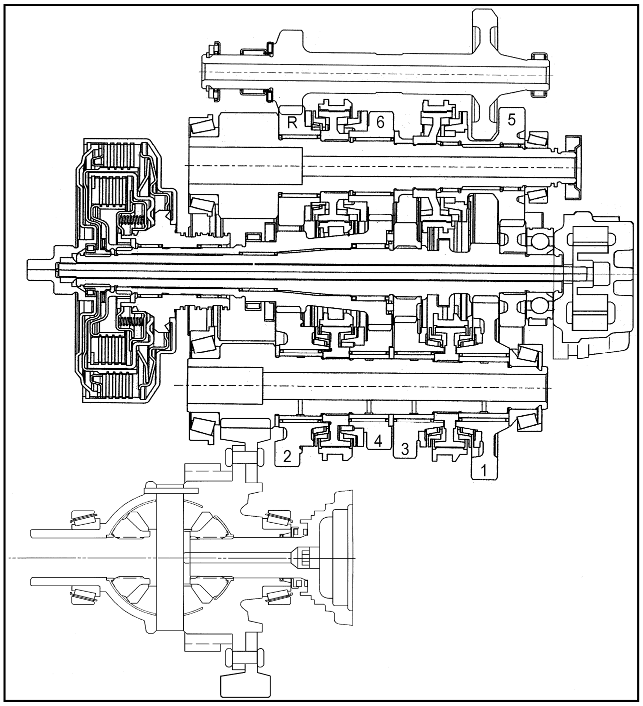

Figure 4.12: Typical transverse wet clutch DCT arrangement. (Ricardo and PQA, 2008)

4.4.5 Launch Device: Multi-Damper Torque Converter

Dampers added to the torque converter enable a lower lockup speed, therefore decreasing the more fuel-intensive period of hydrodynamic power transfer. Multi-damper systems provide earlier torque converter clutch engagement; however, drivability and limited ratio coverage have limited the deployment of this technology to date. The technology must be integrated during transmission design. The GHG emissions benefit should come from reduced slippage and smoother shifting.

4.4.6 Shifting Clutch Technology

Shift clutch technology improves the thermal capacity of the shifting clutch to reduce plate count and lower clutch losses during shifting. Reducing the number of plates for the shifting process and reducing the hydraulic cooling requirements will increase the overall transmission efficiency for similar drivability characteristics. Technology deployment has been limited by industry prioritization of drivability over shift efficiency, especially since shift events are a very small portion of typical driving. The technology will be best suited to smaller vehicle segments because of reduced drivability expectations—this technology may not be suitable for higher torque applications.

4.4.7 Improved Kinematic Design

Improved kinematic design uses analysis to improve the design for efficiency by selecting the kinematic relationships that optimize the part operational speeds and torques. Large improvements in efficiency have been noted for clean sheet designs for six-speed and eight-speed transmissions. This approach will provide a GHG emissions benefit across all vehicle classes and operating conditions.

4.4.8 Dry Sump

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

4.4.9 Efficient Components

Continuous improvement in seals, bearings and clutches aimed at reducing drag in the system should provide GHG emissions benefits without compromising transmission performance.

4.4.10 Super Finishing

This technology approach chemically treats internal gearbox parts for improved surface finish. The improved surface finish reduces drag which increases efficiency over the full range of operation.

4.4.11 Lubrication

New developments in base oils and additive packages will reduce oil viscosity while maintaining temperature requirements, thereby improving transmission efficiency over the full range of operation.

4.5 Vehicle Technologies

Several vehicle technologies were also considered for the study to the extent that they help support future ranges of vehicle mass, aerodynamic drag, and rolling resistance for each of the vehicle classes in the study. The potential levels of improvement for these "road load reduction" technologies were not explicitly quantified; rather, they were included as independent input variables within the complex systems modeling approach.

Technologies considered include mass reduction through use of advanced materials with a higher strength to mass ratio and through consolidation and optimization of components and systems. Aerodynamic drag is expected to see improvements through adoption of both passive and active aerodynamic features on vehicles in the 2020–2025 timeframe. Continued improvement in tire design is expected to reduce rolling resistance and thereby provide a benefit to fuel consumption.

In addition, vehicle accessory systems such as the cooling pumps and power steering systems are expected to become electrified by the 2020–2025 timeframe. These electrified accessories should reduce the power required to keep them active, which will also improve fuel consumption, and are described in greater detail below.

4.5.1 Intelligent Cooling Systems

Intelligent cooling systems use an electric coolant pump to circulate engine coolant, removing the power required for this pump from the FEAD. Removing the coolant pump from the FEAD also enables independent pump speed control. Rather than running at a fixed multiple of the engine speed, the coolant pump can spin at the appropriate speed for the current cooling requirements. Standard cooling systems are sized to provide cooling at maximum load and ambient conditions, but most vehicles only rarely operate under these extreme conditions.

Intelligent cooling also enables quicker warm-up of the engine by controlling coolant flow. This reduces engine friction by increasing engine temperature during the warm up process. The effects of the cooling system performance were integrated into the vehicle performance model.

Ricardo estimates this technology will lower fuel consumption over the FTP cycle. BMW is implementing this technology on their twin-turbo 3-L inline-6 cylinder engine, introduced in 2007 in their 335i model. This technology is projected to be readily available by the 2020–2025 timeframe.

4.5.2 Electric Power Assisted Steering

Electric Power Assisted Steering (EPAS) uses either rack or column-drive electric motors to assist driver effort instead of a hydraulic power assist system. EPAS replaces the engine-driven hydraulic pump, hydraulic hoses, fluid reservoir, fluid, and hydraulic rack. The efficiency of this system is a result of reduced FEAD losses and improved energy management that comes from decoupling the load from the engine. This technology is currently available for small and medium sized passenger vehicles, and it is likely that this will be commercially available for LDVs up to the LDT class by the 2020–2025 timeframe. This technology is required for vehicles with any electrical launch or EV mobility, so that the vehicle can be steered during EV mode.

5. TECHNOLOGY BUNDLES AND SIMULATION MATRICES

The program team and EPA, with input from the Advisory Committee, bundled the technologies described in Chapter 4, Technology Review, into a set of technology packages to be evaluated in the seven LDV classes described in Section 2.2, Ground Rules for Study. These LDV classes are Small Car, Standard Car, Small MPV, Full Size Car, Large MPV, LDT, and LHDT. Engineering judgment was used to select technology combinations deemed most appropriate for each vehicle class. For example, the larger LDV classes were assumed to have wet clutch DCTs to accommodate the higher torques from their engines.

5.1 Technology Options Considered

Definitions of the hybrid powertrain, engine, and transmission technology packages are presented in Tables 5.1–5.3. The engine technologies are defined in Table 5.1; hybrids, in Table 5.2; and transmissions, in Table 5.3. Many of the engines in Table 5.1 use some measure of internal EGR, but for this table "Yes" means significant EGR flow through an external EGR system. All of the advanced transmissions in Table 5.3 include the effects of the transmission technologies described in Section 4.4, including dry sump, improved component efficiency, improved kinematic design, super finish, and advanced driveline lubricants.

5.2 Vehicle configurations and technology combinations

Vehicles were assessed using three basic powertrain configurations: conventional stop-start, P2 hybrid, and Input Powersplit hybrid. Each vehicle class considered in the study was modeled with a set of technology options, as shown in Table 5.4 for the baseline and conventional powertrains and Table 5.5 for the hybrid powertrains. Each of the 2020 engines marked for a given vehicle class in Table 5.4 was paired with each of the advanced transmissions marked for the same vehicle class. Tables 5.4 and 5.5 also show the ranges of the continuous parameters—expressed as a percentage of the nominal value—used in the DoE study for the conventional and hybrid powertrains, respectively. The ranges were kept purposely broad, to cover the entire span of practical powertrain design options, with some added margin to allow a full analysis of parametric trends.

Table 5.1: Engine technology package definition.

Engine	Air System	Fuel Injection	EGR	Valvetrain CPS	Valvetrain DVA
2010 Baseline	NA	PFI	No	No	No
Stoich DI Turbo	Boost	DI	No	Yes	No
Lean-Stoich DI Turbo	Boost	DI	No	Yes	No
EGR DI Turbo	Boost	DI	Yes	Yes	No
Atkinson	NA	DI	No	Yes	Yes
Diesel	Boost	DI	Yes	Yes	No

Table 5.2: Hybrid technology package definition.

Function	Powertrain Configuration 2010 Baseline	Stop-Start	P2 Parallel	Powersplit
Engine idle-off	No	Yes	Yes	Yes
Launch assist	No	No	Yes	Yes
Regeneration	No	No	Yes	Yes
EV mode	No	No	Yes	Yes
CVT (Electronic)	No	No	No	Yes
Power steering	Belt	Electrical	Electrical	Electrical
Engine coolant pump	Belt	Belt	Electrical	Electrical
Air conditioning	Belt	Belt	Electrical	Electrical
Brake	Standard	Standard	Blended	Blended

Table 5.3: Transmission technology package definition.

Transmission	Launch Device	Clutch
Baseline Automatic	Torque Converter	Hydraulic
Advanced Automatic	Multidamper Control	Hydraulic
Dry clutch DCT	None	Advanced Dry
Wet clutch DCT	None	Advanced Damp

Table 5.4: Baseline and Conventional Stop-Start vehicle simulation matrix.

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

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

Table 5.5: P2 and Input Powersplit hybrid simulation matrix.

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

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

6. VEHICLE MODEL

Vehicle models were developed to explore the complete design space defined by the technologies, vehicle classes, and powertrain architectures included for the 2020–2025 timeframe. The modeling process started by developing baseline models to compare against data for current (2010) vehicles, as described in Section 6.1, Baseline Conventional Vehicle Models, and Section 6.2, Baseline Hybrid Vehicle Models. Specific subsystems were also implemented into the simulation package for the study, and these modeling activities are described in Sections 6.3–6.8.

6.1 Baseline Conventional Vehicle Models

For each of the seven LDV classes considered in this project, vehicle models were developed and correlated to a corresponding 2010 exemplar for each LDV class for the purposes of establishing a comparison against known vehicle data. A detailed comparison between baseline model results and vehicle test data were used to validate the models. These correlation models were then modified to form the 2010 baseline models by converting all of them to use a 2010-level six-speed automatic transmission and stop-start systems. These baseline models, while representing an advance from current production vehicles, provide a better basis for comparison with the advanced LDVs for the 2020–2025 timeframe.

The starting point for the vehicle models was to use the existing road-load coefficients from the EPA Test Car List, which are represented as the target terms for the chassis dynamometer. Known as target A-B-C terms, the coefficients were used to derive the physical properties of rolling resistance, linear losses, and aerodynamic drag. These properties were then used in the simulation to provide the appropriate load on the vehicle at any given speed.

A physics-based vehicle and powertrain system model such as the one shown in Figure 6.1 was developed and implemented in MSC.Easy5™. MSC.Easy5™ is a commercially available software package widely used in industry for vehicle system analysis, which models the physics in the vehicle powertrain during a drive cycle. Examples of vehicle performance simulation using MSC.Easy5™ include work by Anderson, *et al.* (2005) and Fulem, *et al.* (2006), as well as the previous EPA study for 2012–2016 LDV configurations (Ricardo and PQA, 2008). Torque reactions are simulated from the engine through the transmission and driveline to the wheels. The model reacts to simulated driver inputs to the accelerator or brake pedals, thus enabling the actual vehicle acceleration to be determined based on a realistic control strategy. The model is divided into a number of subsystem models. Within each subsystem the model determines key component outputs such as torque, speeds, and heat rejection, and from these outputs, appropriate subsystem efficiencies can be calculated or reviewed as part of a quality audit.

The seven vehicle classes considered in this study are shown in Table 6.1, along with the baseline vehicles for each class. Each of the baseline exemplar vehicle models had vehicle-specific vehicle, engine, and transmission model parameters. The models were exercised over the FTP75 and HWFET fuel economy drive cycles, and the results compared with the EPA Vehicle Certification Database (Test Car List) fuel economy data for each of the baseline exemplar vehicles.

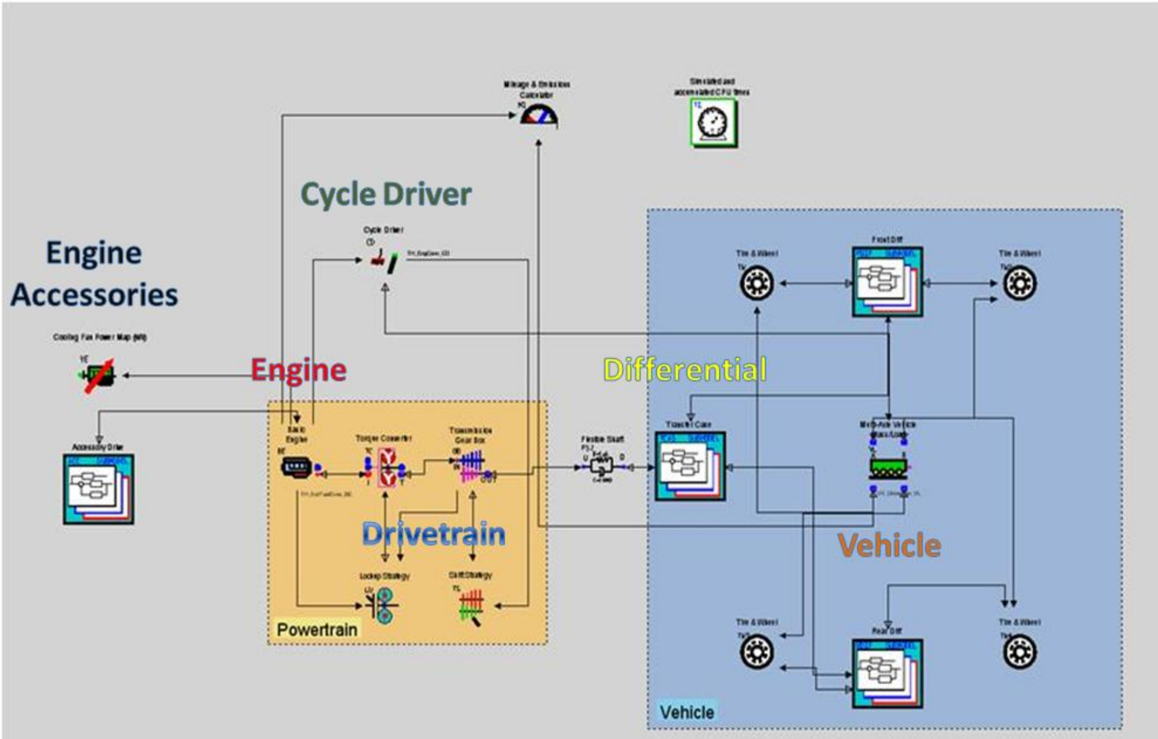

Figure 6.1: MSC.Easy5 conventional vehicle model.

Table 6.1: Vehicle classes and baseline exemplar vehicles.

Vehicle Class	Baseline Exemplar
Small car	Toyota Yaris
Standard car	Toyota Camry
Small MPV	Saturn Vue
Full sized car	Chrysler 300
Large MPV	Dodge Grand Caravan
LDT	Ford F150
LHDT	Chevy Silverado 3500HD

6.2 Baseline Hybrid Vehicle Models

For each hybrid technology, Ricardo developed a baseline model to calibrate the hybrid control strategy and vehicle, engine, and driveline parameters. As with the conventional vehicles described in Section 6.1, a full physical model of each baseline hybrid vehicle was developed and implemented in MSC.Easy5™. The hybrid control algorithms are also implemented in the respective MSC.Easy5™ models. The vehicles were modeled using published information from various sources and Ricardo proprietary data.

6.3 Engine Models

The engines considered in the design space are defined by their torque curve, fueling map, and other input parameters. For the 2010 baseline vehicles, the engine fueling maps and related parameters were developed for each specific baseline exemplar vehicle. For the engines used in the 2020–2025 vehicles, reference engine models were developed, which were then scaled to each of the LDV classes.

As described in Section 4.2, Engine Configurations, and illustrated in Section 4.2.6, Fueling Map Development Examples, the program team used two methods to develop the engine models for the 2020–2025 timeframe. The first was to look at the reported performance of current research engines, and translate these to the production engines of the 2020–2025 timeframe. With this method, current research engines would be refined to meet production standards, including manufacturability, cost, and durability. The second method was to start from current production engines and then determine a pathway of technology improvements over the next 10–15 years that would lead to an appropriate engine configuration for the 2020–2025 timeframe.

The fueling maps and other engine model parameters used in the study were based on published data and Ricardo proprietary data. These initial maps were then developed into a map reflecting the effects on overall engine performance of the combination of the future technologies considered. Specifically, the effects of the valve actuation system, fueling system, anti-knock calibration, and boost system were integrated into the final torque curves and fueling maps, therefore subsystem performance maps, such as turbine and compressor efficiency maps, are not relevant to this study.

Each proposed map was then reviewed and approved by EPA and the Advisory Committee. This process was repeated for each of the engine technologies included in the simulation matrix, as shown in Tables 5.4 and 5.5 for conventional stop-start and hybrid powertrain configurations, respectively.

Engine downsizing effects were captured using a standard engineering method, by changing the engine displacement in the given vehicle. This approach assumes that the downsized engines have the same brake mean effective pressure (BMEP), which scales the engine's delivered torque by the engine swept volume, or displacement. The BSFC of the scaled engine map is also adjusted by a factor that accounts for the change in heat loss that comes with decreasing the cylinder volume, and thereby increasing the surface to volume ratio of the cylinder. These adjustment factors are plotted in Figure 6.2, and are drawn from Ricardo proprietary data on the effect of displacement on BSFC. The minimum number of cylinders in an engine was set to three, and the minimum per-cylinder volume, to 0.225 liters. These constraints then set the minimum engine displacement in the design space to 0.675 liters.

Engine efficiency is therefore function of engine speed and BMEP, with specific fueling rates (mass per unit time) calculated from the torque. Thus, downsizing the engine directly scales the delivered torque, and the fueling map is adjusted accordingly. The engine speed range was held constant over the engine displacement ranges of interest.

Turbo lag was represented in the model by applying a first order transfer function between the driver power command and the supplied engine power at a given speed. This transfer function was only used during the performance cycle, which is a hard acceleration from a full stop used to assess vehicle acceleration performance. The transfer function approximates the torque rise rate expected in the engines with turbocharger systems during vehicle launch. Adjusting the time constant in the transfer function allowed the acceleration performance to see the effect of turbo lag. A time constant of 1.5 seconds was selected to represent the expected delay in torque rise on the advanced, boosted engines from the spool up of the turbine. Referring back to the General Motors 2.0-ℓ SIDI engine, turbo transient performance is also characterized by Schmuck-Soldan, *et al.* (2011), as shown in Figure 4.5. The transient response depicted here is in line with the representation used in this study. EPA also reviewed its own engine development data and corroborated the 1.5 second time constant.

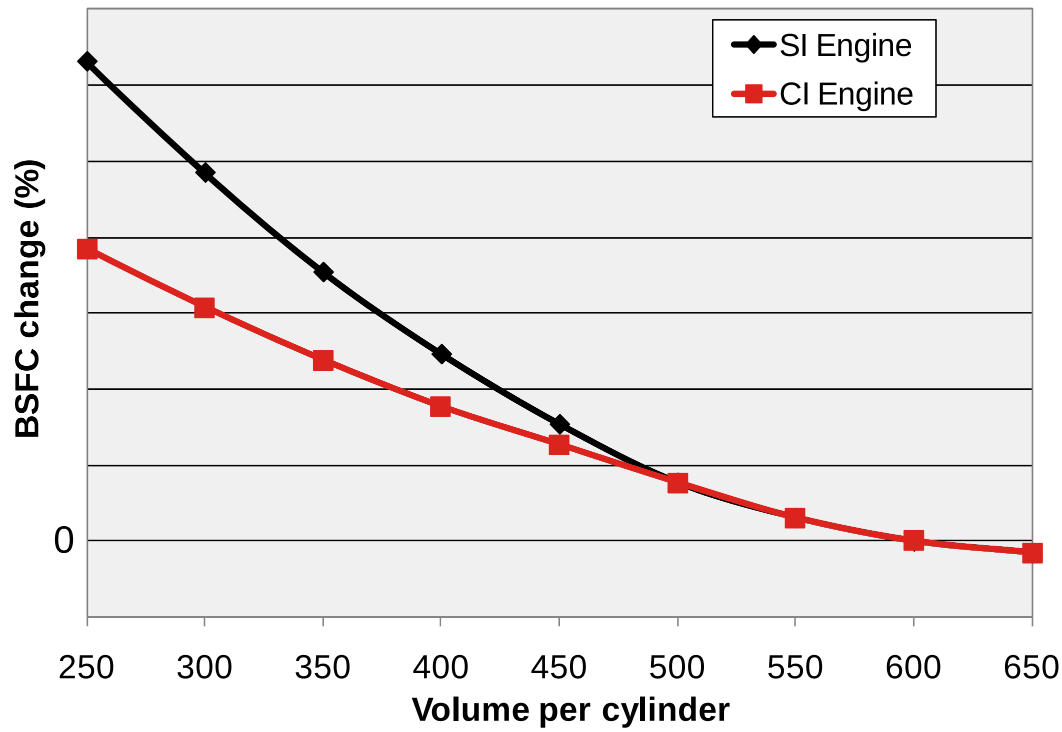

Figure 6.2: Change in BSFC resulting from cylinder heat loss.

6.3.1 Warm-up Methodology

A consistent warm-up modeling methodology was developed for the study to account for the benefits of an electrical water pump and of warm restart for the advanced vehicles. To account for engine warm-up effects, Ricardo used company proprietary data to develop an engine warm-up profile. This engine warm-up profile is used to increase the fueling requirements during the cold start portion of the FTP75 drive cycle. This correction factor for increased fueling requirements is applied to the fuel flow calculated during the warm-up period in the FTP75 drive cycle. Section 6.7 provides additional details on how this correction factor was modeled.

6.3.2 Accessories Models

Parasitic loads from the alternator were assumed constant over the drive cycles and were included in the engine model. Alternator efficiency was assumed to be 55% for baseline vehicle simulations. Ricardo suggested a 70% efficient alternator in all of the advanced technology package simulations to represent future alternator design improvements. EPA agreed that this assumption was consistent with confidential industry projections.

Power-assisted steering (PAS) systems—full electric or electric hydraulic—were modeled as being independent of engine speed and were included in the engine model for each baseline vehicle. The EPAS systems assumed no engine parasitic loads on the EPA drive cycles and acceleration performance cycles, which require no steering input. All advanced package simulations included the benefit of EPAS. The LHDT and LDT classes used electric hydraulic PAS, whereas the five smaller vehicle classes used full electric PAS.

The LDT and LHDT models also include engine parasitic losses due to a belt-driven engine cooling fan. The other vehicles were assumed to have electric radiator fans, with the load being drive cycle dependent and added to the vehicle's base electrical load. These accessory loads are shown in Tables 6.3 and 6.4.

Table 6.3: Accessory loads for conventional stop-start and P2 hybrids.

	Conventional Accessories (W)			P2 Hybrid Accessories (W)		
Vehicle Class	Base	FTP cooling fan	HWFET cooling fan	Base	FTP cooling fan	HWFET cooling fan
Small car	153	127	280	84	70	154
Standard car	153	127	280	84	70	154
Small MPV	153	127	280	84	70	154
Full sized car	153	127	280	84	70	154
Large MPV	153	127	280	84	70	154
LDT	153	*	*	84	*	*
LHDT	153	**	**	—	—	—

Table 6.4: Mechanical cooling fan loads for LDT and LHDT.

Engine Speed (rpm)	Cooling Fan (W) *LDT	Cooling Fan (W) **LHDT
500	242	290
1000	500	600
2000	1058	1270
2500	1323	1588
6200	3550	4260

Current production cars have begun incorporating advanced alternator control to capture braking energy through electrical power generation. This is done by running the alternator near or at full capacity to apply more load on the engine when the driver demands vehicle deceleration. It is believed that this feature will be widespread in the near future and, hence, the study captures it by incorporating this function into the Conventional Stop-Start model. As in the earlier study (Ricardo and PQA, 2008), the alternator efficiency was increased to 70% to reflect an improved efficiency design for 2020 vehicle configurations. The advanced alternator control strategy monitors vehicle brake events and captures braking energy when available. The control strategy also limits the maximum power capture to 2800 Watts based on the assumption that the advanced alternator is limited to 200 Amps at 14 Volts charging for a standard (12V) advanced glass-mat battery. By integrating power, energy is accumulated from every brake event and when there is available "stored" brake energy, the control strategy switches the parasitic draw from the engine to the battery until the accrued energy is consumed, at which point the load switches back to the engine. For the five smaller LDV classes, both the fan and base electrical loads are included in the advanced charging system as electric fans are employed. The system will only benefit the two truck classes, LDT and LHDT, in terms of base electrical load as these vehicle classes use mechanical fans.

6.4 Transmission Models

The transmission models use a simplified efficiency curve, where the gearbox efficiency is a function of gear ratio, as shown in Figure 4.11. Efficiencies for each gear ratio were calculated based on data from several transmission and final drive gear tests, were averaged over the expected speed and load ranges for the transmission in a given gear, and incorporate hydraulic pumping losses. Transmission efficiencies were calculated to represent the average of the leading edge for today's industry and not one particular manufacturer's design.

Different efficiency curves were mapped for planetary, automatics, and dual-clutch, with the DCT efficiency modified depending on whether a dry or wet clutch is used. Advanced automatic transmission designs are projected to reduce losses by 20–33% from current automatic transmissions. In addition, the advanced automatic transmissions use advanced torque converters, described below in Section 6.5. Wet clutch DCT efficiencies are also projected to approach current dry clutch DCT efficiencies.

The gear ratios chosen for the six and eight speed advanced transmission are taken from current production values for gear ratios. These are shown below in Table 6.5. Moreover, transmission inertias were adapted from Ricardo proprietary data on contemporary transmissions and reflect the effects of the technologies described in Sections 4.4.6–4.4.11.

Table 6.5: Transmission gear ratios for six-speed and eight-speed transmissions.

Gear	Ratio	
	8 Spd Advanced	6 Spd Baseline
1	4.700	4.148
2	3.130	2.370
3	2.100	1.556
4	1.670	1.155
5	1.290	0.859
6	1.000	0.686
7	0.840	
8	0.670	

In anticipation of future technology packages, it is expected that some advanced level of transmission shift optimization will be implemented in year 2020–2025 vehicles. For the 2020–2025 Conventional Stop-Start architecture, an advanced transmission controller was implemented to determine the most favorable gear for a given driver input and vehicle road load. This approach takes the place of predefined calibration shift maps based on throttle and vehicle speed.

