EPA Staff Technical Report: Cost and Effectiveness Estimates of Technologies Used to Reduce Light-duty Vehicle Carbon Dioxide Emissions

United States
Environmental Protection
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Executive Summary

The National Research Council's Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy is tasked with providing updated estimates of the costs and potential efficiency improvements that might be employed to improve fuel economy. On March 4, 2008 the NRC Committee requested that EPA provide it with EPA's technical analysis on the control of greenhouse gas emissions from light-duty vehicles, to aid the committee in its work.[A]

This report presents EPA technical staff current assessment of the costs and effectiveness from a broad range of technologies which can be applied to cars and light-duty trucks. The report is divided into four major sections. In Section 1, we discuss the methodology used to develop cost and effectiveness estimates, including what data sources we relied upon. In Section 2, we present our estimates of the carbon dioxide (CO_2) reduction potential of nearly 40 individual technologies covering five broad categories: engines, transmissions, hybrids, accessories, and others (e.g., aerodynamic improvements). These estimates are for individual technologies compared to a baseline vehicle, and the estimated effectiveness cannot simply be added up when considering a combination of technologies. This issue is addressed in Section 3 of the report, which discusses the synergistic effects of combining multiple technologies and provides an estimate of the magnitude of this impact on CO_2 reduction effectiveness. Finally, Section 4 provides an estimate of the direct costs associated with each of the technologies, as well as a discussion of estimating indirect costs and the potential for future cost reductions.

The majority of the technologies discussed in this report are in production and available on vehicles today, either in the United States, Japan, or Europe. A number of the technologies are commonly available, while others have only recently been introduced into the market. In a few cases, we provide estimates on technologies which are not currently in production, but are expected to be so in the next few years.

In general, we believe these estimates we present are conservative. They rely on data sources from the past one to six years, which in some cases are relatively old. The automotive industry is a technology-driven industry, and new technologies are developed and introduced quickly. A number of technologies which have only recently been introduced or will be within the next year are likely to see improvements in their effectiveness and cost reductions beyond what we estimate today. Nevertheless, we believe that the estimates presented in this report are defensible and reasonable predictions for the next few years.

This report is based on our assessment of currently available data, much of which is in the public domain. Based on this assessment, EPA technical staff concludes there are a large number of technologies which can be applied to cars and trucks that are capable of achieving significant reductions in greenhouse gas emissions, and improve vehicle fuel economy, at reasonable costs.

[A] See Attachment 1, which includes the request letter from the Committee.

1 Methodology

In estimating the cost and effectiveness for vehicle CO_2 reduction technologies, we relied upon a number of sources for technical information. We utilized those sources of information which were determined to be credible for projecting the CO_2 reduction effectiveness of individual vehicle technologies which are either currently available, or which we project will be available in the next two to ten years. These data sources included: vehicle fuel economy certification data; peer reviewed or publicly commented reports; peer reviewed technical journal articles and technical papers available in the literature; and confidential data submissions from vehicle manufacturers and automotive industry component suppliers. The following summarizes our use of the most commonly utilized data sources. The discussion of each individual technology in Section 2 (CO_2 reduction effectiveness) and Section 4 (technology cost estimates) includes the citation to the source(s) of information we used for evaluating CO_2 reduction potential of that specific technology.

EPA has conducted on-going technical analysis on the control of greenhouse gases considered control of carbon dioxide (CO_2), methane, nitrous oxide, and hydroflourocarbons. In addition, the technical work on control of CO_2 emissions includes, but is not limited to, emissions measured over EPA's traditional test cycles for measuring fuel economy. As EPA acknowledged in a regulatory action completed in 2006, these test cycles, which are more than 20 years old, do not accurately represent the true fuel economy values which today's vehicles will typically achieve on the road. These traditional tests also cannot account for the CO_2 or fuel economy reduction potential of all available technologies, in particular efficiency improvements for vehicle air conditioning systems. Given the charge to the NAS Committee, this technical report has been limited to information on the effectiveness and cost of technologies to reduce CO_2 emissions over the test cycles used for measuring fuel economy, and our estimates of percentage improvements in CO_2 reduction are based on the traditional fuel economy test cycles.