The advanced transmission shift optimization strategy tries to keep the engine operating near its most efficient point for a given power demand. In this way, the new shift controller emulates a traditional CVT by selecting the best gear ratio for fuel economy at a given required vehicle power level. In conjunction, gear efficiency of the desired gear is also taken into account. More often than not, the optimal gear ratio will be in between two of the fixed ratios, and the shift optimizer will then decide when to shift up or down based on a tunable shift setting. This will enable the shift optimizer to make proper shift decisions based on the type of vehicle and the desired aggressiveness of the shift pattern. To protect against operating conditions out of normal range, several key parameters were identified, such as maximum engine speed, minimum lugging speed, and minimum delay between shifts. For automatic transmissions, the torque converter is also controlled by the shift optimizer, with full lockup only achievable when the transmission is not in first gear. Shift time for all transmissions was kept constant at 0.7 second duration as the sensitivity of this parameter was not enough to alter fuel economy predictions over the EPA drive cycles. Furthermore, torque interrupt during shift is handled automatically by the MSC.Easy5™ model component. During development of this strategy, it was noted that fuel economy benefits of up to 5% can be obtained when compared to traditional shift maps. Figure 6.4 compares the desired gear ratio from a CVT and the comparable DCT fixed gear ratio selected by the shift optimizer strategy.

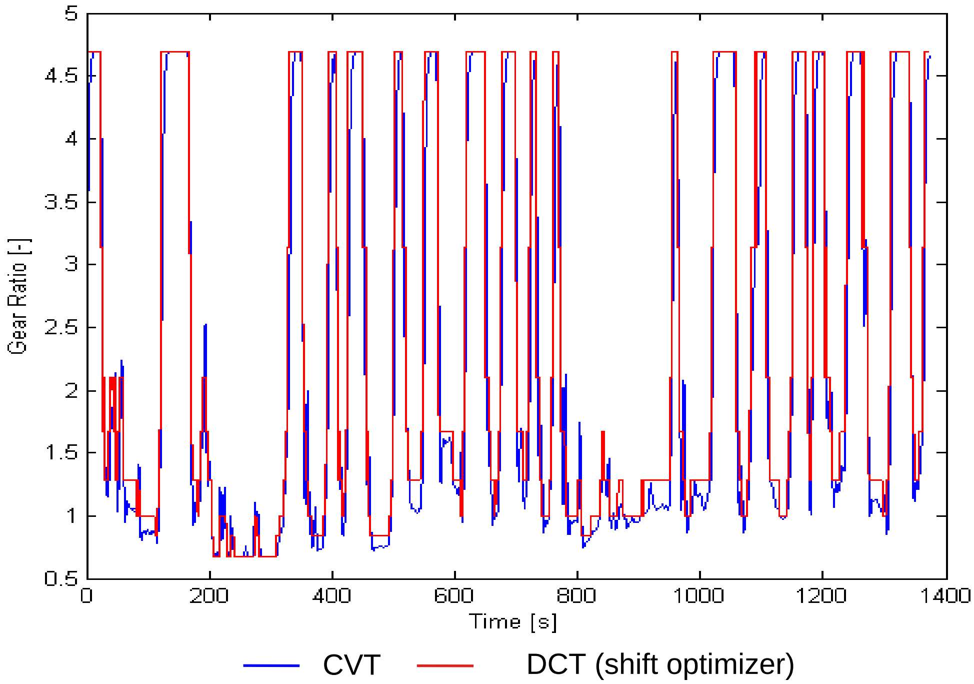

Figure 6.4: Comparison of CVT and optimized DCT gear ratios over drive cycle.

Analysis of the optimized shift strategy model output data shows no evidence to suggest an increase in shift busyness compared to a baseline transmission shift strategy for a given gearset. Figure 6.5 shows transmission gear plotted over time for a section of the FTP drive cycle for the 2020 Small Car with 6-speed automatic transmission (and stoichiometric DI turbo engine) nominal run with optimized shifting, compared to the 2010 Small Car baseline. For the complete FTP cycle, the baseline vehicle shifted a total of 238 times, whereas the 2020 vehicle with optimized shifting strategy shifted 228 times—in this case, leading to a decrease in shift busyness.

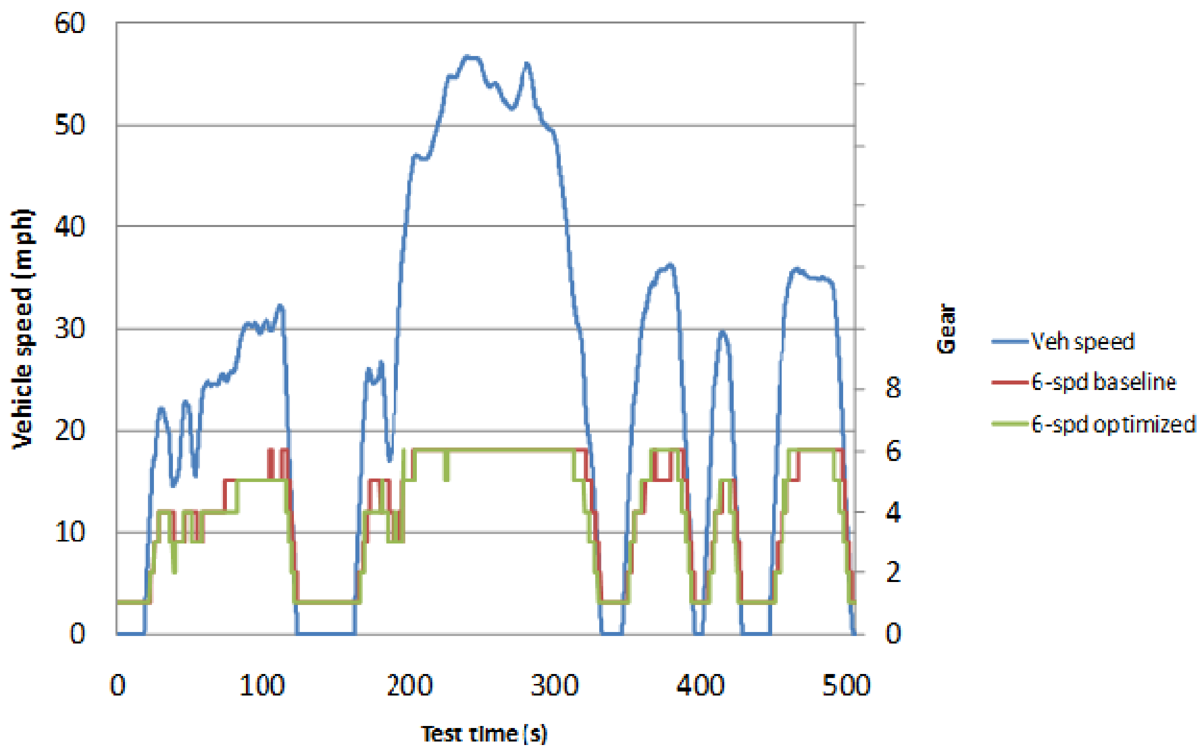

Figure 6.5: Comparison of shift activity for traditional and optimized shifting strategies.

6.5 Torque Converter Models

Torque converter characteristics curves for torque ratio and K-factor were generated using typical industry standards for efficiency. Each vehicle's torque converter characteristics for torque ratio and K-factor were tailored for the application based on Ricardo experience with production systems. Impeller and turbine rotational inertias are also input to the model and were estimated based upon Ricardo experience and benchmarking data. Vehicle simulations with advanced automatic transmissions include a slight improvement in torque converter efficiency.

A lockup clutch model was used with all torque converters and was of sufficient capacity to prevent clutch slip during all simulation conditions. For the baseline models with six-speed automatics, lockup was allowed in fourth, fifth, and sixth gears. During light throttle conditions a minimum engine operating speed of 1400 rpm for I3 engines, 1300 rpm for I4 engines, 1200 rpm for V6 engines, and 1100 rpm for V8 engines with the converter clutch locked was considered in developing the baseline lock/unlock maps. The advanced automatic transmission applications allow torque converter lockup in any gear except first gear, up to sixth for the Small Car or eighth for the other LDV classes. This aggressive lockup strategy minimizes losses in the torque converter.

6.6 Final Drive Differential Model

Baseline final drive ratios were taken from published information and driveline efficiencies and spin losses were estimated based upon Ricardo experience for typical industry differentials. The spin losses of the 4-wheel-drive LDT and LHDT front axle and transfer case were included in the model to capture the fuel economy and performance of the 4-wheel-drive powertrain operating in 2-wheel-drive mode. This approach is similar to the EPA procedure for emissions and fuel economy certification testing.

6.7 Driver Model

The vehicle model is forward facing and has a model for the driver. The driver model applies the throttle or brake pedal as needed to meet the required speed defined by the vehicle drive cycle within the allowed legislative error. This allows the modeling of the actual vehicle response to meet the target drive cycle.

The driver model contains the drive cycle time/velocity trace, controls the throttle and brake functions, and maintains vehicle speed to the desired set point. Vehicle simulations for fuel economy were conducted over the EPA FTP75 (city), HWFET (highway) and US06 drive cycles. The FTP75 cycle consists of three "bags" for a total of 11.041 miles on the conventional vehicles and an additional bag 4 on hybrid vehicles for a total of 14.9 miles. A ten minute engine-off soak is performed between bags 2 and 3 (after 1372 seconds of testing). A bag 1 correction factor is applied to the simulated "hot" fuel economy result of the vehicles to approximate warm-up conditions of increased engine and driveline friction and sub-optimal combustion. The correction factor reduces the fuel economy results of the FTP75 bag 1 portion of the drive cycle by 20% on the current baseline vehicles and 10% on 2020–2025 vehicles that take advantage of fast warm-up technologies.

6.8 Hybrid Models

The hybrid models include all of the conventional vehicle components with the addition or replacement of components for electric motor-generators, high voltage battery, high voltage battery controller/bus, transmission, regenerative braking and hybrid supervisory controller. Of these, the critical systems for the model were the electric machines (motor-generators), power electronics, and high-voltage battery system. For each of these systems, current, state of the art technologies such as those described in Staunton, *et al*. (2006) or Burress, *et al*. (2008) were adapted to an advanced, 2020–2025 version of the system.

Technology improvements applied included decreasing losses in the electric machine and power electronics to represent continued improvements in technology and implementation, so that a contemporary motor-inverter efficiency map such as that shown in Figure 6.6 would end up with higher peak efficiency and a broader island of good efficiency. There are several potential sources of losses in both the inverter and the motor, and the program team assumed each source would be improved somewhat, leading to an overall 10% reduction in losses in the inverter and an overall 25% reduction in losses in the motor.

As for the battery pack, a ground rule of the study is that the battery pack would use a generic lithium ion chemistry representative of what is expected to be in production by the 2020–2025 timeframe. The assumptions for this future class of batteries include a lower overall internal resistance. Likewise, future hybrid vehicles are assumed to use 40% of the overall SOC range of the pack, which will reduce the overall battery pack size for a given energy storage requirement. The capacity of the battery packs in the model was assumed to be sufficiently large that it did not limit the vehicle performance. The electric machines were swept over a sufficiently large range such that the design space included configurations where 90% of the mechanical braking energy on the US06 to be captured by the hybrid electrical system. The electrical system architecture assumes a DC/DC converter between the battery pack and the inverter, so the specific pack architecture and voltage are not relevant to the simulation.

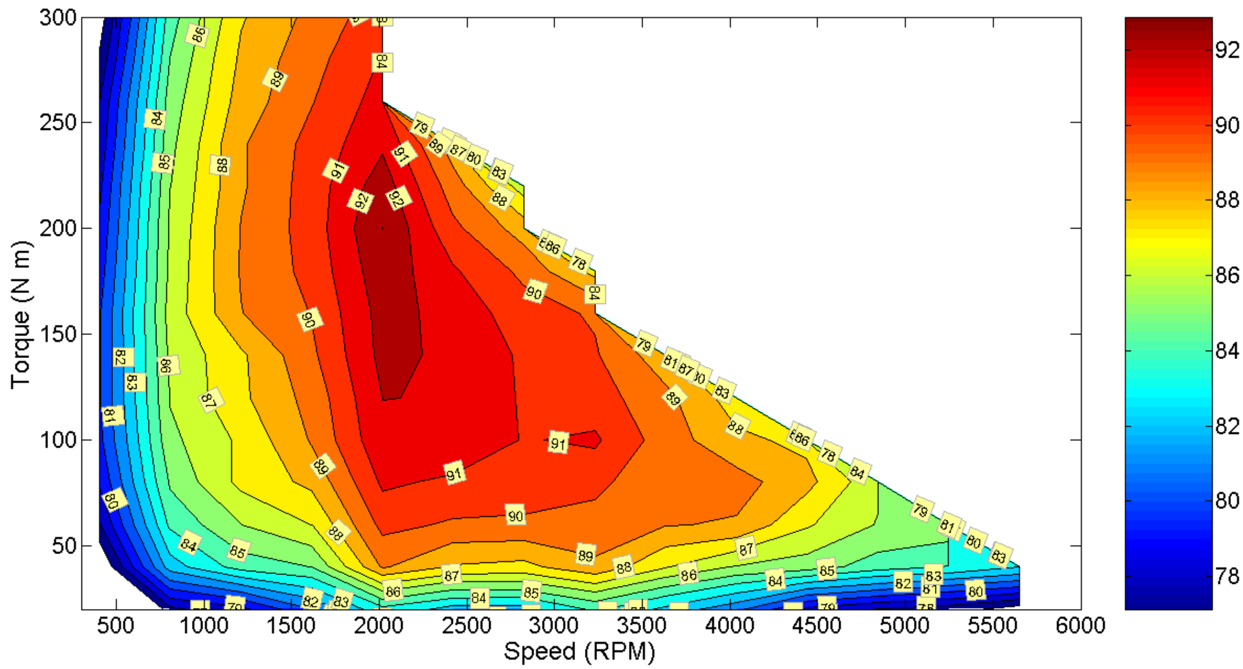

Figure 6.6: 2007 Camry motor-inverter efficiency contour map. (Burress, *et al.*, 2008)

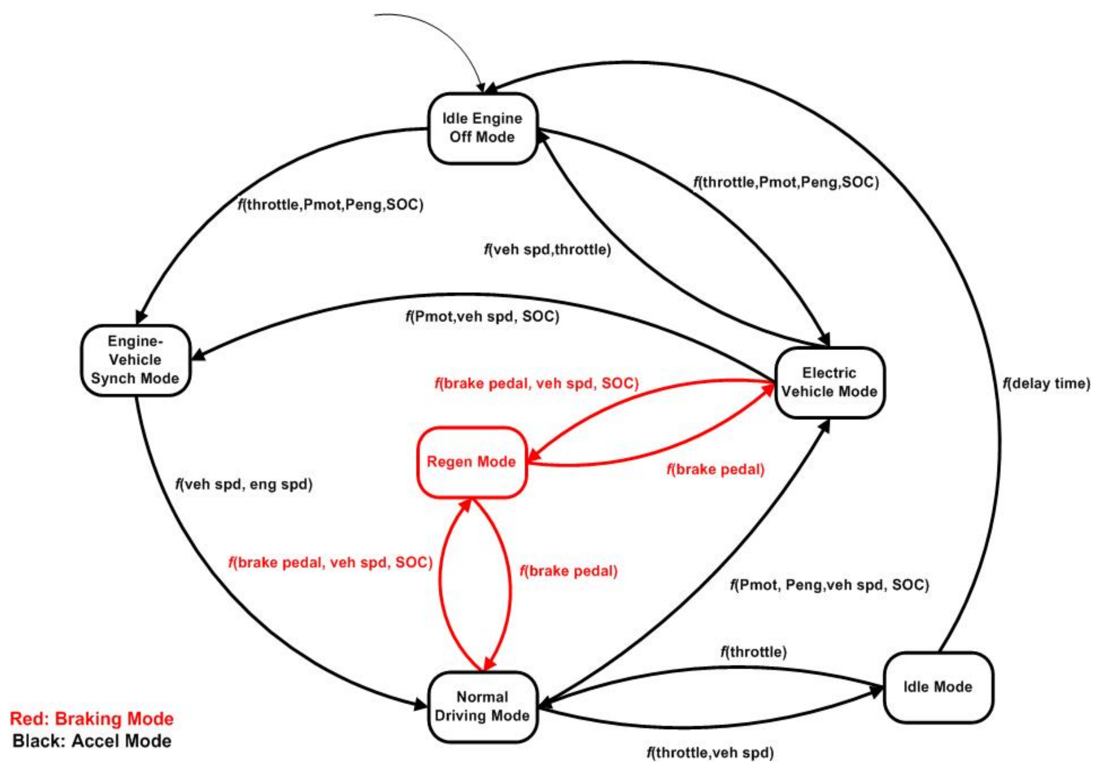

Figure 6.7: High level state flow diagram for the hybrid control strategy.

In addition, a Ricardo proprietary methodology was used to identify the optimum boundaries of fuel consumption for a given hybrid powertrain configuration over the drive cycles of interest: FTP, HWFET, and US06. The methodology used the drive cycle profile to identify the features and thresholds of a control strategy that could provide fuel consumption over the drive cycle that approaches the boundary value. The result of this assessment enabled the development of a robust energy management system to control power flow. The simulation results using the hybrid controller were then compared against the offline strategy to ensure that the hybrid controller in the models is obtaining the most out of the hybrid powertrain. Furthermore, the control strategy was designed to allow for a wide range of input parameters while striving for the most efficient operation modes. Figure 6.7 illustrates the state flow diagram for the hybrid control strategy used as the baseline for the hybrid control algorithm implemented in MSC.Easy5™, as well as the state variables, driver inputs and system parameters that were used to define the state transitions. There are six main operation state modes,

- Idle engine off mode: This mode will shut the engine off and set the throttle command to zero.
- Electric vehicle mode: This mode will leave the engine off and use the throttle command from the driver to determine the torque command for the electrical machine.
- Engine-Vehicle synch mode: This mode will start the engine.
- Normal driving model: This mode determines the ratio of electrical machine and engine power that will be transmitted to the wheel to achieve the desired demand.
- Idle mode: This mode starts the countdown for idle engine off mode.
- Regen mode: This mode determines if regenerative braking is possible and how much of the requested brake torque will be assigned to foundation brakes and to the electrical machine.

The following inputs and variables or states should be defined and available within the controller in order to full define the state transitions,

- Driver inputs: throttle and brake pedals
- Battery State of Charge (SOC)
- Vehicle speed
- Engine: power and speed
- Motor: max power, max torque, speed, and torque/power.

Because the design space encompasses a large range of engine displacement and motor sizes, the input parameters were normalized to take into account these changes and automatically adjust the controller thresholds to meet the new demands. Figure 6.8 depicts the engine demand curve that targets high efficiency operation.

A key feature of the hybrid controller is that it used a hybrid load following and load averaging strategy to help keep the engine on or near its line of best efficiency on the engine operating map with some accommodation for the efficiency of the overall powertrain. If the engine is required to be on during low-load conditions, the engine can be made to work harder and more efficiently and store the excess energy in the battery. While there have been concerns about the effectiveness of a load averaging strategy given the roundtrip efficiency of energy storage and retrieval, with the improvements expected in the 2020–2025 timeframe, the engine is likely to be a critical factor in the balance of efficiency improvements. In the simulation environment, two identical vehicles were analyzed, one with load averaging active and the other, not. The case with load averaging showed a slight improvement in fuel consumption over the EPA drive cycles. In other cases, the energy in the battery can be used to provide launch assist or EV mode driving. All hybrid vehicle simulations were repeated over the drive cycles until the change in SOC from start to finish was within 1% of total capacity. Therefore, there is no net accumulation or net depletion of energy in the battery, and the fuel consumption value reported is an accurate measure of the effectiveness of technologies. Figure 6.9 shows the energy supervisory strategy of the hybrid powertrains.

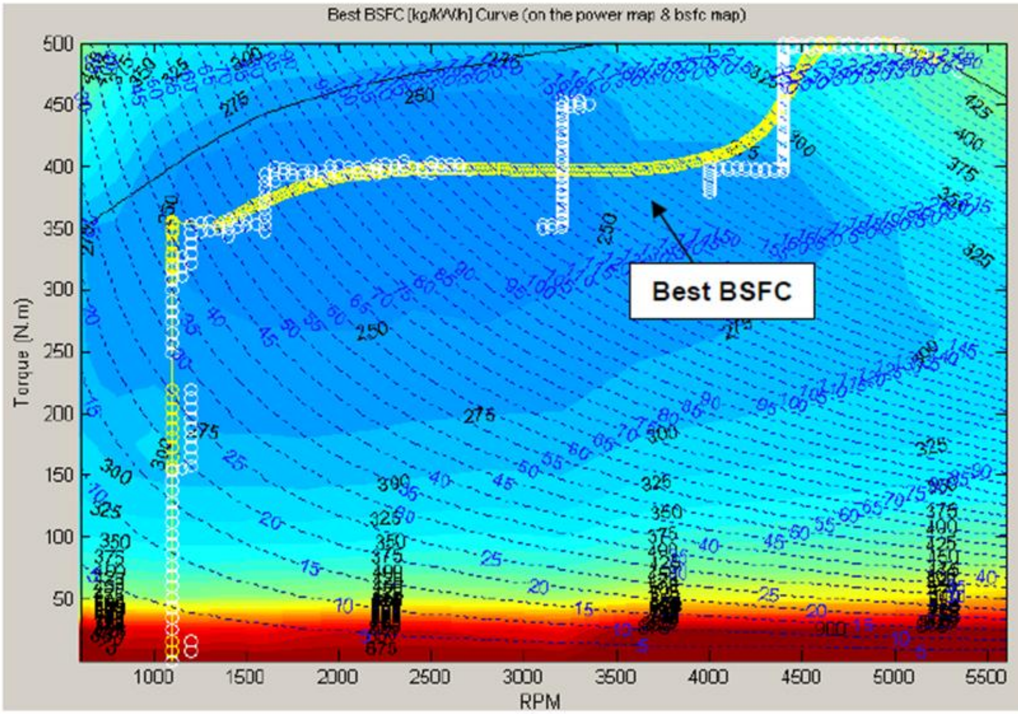

Figure 6.8: Best BSFC curve superimposed on fueling map.

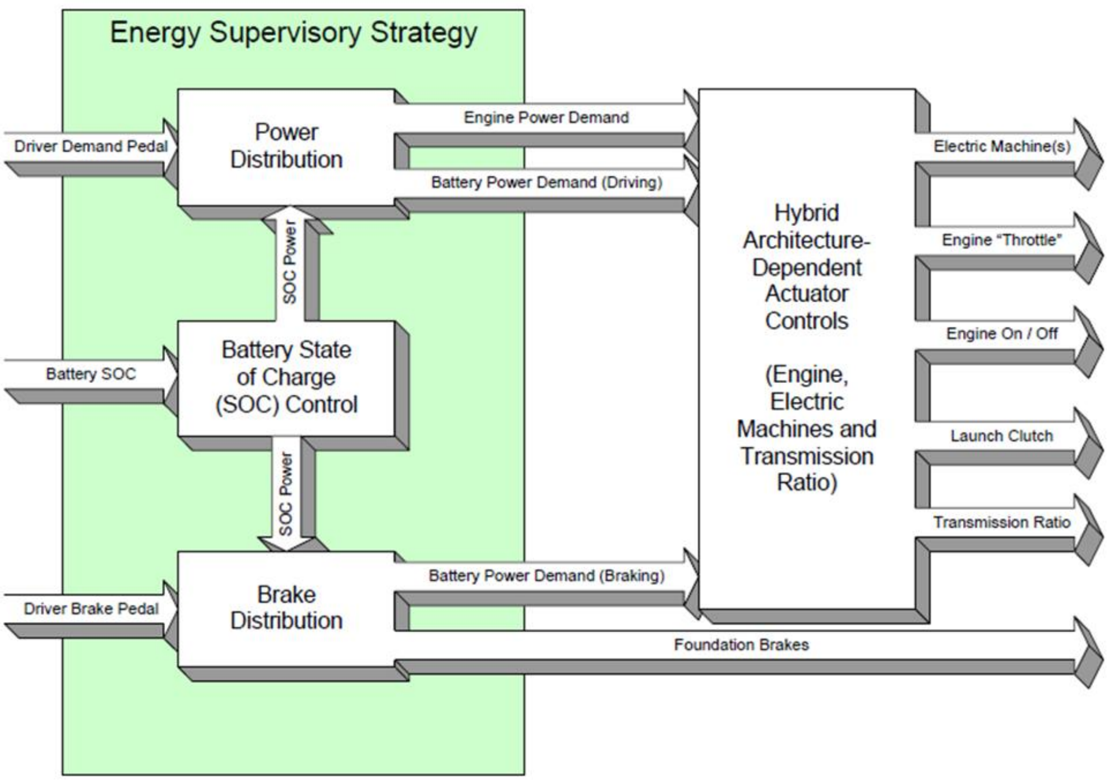

Figure 6.9: Hybrid powertrain energy supervisory strategy.

7. MODEL VALIDATION RESULTS

Before executing the DoE simulation matrix, the vehicle models described in Chapter 6 were validated. Baseline exemplar vehicles were modeled, and the simulation results compared against publicly available data on vehicle performance, including acceleration times and fuel economy. Details of the model validation process and results are presented below. In addition, nominal runs were prepared for each major powertrain type to provide a reference point for the input parameters against which to compare the full design space explored in the DoE simulation matrix.

7.1 Validation Cases and 2010 Baseline Vehicle Models

Vehicle models were developed for a 2010 validation case for each of the seven LDV classes. Each LDV class was assigned a representative exemplar vehicle for the purposes of establishing a baseline against known vehicle data. Ricardo leveraged the peer-reviewed validation baseline models from its 2008 study with PQA (now SRA) for the five LDV classes from Standard Car through LDT to provide the validation case models, and to build new validation case models for the Small Car and LHDT classes. The validation case models are based on the corresponding exemplar vehicles listed in Table 6.1, and therefore use automatic transmissions and engines with comparable characteristics, including number of gears, peak torque, and displacement.

Vehicle performance simulation results for the validation case models are shown below in Table 7.1, comparing the raw fuel economy results in the EPA Test Car List (EPA, 2010) against the calculated results. In addition to the fuel economy tests, the launch performance was also assessed for each of the exemplar vehicles, with particular attention paid to the 0–60 mph acceleration time, as this is readily available for validation. 0–60 mph acceleration times for the exemplar models were within a few tenths of a second of published times for each vehicle. Because production P2 hybrids were not available to provide data in 2010, no direct comparison was made. Furthermore, any production hybrid vehicle will be optimized for a specific combination of engine, electric machine, and battery, whereas this study used a generic but effective controller that allowed the entire design space to be robustly simulated.

Table 7.1: Validation vehicle fuel economy performance.

		EPA Test List (mpg)		Simulation Results (mpg)		Difference (%)	
Vehicle Class	**Baseline Exemplars**	**FTP75**	**HWFET**	**FTP75**	**HWFET**	**FTP75**	**HWFET**
Small car	2010 Toyota Yaris	37	48	37	48	-0.8%	0.2%
Standard car	2007 Toyota Camry	27	42	27	42	0.9%	-1.0%
Small MPV	2008 Saturn Vue	24	37	25	36	3.9%	-2.6%
Full sized car	2007Chrysler 300	21	34	22	33	3.7%	-4.6%
Large MPV	2007 Dodge Grand Caravan	20	32	20	29	1.6%	-9.1%
LDT	2007 Ford F150	16	23	15	23	-4.1%	-0.4%
LHDT	2010 Chevy Silverado 3500HD (diesel)	—	—	13	21	—	—

Following the model validation phase, 2010 baseline vehicles were established. Rather than using the validation vehicles and corresponding fuel economy results, a new set of baseline values were determined to facilitate a uniform comparison between the advanced (future) concepts and today's current technologies. These new reference 2010 baseline vehicles add an efficient alternator and stop-start operation to a common 6-speed automatic transmission, and retain the engine maps from the validation case models. Appendix 3 presents the 2010 baseline model fuel economy and CO_2 output equivalents for all classes of vehicles considered in this study. Note that the CO_2 equivalents used in these tables were provided by the EPA as 9,087 g/gal of fuel for gasoline and 10,097 g/gal for diesel.

7.2 Nominal Runs

Once the models were developed and validated, a series of nominal runs were prepared to assess the accuracy and robustness of the model. For the conventional vehicles, the nominal condition was calculated using the same vehicle parameter values, such as for mass and aerodynamic drag, as the 2010 baseline vehicles. The advanced engine size was then adjusted to match the baseline 0–60 mph acceleration time, thus defining the nominal displacement for each advanced engine. In addition, the nominal condition includes use of a baseline six-speed automatic transmission for all LDV classes and implementation of stop-start technology. In this way, the nominal condition is placed on a corner of the design space for each LDV class and therefore, the nominal conditions serve as the reference point for the design space explored by the DoE simulations.

For the Powersplit and P2 hybrids, the nominal engine size was reduced by 20% from the conventional nominal engine size to allow for motor assist to match the aforementioned 0–60 mph performance metric. The 20% engine displacement reduction for the Powersplit and P2 hybrids was determined using Ricardo's engineering judgment and an assessment of existing hybridization strategy. The nominal electric machine size was then set so that the 0–60 mph acceleration time was matched for the hybrid nominal cases.

It is not possible to provide validation examples of the nominal vehicle models as they represent predicted 2020 technology. Also, separate models showing the incremental benefits of individual technologies were not studied as steps to the overall advanced packages. However, the program team reviewed detailed output data for over one hundred distinct variables at a 10 Hz sampling rate to confirm that all of the nominal runs reflected reasonable real-world vehicle behavior. After the nominal runs passed these quality checks, Ricardo proceeded to the DoE simulation phase of the project.

The full table of nominal runs results for the conventional stop-start, P2 hybrid, and Input Powersplit hybrid vehicle combinations is in Appendix 5, and presents the key output factors defined in Appendix 4. These summary results and the rest of the simulation output data were used to assess the quality of the simulation results before executing the DoE simulation matrix, for example, by assessing power flows to and from the battery over the drive cycle.

8. COMPLEX SYSTEMS MODEL VALIDATION

Complex systems modeling (CSM) is an objective, scientific approach for evaluating several potential options or configurations for benefits relative to each other and to a baseline. For this program, the CSM methodology was used to define the design space for LDVs in the 2020–2025 timeframe, and then to effectively evaluate LDV performance over this large design space.

8.1 Evaluation of Design Space

The purpose of the DoE simulation matrix is to efficiently explore the potential design space for LDVs in the 2020–2025 timeframe. The simulation matrix was designed to generate selected performance results, such as fuel consumption or acceleration times, over selected drive cycles.

The DoE approach allows an efficient exploration of the design space while limiting the number of runs needed to survey the design space.

For each discrete combination of vehicle class, powertrain architecture, engine, and transmission in the design space, the continuous input variables, including applied road load reductions, were varied over the ranges shown in Tables 8.1 and 8.2 for the conventional and hybrid powertrains, respectively. These continuous input variable ranges are with respect to the nominal value for each LDV class. In the analysis, continuous input variables are evaluated using a combination of the design corner points in a two-level full factorial design and design points within the space based on a Latin hypercube sampling methodology. Note that vehicle mass is considered independently of the combination of discrete technologies; for example, switching from an automatic transmission to a DCT does not automatically adjust the vehicle mass in the simulation.

To size the electric machines, hybrid vehicle simulations were performed with the conventional vehicle counterparts to assess the overall braking energy over the drive cycles. This knowledge was then applied to the hybrid models by sweeping the electric machine sizes over the ranges shown in Table 8.2 until the overall regenerative energy equaled or exceeded 90% of the total braking energy, excluding the innate vehicle road load losses.

Table 8.1: Continuous input parameter sweep ranges with conventional powertrain.

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

Table 8.2: Continuous input variable ranges for P2 and Powersplit hybrid powertrains.

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

Latin hypercube sampling is a statistical method originally developed by McKay *et al.* (1979), used to generate a set of parameter values over a multidimensional parameter space. The method randomly samples the multidimensional parameter space in a way that provides comprehensive and relatively sparse coverage for best efficiency. It also allows one to efficiently continue to fill the multidimensional parameter space by further random sampling. It provides more flexibility than traditional multi-level factorial designs for assessing a large parametric space with an efficient number of experiments.

The vehicle simulations were run in batches and the results were collected and processed. Vehicle fuel economy and performance metrics were recorded as well as diagnostic variables such as the total number of gear shifts and the distance traveled during the drive cycle. The data were reviewed using a data mining tool and outliers were analyzed, and, as necessary, debugged and re-run. This approach allowed issues to be detected and diagnosed very quickly within a large amount of data. Once the data were reviewed and approved, response surface models were generated.

8.2 Response Surface Modeling

Response surface models (RSM) were generated in the form of neural networks. The goal was to achieve low residuals while not over-fitting the data. Initially, 66% of the data were used for fitting the model while the remainder was used to validate the response surface model's prediction performance. Once a good fit was found, all the data were used to populate the RSM. Each neural network fit contains all of the continuous and discrete variables used in the study for a given transmission. One neural network fit per transmission was generated to improve the quality of the fits.

9. RESULTS

The key project results consist of the raw data sets obtained from over 350,000 individual vehicle simulation cases, the Data Visualization Tool developed to query the response surfaces based upon the raw data sets, and this report describing these results. These key results are discussed below. A separate User Guide for the Data Visualization Tool will be released with the tool.

9.1 Basic Results of Simulation

Each of the simulation cases generated data at 10 Hz[2] which allowed evaluation of the performance of a specific vehicle configuration in the design space over each of the drive cycles. These results include parameters such as vehicle speed, calculated engine power, and instantaneous fueling rate. The detailed data from each simulation run were then distilled into the main output factors of interest, such as acceleration time and fuel economy, that were then used in the parametric fit of the RSM.

For this study, the main output factors include raw fuel economy and GHG emissions over each of the drive cycles studied and performance metrics, such as 0–60 mph acceleration times. The complete list of output factors is listed in Appendix 4.

9.2 Design Space Query

The Design Space Query within the Data Visualization Tool allows the user to assess a specific vehicle configuration in the design space by selecting a platform, engine, and transmission and then setting the continuous variables within the design space range. The generated performance results are then reported in a table that is exportable to Excel. The user can assess multiple vehicle configurations and compare them in Excel. The tool table also allows the user to apply spreadsheet formulas for quick, on-the-side computation. An example of the Design Space Query is shown in Figure 9.1.

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[2] To maintain manageable file sizes at an adequate level of fidelity, EPA requested that output files be generated at a 10 Hz sampling rate—far slower than the Easy5 process rate—for its own data quality checks.

9.3 Exploration of the Design Space

A more comprehensive survey of the design space can be conducted using the Design Space Analysis in the Data Visualization Tool, which allows the user to assess the performance of multiple vehicle configurations from a significant portion of the design space simultaneously. Each design is generated by selecting a vehicle platform, engine, and transmission, and then by selecting ranges for the continuous input variables. Figure 9.2 shows the screen where the design space analysis is set up. For each of the continuous variables, values are generated using a Monte Carlo analysis from a uniform distribution over the range selected.

Once generated, the results at the design points are stored and may be plotted to visualize the effects of varying vehicle parameters over the design space. By carefully building a design and varying the parameters, the user can gain an understanding of the effect of each technology and the interactions between technologies. Figures 9.3–9.5 show examples of plots that compare two design space analyses. In these cases, the red points are for a Full Size Car with advanced diesel engine and dry-clutch DCT, whereas the blue points are for a Full Size Car with stoichiometric DI turbo engine and automatic transmission. The black point is the 2010 baseline value. For these examples, the engine displacement was varied from 50% to 125% of nominal, or 0.71 to 1.8 ℓ displacement for the stoichiometric DI turbo engine and 1.4 to 3.6 ℓ for the diesel, and the vehicle mass, from 70% to 100% of nominal, or 2800 to 4000lb.

The example in Figure 9.6 compares various configurations of the Standard Car, all with the EGR DI Turbo engine but with different powertrains. The two Conventional Stop-Start cases have the advanced eight-speed automatic and dry-clutch DCT, shown in blue and gray, respectively. The Powersplit hybrid is shown in green, and the P2 Hybrid, in red. Again, the black point is the 2010 baseline value. By contrast, the example in Figure 9.7 compares fuel economy performance across all seven LDV classes. Here, each LDV class has had its engine displacement and vehicle mass varied from the minimum to the maximum of the design space.

9.4 Identification and Use of the Efficient Frontier

Part of assessing the selected regions of the design space is to find configurations that balance efficiency and performance. The Data Visualization Tool identifies an Efficient Frontier, which is the bound of the sampled design space that has the most desirable performance. The user must first define a dataset using the Design Space Query, described above in Section 9.2, and then select the Efficient Frontier tab in the Data Visualization Tool. An example of the Efficient Frontier screen is shown in Figure 9.8. The Efficient Frontier is marked out in red, and the user can click on the data points along the frontier to discover the vehicle configurations that lie on the frontier.

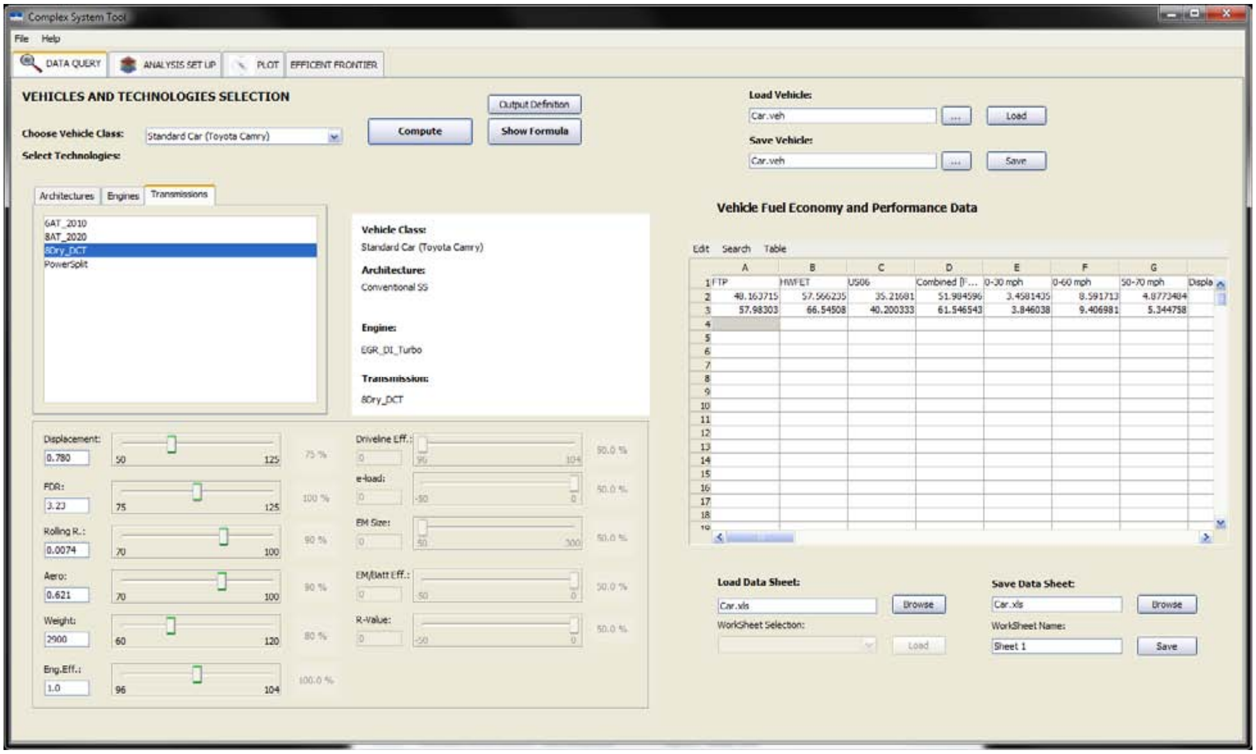

Figure 9.1: Design Space Query screen in Data Visualization Tool.

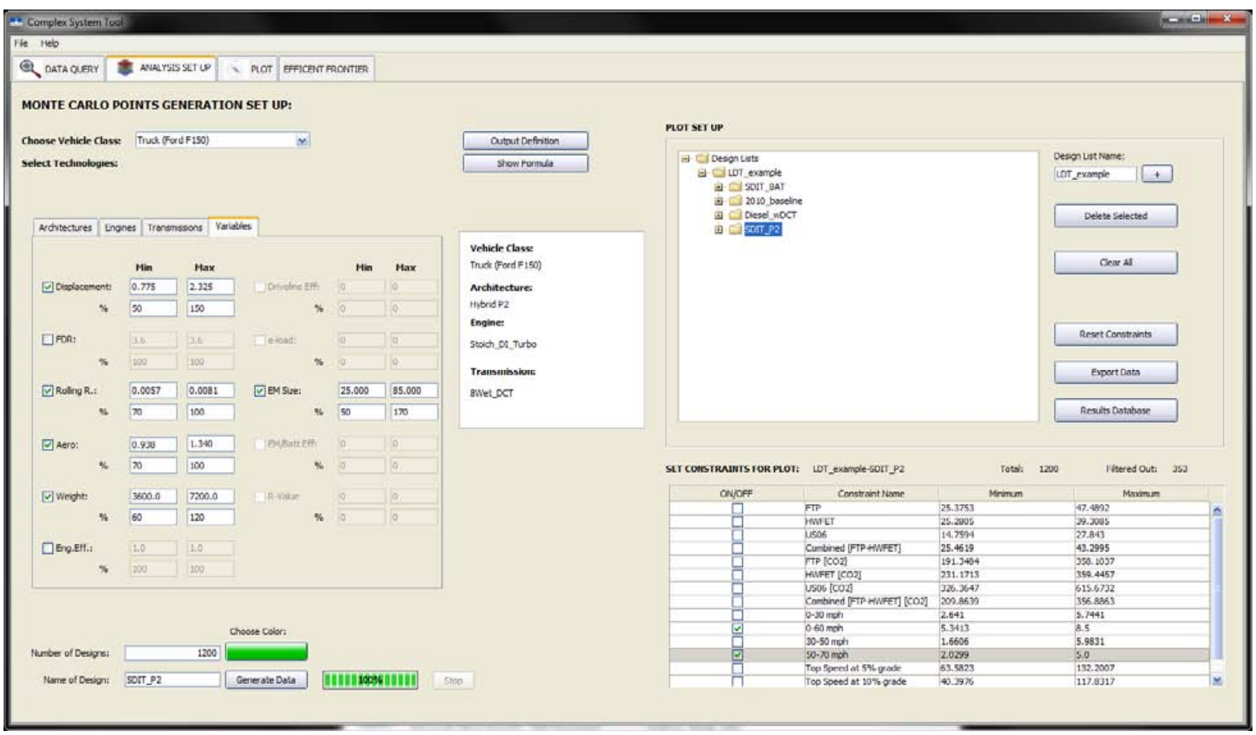

Figure 9.2: Design Space Analysis screen in Data Visualization Tool.

Figure 9.3: Full Size Car Design Space Analysis example. Black point is 2010 baseline; red points are for advanced diesel and dry-clutch DCT; blue points, Stoichiometric DI Turbo with advanced automatic transmission.

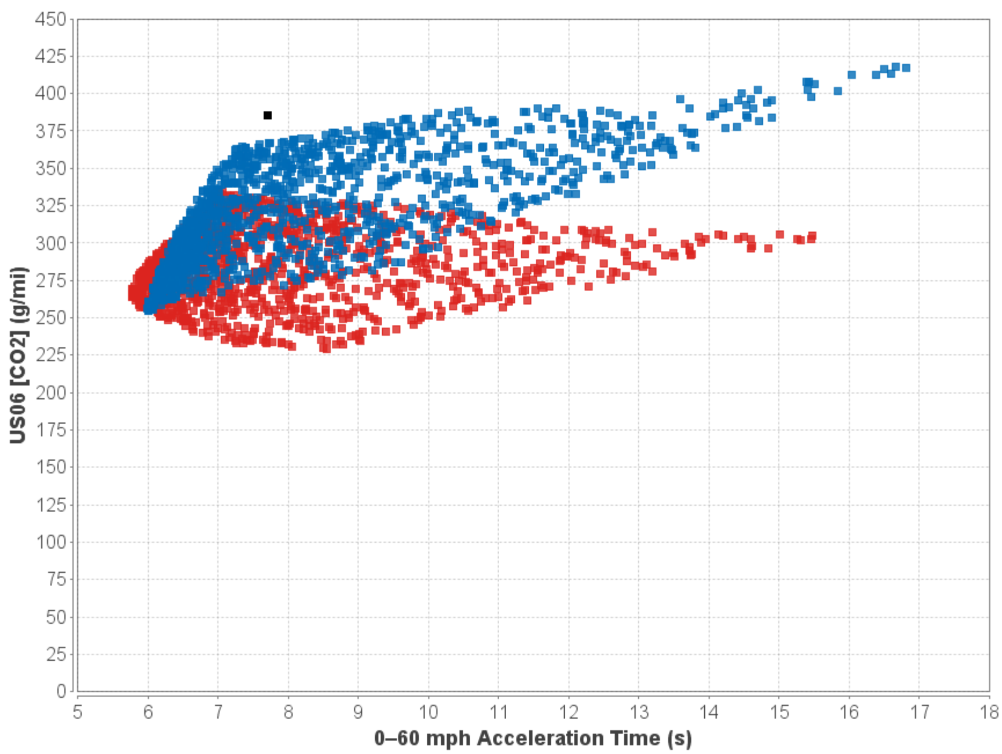

Figure 9.4: Full Size Car Design Space Analysis example. Black point is 2010 baseline; red points are for advanced diesel and dry-clutch DCT; blue points, Stoichiometric DI Turbo with advanced automatic transmission.

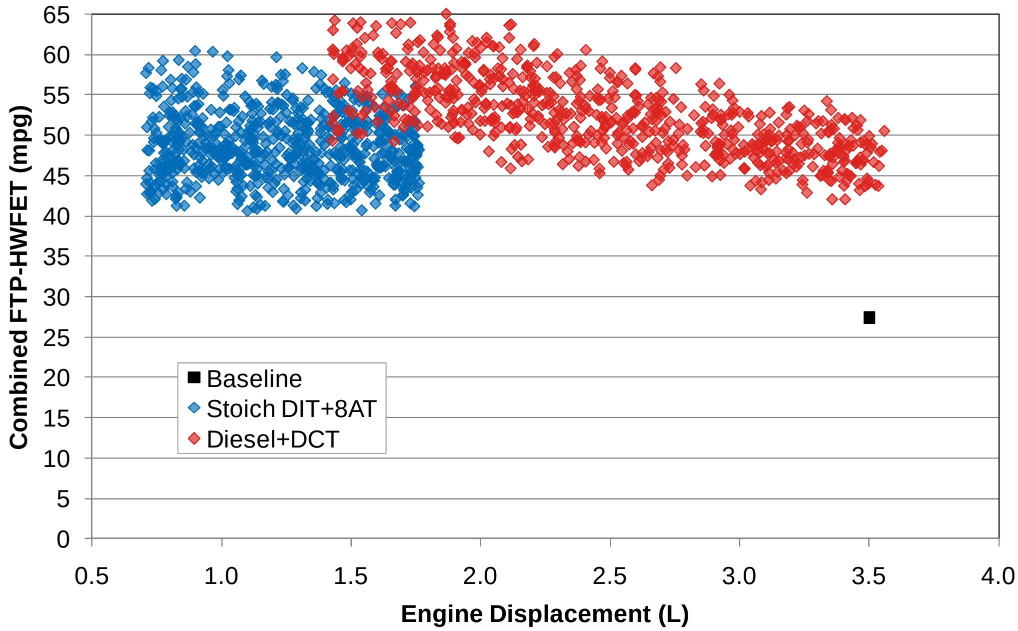

Figure 9.5: Full Size Car Design Space Analysis example. Black point is 2010 baseline; red points are for advanced diesel and dry-clutch DCT; blue points, Stoichiometric DI Turbo with advanced automatic transmission.

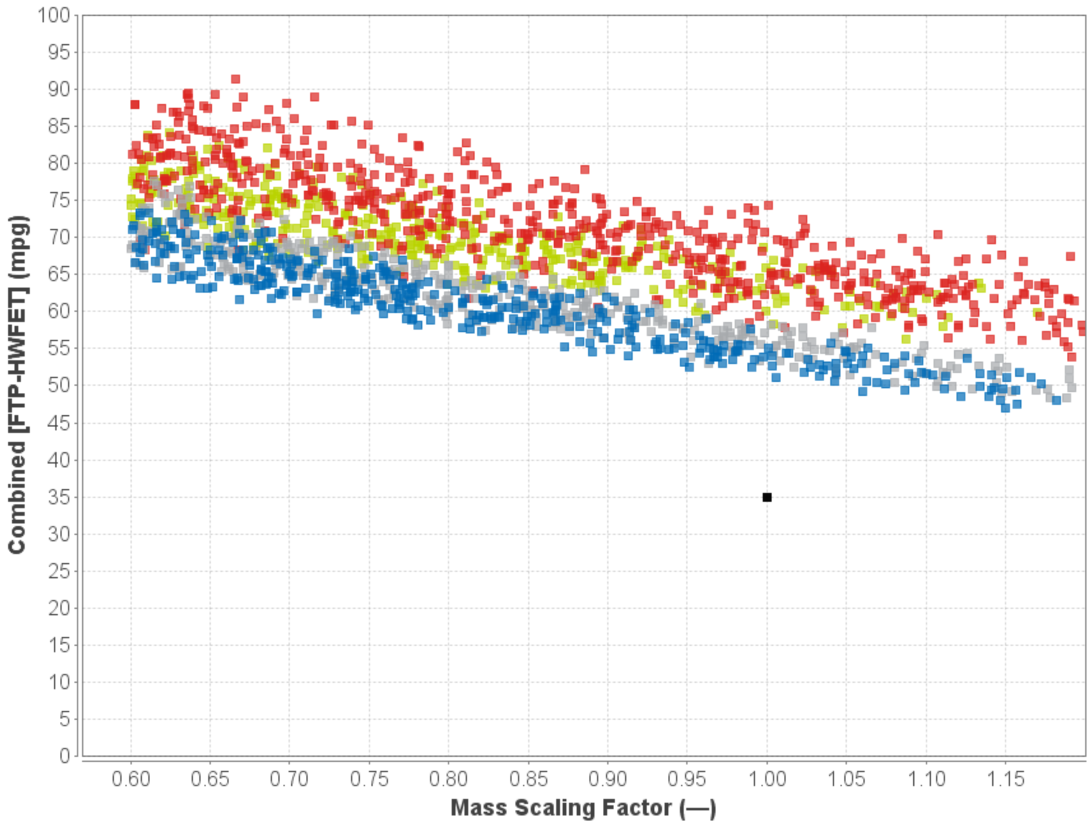

Figure 9.6: Standard Car design space analysis example comparing powertrains with EGR DI Turbo engine. Blue points are with advanced automatic; gray, dry-clutch DCT; green, Powersplit; and red, P2 Hybrid. Black point is 2010 baseline.

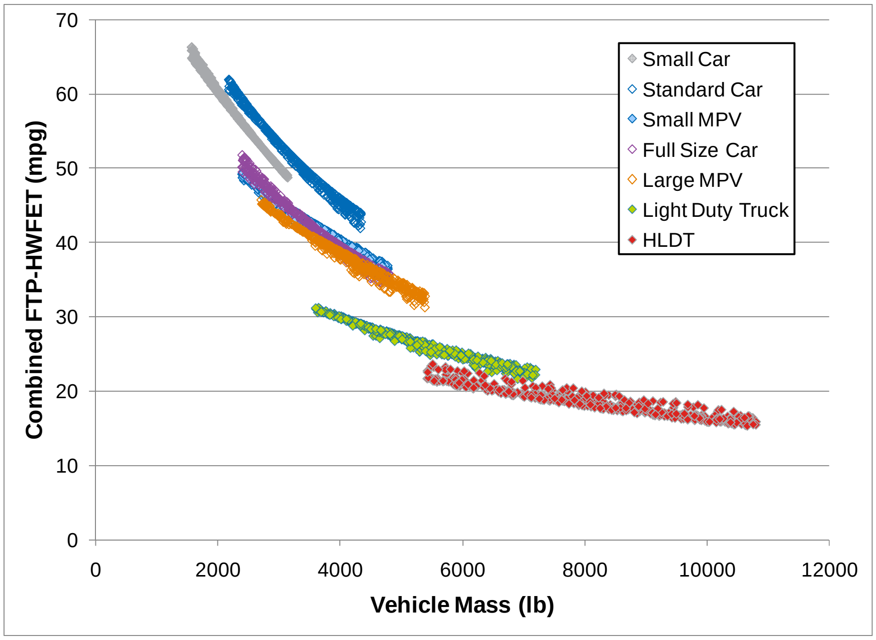

Figure 9.7: Full design space example showing all seven vehicle classes using Stoichiometric DI Turbo engine and advanced automatic transmission with varying vehicle mass and engine displacement.