1.1 Fuel Economy Certification Data

Where available, we considered data from recent model years from EPA's Fuel Economy Certification Data. These CO_2 reduction estimates were estimated from EPA's fuel economy database on the two-cycle (FTP city & highway) fuel economy test results. During the standard fuel economy test cycles, direct measurements of CO_2 emissions are made. This data, along with other measurements, are then used to calculate the estimated fuel economy performance in gallons of fuel consumed per mile. Vehicle certification data are an obviously reliable source for determination of the CO_2 reduction potential when a directly comparable vehicle was offered both with and without the specific CO_2 reducing technology, because a comparison between the emissions data between the two vehicles directly reflect the application of the technologies on the vehicle test cycles. Technology-specific effectiveness numbers were extracted for vehicles where only the specific technology would be changed from a reference vehicle, in order to eliminate any confounding of values across several technologies. In some hybrid vehicle cases, the exact same vehicle may not be offered, and we selected a similar vehicle for comparison. Examples of the use of such vehicle certification data are:

- Honda Civic Hybrid compared to a directly comparable Honda Civic conventional drive;
- GM's 2008 model year ("2-mode") hybrid full-size SUV powered by a V8 with cylinder deactivation compared to a similar vehicle without a hybrid system but with cylinder deactivation; and
- Honda’s 2005 model year Odyssey V6 minivan with and without cylinder deactivation.

1.2 Reports and Papers in the Literature

A large number of technical reports and papers are available which contain data and estimates of the CO_2 reduction potential of various vehicle technologies. In addition to specific peer-reviewed papers respecting individual technologies, we also utilized a number of recent reports which had been utilized by various State and Federal Agencies and which were specifically undertaken for the purpose of estimating future vehicle CO_2 reduction effectiveness or improvements in fuel economy. The reports we utilized most frequently were:

- 2002 National Academy of Science (NAS) report titled "Effectiveness and Impact of Corporate Average Fuel Economy Standards”. At the time it was published, the NAS report was considered by many to be the most comprehensive summary of current and future fuel efficiencies improvements which could be obtained by the application of individual technologies. The focus of this report was fuel economy, which can be directly correlated with CO_2 emissions. In many cases, more recent information has become available on the CO_2 reduction effectiveness of individual technologies. We therefore assessed and, where reliable, utilized the updated information. For those technologies for which we were not able to determine more recent, credible data than were reported in the 2002 NAS report, we utilized the NAS report information. In addition, the 2002 NAS report contains effectiveness estimates for ten different vehicle classifications (small car, mid-SUV, large truck, etc), but did not differentiate these effectiveness values across the classes. Where other sources or engineering principles indicated that a differentiation was warranted, we utilized the 2002 NAS effectiveness estimates as a starting point and further refined the estimate to one of five vehicle classes using engineering judgment or by consulting additional reliable sources.

- 2004 Northeast States Center for a Clean Air Future (NESCCAF) report "Reducing Greenhouse Gas Emissions from Light-Duty Motor Vehicles". This report, which was utilized by the California Air Resources Board for their 2004 regulatory action on vehicle CO_2 emissions, includes a comprehensive vehicle simulation study undertaken by AVL, a world-recognized leader in automotive technology and engineering. In addition, the report included cost estimates developed by the Martec Group, a market-based research and consulting firm which provides services to the automotive industry. The NESCCAF report considered a number of technologies not examined in the 2002 NAS report. In addition, through the use of vehicle simulation modeling, the 2004 NESCCAF report provides a scientifically rigorous estimation of the synergistic impacts of applying multiple CO_2 reduction technologies to a given vehicle.

1.3 Confidential Data from Vehicle Manufacturers and Component Suppliers

We also evaluated confidential data from a number of vehicle manufacturers as well as a number of technology component suppliers. Over the past several years, EPA has met numerous times with the worlds leading automotive companies as well as many of the major automotive supply firms. During these meetings, EPA has received confidential briefings regarding companies near and long-term plans for future technologies which can reduce criteria pollutants (e.g., oxides of nitrogen and particulate matter), reduce CO_2 emissions, and improve vehicle fuel economy. EPA reviewed this information in the development of this report.