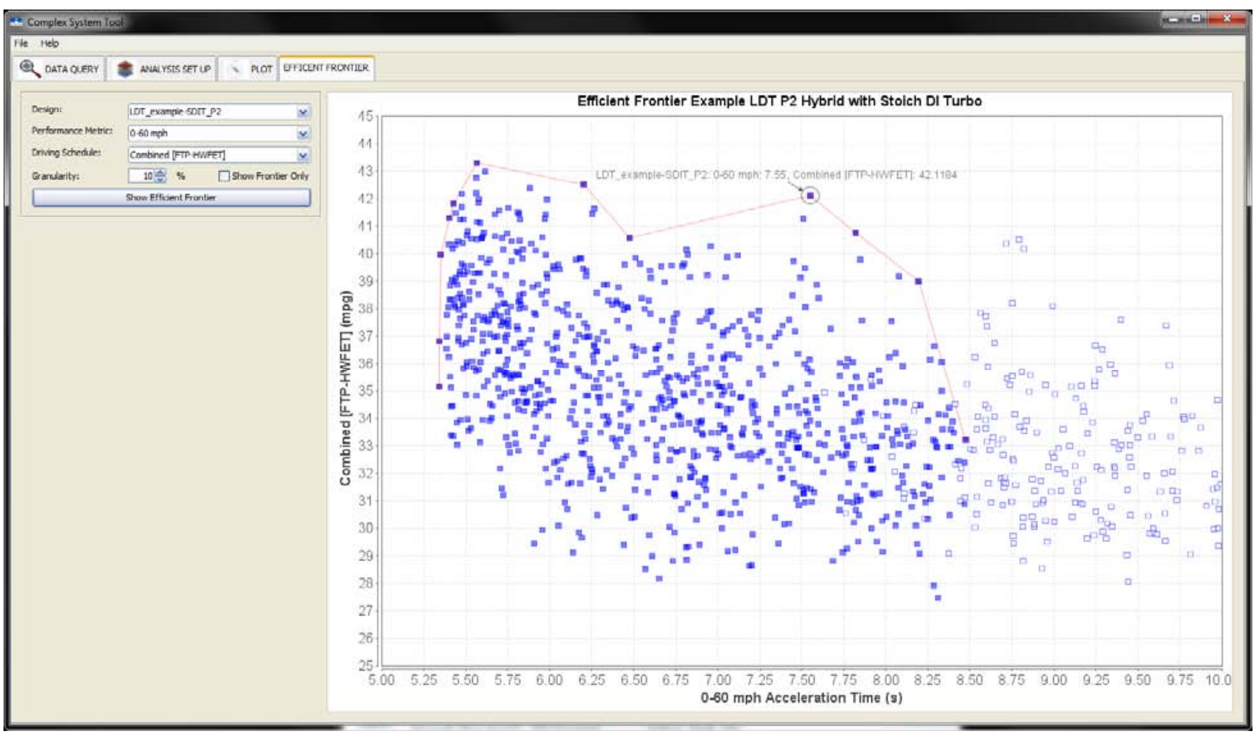

Figure 9.8: Efficient Frontier screen of Data Visualization Tool with example plot.

10. RECOMMENDATIONS FOR FURTHER WORK

Ricardo has the following recommendations for further work on this program:

- Thoroughly analyze and simulate turbo lag effects in the advanced, boosted engines through engine performance simulation tied in with the vehicle models.
- Run the models over additional drive cycles, such as the NEDC, JC08, or the cold ambient FTP, to understand how the technology packages may apply to other global regions.
- Expand the design space to mix 2010 baseline engines and transmissions with the advanced technologies to better understand the relative contributions of engine or transmission technology to the performance of the advanced vehicles.
- Include additional engines with different technology packages, such as a version of the Stoichiometric DI Turbo engine that has a single, fixed cam profile instead of using the CPS valvetrain.
- Develop correlation models for the P2 and Input Powersplit hybrid powertrains to establish a baseline within the simulated design space.
- Implement a Two-Mode Powersplit hybrid powertrain to assess the benefits of hybridization in the larger LDV classes.
- Study the simulation results to understand main and interaction effects between technologies.

11. CONCLUSIONS

The following conclusions are supported by this program's results:

- An independent, objective, and robust analytical study of the effectiveness of selected LDV technologies expected to be prevalent in the 2020–2025 timeframe, and their effects on vehicle performance has been completed.

- A comprehensive review process was completed to identify technologies likely to be available in the 2020–2025 timeframe and to estimate their future performance given current trends and expected developments.

- The vehicle performance models were based upon the underlying physics of the technologies and have been validated with good result to available test data. Quality assurance checks have been made throughout the study to ensure accuracy of the trends in the results.

- The Data Visualization Tool allows EPA and other stakeholders to efficiently examine the design space developed through the program's complex systems modeling approach and to assess trade-offs between various vehicle configurations and their performance. The tool provides the necessary functionality to assess specific vehicle designs or more comprehensively explore the design space.

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- Daniel Gross, Project Engineer
- Tom Gutwald, Innovations Department Manager
- Stuart Horswill, Chief Engineer and Subject Matter Expert
- Henry Huang, Project Engineer
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- Fred Jacquelin, Technical Specialist
- Carl Jenkins, Product Group Director
- Angela Johnson, Principal Engineer
- Neil Johnson, Project Engineer and Subject Matter Expert
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- Chris Mays, Project Director and Subject Matter Expert
- Shaun Mepham, Product Group Director
- Richard Osborne, Chief Engineer and Subject Matter Expert
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- Wayne Thelen, Chief Engineer and Subject Matter Expert
- Marc Wiseman, Principal (Ricardo Strategic Consulting)

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APPENDICES

Appendix 1, Abbreviations

AMT	Automated manual transmission
ARB	California Air Resources Board
BEV	Battery electric vehicle
BMEP	Brake mean effective pressure
BSFC	Brake specific fuel consumption
CI	Compression ignition
CPS	Cam profile switching
CSM	Complex systems modeling
CVT	Continuously variable transmission
DCT	Dual clutch transmission
DI	Direct injection
DoE	Design of experiments
DVA	Digital valve actuation
EGR	Exhaust gas recirculation
EPA	United States Environmental Protection Agency
EPAS	Electric power assisted steering
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FEAD	Front end accessory drive
FIE	Fuel injection equipment
FMEP	Friction mean effective pressure
GHG	Greenhouse gas
ICCT	International Council on Clean Transportation
ICE	Internal combustion engine
IMEP	Indicated mean effective pressure
KERS	Kinetic energy recovery system
LDT	Light-duty truck
LDV	Light-duty vehicle
LEV	Low emissions vehicle
LHDT	Light heavy-duty truck
LNT	Lean NOx trap
MPV	Multi-purpose vehicle
NA	Naturally aspirated
NMEP	Net mean effective pressure
NOx	Nitrogen oxides
NVH	Noise, vibration, and harshness
OEM	Original equipment manufacturer
ORNL	Oak Ridge National Laboratory
OTAQ	Office of Transportation and Air Quality
PAS	Power assisted steering
PFI	Port fuel injection
PHEV	Plug-in hybrid electric vehicle
PMEP	Pumping mean effective pressure
PQA	Perrin Quarles Associates
RSM	Response surface model
SCR	Selective catalytic reduction
SI	Spark ignited
SME	Subject matter expert
SOC	State of charge
SULEV	Super ultra low emissions vehicle
V2I	Vehicle to infrastructure
V2V	Vehicle to vehicle
VA	Valve actuation

Appendix 2, Assessment of Technology Options

At the start of the program, Ricardo and EPA, with input from the Advisory Committee, developed a comprehensive list of technology options for further consideration by Ricardo's Subject Matter Experts. The technologies are listed below. The technologies considered further for assessment are in the related document "Assessment of Technology Options" (Ricardo reference RD.11/ 342305.1), included as Attachment A.

Engine technologies considered included the following:

- Engine downsizing
- Direct injection
- Turbocharging
- Valvetrain technologies and subsystems, including
    - CPS valvetrains
    - DVA or variable valve timing (VVT) valvetrains
- Stratified charge DI
- Homogeneous charge compression ignition (HCCI) or controlled auto-ignition (CAI) combustion
- Exhaust energy recovery, including
    - Mechanical turbo-compounding
    - Electrical turbo-compounding
    - Thermoelectric devices
- Second-generation biofuels
- Friction reduction technologies
- Closed-loop combustion control
- Adjustments to compression ratio
- Advanced boosting technologies
- Enhanced EGR and charge air cooling
- Pre-turbine catalysis
- Calibration optimization for low GHG emissions
- Narrow speed range operation
- Optimization of engines for use with hybrid powertrains

Engine configurations considered included the following:

- Stoichiometric DI turbocharged
- Lean DI turbocharged
- High-load EGR engines
- Multi-mode (2 stroke–4 stroke)
- Engines optimized for hybrid powertrains, including
    - Stop-start powertrains
    - Full hybrid powertrains

Hybrid powertrain technologies, including

- Micro hybrid or stop-start system
- Integrated belt starter-generator (BSG)
- Integrated crank starter-generator (ISG) or Integrated motor assist (IMA)
- P2 parallel hybrid powertrain
- Input Powersplit hybrid powertrain
- Two-mode Powersplit hybrid powertrain

- Series hybrid
- Parallel hydraulic hybrids

Transmission technologies, including
- Advanced automatic transmissions
- AMTs
- CVTs
- DCTs
- Launch devices
    - Wet clutch
    - Damp clutch
    - Dry clutch
    - Multi-damper torque converter
    - Magnetic clutch
- Shifting clutch technology
- Smart kinematic design
- Dry sump
- Efficient components
- Super finishing
- Lubricant improvements

Vehicle technologies, including
- Mass reduction through use of
    - Advanced high strength steels
    - Aluminum alloys
    - Magnesium alloys
    - Plastics and fiber-reinforced composites
- Mass reduction through component optimization
- Passive and active aerodynamics improvements
- Active aerodynamics systems
- Thermoelectric generators
- HVAC system load reduction
- Tire rolling resistance
- Intelligent cooling systems
- Electric PAS

Appendix 3, Baseline Vehicle Parameters and Runs Results

Vehicle Class	Baseline Exemplars	ETW (lb)	Mass (kg)	Cd·A (m^2)	Tire RR Coeff	Wheel velocity coeff (N·s)	Tire rolling radius (m)	Wheel inertia (kg·m^2)	Roadload Power at 50 mph (hp)
Small car	2010 Toyota Yaris	2625	1191	0.736	0.0094	0.100	0.282	0.90	10.8
Standard car	2007 Toyota Camry	3625	1644	0.690	0.0082	0.137	0.320	0.91	11.3
Small MPV	2008 Saturn Vue	4000	1814	0.925	0.0069	0.400	0.340	0.97	15.1
Full sized car	2007Chrysler 300	4000	1814	0.792	0.0113	0.205	0.342	0.97	14.8
Large MPV	2007 Dodge Grand Caravan	4500	2041	0.952	0.0072	0.400	0.330	0.94	15.8
LDT	2007 Ford F150	6000	2722	1.341	0.0081	0.580	0.382	1.00	22.9
LHDT	2010 Chevy Silverado 3500HD (diesel)	9000	4082	1.394	0.0083	1.192	0.374	1.05	31.1

Baseline Vehicles

Vehicle Class	Representative Vehicle	Engine	Peak Torque Output (N-m)	Transmission	ETW (lb)	GCW (lb)	Other Technologies	EPA City FE, CO_2 Equivalent **(mpg,** g/mile)	EPA Highway FE, CO_2 Equivalent **(mpg,** g/mile)	EPA Combined FE, CO_2 Equivalent **(mpg,** g/mile)
Small Car	Yaris	1.5L I4 DOHC 4V	145	6 Speed Auto	2,625	N/A	70% Eff. Alt w/Regen, Stop-Start	**39.8**, 228.3	**48.7**, 186.6	**43.4**, 209.5
Standard Car	Camry	2.4L I4 DOHC 4V	219	6 Speed Auto	3,625	N/A	70% Eff. Alt w/Regen, Stop-Start	**30.0**, 302.9	**43.5**, 208.9	**34.9**, 260.6
Full Size Car	300	3.5L V6 SOHC 4V	335	6 Speed Auto	4,000	N/A	70% Eff. Alt w/Regen, Stop-Start	**23.8**, 381.8	**33.7**, 269.6	**27.4**, 331.3
Small MPV	Vue	2.4L I4 DOHC 4V	219	6 Speed Auto	4,000	N/A	70% Eff. Alt w/Regen, Stop-Start	**27.0**, 336.6	**36.1**, 251.7	**30.5**, 298.4
Large MPV	Caravan	3.8L V6 OHV 2V	319	6 Speed Auto	4,250	N/A	70% Eff. Alt w/Regen, Stop-Start	**22.0**, 413.0	**30.7**, 296.0	**25.2**, 360.4
Light-Duty Truck	F150	5.4L V8 SOHC 3V	495	6 Speed Auto	4,500	N/A	70% Eff. Alt w/Regen, Stop-Start	**16.2**, 560.9	**22.6**, 402.1	**18.6**, 489.4
Light Heavy-Duty Truck	3500HD	6.0L V8 OHV 2V	515	6 Speed Auto	6,000	15,800	70% Eff. Alt w/Regen, Stop-Start	**11.2**, 811.3	**15.1**, 601.8	**12.7**, 717.0
Light Heavy-Duty Truck	3500HD	6.6L V8 OHV 4v	895	6 Speed Auto	9,000	21,200	70% Eff. Alt w/Regen, Stop-Start	**15.6**, 647.2	**19.0**, 531.4	**17.0**, 595.1

Appendix 4, Output Factors for Study

Raw fuel economy in miles per US gallon and GHG emissions in grams of CO_2 per mile over

- FTP75
- HWFET
- US06
- HWFET and FTP combined

Acceleration performance metrics, including

- 0–10 mph acceleration time
- 0–30 mph acceleration time
- 0–50 mph acceleration time
- 0–60 mph acceleration time
- 0–70 mph acceleration time
- 30–50 mph acceleration time
- 50–70 mph acceleration time
- Top speed at 5% grade
- Top speed at 10% grade
- Velocity at 1.3 sec
- Velocity at 3.0 sec
- Distance at 1.3 sec
- Distance at 3.0 sec
- Maximum grade at 70 mph at GCW
- Maximum grade at 60 mph at GCVW (LDT and LHDT only)

Appendix 5, Nominal Runs Results

The table lists the baseline (2010) vehicles first, followed by results by vehicle class. The P2 Hybrids have an electric machine size listed, and all use the DCT. There were no Conventional Stop-Start nominal runs that used the DCT. For the Input Powersplit hybrids, only the traction motor size is listed, as the generator size is a function of the engine and traction motor sizes.

Abbreviations used exclusively in the following table of Nominal Runs Results include the following:

Baseline	The 2010 baseline engine for the given vehicle class
Stoich DIT	Stoichiometric DI Turbo engine
Lean DIT	Lean-Stoichiometric DI Turbo engine
EGR DIT	EGR DI Turbo engine
Adv Diesel	Advanced (2020) diesel
Atk CS	Atkinson cycle engine with CPS
Atk DVA	Atkinson cycle engine with DVA
AT6	Six-speed automatic transmission (baseline or advanced, as appropriate)
AT8	Eight-speed automatic transmission (advanced only)
DCT	Dry or wet clutch DCT, per simulation matrix.
PS	Powersplit planetary gearset

Vehicle Class	Engine Type	Displ (L)	Peak Trq (N.m)	EM Pwr (kW)	Trans-mission	Raw fuel economy (mpg) FTP75	HWFET	US06	Acceleration times (s) 0-10mph	0-30mph	0-50mph	0-60mph	0-70mph	30-50mph	50-70mph	Top Speed (mph) on 5% Grade	10% Grade	Max grade at 60 mph	70 mph	Distance (m) in 1.3 sec	3 sec	Velocity (mph) at 1.3 sec	3 sec
Small Car	Baseline	1.5	145	—	AT6	39.8	48.7	30.3	1.4	4.0	7.4	9.9	13.0	3.4	5.6	94.6	82.2	—	10	2.6	14.7	9.3	22.8
Standard Car	Baseline	2.4	219	—	AT6	30.0	43.5	29.1	1.0	3.1	6.3	8.3	11.4	3.2	5.1	110.4	86.7	—	15	3.9	20.5	14.1	29.5
Full Size Car	Baseline	3.5	335	—	AT6	23.8	33.7	23.6	1.2	3.2	6.1	7.7	9.5	2.9	3.4	127.5	99.6	—	33	3.2	19.3	12.0	29.2
Small MPV	Baseline	2.4	219	—	AT6	27.0	36.1	24.1	1.1	3.4	6.8	9.0	12.6	3.4	5.8	97.9	85.1	—	13	3.3	18.4	12.5	26.9
Large MPV	Baseline	3.8	319	—	AT6	22.0	30.7	21.0	1.1	2.9	6.1	8.6	11.5	3.2	5.4	95.7	82.2	—	16	3.4	20.4	12.9	31.2
LDT	Baseline	5.4	495	—	AT6	16.2	22.6	15.1	1.1	3.1	6.0	8.2	10.8	2.9	4.8	101.4	88.3	20	—	3.4	19.9	12.6	29.8
LHDT	Base SI	6.0	515	—	AT6	11.2	15.1	9.8	1.0	3.1	6.9	9.9	13.3	3.8	6.4	92.8	69.8	15	—	3.7	20.7	14.2	29.9
LHDT	Base Diesel	6.6	895	—	AT6	15.6	19.0	12.3	1.0	3.0	6.7	9.4	13.1	3.7	6.4	99.3	79.3	17	—	4.0	21.3	14.7	30.4
Small Car	Stoich DIT	0.74	157	—	AT6	53.2	55.1	32.4	1.5	4.0	7.4	10.0	13.1	3.4	5.7	96.2	79.3	—	14	2.4	14.1	8.8	22.3
Small Car	Lean DIT	0.74	157	—	AT6	55.1	56.0	32.6	1.5	4.0	7.4	10.0	13.1	3.4	5.7	96.2	79.3	—	14	2.4	14.1	8.8	22.3
Small Car	EGR DIT	0.74	157	—	AT6	55.1	57.4	33.9	1.5	4.0	7.4	10.0	13.1	3.4	5.7	96.2	79.3	—	14	2.4	14.1	8.8	22.3
Small Car	Adv Diesel	1.23	221	—	AT6	55.8	59.4	41.5	1.2	3.7	7.3	9.8	13.2	3.6	5.9	94.0	76.0	—	13	3.2	16.8	10.9	25.1
Small Car	Atk CS	1.66	138	14	DCT6	70.8	59.0	38.1	1.4	3.7	7.5	10.0	13.6	3.8	6.1	85.4	62.1	—	8	2.5	15.5	9.8	24.4
Small Car	Atk DVA	1.66	138	14	DCT6	71.7	60.5	39.4	1.4	3.7	7.5	10.0	13.6	3.8	6.1	85.4	62.1	—	8	2.5	15.5	9.8	24.4
Small Car	Stoich DIT	0.59	124	14	DCT6	68.2	57.3	37.0	1.4	3.8	7.2	9.6	12.6	3.4	5.4	87.5	70.7	—	10	2.4	15.1	9.4	23.6
Small Car	Lean DIT	0.59	124	14	DCT6	68.4	57.7	37.3	1.4	3.8	7.2	9.6	12.6	3.4	5.4	87.5	70.7	—	10	2.4	15.1	9.4	23.6
Small Car	EGR DIT	0.59	124	14	DCT6	70.2	59.9	39.0	1.4	3.8	7.2	9.6	12.6	3.4	5.4	87.5	70.7	—	10	2.4	15.1	9.4	23.6
Small Car	Atk CS	1.66	138	40	PS	64.2	59.5	38.0	1.8	4.7	7.9	9.8	12.2	3.2	4.3	93.5	77.4	—	8	1.5	11.1	6.7	18.5
Small Car	Atk DVA	1.66	138	40	PS	67.3	60.0	39.0	1.8	4.7	7.9	9.8	12.1	3.2	4.2	93.5	77.9	—	8	1.5	11.1	6.7	18.5
Small Car	Stoich DIT	0.59	124	40	PS	64.7	57.2	35.2	1.9	4.8	8.2	10.4	13.1	3.4	4.9	89.5	71.3	—	8	1.5	10.8	6.5	18.1
Small Car	Lean DIT	0.59	124	40	PS	65.8	57.4	35.2	1.9	4.8	8.2	10.4	13.1	3.4	4.9	89.1	71.3	—	8	1.5	10.8	6.5	18.1
Small Car	EGR DIT	0.59	124	40	PS	67.7	60.1	36.7	1.9	4.8	8.2	10.4	13.1	3.4	4.9	89.1	71.3	—	8	1.5	10.8	6.5	18.1
Standard Car	Stoich DIT	1.04	220	—	AT8	44.8	54.5	32.5	1.0	3.1	6.2	8.5	11.4	3.1	5.2	107.7	86.2	—	15	3.7	20.7	14.0	29.7
Standard Car	Lean DIT	1.04	220	—	AT8	46.6	55.5	32.8	1.0	3.1	6.2	8.5	11.4	3.1	5.2	107.7	86.2	—	15	3.7	20.7	14.0	29.7
Standard Car	EGR DIT	1.04	220	—	AT8	46.4	56.7	34.0	1.0	3.1	6.2	8.5	11.4	3.1	5.2	107.7	86.2	—	15	3.7	20.7	14.0	29.7
Standard Car	Atk CS	2.40	200	24	DCT8	64.6	59.7	39.8	1.2	3.4	6.5	8.6	11.4	3.1	4.9	101.3	78.4	—	11	2.8	17.4	11.0	27.3
Standard Car	Atk DVA	2.40	200	24	DCT8	65.9	61.0	40.5	1.2	3.4	6.5	8.6	11.4	3.1	4.9	101.3	78.4	—	11	2.8	17.4	11.0	27.3
Standard Car	Stoich DIT	0.83	176	24	DCT8	61.9	57.2	36.9	1.3	3.6	6.5	8.6	11.3	2.9	4.8	98.1	77.4	—	12	2.6	16.6	10.5	25.8
Standard Car	Lean DIT	0.83	176	24	DCT8	62.9	58.0	36.7	1.3	3.6	6.5	8.6	11.3	2.9	4.8	98.1	77.4	—	12	2.6	16.6	10.5	25.8
Standard Car	EGR DIT	0.83	176	24	DCT8	65.1	59.7	38.4	1.3	3.6	6.5	8.6	11.3	2.9	4.8	98.1	77.4	—	12	2.6	16.6	10.5	25.8
Standard Car	Atk CS	2.40	200	80	PS	53.3	51.7	36.8	1.4	3.6	6.2	8.0	10.2	2.6	4.0	105.2	85.5	—	10	2.2	15.2	9.3	25.1
Standard Car	Atk DVA	2.40	200	80	PS	56.4	53.3	37.6	1.4	3.6	6.2	8.0	10.2	2.6	4.0	105.2	85.8	—	10	2.2	15.2	9.3	25.1
Standard Car	Stoich DIT	0.83	176	80	PS	55.6	51.7	35.4	1.5	3.7	6.6	8.7	11.3	2.9	4.7	99.0	78.1	—	10	2.1	14.9	9.1	24.4
Standard Car	Lean DIT	0.83	176	80	PS	57.9	53.5	36.0	1.5	3.7	6.6	8.7	11.3	2.9	4.7	99.0	78.1	—	10	2.1	14.9	9.1	24.4
Standard Car	EGR DIT	0.83	176	80	PS	58.0	54.8	37.1	1.5	3.7	6.6	8.7	11.3	2.9	4.7	99.0	78.1	—	10	2.1	14.9	9.1	24.4
Small MPV	Stoich DIT	1.13	239	—	AT8	38.8	42.6	25.7	1.2	3.3	6.5	8.9	12.0	3.2	5.5	99.8	81.2	—	14	3.1	18.7	11.6	28.3
Small MPV	Lean DIT	1.13	239	—	AT8	40.3	43.1	25.9	1.2	3.3	6.5	8.9	12.0	3.2	5.5	99.8	81.2	—	14	3.1	18.7	11.6	28.3
Small MPV	EGR DIT	1.13	239	—	AT8	40.3	44.4	27.0	1.2	3.3	6.5	8.9	12.0	3.2	5.5	99.8	81.2	—	14	3.1	18.7	11.6	28.3
Small MPV	Atk CS	2.60	217	20	DCT8	52.9	45.5	29.6	1.4	3.7	7.1	9.3	12.6	3.4	5.5	91.3	76.7	—	10	2.3	15.4	9.4	25.1
Small MPV	Atk DVA	2.60	217	20	DCT8	54.1	46.8	30.3	1.4	3.7	7.1	9.3	12.6	3.4	5.5	91.3	76.7	—	10	2.3	15.4	9.5	25.1
Small MPV	Stoich DIT	0.90	190	20	DCT8	50.1	44.2	28.5	1.5	3.9	7.0	9.4	12.3	3.1	5.3	90.6	72.7	—	11	2.1	14.6	8.9	23.7
Small MPV	Lean DIT	0.90	190	20	DCT8	50.8	44.5	28.5	1.5	3.9	7.0	9.4	12.3	3.1	5.3	90.6	72.7	—	11	2.1	14.6	8.9	23.7
Small MPV	EGR DIT	0.90	190	20	DCT8	52.0	46.1	29.8	1.5	3.9	7.0	9.4	12.3	3.1	5.3	90.6	72.7	—	11	2.1	14.6	8.9	23.7
Small MPV	Atk CS	2.60	217	70	PS	44.3	39.6	25.1	1.9	4.6	7.4	9.1	11.1	2.8	3.7	98.3	81.4	—	9	1.4	10.5	6.1	18.0
Small MPV	Atk DVA	2.60	217	70	PS	49.3	42.3	28.6	1.9	4.6	7.4	9.1	11.1	2.8	3.7	98.3	81.6	—	9	1.4	10.5	6.1	18.0
Small MPV	Stoich DIT	0.90	190	70	PS	49.1	42.2	27.4	1.9	4.7	8.0	10.3	13.1	3.3	5.1	92.2	73.3	—	8	1.4	10.4	6.1	17.7
Small MPV	Lean DIT	0.90	190	70	PS	50.8	42.7	27.3	1.9	4.7	8.0	10.3	13.2	3.3	5.2	92.2	73.3	—	8	1.4	10.4	6.1	17.7
Small MPV	EGR DIT	0.90	190	70	PS	51.3	44.9	28.8	1.9	4.7	8.0	10.3	13.2	3.3	5.2	92.2	73.3	—	8	1.4	10.4	6.1	17.7

Vehicle Class	Engine Type	Displ (L)	Peak Trq (N.m)	EM Pwr (kW)	Trans-mission	Raw fuel economy (mpg) FTP75	HWFET	US06	Acceleration times (s) 0-10mph	0-30mph	0-50mph	0-60mph	0-70mph	30-50mph	50-70mph	Top Speed (mph) on 5% Grade	10% Grade	Max grade at 60 mph	70 mph	Distance (m) in 1.3 sec	3 sec	Velocity (mph) at 1.3 sec	3 sec
Full Size Car	Stoich DIT	1.41	298	—	AT8	37.1	43.2	27.2	1.2	3.0	5.7	7.4	9.8	2.7	4.1	116.1	95.8	—	20	3.2	19.7	12.1	30.7
Full Size Car	Lean DIT	1.41	298	—	AT8	38.8	44.0	27.6	1.2	3.0	5.7	7.4	9.8	2.7	4.1	116.1	95.8	—	20	3.2	19.7	12.1	30.7
Full Size Car	EGR DIT	1.41	298	—	AT8	38.6	44.9	28.5	1.2	3.0	5.7	7.4	9.8	2.7	4.1	116.1	95.8	—	20	3.2	19.7	12.1	30.7
Full Size Car	Adv Diesel	2.85	503	—	AT8	38.2	46.5	32.5	1.1	2.9	5.6	7.5	9.8	2.7	4.2	113.7	94.9	—	19	3.5	20.2	12.4	31.1
Full Size Car	Atk CS	3.80	317	28	DCT8	49.9	46.2	31.5	1.2	3.0	5.5	7.1	9.0	2.5	3.5	113.4	87.9	—	22	2.8	18.6	11.4	30.1
Full Size Car	Atk DVA	3.80	317	28	DCT8	51.1	47.4	31.9	1.2	3.0	5.5	7.1	9.0	2.5	3.5	113.4	87.9	—	22	2.8	18.6	11.4	30.1
Full Size Car	Stoich DIT	1.13	238	28	DCT8	49.8	46.5	31.3	1.3	3.4	6.1	7.7	10.0	2.7	3.9	105.9	86.6	—	15	2.5	16.9	10.5	27.1
Full Size Car	Lean DIT	1.13	238	28	DCT8	50.4	46.8	31.4	1.3	3.4	6.1	7.7	10.0	2.7	3.9	105.9	86.6	—	15	2.5	16.9	10.5	27.1
Full Size Car	EGR DIT	1.13	238	28	DCT8	51.7	48.3	32.6	1.3	3.4	6.1	7.7	10.0	2.7	3.9	105.9	86.6	—	15	2.5	16.9	10.5	27.1
Full Size Car	Atk CS	3.80	317	120	PS	40.3	38.7	29.2	1.3	3.2	5.6	7.1	8.7	2.4	3.1	119.2	103.5	—	16	2.7	17.7	10.7	28.6
Full Size Car	Atk DVA	3.80	317	120	PS	43.0	40.8	29.8	1.3	3.2	5.6	7.1	8.7	2.4	3.1	119.2	103.5	—	16	2.7	17.7	10.7	28.7
Full Size Car	Stoich DIT	1.13	238	120	PS	46.6	42.0	29.8	1.3	3.2	6.0	7.8	10.0	2.8	4.0	106.2	87.6	—	12	2.6	17.2	10.4	28.2
Full Size Car	Lean DIT	1.13	238	120	PS	48.0	41.8	29.9	1.3	3.2	5.9	7.8	10.0	2.7	4.1	106.2	87.7	—	12	2.6	17.2	10.4	28.3
Full Size Car	EGR DIT	1.13	238	120	PS	47.9	43.6	31.1	1.3	3.2	6.0	7.8	10.0	2.8	4.0	106.2	87.7	—	12	2.6	17.2	10.4	28.2
Large MPV	Stoich DIT	1.31	277	—	AT8	34.8	39.2	23.7	1.1	3.2	6.4	8.6	11.5	3.2	5.1	103.7	84.5	—	15	3.4	19.8	13.2	29.1
Large MPV	Lean DIT	1.31	277	—	AT8	36.0	39.8	23.9	1.1	3.2	6.4	8.6	11.5	3.2	5.1	103.7	84.5	—	15	3.4	19.8	13.2	29.1
Large MPV	EGR DIT	1.31	277	—	AT8	36.2	40.9	24.9	1.1	3.2	6.4	8.6	11.5	3.2	5.1	103.7	84.5	—	15	3.4	19.8	13.2	29.1
Large MPV	Adv Diesel	2.61	460	—	AT8	37.3	43.3	29.4	1.1	3.0	6.2	8.6	11.5	3.2	5.3	101.9	83.9	—	14	3.7	20.9	13.3	30.5
Large MPV	Atk CS	3.15	263	25	DCT8	48.3	42.4	27.5	1.4	3.6	6.7	8.8	11.6	3.1	4.9	95.5	82.3	—	11	2.4	15.7	9.7	26.0
Large MPV	Atk DVA	3.15	263	25	DCT8	48.8	43.5	27.7	1.4	3.6	6.7	8.8	11.6	3.1	4.9	95.5	82.3	—	11	2.4	15.7	9.7	26.0
Large MPV	Stoich DIT	1.05	221	25	DCT8	47.7	42.2	26.2	1.5	3.8	6.9	9.1	11.9	3.1	5.0	94.3	75.6	—	12	2.2	14.7	9.0	23.9
Large MPV	Lean DIT	1.05	221	25	DCT8	47.4	42.6	26.8	1.5	3.8	6.9	9.1	11.9	3.1	5.0	94.3	75.6	—	12	2.2	14.7	9.0	23.9
Large MPV	EGR DIT	1.05	221	25	DCT8	47.6	43.0	27.6	1.5	3.8	6.9	9.1	11.9	3.1	5.0	94.3	75.6	—	12	2.2	14.7	9.0	23.9
Large MPV	Atk CS	3.15	263	90	PS	41.7	38.6	26.5	1.8	4.2	7.0	8.8	11.1	2.8	4.1	103.4	86.0	—	11	1.5	11.7	6.8	20.2
Large MPV	Atk DVA	3.15	263	90	PS	44.3	39.6	27.0	1.8	4.2	7.0	8.8	11.1	2.8	4.1	103.4	86.5	—	11	1.5	11.7	6.8	20.2
Large MPV	Stoich DIT	1.05	221	90	PS	44.8	39.3	25.8	1.8	4.3	7.5	9.7	12.5	3.2	5.0	100.2	76.5	—	9	1.5	11.5	6.7	19.7
Large MPV	Lean DIT	1.05	221	90	PS	45.7	40.6	25.7	1.8	4.3	7.5	9.7	12.5	3.2	5.0	100.8	76.5	—	9	1.5	11.5	6.7	19.7
Large MPV	EGR DIT	1.05	221	90	PS	47.0	41.5	27.3	1.8	4.3	7.5	9.7	12.5	3.2	5.0	100.8	76.5	—	9	1.5	11.5	6.7	19.7
LDT	Stoich DIT	1.94	410	—	AT8	23.8	26.6	16.3	1.1	3.0	6.0	8.1	10.8	3.0	4.8	105.6	86.9	21	—	3.4	20.5	13.2	30.5
LDT	Lean DIT	1.94	410	—	AT8	24.6	27.0	16.4	1.1	3.0	6.0	8.1	10.8	3.0	4.8	105.6	86.9	21	—	3.4	20.5	13.2	30.5
LDT	EGR DIT	1.94	410	—	AT8	24.8	27.7	17.1	1.1	3.0	6.0	8.1	10.8	3.0	4.8	105.6	86.9	21	—	3.4	20.5	13.2	30.5
LDT	Adv Diesel	4.28	694	—	AT8	26.4	30.4	20.5	1.0	2.9	5.8	8.0	10.6	2.9	4.8	104.6	87.2	20	—	3.7	21.4	13.5	31.5
LDT	Atk CS	4.60	384	50	DCT8	33.2	29.0	19.4	1.1	3.1	5.9	7.8	10.3	2.8	4.4	95.6	83.8	17	—	3.1	19.1	12.2	29.5
LDT	Atk DVA	4.60	384	50	DCT8	33.9	29.7	19.7	1.1	3.1	5.9	7.8	10.3	2.8	4.4	95.6	83.8	17	—	3.1	19.1	12.2	29.5
LDT	Stoich DIT	1.55	327	50	DCT8	32.5	28.4	18.9	1.2	3.3	6.1	7.9	10.4	2.8	4.3	96.1	78.0	16	—	3.0	18.2	11.7	27.9
LDT	Lean DIT	1.55	327	50	DCT8	33.0	28.6	18.8	1.2	3.3	6.1	7.9	10.4	2.8	4.3	96.1	78.0	16	—	3.0	18.2	11.7	27.9
LDT	EGR DIT	1.55	327	50	DCT8	33.8	29.6	19.7	1.2	3.3	6.1	7.9	10.4	2.8	4.3	96.1	78.0	16	—	3.0	18.2	11.7	27.9
LHDT	Stoich DIT	2.30	486	—	AT8	16.5	18.3	11.1	1.0	3.2	7.0	9.8	13.4	3.8	6.4	95.1	74.8	16	—	3.6	20.2	13.9	28.6
LHDT	Lean DIT	2.30	486	—	AT8	16.8	18.4	11.2	1.0	3.2	7.0	9.8	13.4	3.8	6.4	95.1	74.8	16	—	3.6	20.2	13.9	28.6
LHDT	EGR DIT	2.30	486	—	AT8	17.2	19.1	11.7	1.0	3.2	7.0	9.8	13.4	3.8	6.4	95.1	74.8	16	—	3.6	20.2	13.9	28.6
LHDT	Adv Diesel	6.60	895	—	AT8	19.8	21.5	14.1	0.9	2.9	6.3	8.8	11.8	3.4	5.5	101.5	79.3	17	—	4.2	22.2	15.1	31.0

DISCLAIMER

ATTACHMENT A

Attachment A is the document "Assessment of Technology Options", which includes Ricardo SME assessments of the technologies considered in study "Computer Simulation of Light Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020–2025 Timeframe".

These assessments were made of the technologies listed in Appendix 2.

Assessment of Technology Options

Technologies considered in study "Computer Simulation of Light Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020–2025 Timeframe"

Date	**30 September 2011**
Report	**RD.11/342305.1**
Project	**CG001019**
Prepared for	**EPA Office of Transportation and Air Quality**
Report by	**Jennifer Durfy Stuart Horswill Chris Mays Richard Osborne John Stokes Wayne Thelen**
Approved	**John J. Kasab**

Outline

- **Introduction**
- Spark ignited engine technologies
- Diesel engine technologies
- Hybrid vehicle technologies
- Transmission technologies
- Vehicle technologies
- Conclusions

Introduction

- The following technology assessments were discussed by Ricardo, EPA, and the Advisory Committee at the start of the study, "Computer Simulation of Light Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020–2025 Timeframe"
- Purpose of the assessments was to evaluate a large set of potential future technologies against the following criteria:
  - Effectiveness of Technology
  - Availability of Technology in 2020–2025
  - Market Penetration of Technology in 2020–2025
  - Long-Term Cost Viability
  - Current Technology Maturity
- Assessments used the scale on the following slide and were based on the Ricardo Subject Matter Experts' experience with the systems considered
- Based on the evaluation and discussion, a subset of these technologies was included in the final study.

Details of the rating system

Effectiveness of Technology (tank to wheels basis)

- 1 = Worst = no CO_2 benefit
- 2 = 1% CO_2 benefit
- 5 = 5% CO_2 benefit
- 8 = 10% CO_2 benefit
- 10 = Best = ≥20% CO_2 benefit

Availability of Technology in 2020–2025

- 1 = University Research Laboratory
- 3 = Technology available but not in vehicles
- 4 = First Prototype in vehicles
- 6 = In Fleet Trials
- 7 = First entry into market
- 10 = Predominant technology in market place

Market Penetration of Technology in 2020–2025

- 1 = Worst = Demonstrated technology by 2025
- 3 = Only in niche applications
- 5 = Available, but not widespread (≥5% of market)
- 7 = Mass-market availability (≥10% of market)
- 10 = Best = Widespread (≥25% of market)

Long-Term Cost Viability

- 1 = WORST = no pathway to long-term cost viability
- 3 = Needs to "cross commercialization chasm"
- 5 = Pathway to volume production costs
- 7 = Return on investment clear
- 10 = Profitable in 2020-2025

Current Technology Maturity

- 1 = University Research Laboratory
- 3 = Technology available but not in vehicles
- 4 = First Prototype in vehicles
- 6 = In Fleet Trials
- 7 = First entry into market
- 10 = Predominant technology in market place

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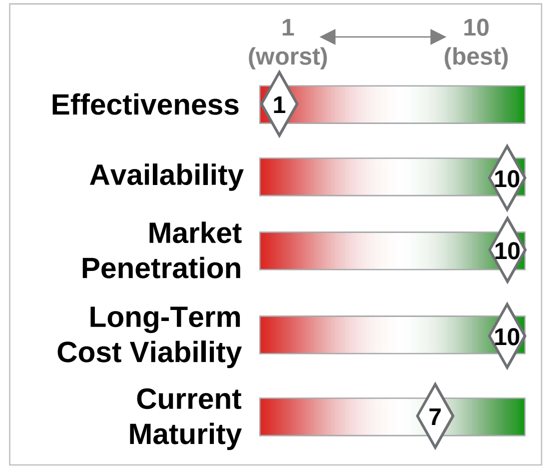
Baseline Gasoline Engines

Technology and Status

- **Concept:** The baseline gasoline engines for 2020–2025 light-duty vehicles in the US market are a range of naturally-aspirated port fuel-injected (PFI) engines, featuring dual-independent cam phaser (VVT) systems
- **Base Functioning:** The baseline vehicles will achieve a fleet average emissions level of SULEV 2 (approximately EPA Tier 2 Bin 2)
- **CO_2 Benefit:** Baseline (>35.5 mpg fleet average)
- **Costs:** Baseline – powertrain and aftertreatment cost of ~$1500–$2000 for standard car segment

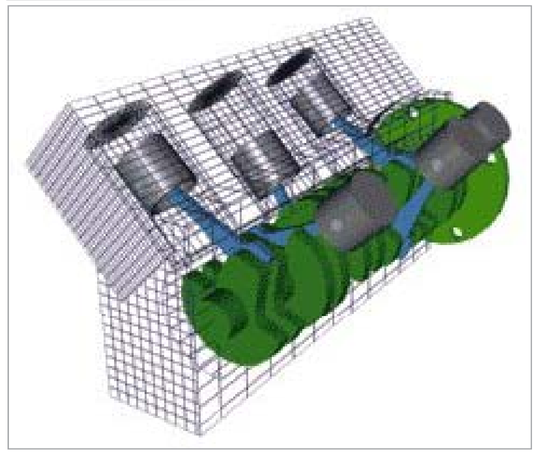
Ratings of Technology



Technology Applicability

- The following vehicle classes are the subject of this study:
  - Small car (Ford Focus)
  - Standard car (Toyota Camry)
  - Small MPV (Saturn Vue)
  - Full-size car (Chrysler 300C)
  - Large MPV (Dodge Grand Caravan)
  - Truck (Ford F150)
  - Heavy light-duty truck (Ford F250/F350)

Visualization



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Stoichiometric Direct-Injection Turbocharged Engines

RICARDO

Technology and Status

- **Concept:** Downsizing describes the replacement of a naturally-aspirated engine with a smaller-displacement turbocharged engine, having equivalent torque and power
- **Base Functioning:** Downsizing reduces pumping work by shifting operating points to higher load factors, and can also produce reductions in frictional losses
- **CO_2 Benefit:** Drive-cycle benefit of 8–10%
- **Costs:** 15–25% increase in engine and aftertreatment cost

Ratings of Technology

1 (worst) ↔ 10 (best)

Effectiveness	7
Availability	8
Market Penetration	5
Long-Term Cost Viability	9
Current Maturity	8

Technology Applicability

- Downsized DI turbo engines are applicable in all light-duty vehicle classes
  - Likely to predominate in mid-size vehicles
- As a high compression ratio is maintained, downsized DI turbo engines provide fuel economy benefits across the majority of the operating map
  - As a result, both city and highway fuel economy will benefit

Visualization

Lean Direct-Injection Turbocharged (LDIT) Engines

Technology and Status

- **Concept:** In the LDIT concept the octane requirement is controlled using direct injection and lean operation at full load
- **Base Functioning:** LDIT engines combine the downsizing benefits described on the previous slide with the additional efficiency benefit of homogeneous lean operation at high load
- **CO_2 Benefit:** Drive-cycle benefit of 20–22%
- **Costs:** 50–60% increase in engine and aftertreatment cost

Ratings of Technology

Technology Applicability

- LDIT engines are applicable to all vehicle classes
  - Likely to predominate in mid-size vehicles and premium vehicles
- As a high compression ratio is maintained and lean operation is applied at all conditions LDIT engines provide fuel economy benefits across the majority of the operating map
  - As a result, both city and highway fuel economy will benefit

Visualization

High-Load EGR Engines

Technology and Status

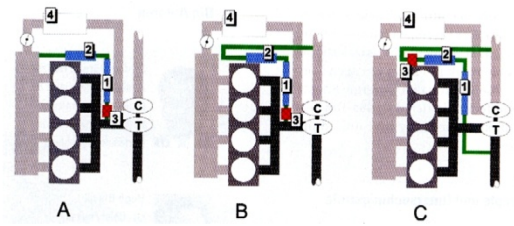
- **Concept:** This downsized DI engine concept is analogous to LDIT, but octane requirement is controlled by EGR dilution at full load rather than lean operation.
- **Base Functioning:** High-load EGR engines combine the benefits of downsizing described previously with the additional efficiency improvement of EGR dilution at high load
- **CO_2 Benefit:** Drive-cycle benefit of 15–18%
- **Costs:** 40–45% increase in engine and aftertreatment cost

Ratings of Technology

Technology Applicability

- High-load EGR engines are applicable to all vehicle classes
- As a high compression ratio is maintained and EGR dilution is applied at all conditions, High-load EGR engines provide fuel economy benefits across the operating map
  - As a result, both city and highway fuel economy will benefit

Visualization



Two-Stroke/Four-Stroke (2S-4S) Switching Engines

Technology and Status

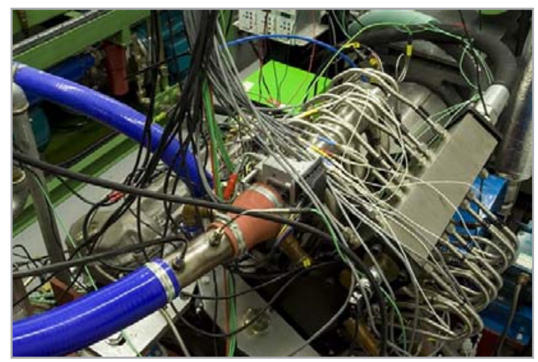
- **Concept:** The vast majority of passenger cars use the four-stroke cycle, but some characteristics of two-stroke engines—especially high specific torque—remain attractive for automotive application. 2S-4S engines combine a combustion system capable of operating as both two-stroke and four-stroke with advanced valvetrain and boosting systems.
- **Base Functioning:** 2S-4S engines offer the greatest opportunity for engine downsizing, and hence improvement in efficiency
- **CO_2 Benefit:** Drive-cycle benefit of 25–27%
- **Costs:** 70–80% increase in engine and aftertreatment cost

Ratings of Technology

Technology Applicability

- 2S-4S engines operate in four-stroke mode for the majority of drive-cycle operation, so the emissions and fuel economy characteristics are those of a heavily downsized 4S DI turbo engine
- 2S-4S engines are most likely to be applied in premium vehicle segments

Visualization



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Cam-Profile Switching Engines

Technology and Status

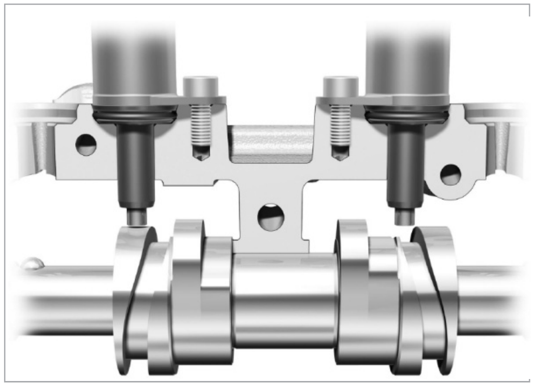
- **Concept:** Cam-profile switching (CPS) systems allow selection between two or three cam profiles by means of a hydraulically-actuated mechanical system
  - CPS systems have been developed by a number of Japanese and European OEMs, such as the Honda VTEC, Mitsubishi MIVEC, Porsche VarioCam and Audi Valvelift (pictured)
- **Base Functioning:** CPS systems can be optimised either to improve low-speed torque, or to improve fuel economy by reducing pumping losses at light load
- **CO_2 Benefit:** Drive-cycle benefit of 5–7%
- **Costs:** 8–10% increase in engine and aftertreatment cost

Ratings of Technology

Technology Applicability

- Cam-profile switching systems are applicable in all light-duty vehicle classes
- CPS systems produce most fuel economy benefit for part-load operation, so most benefit occurs for city driving and less for highway use

Visualization



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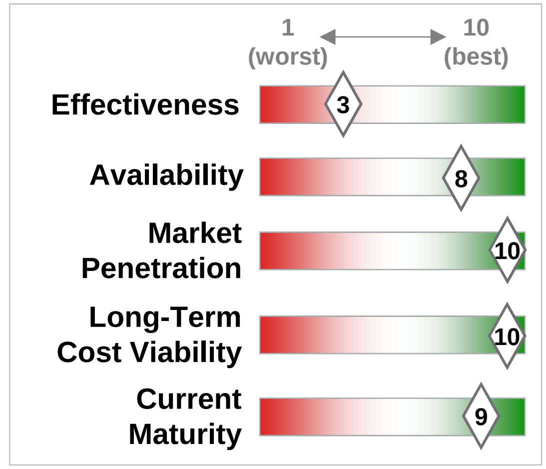
Stoichiometric Direct-Injection Engines

Technology and Status

- **Concept:** Stoichiometric, homogeneous direct-injection gasolines operate in a very similar manner to port fuel-injected engines, except that fuel is injected directly into the cylinder. GDI engines were first introduced in Japan in 1996, and a significant number of new gasoline engines now feature direct injection.
- **Base Functioning:** The application of direct injection produces modest fuel economy benefits, resulting from the ability to apply higher compression ratio.
- **CO_2 Benefit:** Drive-cycle benefit of ~3%
- **Costs:** 8–10% increase in engine and aftertreatment cost

Ratings of Technology



Technology Applicability

- Stoichiometric DI engines are applicable in all vehicle classes
- The higher compression ratio facilitated by DI improves both part-load and high-load efficiency, and therefore both highway and city fuel economy

Visualization

Stratified Charge Direct-Injection Engines

Technology and Status

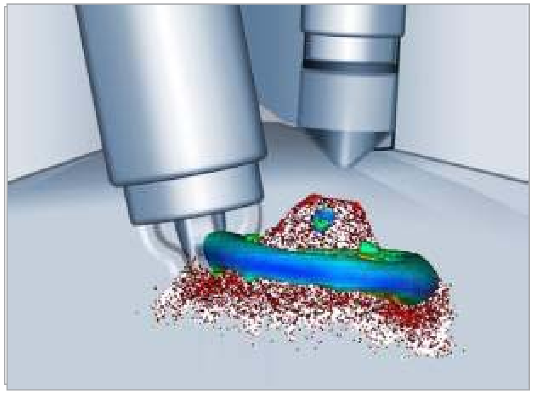
- **Concept:** In stratified-charge engines the fuel is injected late in the compression stroke with single or multiple injections. The aim is to produce an overall lean, stratified mixture, with a rich area in the region of the spark plug to enable stable ignition.
- **Base Functioning:** Stratified lean operation allows the gasoline engine to operate unthrottled, eliminating the majority of pumping losses.
- **CO_2 Benefit:** Drive-cycle benefit of 8–10%
- **Costs:** 15–25% increase in engine and aftertreatment cost

Ratings of Technology

Technology Applicability

- As a result of the FIE and aftertreatment costs, lean DI systems are most applicable in premium vehicles
- As the fuel economy benefit derives from the reduction of pumping work, lean DI engines produce most improvement in city driving
  - There is limited benefit for highway driving

Visualization



HCCI/CAI Combustion

Technology and Status

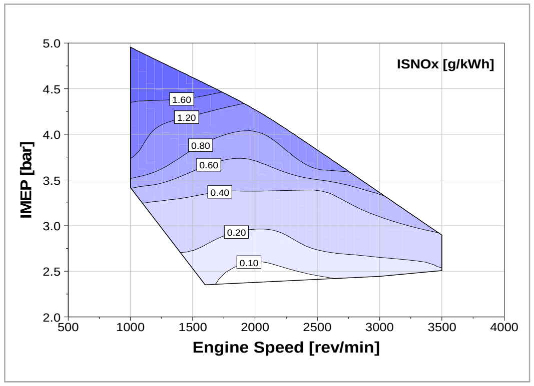
- **Concept:** Homogeneous charge compression ignition (HCCI), also known as controlled auto-ignition (CAI) combustion are distinct from the conventional SI and CI engine operating modes
  - In the idealized case HCCI/CAI combustion initiates simultaneously at multiple sites within the combustion chamber, and there is little or no flame propagation
- **Base Functioning:** Dual mode operation, with HCCI/CAI at part-load, and SI for high-load, idle and starting
- **CO_2 Benefit:** Drive-cycle benefit of 2–10% (depending on whether the benefits of the constituent technologies are included or not)
- **Costs:** 20–30% increase in engine and aftertreatment cost

Ratings of Technology

Technology Applicability

- HCCI/CAI combustion is unlikely to be an attractive technology for light-duty gasoline vehicles in 2020–2025
  - The operating envelope for HCCI/CAI combustion is very limited, and the additional benefits over the necessary constituent technologies (advanced valvetrains, GDI etc.) are also small

Visualization



Exhaust Energy Recovery

Technology and Status

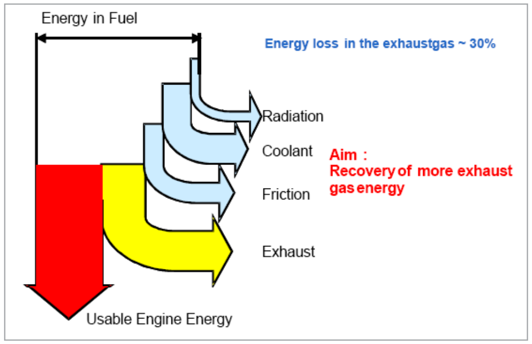
- **Concept:** Exhaust energy recovery encompasses a number of technologies, such as turbo-compounding and thermoelectric devices
  - In turbo-compounding a radial turbine is connected through a mechanical transmission directly to the crankshaft
- **Base Functioning:** Turbines are generally sized to recover energy at high load operation; a variable-speed transmission between engine and turbine can be used to improve the efficient operating range
- **CO_2 Benefit:** Turbo-compounding has a drive-cycle benefit of 3–5%
- **Costs:** Not established for light-duty vehicles

Ratings of Technology

Technology Applicability

- Turbo-compounding is currently only applied to premium long-haul trucks
  - In 2020 it will still be most applicable to the heavy light-duty truck segment, and the benefits will be reduced in comparison to heavy-duty vehicles

Visualization



Second-Generation Biofuels

Technology and Status

- **Concept:** Second-generation biofuels refer to fuels coming from non-food sources (in this case gasoline-like fuels)
- **Base Functioning:** Wherever possible biofuels should operate in a manner identical to conventional gasoline
  - Increasing blending of conventional gasoline and biofuels is likely to occur
- **CO_2 Benefit:** The CO_2 benefits from the use of biofuels are complex and disputed
- **Costs:** There is no significant engine cost associated with the use of single-fuel biofuels (although appropriate materials must be applied in the fuel system)

Ratings of Technology

Technology Applicability

- Biofuels are applicable to all vehicle classes
- Tank-to-wheels fuel economy for biofuels is similar to that for conventional gasoline engines – benefits occur from the higher octane number of ethanol-based fuels
- Additional CO_2 benefits can be attributed to biofuel use if the complete life-cycle is considered (cellulosic ethanol, etc.)