In February of 2007, the National Highway Traffic Safety Administration published a detailed Request for Comment (RFC) in the Federal Register. This RFC included, among other items, a request for information from automotive manufacturers and the public on the fuel economy improvement potential of a large number of vehicle technologies. EPA has been furnished this information by NHTSA (or in some cases directly from the vehicle manufacturer) pursuant to a Memorandum of Understanding between NHTSA and EPA which conforms to the Confidential Business Information rules of both agencies. The manufacturer's submissions to this RFC were supplemented by confidential briefing and data provided by vehicle component suppliers, who for many of the technologies considered are the actual manufacturers of the specific technology and often undertake their own development and testing efforts to investigate the CO_2 reduction potential of their products.

In considering the confidential data from vehicle manufacturers and component suppliers, it was sometimes the case where the specific basis of a technology's effectiveness was not described (e.g., was the estimate based on production vehicle testing, vehicle simulation modeling, engineering judgment, or some other basis). In addition, it was also sometimes the case where a manufacturers projection of the effectiveness of a technology for fuel economy improvement (or CO_2 reduction) was also coupled with improvements in other vehicle attributes, such as an increase in vehicle weight, or an increase in engine power or torque – making it more difficult to distinguish the technology's impact only on CO_2 reduction effectiveness. For these reasons, we tended to rely less solely on the manufacturers estimates for technology effectiveness than on other data sources. Nevertheless, the confidential submissions from automotive companies and technology suppliers were utilized in some cases, and were often used to validate the estimates from other sources.

2 CO_2 Reduction for Individual Vehicle Technologies

The following sections detail the CO_2 reduction effectiveness of individual technologies. In order to estimate CO_2 reduction effectiveness, it is necessary to clearly define the baseline technology from which the new technology is being estimated, this is discussed in Section 2.1. As also discussed in Section 2.1, we have developed CO_2 reduction effectiveness estimates for five broad categories of vehicles in order to represent the range of products available in the light-duty vehicle fleet. These five categories are labeled small car, large car, minivan, small truck and large truck. The technologies are organized by six broad categories: engine technologies (Section 2.3), transmission technologies (Section 2.4), hybrid technologies (Section 2.5), electric vehicles (Section 2.6), accessory technologies (Section 2.7) and other vehicle technologies (Section 2.8). A summary of our estimates for all technologies for the five vehicle classes is presented in Section 2.2

Please note that the estimated CO_2 reduction effectiveness discussed in Section 2 do not account for synergistic impacts between certain technologies. These synergistic impacts are discussed in Section 3 of this report.

2.1 Baseline Definition and Vehicle Classes

In order to estimate both technology costs and CO_2 reduction estimates, it is necessary to describe the vehicle characteristics baseline from which the estimates can be compared. For this report, unless noted elsewhere, the baseline vehicle is defined as a vehicle with a port-fueled injected, naturally aspirated gasoline engine with two intake and two exhaust valves and fixed valve timing and lift. The baseline transmission is a 4-speed automatic, and the vehicle has no hybrid systems. Our assessment attempted to maintain vehicle performance equivalent to todays products, that is, we have provided estimates of the ability of various technologies to reduce CO_2 emissions without improving or reducing other vehicle performance characteristics when compared to today's vehicles.

It is well known that both the costs and the effectiveness of any given CO_2 reduction technology will not be the same on every vehicle, given the wide range of characteristics of vehicle sizes and performance being offered today.

Existing reports in the literature typically group vehicles into categories or classes based on those characteristics which can have a discernable impact on the application of a given technology. For example, the 2002 NAS report divided the car and light-truck fleet into ten different vehicle classes. However, the 2002 NAS provided the same range of estimates for fuel consumption improvement and incremental costs for each of the ten vehicle classes discussed in the report. The 2004 NESCCAF report provided five vehicle classes, and, where the authors deemed it appropriate, different estimated values were provided for the five different vehicle classes.

In this report, we provide effectiveness and cost estimates for five classes of vehicles, which are generally intended to represent broad groupings of a wide variety of products offered in the US car and light-duty truck market. In some cases, we have provided further differentiation within a given class (e.g., between unibody and ladder-frame constructed vehicles for axle disconnect technologies). Where the data sources we reviewed provided sufficient detail, we refined estimates to provide further effectiveness refinement within sub-division of the classes.

The names used to distinguish these five classes are for ease of reference in the report; they are not intended to be viewed narrowly. We use these five categories to represent the following types of vehicles.