Visualization

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Engines Optimized Micro-Hybrid (Stop-Start) Vehicles

Technology and Status

- **Concept:** Application of stop-start or micro-hybrid concepts requires only very minor changes in base engine architecture. Typically a belt-driven starter-generator is applied in place of a separate starter motor and alternator.
- **Base Functioning:** *See hybrid vehicle slides*
- **CO_2 Benefit:** *See hybrid vehicle slides*
- **Costs:** Base engine costs are largely unchanged for stop-start systems. Additional engineering cost is required to implement the stop-start calibration.

Ratings of Technology

Technology Applicability

- Stop-start should applied in all vehicle segments for the 2020 timeframe
- Given hybrid inititives, it is likely that most new engine development projects will consider integrating stop start functionality in program.

Visualization

Engines Optimized for Full Hybrid Vehicles

Technology and Status

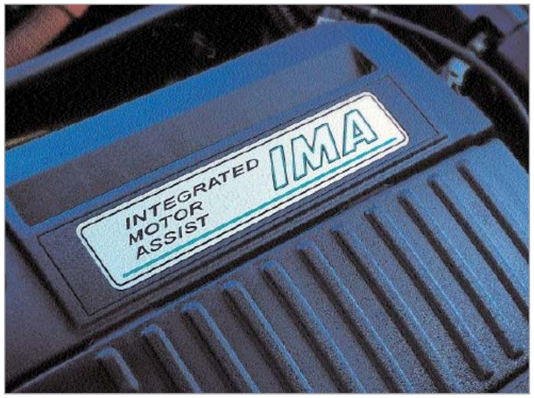
- **Concept:** In hybrid electric vehicle applications the gasoline engine can be optimised for use in the limited modes required by the full hybrid powertrain.
- **Base Functioning:** *See hybrid vehicle slides*
- **CO_2 Benefit:** *Strong function of degree of limited operating conditions.*
- **Costs:** Base engine costs may be slightly reduced for hybrid vehicle applications through the use of lower specification engines.

Ratings of Technology

Technology Applicability

- Engine technology optimization for hybrid powertrains in infancy. Clear trend towards system level optimization to obtain best overall performance.
- Hybrid features such as stop-start, CVT operation, electrical launch, and electrical assist provide an oportuntity to optimize the engine system in ways not offered by conventional drivelines.
- Electrical assist offers opportunity to reduce engine size and specific power in hybrid vehicle and utilize lower specific power / increased BSFC technologies

Visualization



SI Engine Technology Applicability

- Please note that the applicability of hybrid powertrains is covered elsewhere in this report

		Stoichiometric DI Turbo	Lean Boost DI	EGR Boost DI	2S-4S Switching Engine	Cam-Profile Switching	Stoichiometric Direct injection	Stratified-Charge DI	HCCI/CAI Combustion	Exhaust Energy Recovery	Second-Generation Biofuels
Vehicle Classification	**Small Car (Ford Focus)**	X	X	X			X				X
	Standard Car (Toyota Camry)	X	X	X		X	X				X
	Small MPV (Saturn Vue)	X	X	X		X	X				X
	Full-sized Car (Chrysler 300C)	X	X	X	X	X	X	X			X
	Large MPV (Dodge Grand Caravan)	X	X	X	X	X	X	X			X
	Truck (Ford F150)	X	X	X	X	X	X	X			X
	Heavy light-duty truck (Ford F250/F350)	X	X	X	X	X	X	X		X	X

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Technology Area Overview

- For this technology area, we have the following thoughts for the situation in 2020–2025:
- Diesel Technology will continue to be developed driven largely by the European market but a gradual penetration will be seen in the US market
- Improvement is required in technology cost, particularly turbocharging and aftertreatment for significant penetration
- US market penetration for domestic producers is assumed to commence from the heavier vehicles in the study cascading down in size as technology matures, acceptance improves, and CO_2 legislation drives incremental fleet actions
- Baseline is T2B5 (LEV II) applications currently in market
  - Represents ca. 20% CO_2 benefit from current baseline SI engine
  - 2020 diesel engines assumed to meet LEV III (approximately current SULEV II) emissions

Technology Status – Diesel Powertrain Consideration made across all sectors of study

- Technology has very low take rate in US market in passenger car and light duty truck applications versus Europe
  - Product typically only available in imported passenger car (e.g., VW, Audi, BMW and Mercedes)
  - Domestic Product generally offered in LHDT (e.g. Ford Superduty)
  - European Diesel share is half of market and covers all product families from sub-B (Fiat 500 class) to LHDT (Dodge Sprinter Class)
  - European Market has a competitive CO_2 driver leading to Diesel green branding (e.g. Ford Econetic, Mercedes Bluetec, VW Bluemotion)
- European Diesel Technology has seen many technology advances
  - Sequential turbocharging
  - Combustion correction techniques (e.g. UEGO, cylinder pressure)
  - Large EGR coolers with hot gas bypass
  - Third generation FIE – 2000 Bar and multiple injections
  - Mature DPF technology
  - SCR technology applied
  - Advanced materials – Al alloy heads and blocks, CGI blocks

Diesel Technology List for US Applications

- Closed Loop Combustion Control
- Reduced Compression Ratio
- Advanced Boosting Technologies
- Enhanced EGR and Charge Air Cooling
- Variable Valve Timing (With Application To Vary Compression Ratio)
- Pre-Turbine Catalysis
- Electric Turbo-Compounding
- Calibration "System" Optimization for CO_2 (Engine + Trans + Aftertreatment)
- Narrow Speed Range Operation
- System Integration at Engine Level
- Engine Downsizing – no slide – duplication with SI Engine
- Engine Friction Reduction – no slide

Closed Loop Combustion Control

Technology and Status

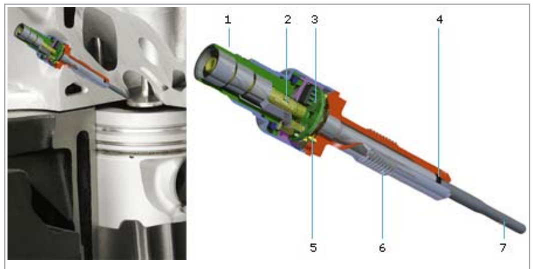
- **Concept:** Provide feedback from combustion by means of direct cylinder pressure measurement and analysis in EMS
- **Base Functioning:** Measure cylinder pressure during combustion to provide feedback for air, EGR, and fuel injection control to minimize error and correct for fuel quality allowing better trade-off for CO_2 emissions versus NOx and PM
- **CO_2 Benefit:** <1% from maintaining optimal combustion and facilitates further combustion optimization
- **Costs:** Added variable costs for glowplug, added inputs and processing power in engine control unit. Additional development time will be required to characterize the signal responses and tune calibration correction responses

Ratings of Technology

Technology Applicability

- Technology is applicable to light duty diesel applications commonly fitted with glowplugs. For heavier duty applications not engineered for glowplug alternate head gasket technology would need to be employed
- Highway benefits – closed loop combustion feedback allows for real world benefit plus closer margin between legal limits and development targets allowing further CO_2 combustion optimization
- City benefits – Further real world benefit available from combustion correction during transient events
- Other – lower cylinder to cylinder variation

Visualization



1. Plug
2. High voltage connection
3. Circuit board with electronics
4. Gasket
5. Measuring diaphragm
6. Glow plug body
7. Glow plug heating rod

Picture: www.beru.com

Reduced Compression Ratio

Technology and Status

- **Concept:** Reduction of the compression ratio reduces the peak firing pressure of the engine. This reduces the pumping losses and allows for higher specific power to be achieved
- **Base Functioning:** Pumping losses contribute to the total frictional losses (FMEP) of an engine. Reduction of the losses means less fuel energy is wasted resulting in higher fuel efficiency
- **CO_2 Benefit:** 1% per ratio plus additional from downsizing opportunity
- **Costs:** Reduced compression ratio requires additional effort to start the engine in colder ambient conditions. An enabler for significant compression ratio reduction would be increased starter energy availability allowed by high voltage hybrid ISG systems

Ratings of Technology

Technology Applicability

- Applicable to Diesel ISG applications to enable increased cranking speed for start performance
- Highway benefits – Increased specific power from the engine enables engine downsizing. Reduced pumping loss gives benefit across the full speed and load range
- City benefits – As pumping losses are a greater proportion of part load operation the benefit should be more marked in city operation
- Idle-stop benefits – Idle fuelling will be reduced although pre-cursor of ISG enables full stop-start benefit

Visualization

Visualization

Not

Applicable

Advanced Boosting Technologies

RICARDO

Technology and Status

- **Concept:** Improvements in air handling through a suite of boosting technologies either standalone or in combination
- **Base Functioning:** Provision of higher specific torque and power to enable downsized engines. Technologies include eBoost (e-machine in CHRA or electrical separation by e-Turbine and e-Compressor); supercharging (advances to avoid variable drive); variable nozzle compressor
- **CO_2 Benefit:** 2% (more if engine downsized for equivalent performance)
- **Costs:** Increase in turbocharger air system matching and development time, increased complexity in engine controller. Variable cost of turbocharger doubles plus additional air cooling requirement, sensors and actuators

Ratings of Technology

Technology Applicability

- Technology applicable to all sectors of diesel application
- Highway benefits – improved transient response from engine allows downsizing. More air allows improved emission performance for NOx and PM control giving leeway for CO_2 reduction.
- City benefits – much improved transient performance allowing downsizing. Operation in more efficient area of turbocharger map gives more noticeable CO_2 benefit in city driving
- In conjunction with enhanced EGR allows for premixed or homogeneous combustion in part load operation for very clean emissions. Design can facilitate the use of pre-TC catalyst for quick aftertreatment light-off

Visualization

Picture: http://honeywellbooster.com

Enhanced EGR Flow & Cooling (Plus Increased Charge Air Cooling)

Technology and Status

- **Concept:** Low Pressure EGR Circuit for increased EGR flow rate in conjunction with separate low temperature cooling circuit to cool EGR and provide additional charge air cooling
- **Base Functioning:** Increased EGR and cooler charger enables homogeneous, fully premixed and partially premixed combustion concepts. These concepts reduce NOx and PM emissions allowing more margin for CO_2 optimization. Lower charge temperature provides a larger P-V area and increases specific power and economy
- **CO_2 Benefit:** 2–4% from combined emission and cooling benefit
- **Costs:** Increased development cost for EGR and cooling system packaging. Additional work to optimize cooling pack. EGR cost increases 40–50% plus incremental costs for additional cooling system components and material revisions necessary to cope with corrosive environment in charge cooler with EGR present

Technology Applicability

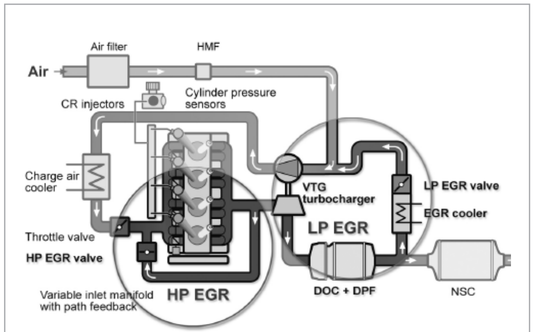
- Applicable to Light Duty Chassis Certification Applications requiring EGR at low speed and load:
- Highway benefits – Fuel economy improvement from increased charge cooling and improved compressor efficiency (EGR flows through TC compressor)
- City benefits – Significant emission benefit allowing combustion to be optimized more for CO2. Compressor efficiency improved for reduced pumping loss
- A significant challenge remains for TC compressor durability with heavy EGR flow rates

Ratings of Technology

1 (worst) ↔ 10 (best)

Effectiveness	4
Availability	8
Market Penetration	7
Long-Term Cost Viability	6
Current Maturity	7

Visualization



Picture: VW Tech Report
29. Internationales Wiener Motorensymposium 2008

Variable Valve Timing
(With Application To Vary Compression Ratio)

Technology and Status

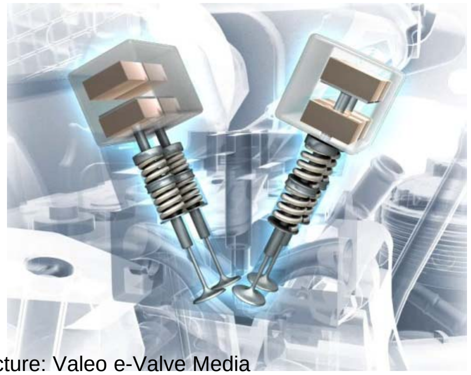
- **Concept:** Variable Valve Events enable valve events to be optimzed for oeprating point and also enable effective compression ratio variation
- **Base Functioning**: Intake and Exhaust Valve Events varied for rapid aftertreatment warm-up and best breathing at operating condition rather than global optimization. With more complex system, compression ratio can also be varied to reduce frictional losses and increase specific power
- **CO_2 Benefit:** 1–2% from warm-up & improved breathing. Additional gain if aftertreatment warmup creates NOx advantage to be used for CO_2 benefit
- **Costs:** Costs increase for valvetrain technology with some offset in aftertreatment cost. Additional development cost to develop for diesel engine application with incremental engine controller costs for drive circuits

Ratings of Technology

Technology Applicability

- Applicable to complete diesel line-up from small car to MDV
- Highway benefits – Increased specific power from the engine enables engine downsizing. Reduced pumping loss gives benefit across the full speed and load range
- City benefits – As pumping losses are a greater proportion of part load operation the benefit should be more marked in city operation
- Idle-stop benefits – ability to raise compression ratio allows stop start to be more readily employed than reduced compression ratio alone as ISG is not necessary for restart

Visualization



Picture: Valeo e-Valve Media

Pre-Turbine Catalysis

Technology and Status

- **Concept:** Small Oxidation Catalyst (DOC) is placed before first turbocharger very close to the engine
- **Base Functioning:** Small pre-turbine catalyst with low thermal inertia lights off quickly allowing further exotherm to warm up rest of aftertreatment more rapidly. Reduced warm-up will require lower use of fuel for heating strategies reducing CO_2 emissions
- **CO_2 Benefit:** <1% – more for cold start cycles.
- **Costs:** Additional cost for pre-turbine catalyst precious metal partially offset by reduced precious metal in remainder of aftertreatment system

Technology Applicability

- Applicable to all diesel technology applications but with more relevance on applications with larger engines and large aftertreatment systems with greater thermal inertia
- Highway benefits – Minimal benefit and only soon after starting when aftertreatment is cold
- City benefits – Benefit most noticeable for real world situations when vehicle is used frequently for short journeys from cold or cool start when aftertreatment is below effective operating temperature
- Pre-turbine catalyst allows for less aggressive heating strategies to keep aftertreatment in correct operating temperature window
- Component durability must be considered in placing catalyst closer to engine and may require metallic catalyst substrate

Ratings of Technology

Visualization

Picture: www.emitec.com

Electric Turbo-Compounding

Technology and Status

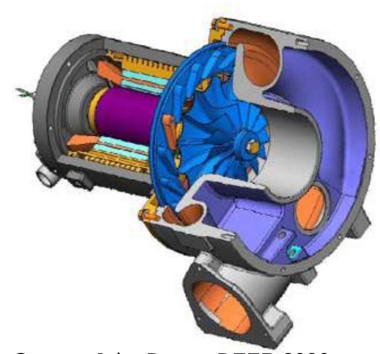
- **Concept:** Electric turbo-compounding device recovers waste exhaust energy and converts this to electrical energy
- **Base Functioning:** Exhaust energy that would otherwise be wasted is used to drive a turbine coupled to an electrical generator to generate electrical power. The electrical power can be stored in conjunction with hybridization or fed back as shaft power directly to reduce fuel demand on engine
- **CO_2 Benefit:** 4–5% improvement in fuel efficiency depending on cycle
- **Costs:** Technology is proven on heavy duty applications but specific development would be required for lighter duty matching and application. Incremental variable cost for ETC and power electronics.

Ratings of Technology

Technology Applicability

- Already applied to heavy duty applications – more applicable to heavier applications
- Highway benefits – significant benefit – up to 5% depending on duty cycle and engine load on highway
- City benefits – transient low speed and load does not offer the same quality of exhaust energy for energy recovery. There is potential for worsened fuel economy due to increased back-pressure at some parts of operation
- Idle-stop benefits would be acheived if coupled with hybridization
- More benefit would be obtained with electrification of accessories.

Visualization



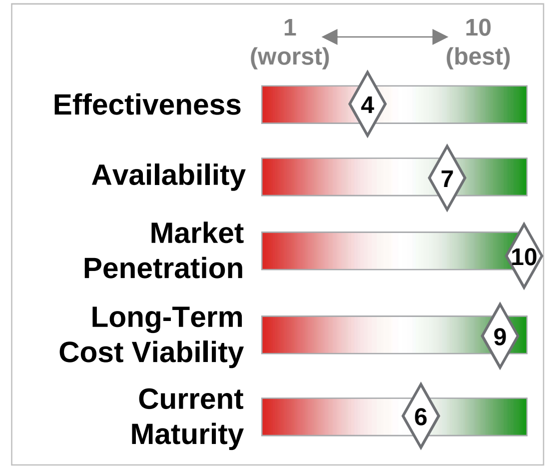
Picture: Source: John Deere, DEER 2006

Calibration "System" Optimization for CO_2 (Engine + Transmission + Aftertreatment)

Technology and Status

- **Concept:** Application of a sytem level technology selection to add increased NOx aftertreatment allowing optimization of engine out emissions for lower CO_2 and higher NOx (and revised total gearing)
- **Base Functioning:** Instead of minimizing engine out NOx for smaller NOx aftertreatment a system approach for CO_2 could oversize NOx aftertreatment and allow increased engine out NOx emissions with reduced engine out CO_2. Combined with transmission ratio selection for CO_2 rather than NOx
- **CO_2 Benefit:** 2–4% offset by increased DEF utilization and partially offset by increased fuel consumption during warm-up to light off aftertreatment
- **Costs:** Aftertreatment cost would rise in line with additional reduction capacity. DEF system would also need to be resized to account for additional DEF consumption

Ratings of Technology



Technology Applicability

- Technology applicable to all areas of diesel application
- Highway benefits – lower CO_2 emission by reduced engine speed operation from higher gearing and more optimal CO_2 calibration with increased engine out NOx
- City benefits – lower engine speed and improved transient CO_2 provide lower speed and load benefits
- Idle-stop – stop start operation would need to be treated carefully to maintain aftertreatment operating temperature
- Increase DEF consumption woudl offset cost benefit to end-user and extend payback duration

Visualization

Picture: Ricardo, Inc.

Narrow Speed Range Operation

Technology and Status

- **Concept:** Powertrain designed to enable the engine to operate within a narrow speed band range with full emissions and economy optimization in this range
- **Base Functioning:** Powertrain coupled to hybrid systems and/or highly flexible transmissions allowing engine to be optimized for narrow speed band for best emissions and economy. Contrast to traditional optimization that considers entire speed load range requirements with many compromises
- **CO_2 Benefit:** 2–4% from optimization of combustion plus more opportunity by limiting higher engine speed for friction reduction with design factors for narrow speed range envelope
- **Costs:** Little impact to cost if highly flexible transmissions and/or hybrid already selected. Reduced engine optimization development offset by increased powertrain system development

Ratings of Technology

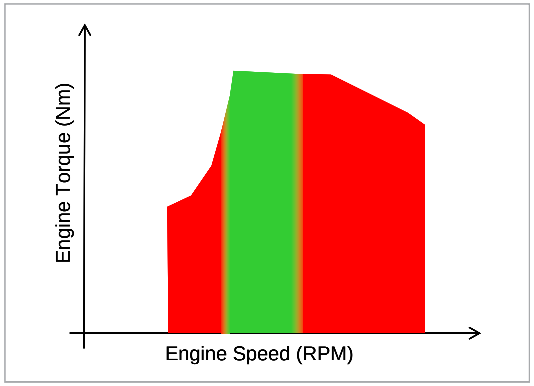
1 (worst) ← → 10 (best)

Effectiveness	4
Availability	4
Market Penetration	3
Long-Term Cost Viability	5
Current Maturity	2

Technology Applicability

- Applicable to all classes of vehicles using hybrid systems or high numbers of gear ratios that allow engine speed range to be very narrow
- Highway benefits – Improved economy by maintaining engine in high efficiency island. Enhanced benefit if emission spikes in transient operation can be avoided allowing further optimization for fuel economy
- City benefits – As highway plus ability to set speed and load on engine for rapid aftertreatment warm-up. Engine speed set point can be matched to provide optimal electrical energy generation efficiency for recharging hybrid energy reserve enhancing idle and stop benefits
- Constant speed operation may prove un-desirable noise characteristic compared to traditional powertrain solutions

Visualization



Picture: Ricardo Inc.

System Integration at Engine Level

Technology and Status

- **Concept:** Combine components to reduce mass and thermal inertia giving improved package and faster warm-up. Electrify ancillaries to eliminate FEAD and allow variable performance independent of engine speed
- **Base Functioning:** Combination of components (e.g. exhaust manifold and cylinder head) to improve response time for turbocharging and aftertreatment warm-up. Electrification of FEAD reduces parasitic losses and allows operation to be optimized to most efficient condition for operating point (e.g electrical coolant pump, oil pump or AC compressor)
- **CO_2 Benefit:** 1–2%
- **Costs:** Added variable costs for more complex production offset by reduced material. Electrification in conjunction with hybridization.

Ratings of Technology

Technology Applicability

- Technology is applicable to all diesel technology sectors
- Highway benefits – reduced frictional losses at higher speed and load points by designing and running ancillaries at optimal conditions
- City benefits – Rapid aftertreatment warm-up reduces fuel consumption in warm-up phase and allows earlier transition to warm fuel efficient maps. Ability to run ancillaries faster at lower engine speeds will enable lower power loss and should enable component downsizing

Visualization

Picture: Ricardo, Inc.

Diesel Engine Technology Applicability

- Please note that the applicability of hybrid powertrains is covered in a separate part of this report

		Closed Loop Combustion Control	Reduced Compression Ratio	Advanced Boosting Technologies	Enhanced EGR and Charge Air Cooling	Variable Valve Timing	Pre-Turbine Catalysis	Electric Turbo-Compounding	Calibration "System" Optimization	Narrow Speed Range Operation	Engine System Integration
Vehicle Classification	**Small Car (Ford Focus)**	X	X	X	X	X			X	X	X
	Standard Car (Toyota Camry)	X	X	X	X	X			X	X	X
	Small MPV (Saturn Vue)	X	X	X	X	X			X	X	X
	Full-sized Car (Chrysler 300C)	X	X	X	X	X		X	X	X	X
	Large MPV (Dodge Grand Caravan)	X	X	X	X	X	X	X	X	X	X
	Truck (Ford F150)	X	X	X	X	X	X	X	X	X	X
	Heavy light-duty truck (Ford F250/F350)		X	X	X	X	X	X	X	X	X

Outline

- Introduction
- Spark ignited engine technologies
- Diesel engine technologies
- **Hybrid vehicle technologies**
- Transmission technologies
- Vehicle technologies
- Conclusions

Hybrid Functionality Matrix

Hybrid technology's primary purpose is to enable vehicle functionally that offers fuel efficiency.

	None	Micro	Micro	Mild	Full	Full	Full	Full	Full	Full
	Conventional	Belt starter / generator	Belt mounted parallel	Crank mounted parallel (IMA)	P2 parallel hybrid	Input Powersplit	Compound powersplit	2-mode powersplit	Series hybrid - Electrical	Series hybrid - Hydraulic
Engine idle off	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Launch assist	No	No	Small amount	Some	Yes	Yes	Yes	Yes	No	No
Regeneration	No	No	Small amount	Some	Yes	Yes	Yes	Yes	Yes	Yes
Electrical only mobility	No	NO	No	No	Yes	Yes	Yes	Yes	Yes	Yes
CVT	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Power Steering	Belt	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical	Electrical
Air conditioning	Belt	Belt	Belt	Belt	Belt or electrical	Belt or electrical	Belt or electrical	Belt or electrical	Belt or electrical	Belt or electrical
Brakes	Standard	Standard	Standard	Standard or blended	Blended	Blended	Blended	Blended	Blended	Blended
City Driving	0	+	++	++	+++	++++	++++	++++	++++	++++
Highway Driving	0	0	0	+	+	+	+	+	-	-

Hybrid Technology Area Considerations

- Hybrid technology largely available now but needs cost reduction efforts to provide financial justification to consumers; largely expected to come through volume increases (economy of scale) & commodity mindset
- Pace of development
  - Change in fuel prices (or fuel tax legislation) could dramatically accelerate (or slow) hybrid development and implementation. CAFE requirements will drive technology development in near term.
  - Li-ion battery development largely in flux as well, but not necessarily an impact to hybrid development, as NiMH is sufficient (i.e., Li-ion required for EV and PHEV but not current strong hybrid technology)
- Many hybrid applications today being consumed by early (technology) adopters and/or those focused on environmental impact and energy independence
  - Hybridization still difficult to justify based purely on financial business case
  - Governmental legislation (e.g., CAFE or CO_2 requirements) largely responsible for hybrid investment
- Benefits of hybrid technologies are generally independent of component technologies (Electrical machine & energy storage) due to good round trip efficiency attributes of current technologies.
  - Some small correlation exists, and with parameterization in model, opportunity to sweep parameters to evaluation sensitivity.

Micro Hybrid: Stop-Start

Technology Description and Status

- **Concept:** Most basic of hybridization, allows for simple engine shut-off during idle periods; typically employs enhanced starter motor and limited use of driver comfort features during engine off (e.g. Radio, some heat, but no A/C)
- **Base Functioning:** Decreases wasted fuel by minimzing idling but provides no benefit for highway use or when air conditioning is required/desired
- **CO_2 Benefit:** 3–5% over city cycles. 0% over highway
- **Costs:** This is the lowest cost hybrid system and can be implemented relatively quickly on most vehicles on the market today. Stop-start systems are somewhat mature and readily available off the shelf. Further development will yield increased user acceptance (e.g. Transparent integration with little to no detriment to existing vehicles in terms of NVH, acceleration, etc.)

Ratings of Technology

Technology Applicability

- Stop-start technology can be applied to almost all vehicles including passenger cars, medium and heavy duty trucks and even off-highway or agricultural vehicles.
- Benefits are limited, though, to vehicle applications that have some periods of idling. For example, long-haul trucks with extended highway operation will see little to no benefit. Similiarly, as air conditioning is not available during engine-off periods, users may experience some degradation in performance that could be unacceptable.

Visualization

Mild Hybrid: Integrated Belt Starter-Generator (IBSG)

Technology Description and Status

- **Concept:** The alternator is replaced with a new electric machine that can provide lauch assist as well as replacing the electrical supply of the alternator during normal vehicle operation. Typically this machine can also be used for energy recapture during braking..
- **Base Functioning:** Provides stop-start functionality (see “Stop-Start“ slide) as well as electric launch assist, which, when coupled to a dedicated energy storage system with a charge sustaining strategy, can decrease fuel consumption during acceleration from a stop.
- **CO_2 Benefit:** 3–7% over city cycles, ~0% over highway cycles
- **Costs:** Several IBSG systems are on the market today so development costs are largely sunk. Purchase costs of the system are now decreasing as volume grows such that financial payback may be viable soon.

Technology Applicability

- IBSG systems can be applied to a wide variety of applications including passenger cars and medium and heavy duty trucks with benefits seen in city cycles. Due to the small size of the IBSG, relatively limtied ability to downsize, but some bennefit.

Ratings of Technology

Visualization

Mild Hybrid: Integrated Crank Starter-Generator (ICSG) [also known as Integrated Motor Assist (IMA)]

RICARDO

Technology Description and Status

- **Concept:** An e-machine is added to or replaces the flywheel. Larger than the e-machine used in an ISBG, the motor can provide lauch assist and regenerative braking as well additional power during a variety of vehicle operating modes and, thus, is applied in conjunction with a downsized engine.
- **Base Functioning:** Provides stop-start functionality and launch assist. This provides the opportunity to use of a smaller engine to increase efficiency throughout the operating range of the vehicle, not just during launch from a stop.
- **CO_2 Benefit:** 16–20% on city cycles, ~0% on highway cycles
- **Costs:** ICSG systems are on the market today so development costs are largely sunk. Purchase costs of the system are now decreasing as volume grows and the greater fuel efficiency is great enough to provide reasonable financial payback today.

Technology Applicability

- ICSG systems can be applied to a wide variety of applications including passenger cars and medium and heavy duty trucks with benefits mostly seen in city drive cycles. The reduced engine sizes enabled by the hybrid system provide highway bennefits.
- Typically, these systems have been used with a CVT to avoid Torque converter losses.

Ratings of Technology

1 (worst) ↔ 10 (best)

Effectiveness	7
Availability	9
Market Penetration	10
Long-Term Cost Viability	9
Current Maturity	8

Visualization

Full Hybrid: P2 parallel Hybrid

Technology and Status

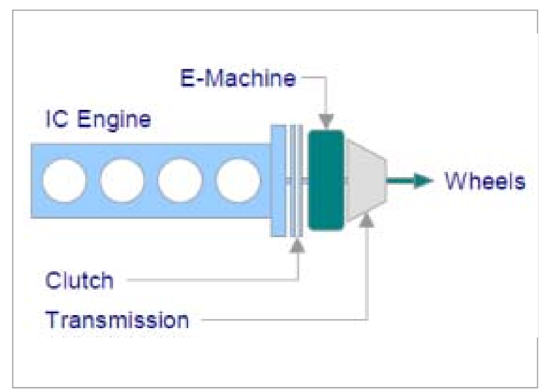
- **Concept:** An e-machine is inserted between the engine and the transmission, typically with a clutch between the engine and e-machine. Larger than the e-machine used in an ISBG, the motor can provide lauch assist and regenerative braking as well additional power during a variety of vehicle operating modes and, thus, is applied in conjunction with a downsized engine.
- **Base Functioning:** Provides stop-start, electrical launch, and launch assit. This optimizes the use of a smaller engine to increase efficiency throughout the operating range of the vehicle, not just during launch from a stop.
- **CO_2 Benefit:** 18–22% on city cycles, ~0% on highway cycles (downsizing offers bennefits)
- **Costs:** No P2 parallel hybrids are in production today, so development costs will still need to be invested, however parts bin exists today. The cost of the system is higher thana ICSG, however, the system has only 1 electrical machine so its costs should be lower than more advanced hybrids

Ratings of Technology

Technology Applicability

- P2 hybrids can be applied to a wide variety of applications including passenger cars and medium and heavy duty trucks with benefits seen mostly in city drive cycles. The reduced engine sizes enabled by the hybrid system provide highway bennefits.
- System can be used with an AT, however, To maintain efficiency, a CVT or DCT should be used to avoid Torque converter losses.

Visualization



Full Hybrid: Input Power Split Hybrid

Technology Description and Status

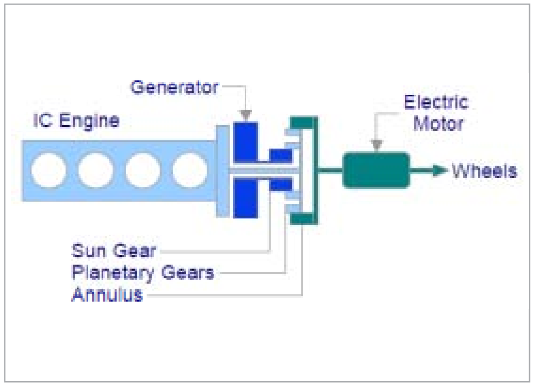
- **Concept:** Power split hybrids use an electric machine directly integrated into the transmission, and either provide an additional input parallel to the engine or act as an additional output from the transmission. Both varieties permit an electric (only) operating mode.
- **Base Functioning:** Power split encompasses all of the aforementioned technology providing stop-start, launch, and engine downsizing benefits in plus the ability to provide an electric-only operating mode, when used in conjunction with the appropriate electric accessories.
- **CO_2 Benefit:** 22–33% in city driving, some bennefit in highway driving
- **Costs:** Development is ongoing with room for both performance improvement and cost reduction but initial systems are now widely spread in the market place (e.g. Ford Fusion and Escape and Toyota Prius).

Technology Applicability

- As a full or strong hybrid, the power split hybrid offers very good benefit of hybridization
- Challange with cost due to two electrical machine solution.
- Fuel efficiency improvement is found across the range and in all operating cycles since engine downsizing and electric accessories optimize performance and efficiency of the combustion engine and the vehicle as a whole

Ratings of Technology

Visualization



Full Hybrid: Two-Mode Power Split

Technology Description and Status

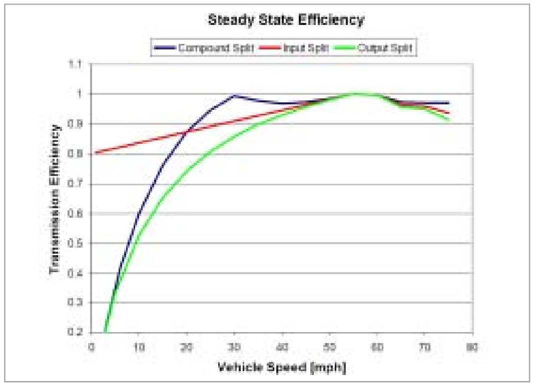
- **Concept:** Two-Mode hybrids use electric machines (usually two) directly integrated into the transmission for maximum operating flexibility with operation as input powersplit or compound power split gearing configuration via clutch actuation.
- **Base Functioning:** Two-Mode encompasses all of the aforementioned technology providing stop-start, launch, and enables engine downsizing benefits in plus the ability to provide an electric-only operating mode, when used in conjunction with the appropriate electric accessories.
- **CO_2 Benefit:** 22–33% in city drive cycle. Some bennefit in highway driving
- **Costs:** Development is ongoing as Two-Mode hardware is still very expensive, providing little commercial payback to the customer currently. However, Two-Mode systems are proliferating in the market place with GM offering truck and SUV variants now, and BMW, Mercedes and Chrysler products coming soon).

Technology Applicability

- As a full or strong hybrid, the Two-Mode hybrid offers maximum benefit of hybridization but is also the most costly and complex of all architectures to implement.
- Fuel efficiency improvement is found across the range and in all operating cycles since engine downsizing and electric accessories optimize performance and efficiency of the combustion engine and the vehicle as a whole

Ratings of Technology

Visualization



Full Hybrid: Series Electrical

Technology and Status

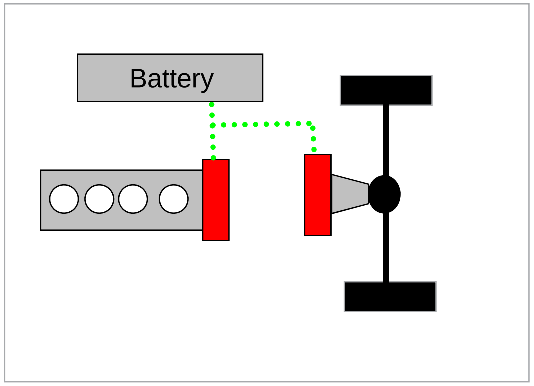
- **Concept:** Series electrical hybrid systems include two electrical machines and a battery. One EM is located on drvie axle and is sized for peak loads, and second EM is located on engine and is sized for average loads.
- **Base Functioning:** Energy storage system enables load averageing and engine off operation. As driveline and engine are decoupled, engine can be single point engine or operate on best-efficiency line engine.
- **CO_2 Benefit:** 22–33% in city drive cycle. Potenally reduced in highway driving, depending on degree of reduced engine size enabled.
- **Costs:** The cost implications of two electrical machines (one large and one small) and a battery have limited the appeal of this technology to the industry.

Ratings of Technology

Technology Applicability

- Series hybrids are not currently in production, and technology approach has not been embraced by industry (has been championed in research community) due to the costs associated with multiple large electrical machine size & a battery.
- With introduction of EVs, opportuntity for industry to gain comfert with series electrical and increase volumes to reduce costs.

Visualization



Full Hybrid: Series Hydraulic

Technology Description and Status

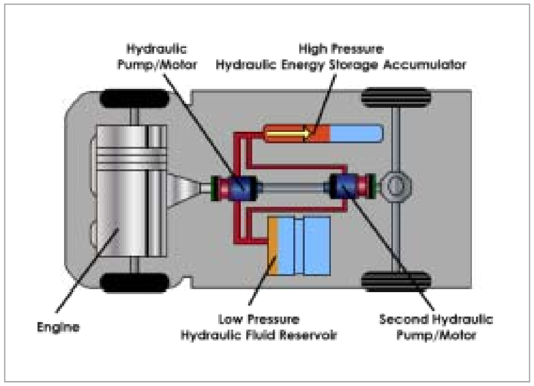
- **Concept:** Hydraulic accumulators are used to aid in deceleration, then the stored energy is released back into the vehicle for launch assist using hydraulic pumps connected to an axle or transmission.
- **Base Functioning:** Kinetic energy that would otherwise be translated to heat in the braking system is recaptured for later use. Can also be used for engine downsizing.
- **CO_2 Benefit:** 22–33% in city drive cycle. Potenally reduced in highway driving, depending on degree of reduced engine size enabled.
- **Costs:** Hydraulic hybridization is still in early development with only a few demonstration vehicles on the road today. Application of hydraulic hybridization is much less costly in vehicles that already employ extensive hydraulic systems for specific vocations (e.g., garbage compactor) and increased efficiency is limited to vocations with extreme stop-start cycles and agressive deceleration.

Technology Applicability

- Hydraulic hybrid systems typically suggested in niche applications such as refuse trucks, where large power required for regeneration is well suited to hydraulic systems.
- Potentially reduced fuel economy in highway driving, depending on degree of reduced engine size enabled.
- Hydraulic hybrid technology development has been significantly slower than electrical hybrid technology development rate, and use of hydraulic driveline is not consistent with other high profile technology initiatives such as EVs, PHEVs and vehicle electrification.

Ratings of Technology

Visualization



Outline

- Introduction
- Spark ignited engine technologies
- Diesel engine technologies
- Hybrid vehicle technologies
- **Transmission technologies**
- Vehicle technologies
- Conclusions

Technology Area Overview

- For this technology area, we have the following thoughts for the situation for in 2020–2025:
  - North American market will continue to be dominated by automatic transmissions for IC engines with emphasis on increasing launch device efficiency and smart kinematics design
  - Higher presence of more fuel efficient AMT's and DCT's expected
  - Increase in simplified single/two speed gearboxes for hybrid applications
  - CVT development expected to be on the decline in the North American market (although still being pursued by Japanese market)
- Pace of development
  - Development of AMT and DCT technology expected to be implemented from European and Japanese efforts
  - Detroit 3 actively pursuing DCT technology, with teaming arrangements established between OEMs and Tier 1 to develop technologies
  - Improvements for automatic transmissions are on-going with new technologies being implemented into luxury vehicles and then cascaded down to other vehicle classes.
  - Single/two speed gearboxes for hybrid applications require minimal investment and lead time
- Comparison to baseline
  - Given 94% of North American transmissions are automatic, improvements in efficiency (resulting in CO_2 improvements) will be realized through:
    - Smart kinematics design (2–5%)
    - Component efficiency improvement or alternative technologies (3%)
    - Launch devices (2–6%)
    - Dry sump technology (2%)
  - Estimates of improvement depend on the drive cycle, are not simply additive, and are subject to quality of baseline

Transmission Summary

Automatic (with Torque Converter)

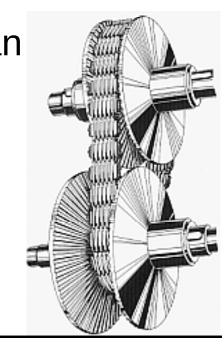
- Hydraulically operated, using a fluid coupling or torque converter and a set of gearsets to provide a range of gear ratios
- Decrease in efficiency associated with viscous losses from torque converter

AMT (Automatic Manual Transmission)

- AMT operates similarly to a manual transmission except that it does not require clutch actuation or shifting by the driver.
- Automatic shifting is controlled electronically (shift-by-wire) and performed by a hydraulic system or electric motor.
- Poor shift quality has excluded this technology from the study

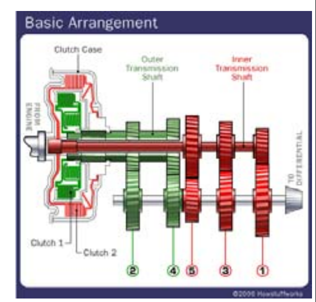
CVT (Continuous Variable Transmission)

- Rather than using gears, the CVTs in currently available vehicles utilize a pair of variable-diameter pulleys connected by a belt or chain that can produce an infinite number of engine/wheel speed ratios.
- Reliability and efficiency issues prevent this technology from roadmap development



DCT (Dual Clutch Transmission)

- Uses two separate clutches for even and odd gear sets
- Eliminates the use of a torque converter and utilizes either wet or dry type launch clutches



Technology Area Summary

- Launch Devices
  - Wet Clutch
  - Damp Clutch
  - Dry Clutch
  - Multi-damper Torque converter
  - Magnetic clutch
- Shifting Clutch Technology
- Smart Kinematic Design
- Dry Sump
- Efficient Components
- Super Finishing
- Lubrication

Launch Device: Wet Clutch

Technology and Status

- **Concept:** provides torque transmission during operation by means of friction action between surfaces wetted by a lubricant
- **Base Functioning:** Increases fuel effieciency by reducing hydraulic parasitic losses over a conventional torque converter when it is slipping.
- **CO_2 Benefit:** Benefit realized at launch and during transient driving
- **Costs:** up to 20% less than a conventional torque converter

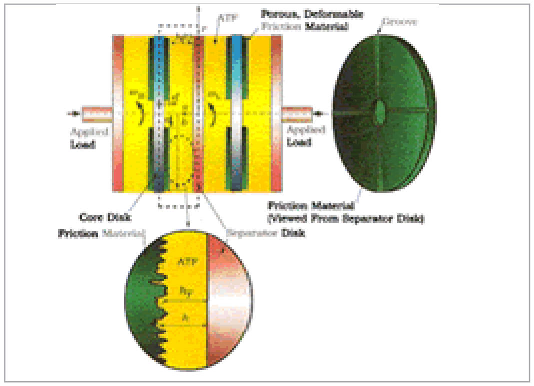
Ratings of Technology

Technology Applicability

- Technology applicable to planetary, parallel-axis, AMT and dual clutch transmissions
- Requires special lubrication system or lubricant to satisfy gearbox lubrication requirements and actuation requirements.
- Parasitic losses of lubrication system diminish overall benefit over torque converter.
- Improvement in city driving, little for highway

*Note: Effectiveness relates to improvement in transmission efficiency

Visualization



Picture: www.cerom.lsu.edu

Launch Device: Damp Clutch

Technology and Status

- **Concept:** Similar concept as a wet clutch but only a limited spray is applied to achieve cooling
- **Base Functioning:** Still requires a lubrication system but is more efficient due to controlled environment (less windage and churning)
- **CO_2 Benefit:** Similar benefits as a dry clutch
- **Costs:** ~$25 above wet clutch

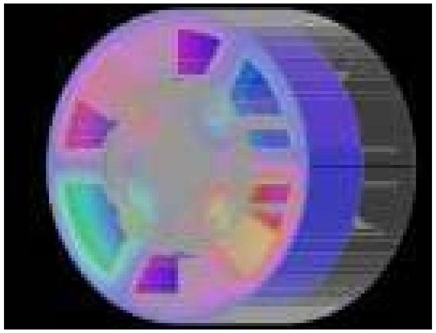
Ratings of Technology

Technology Applicability

- Applicable to most automatic transmissions – best of both worlds, efficiency of a dry clutch matched with the longevity and higher torque capacity of a wet clutch
- As for the other launch devices, the increase in efficiency is applicable mostly to city driving.

*Note: Effectiveness relates to improvement in transmission efficiency

Visualization



Picture: www.cerom.lsu.edu

Launch Device: Dry Clutch Advancements

Technology and Status

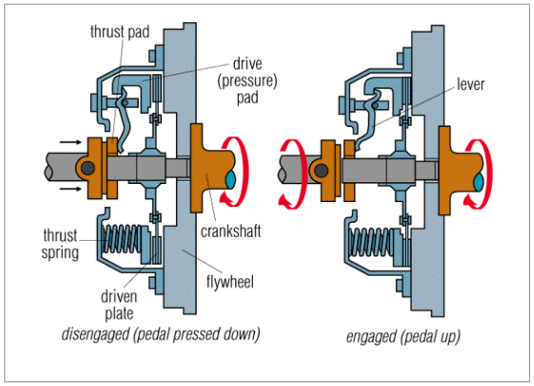
- **Concept:** Standard manual clutch require advanced materials to provide heat dissipation to be used in automatic applications or electric assist (on/off) to prevent slipping
- **Base Functioning:** Thermal load resulting from engagement prevent dry clutches from being used in high torque and heavy duty cycle applications but are more effiecient since they don't require an additional lubrication system and significatntly reduce parasitic shear fluid losses.
- **CO_2 Benefit:** Benefit realized at launch and during transient driving
- **Costs:** Dry Clutch materials +10-20%, Electric motor $1500

Ratings of Technology

Technology Applicability

- Advancements in material or electric assist could enable this technology to be used in larger vehicles and more severe duty cycles
- City driving improvement

Visualization



Picture: www.cerom.lsu.edu

*Note: Effectiveness relates to improvement in transmission efficiency

Launch Device: Multi-Damper Torque Converter

Technology and Status

- **Concept:** Dampers in torque converter enable lower lock-up speed
- **Base Functioning:** The more fuel-intensive period of hydrodynamic power transfer is shorter
- **CO_2 Benefit:** Increase in efficiency from reduced slippage and smoother shifting
- **Costs:** Increase

Ratings of Technology

1 (worst) ↔ 10 (best)

Effectiveness	5
Availability	6
Market Penetration	5
Long-Term Cost Viability	5
Current Maturity	8

Technology Applicability

- Multi-damper systems provide earlier much early TC clutch engagement, however, drivability and limitied ratio coverage have limited the deployment of this technology.
- Technology is best suited for deployment in 6 speed tranmssions and required to be integrated during transmission design.
- Technology provides improved efficiency for automatic transmissions at an increase in cost.

*Note: Effectiveness relates to improvement in transmission efficiency

Visualization

Picture: www.zf.com

Launch Device: Magnetic Clutch

Technology and Status

- **Concept:** Using magnetic force to engage the clutch
- **Base Functioning:** Non contact engagement launch device to prevent frictional losses
- **CO_2 Benefit:** Benefit realized at launch and during transient driving
- **Costs:** Cost impact unclear due to technology in early stage of development

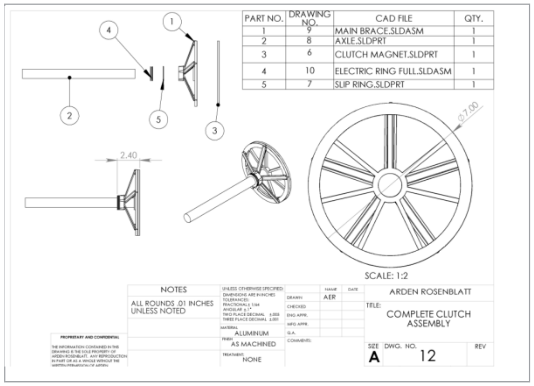
Technology Applicability

- Technology is still under early development and it use will be constrained by limited torque transfer capabilities, uncertian reliability, and significant engineering development to mature.
- Offers opportuinty to remove hydraulic sub-system compoenets and associated losses. Technology requires current draw to operate, thus idealy suited for highly electrified vehicles.
- Technology best suited to low torque applications with miniminal refinement vehicles and technology will need to be integrated in clean sheet transmissions with large ratio coverage.

*Note: Effectiveness relates to improvement in transmission efficiency

Ratings of Technology

Visualization



Picture: www.uweb.ucsb.edu

Shifting Clutch Technology

Technology and Status

- **Concept:** Utilizing high thermal capacity technolgoy to reduce plate count and lower clutch losses during shifting
- **Base Functioning:** Reduced number of plates for shifting process and reduced hydraulic cooling requirements result in increased overall transmission efficiency for similiar drivability.
- **CO_2 Benefit:** Through all driving conditions potentially including idle
- **Costs:** similar to AMT cost

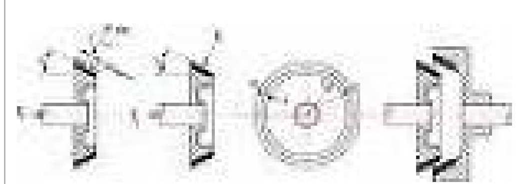
Ratings of Technology

Technology Applicability

- Technology deployment required during transmission design phase and has been limited by industry prioritization to drivability over shift efficiency.
  - Technology will be best suited to smaller vehicle segments due to reduced drivability expectations – there will be a struggle to develop this technology for higher torque applications

*Note: Effectiveness relates to improvement in transmission efficiency

Visualization



Picture: www.cerom.lsu.edu

Smart Kinematic Design

Technology and Status

- **Concept:** Using analysis to design for efficiency by selecting the kinematic relationships to optimize the part operational speeds and torques for efficiency
- **Base Functioning:** Large improvements in efficiency have been noted for clean sheet designs for 6-speed and 8-speed transissions
- **CO_2 Benefit:** Increase in efficiency reduces fuel consumption
- **Costs:** Low cost – analysis part of design phase

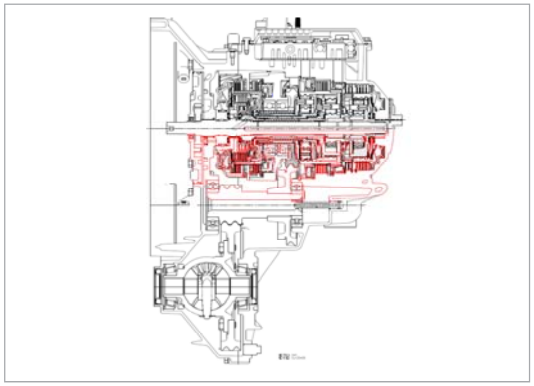
Ratings of Technology

Technology Applicability

- All applications and vehicle classes benefit from this design approach
- Benefits are realized in city and highway driving

*Note: Effectiveness relates to improvement in transmission efficiency

Visualization



Picture: www.adr3.co.uk

Dry Sump

Technology and Status

- **Concept:** Dry sump lubrication systerm keeps the rotating members out of oil
- **Base Functioning:** Reduces losses due to windage and churning
- **CO_2 Benefit:** Fuel efficiency increases with transmission efficiency
- **Costs:** Adds cost (~$50/pc) but as technology matures cost will go down

Ratings of Technology

1 (worst) ↔ 10 (best)

Effectiveness	4
Availability	5
Market Penetration	2
Long-Term Cost Viability	5
Current Maturity	7

Technology Applicability

- All applications and vehicle classes benefit from this lubrication design
- Most benefit achieved at higher speeds

*Note: Effectiveness relates to improvement in transmission efficiency

Visualization

Picture: www.cerom.lsu.edu

Efficient Components

Technology and Status

- **Concept:** Continous improvement in seals, bearings and clutches all aimed at reducing drag in the system
- **Base Functioning:** A reduction in drag with out a reduction in performance increases the efficiency of the transmission
- **CO_2 Benefit:** Fuel efficiency increases with transmission efficiency
- **Costs:** New materials, designs are expensive when they hit market (20%)

Ratings of Technology

Technology Applicability

- All applications and vehicle classes benefit from this lubrication design
- City and highway driving fuel effieciency improvements

*Note: Effectiveness relates to improvement in transmission efficiency

Visualization

Picture: www.cerom.lsu.edu

Super Finishing

Technology and Status

- **Concept:** Chemically treating internal gearbox parts for improved surface finish
- **Base Functioning:** Improved surface finish reduces drag which increases efficiency
- **CO_2 Benefit:** Fuel efficiency increases with transmission efficiency
- **Costs:** Currently ~$0.50/part

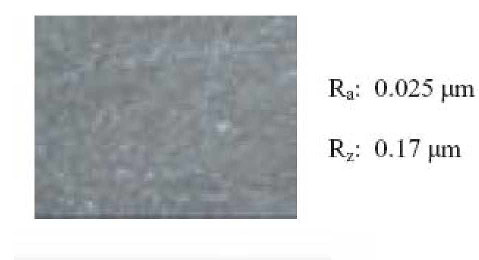
Ratings of Technology

Technology Applicability

- All applications and vehicle classes benefit from this lubrication design
- City and highway driving fuel effieciency improvements

*Note: Effectiveness relates to improvement in transmission efficiency

Visualization



Picture: www.geartechnology.com

Lubrication

Technology and Status

- **Concept:** Development in the area of lubrication properties is ongoing
- **Base Functioning:** New developments in reducing oil viscosity while maintaining temperature requirements will have a positive effect on transmission efficiency
- **CO_2 Benefit:** Benefit across all vehicle classes and operating conditions
- **Costs:** TBD

Ratings of Technology

Technology Applicability

- All applications and vehicle classes benefit from improved lubrications
- City and highway driving fuel effieciency improvements

*Note: Effectiveness relates to improvement in transmission efficiency

Transmission Technology Applicability

		Launch Technology										
		Wet Clutch	Dry Clutch	Damp Clutch	Multi Damper Torque Converter	Magnetic Clutch	Shifting Clutch Technology	Smart Kinematics Design	Dry Sump	Efficient Components	Super Finishing	Improved Lubricants
Base Transmission System	Automatic with Torque Converter				X		X	X	X	X	X	X
	Automatic Manual Transmission	X	X				X	X	X	X	X	X
	Dual Clutch	X	X	?			X	X	X	X	X	X
	CVT	X			X		X	X	X	X	X	X
Vehicle Classification	Small Car (Ford Focus)		X	X		?	X	X	X	X	X	X
	Standard Car (Toyota Camry)	X	X	X			X	X	X	X	X	X
	Small MPV (Saturn Vue)	X		X	X		X	X	X	X	X	X
	Full-sized car (Chrysler 300C)	X			X		X	X	X	X	X	X
	Large MPV (Dodge Grand Caravan)	X			X		X	X	X	X	X	X
	Truck (Ford F150)	X			X		X	X	X	X	X	X
	Heavy light-duty truck (Ford F250/F350)	X			X		X	X	X	X	X	X

Outline

- Introduction
- Spark ignited engine technologies
- Diesel engine technologies
- Hybrid vehicle technologies
- Transmission technologies
- **Vehicle technologies**
- Conclusions

Vehicle Summary (1 of 3)

Mass Reduction: Material Substitution

- For a given set of performance targets, a heavy vehicle will require more power, thus consume more energy. Reductions in weight can occur through material substitution (e.g., steel to aluminum).