- Small car: a subcompact or compact car typically powered by an inline 4 cylinder engine.
- Large car: a midsize or large passenger car typically powered by a V6 cylinder engine.
- Minivan: a minivan or large cross-over unibody constructed vehicle with a large frontal area, typically powered by a V6 engine, capable of carrying ~ 6 or more passengers.
- Small truck: small or mid-sized sports-utility and cross-over vehicles, or a small pick-up truck, typically powered by a 6-cylinder engine.
- Large truck: large sports-utility vehicles and large pickup trucks, typically a ladder-on-frame construction, and typically powered by a V8 engine.

2.2 Summary of Estimates

Table 2.2-1 through Table 2.2-5 summarize our estimates for the CO_2 reduction estimates of various technologies which can be applied to cars and light-duty trucks. A similar summary of costs are provided in Table 4.2-1. Each of these estimates is discussed in more detail in Sections 2.3 through 2.8.

Table 2.2-1 Engine Technology Effectiveness

Technology	Absolute CO_2 Reduction (% from baseline vehicle)				
	Small Car	**Large Car**	**Minivan**	**Small Truck**	**Large Truck**
Low friction lubricants – incremental to base engine	0.5	0.5	0.5	0.5	0.5
Engine friction reduction – incremental to base engine	1-3	1-3	1-3	1-3	1-3
Overhead Cam Branch					
VVT – intake cam phasing	2	1	1	1	2
VVT – coupled cam phasing	3	4	2	3	4
VVT – dual cam phasing	3	4	2	2	4
Cylinder deactivation (includes imp. oil pump, if applicable)	n.a.	6	6	6	6
Discrete VVLT	4	3	3	4	4
Continuous VVLT	5	6	4	5	5
Overhead Valve Branch					
Cylinder deactivation (includes imp. oil pump, if applicable)	n.a.	6	6	6	6
VVT – coupled cam phasing	3	4	2	3	4
Discrete VVLT	4	4	3	4	4
Continuous VVLT (includes conversion to Overhead Cam)	5	6	4	5	5
Camless valvetrain (electromagnetic)	5-15	5-15	5-15	5-15	5-15
Gasoline Direct Injection–stoichiometric (GDI-S)	1-2	1-2	1-2	1-2	1-2
Gasoline Direct Injection–lean burn (incremental to GDI-S)	8-10	9-12	9-12	9-12	10-14
Gasoline HCCI dual-mode (incremental to GDI-S)	10-12	10-12	10-12	10-12	10-12
Turbo+downsize (incremental to GDI-S)	5-7	5-7	5-7	5-7	5-7
Diesel – Lean NOx trap[]*	15-26 [25-35]	21-32 [30-40]	21-32 [30-40]	21-32 [30-40]	21-32 [30-40]
Diesel – urea SCR []*	15-26 [25-35]	21-32 [30-40]	21-32 [30-40]	21-32 [30-40]	21-32 [30-40]

* Note: estimates for % reduction in fuel consumption are presented in brackets.

Table 2.2-2 Transmission Technology Effectiveness

Technology	Absolute CO_2 Reduction (% from baseline vehicle)				
	Small Car	Large Car	Minivan	Small Truck	Large Truck
5-speed automatic (from 4-speed auto)	2.5	2.5	2.5	2.5	2.5
Aggressive shift logic	1-2	1-2	1-2	1-2	1-2
Early torque converter lockup	0.5	0.5	0.5	0.5	0.5
6-speed automatic (from 4-speed auto)	4.5-6.5	4.5-6.5	4.5-6.5	4.5-6.5	4.5-6.5
6-speed AMT (from 4-speed auto)	9.5-14.5	9.5-14.5	9.5-14.5	9.5-14.5	9.5-14.5
6-speed manual (from 5-speed manual)	0.5	0.5	0.5	0.5	0.5
CVT (from 4-speed auto)	6	6	6	n.a.	n.a.

Table 2.2-3 Hybrid Technology Effectiveness

Technology	Absolute CO_2 Reduction (% from baseline vehicle)				
	Small Car	Large Car	Minivan	Small Truck	Large Truck
Stop-Start with 42 volt system	7.5	7.5	7.5	7.5	7.5
IMA/ISA/BSG (includes engine downsize)	30	25	20	20	20
2-Mode hybrid electric vehicle	n.a.	40	40	40	25
Power-split hybrid electric vehicle	35	35	35	35	n.a.
Full-Series hydraulic hybrid	40	40	40	40	30
Plug-in hybrid electric vehicle	58	58	58	58	47
Full electric vehicle (EV)	100	100	n.a.	n.a.	n.a.