Mass Reduction: Component Optimization

- Dependant on the compromises (e.g., for manufacturing flexibility, passenger volume etc), reductions in weight can also occur through component optimization.

Aerodynamics: Passive

- Vehicle Aerodynamics; have a greater influence on drive-cycles with a higher average speed. Dependant compromises chosen, significant opportunity is available in shape development (passive aero).

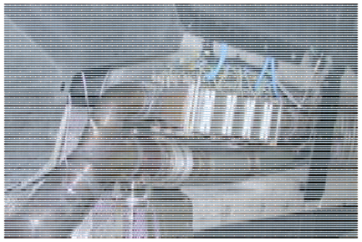
Aerodynamics: Active

- Gains from active aero through controlled cooling apertures, vehicle ride height control etc are also possible.

Vehicle Summary (2 of 3)

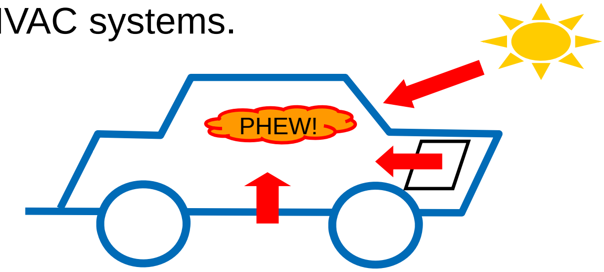
Thermo-Electric Generators

- Thermo-Electric Generation (TEG); use the heat in exhaust gas (waste energy) to generate electricity using the Seebeck effect. This can be used to drive ancillaries etc, reducing the power requirement of the engine.



HVAC System Load Reduction

- Reduced heat loading; by insulating the body of the vehicle, using alternative technologies for the glazing and ventilation systems, it is possible to significantly reduce the energy requirements of the HVAC systems.

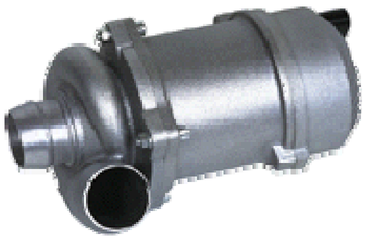


Tire Rolling Resistance

- On-going investment in research by the tire companies is reducing the energy necessary to drive a vehicle forwards.

Intelligent Cooling Systems

- Improved engine thermal control using an electric coolant pump, electric fans and electric 3-way valve.



Vehicle Summary (3 of 3)

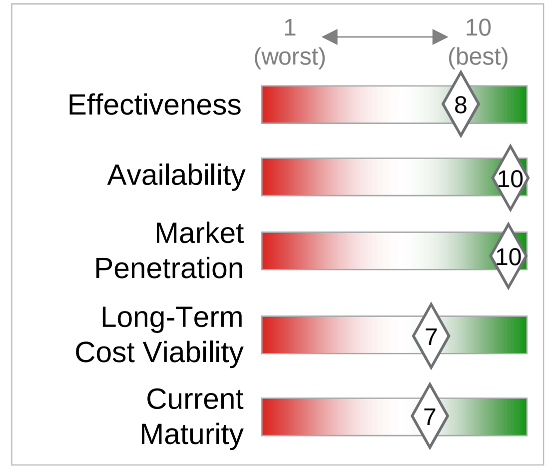
Electric Power Assisted Steering
▪ Replaces FEAD-driven hydraulic steering assistance with electric motor. Increasingly prevalent in small and medium passenger cars (particularly in Europe). 

Mass Reduction: Substitution

Technology and Status

- Concept: Replacement of current material with HSS/AHSS/Al/Mg/CF* etc.
- Base Functioning: Fuel economy improvements are through a reduction in the rolling resistance losses, i.e., the frictional force is reduced by reducing the normal force (weight) of the vehicle. A secondary effect is that a lighter vehicle with lower inertia can use a smaller powertrain to accelerate that reduced mass.
- CO_2 Benefit: A 10% vehicle mass reduction can deliver a 2.7–4.1% fuel economy improvement with constant engine size, but a 4.7–6.7% improvement when the engine is downsized to maintain constant performance.
- Costs: Dependant on material selected and price reductions with increasing volume supply.

Ratings of Technology



Technology Applicability

- Direct benefit, in growing market use, in all market sectors, and all powertrain variations.
- Enables engine down-sizing.
- Lowers inertia.

Visualization

Aluminum-bodied Jaguar XJ

Picture: www.automotive.com

* HSS=High Strength Steel, AHSS=Advanced High Strength Steel, Al=Aluminum, MG=Magnesium, CF=Carbon Fiber

Mass Reduction: Optimization

Technology and Status

- Concept: Optimization of vehicle, vehicle systems and components for weight, not style, manufacturing flexibility or passenger volume. Examples; 30% wheel mass-saving, change from body-on-frame to unibody for trucks.
- Base Functioning: Fuel economy improvements are through a reduction in the rolling resistance losses, i.e. the frictional force is reduced by reducing the normal force, (weight) of the vehicle. A secondary effect is due to a lighter vehicle with lower inertia can use a smaller powertrain to accelerate that reduced mass.
- CO_2 Benefit: 10% mass reduction can improve fuel economy by 6.7%.
- Costs: Can be a cost REDUCTION; optimizing an aluminum wheel with a 30% reduction in weight can give a cost SAVING of 25–40%.

Ratings of Technology

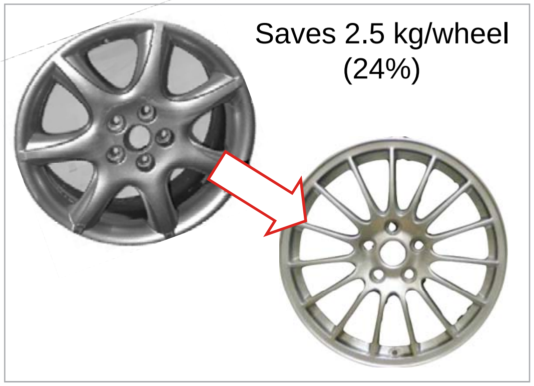
1 (worst) ↔ 10 (best)

Effectiveness	8
Availability	10
Market Penetration	7
Long-Term Cost Viability	10
Current Maturity	7

Technology Applicability

- Has the potential to be applied to many areas of a vehicle. Direct benefit, in growing market use, in all market sectors, and all powertrain variations.
- Enables engine down-sizing.
- Lowers inertia.
- Additional significant opportunity exists with vehicle size. Passenger vehicles have grown SIGNIFICANTLY in the past 3 decades. The manufacturers say that this is due to meet 'market requirements'. If vehicles can be forced to become smaller with each successive iteration, rather than bigger, this equates to lighter. This has the additional benefit of smaller frontal area, thus (aero details remaining constant), the CdA reduces, thus the energy to drive the vehicle through the air is reduced.

Visualization



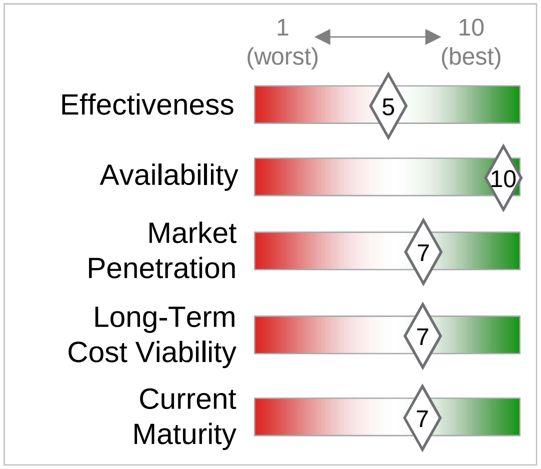
Picture: various sources

Aerodynamics: Passive

Technology and Status

- Concept: Substantial opportunity still exists to lower the coefficient of drag (C_D) through body shape development, smoothing under-floors, faring-in wheels etc.
- Base Functioning: A reduction in C_D has a direct affect on reduction of the force required to enable forward motion. As drag force is dependant on the square of vehicle speed, at higher speeds, the fuel economy gain is increased.
- CO_2 Benefit: A 10% reduction in drag can give a 2.5% improvement in fuel economy.
- Costs: For most items, such as under-floor shields, wheel farings etc, there is some associated on-cost, some items would be low cost or free, such as body shape, and some, such as narrower tires, should be a cost reduction.

Ratings of Technology



Technology Applicability

- The faster the vehicle travels, the greater benefit this is. Most effective where significant freeway travel is required. Suits all powertrain variations.
- Dependant on methods chosen, may have some weight penalty, thus city-only vehicles may be penalized.
- Additional significant opportunity exists with vehicle size. Passenger vehicles have grown SIGNIFICANTLY in the past 3 decades. The manufacturers say that this is due to meet "market requirements". Safety not withstanding, if vehicles can be forced to become smaller with each successive iteration, rather than bigger, frontal area, thus drag force, will reduce (for the same C_D).
- Suggested possible targets; sedans C_D=0.25, SUVs C_D=0.30, minivans C_D=0.29, hatchbacks C_D=0.28.

Visualization

Aptera

Picture: www.green.autoblog.com

Aerodynamics: Active

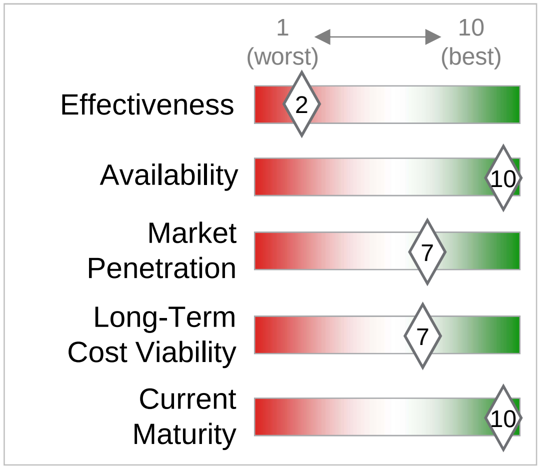
Technology and Status

- Concept: Opportunity exists to reduce overall vehicle drag through improved control of drag-affecting features (cooling apertures, ride-height etc). Radiator grill sizing is designed for maximum thermal rejection; at high ambients / high vehicle loads. Most of the time, the majority of vehicles need much less cooling. Thus openings can be significantly reduced, reducing vehicle drag.
- Base Functioning: A reduction in C_D has a direct affect on reduction of the force required to enable forward motion. As drag force is dependant on the square of vehicle speed, at higher speeds, the fuel economy gain is increased
- CO_2 Benefit: Active cooling aperture control could give an 8-10% vehicle drag reduction. A 10% reduction in drag can give a 2.5% improvement in fuel economy
- Costs: Some associated on-cost

Technology Applicability

- The faster the vehicle is required to travel, the greater benefit this is. Most effective where significant freeway travel is required. Suits all powertrain variations
- Has some (small) weight penalty, thus city-only vehicles may be penalized; however, city-only cars could have altered drive-cycles, as unlikely to need to drive up mountains in Death Valley, at GVW
- Potential improvements through cooling system aperture control C_D 0.008 for small and medium cars and 0.03 for large passenger cars and SUVs
- Where available, ride height reduction with increasing speed reduces the effective frontal area, and increases tire coverage

Ratings of Technology



Visualization

Picture: www.parkviewbmw.com

Thermo-Electric Generators

Technology and Status

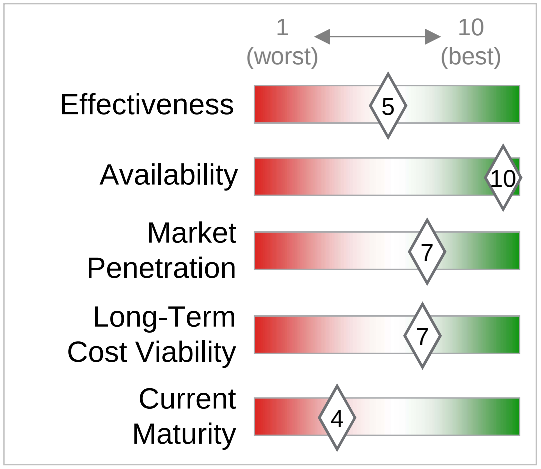
- Concept: Convert temperature differentials directly into electrical energy using the Seebeck effect (temperature differential creates current/voltage same as in thermocouples). A Thermo-Electric Generator (TEG) consists of hot side heat exchanger(s), cold side heat exchanger(s), thermoelectric materials (type and size depends on operating temperature) and compression assembly.
- Base Functioning: 40% of energy from fuel is lost as exhaust heat. TEGs take advantage of high engine exhaust gas temperatures (waste energy) to generate electricity. This can be used to drive accessories or supplement power to an electric motor.
- CO_2 Benefit: Currently expected to give a 5% fuel economy improvement, including the effects of the increased vehicle mass from the system (expected to be in range of stop-start, brake regen, FEAD electrification).
- Costs: Target cost $100/% FE improvement; currently more than this.

Technology Applicability

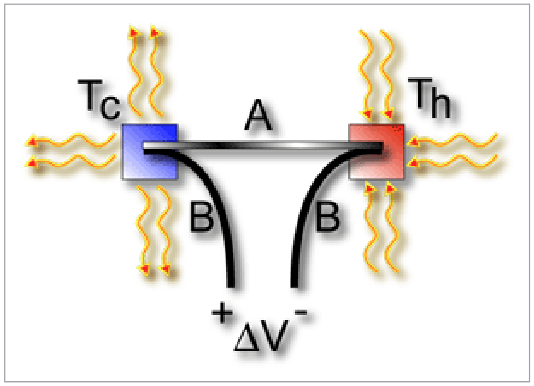
- Well suited to automotive application. Recovers some waste energy; which is up to 40% of the energy from burning fuel.
- More effective at higher temperature differences, thus closer to the engine*, and at high engine loads.
- Has some weight penalty, however the energy developed is expected to more than offset this.
- Currently under development by BSST, Ford, BMW, Visteon and others. Material development underway. Possible to be on production vehicles around 2015.

* May give some packaging challenges

Ratings of Technology



Visualization



Picture: www.customthermoelectric.com

Reduced HVAC System Loading

Technology and Status

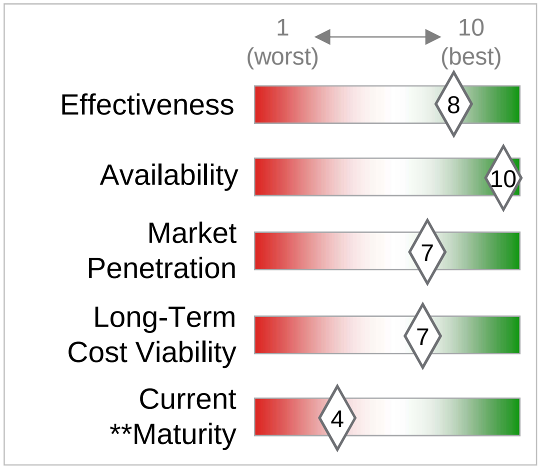
- Concept: Increasingly aerodynamic vehicles typically have larger front and rear windows (for the same class of vehicle). This increases solar loading. Improved thermal insulation reduces solar loading in the Summer and heat loss in the Winter.
- Base Functioning: Reduced thermal loading/heat loss reduces the energy required by HVAC for cooling/heating. Insulated panels, GFPs*, double-glazing, reflective films, active ventilation, reduced thermal mass are all possible methods of realizing this. Optimization then enables smaller A/C components.
- CO_2 Benefit: Suggest 8–10%, application dependant. May enable a doubling of fuel economy. Recent introduction of SC03 drive cycle will clarify A/C effects.
- Costs: Undefined, but expected to improve mpg (or range) for marketability. Use of SC03 cycle may increase demand for reduced HVAC load.

Technology Applicability

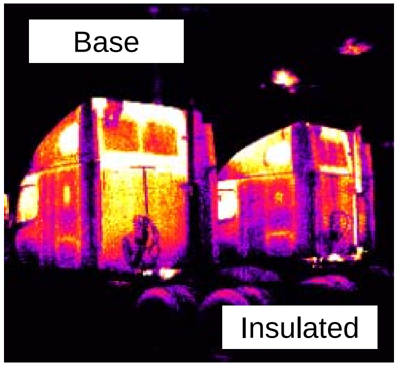
- Technology based on building applications and applies them to automotive use.
- VERY applicable to EVs, hybrids and high-mileage (mpg) vehicles, which are most sensitive to accessory usage as a percentage of the overall vehicle load. Increases mileage and range.
- The insulation on it's own has some weight penalty, however it allows reduction in the sizing of the HVAC components, so potentially weight neutral.
- Reduces degradation of interior panels due to thermal loading / IR attack; may allow for cheaper materials (offsets the cost of the insulation application).

* GFP=Gas Filled Panels **Commercially available technology, to be optimized in vehicles

Ratings of Technology



Visualization



Picture: NREL Vehicle Ancillary Load Reduction Project Close-Out Report

Reduced Tire Rolling Resistance

Technology and Status

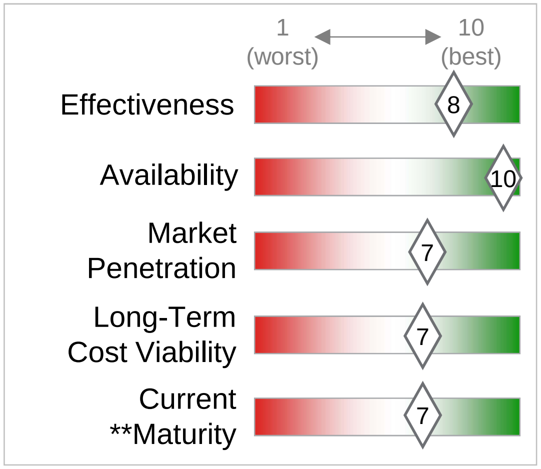
- Concept: Tire rolling resistance is driven by tread and carcass deformation and relaxation as the tire rotates and moves into contact with the road and away. Hysteresis in the tire from this deformation creates heat. Reducing the heat generation reduces the rolling resistance.
- Activity is underway to initiate rolling resistance information labeling for tires, similar to that already shown for wear, traction and temperature performance.
- Base Functioning: Fuel economy improvements are through a reduction in the rolling resistance losses. Lower rolling resistance reduces the amount of energy necessary to drive a vehicle forwards.
- CO_2 Benefit: 10% rolling resistance reduction can improve fuel economy by 2-3%. Currently available tires can offer 10-20% resistance reduction over conventional equipment. Further rolling resistance reductions of up to 50% are predicted to be available in the next 10-15 years.
- Costs: 10% rolling resistance approximates to $5 increase.

Technology Applicability

- Research into rolling resistance, and reducing compromises with traction and wear are on-going.
- Applicable to ALL vehicle types.
- On medium-duty trucks, changing from duallys to single-wides offer a further benefit of a weight reduction, potentially allowing further improving fuel savings.

**Based on current technology, is moving forwards, in all vehicle markets. Further gains dependant on further research by the tire companies

Ratings of Technology



Visualization

Picture: Bridgestone; Tires & Truck Fuel Economy Edition 4

Intelligent Cooling Systems

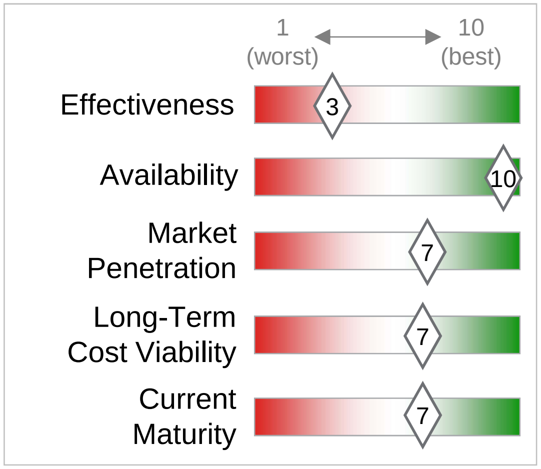
Technology and Status

- Concept: Use an electric coolant pump to remove the FEAD load. By removing it from FEAD also enables speed control, so rather than running at a fixed speed related to engine speed, can be run at a speed suitable to the current vehicle operating condition. Combines well with electric cooling fan and improved flow routing control.
- Base Functioning: Standard cooling systems are sized to provide cooling at maximum load and ambient conditions. For majority of life of most vehicles, this is not required. No FEAD load, more efficient operating point control. Enables quicker warm up from cold. Reduces engine friction by enabling optimum engine temperature operation, rather than over-cooling (on passive systems).
- Further gains possible by controlled high temperature running, subject to suitable NOx after-treatment systems being fitted (when necessary).
- CO_2 Benefit: 3% fuel economy benefit on FTP cycle (assumes gain from electric fan etc already taken).
- Costs: Higher cost (possibly 5-6 times). Provides packaging flexibility as no longer needs to be engine mounted.

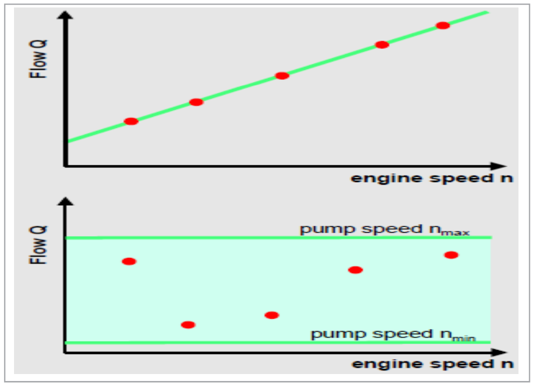
Technology Applicability

- Applicable to all vehicle types using IC engines
- Enables improved soak-condition control using the engine pump

Ratings of Technology



Visualization



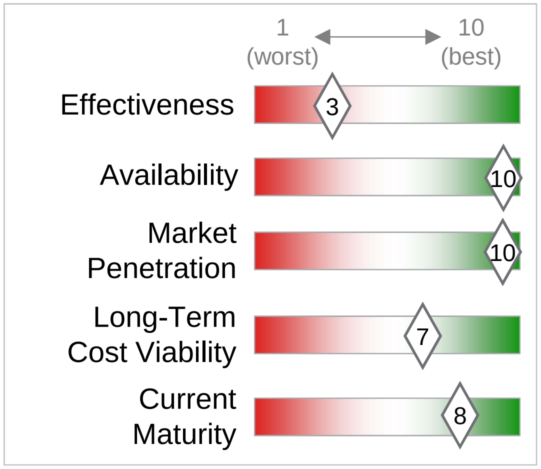
Picture: Pierburg Pump Technology 2008

Electric Power Assisted Steering (EPAS)

Technology and Status

- Concept: Uses either rack or column-drive electric motors to assist driver effort. Replaces engine-driven pump, hoses, reservoir, fluid and hydraulic rack.
- Base Functioning: Removes load on FEAD for a system which isn't used for much of the time (unless cornering or at slow speed).
- CO_2 Benefit: On typical usage cycle, expect 2–3% improvement
- Costs: Reduced warranty, reduced servicing. Cost competitive with hydraulic systems. Enables integration with safety systems such as lane departure warning, stability control (using "anti-skid" feedback) etc.

Ratings of Technology



Technology Applicability

- Currently not available for truck weight-class vehicles. Ongoing developments in this field are making this more likely for all vehicles in the 2020-2025 time-frame
- Required for vehicles with any EV functionality, to allow them to be steered in all situations

Visualization

Picture: www.trwauto.com

Vehicle Technology Applicability

		Mass Reduction; Material Substitution	Mass Reduction; Component Optimization	Aerodynamics; Passive	Aerodynamics; Active	Thermo-electric Generators	HVAC Load Reduction	Rolling Resistance Reduction	Intelligent Cooling Systems	Electric Power Assisted Steering
Vehicle Classification	**Small Car (Ford Focus)**	X	X	X	X	X	X	X	X	X
	Standard Car (Toyota Camry)	X	X	X	X	X	X	X	X	X
	Small MPV (Saturn Vue)	X	X	X	X	X	X	X	X	X
	Full-sized Car (Chrysler 300C)	X	X	X	X	X	X	X	X	X
	Large MPV (Dodge Grand Caravan)	X	X	X	X	X	X	X	X	X
	Truck (Ford F150)	X	X	X	X	X	X	X	X	X
	Heavy light-duty truck (Ford F250/F350)	X	X	X	X	X	X	X	X	X

Outline

- Introduction
- Spark ignited engine technologies
- Diesel engine technologies
- Hybrid vehicle technologies
- Transmission technologies
- Vehicle technologies
- **Conclusions**

Conclusions

- A substantial list of technologies that could offer some benefit to GHG emissions in the 2020–2025 timeframe was developed
- These technologies were assessed by the Ricardo team
  - These assessments were reviewed with EPA
  - Advisory Committee provided input to assessments
- Based on EPA feedback, the large list of potential technologies was reduced to the set considered further in the study, "Computer Simulation of Light Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020–2025 Timeframe"
  - These are described further in the main program report (Ricardo reference RD.10/157405.8)