Table 2.2-4 Accessory Technology Effectiveness

Technology	Absolute CO_2 Reduction (% from baseline vehicle)				
	Small Car	Large Car	Minivan	Small Truck	Large Truck
Improved high efficiency alternator & electrification of accessories (12 volt)	1-2	1-2	1-2	1-2	1-2
Electric power steering (12 or 42 volt)	1.5	1.5-2	2	2	2
Improved high efficiency alternator & electrification of accessories (42 volt)	2-4	2-4	2-4	2-4	2-4

Table 2.2-5 Other Vehicle Technology Effectiveness

Technology	Absolute CO_2 Reduction (% from baseline vehicle)				
	Small Car	Large Car	Minivan	Small Truck	Large Truck
Aero drag reduction (20% on cars, 10% on trucks)	3	3	3	2	2
Low rolling resistance tires (10%)	1-2	1-2	1-2	1-2	n.a.
Low drag brakes (ladder frame only)	n.a.	n.a.	n.a.	1	1
Secondary axle disconnect (unibody only)	1	1	1	1	n.a.
Front axle disconnect (ladder frame only)	n.a.	n.a.	n.a.	1.5	1.5

2.3 Engine Technologies

Unless noted otherwise, the baseline engine for the engine technologies described in this section is a port-fuel injected, spark-ignition, naturally aspirated, 4-valve per cylinder engine with fixed intake and exhaust valve timing.

2.3.1 Low-Friction Lubricants

More advanced multi-viscosity engine and transmission oils are now available with improved performance in a wider temperature band, with better lubricating properties. Manufacturers are moving from 5W-30 to 5W-20 and even 0W-20 engine oils to reduce cold start friction. This may directionally benefit the fuel economy improvements of valvetrain technologies such as cylinder deactivation, which rely on a minimum oil temperature (viscosity) for operation. Confidential manufacturer data submitted by vehicle manufacturers in response to NHTSA's February 2007 Request for Comment (2/2007 RFC) suggests that low-friction lubricants could reduce CO_2 emissions by 0.5 percent for all vehicle types.

2.3.2 Engine Friction Reduction

All reciprocating and rotating components in the engine are candidates for friction reduction, and minute improvements in several components can add to a measurable fuel economy improvement. Several friction reduction opportunities (piston surfaces and rings, crankshaft design, improved material coatings, roller cam followers, etc.) have been identified that are still available to a significant number of engine designs. Additionally, as computer-aided modeling software continues to improve, more opportunities for incremental friction reduction might become apparent. Confidential manufacturer data provided in response to the 2/2007 RFC indicates that the CO_2 reduction potential ranges from 1 to 3 percent for engine friction reduction technologies.

2.3.3 Variable Valve Timing Systems

Variable valve timing has been available in the market for quite a while. By the early 1990s, VVT had made a significant market penetration with the arrival of Honda's "VTEC" line of engines. VVT has now become a widely adopted technology: for the 2006 model year, over half of all new cars and light trucks have engines with some method of variable valve timing.[1] Therefore, the degree of further improvement across the fleet is limited to vehicles that have not already implemented this technology.

Manufacturers are currently using many different types of variable valve timing mechanisms, which have a variety of different names and methods. The major types of VVT are listed below.

2.3.3.1 Intake Camshaft Phasing (ICP)

Valvetrains with ICP – the simplest subset of cam phasing – can modify the timing of the intake valve while the exhaust valve timing remains fixed. We estimate that ICP designs may enable a 1 to 2 percent reduction in CO_2 compared to fixed-valve engines. This estimate is based directly on the work detailed in the 2004 NESCCAF report, which relied on vehicle simulation modeling to predict the CO_2 reduction (by vehicle class) of a long list of vehicle technologies including VVT.[2]

2.3.3.2 Coupled Camshaft Phasing (CCP)

Coupled (or coordinated) cam phasing is a design in which both the intake and exhaust valve timing are varied with the same cam phaser. The 2004 NESCCAF report indicates CCP designs may enable a 2-4% reduction in CO_2 emissions above fixed-cam valvetrains. Vehicles with higher power-to-weight ratios (large cars and large trucks) are at the high of this range, while minivans are at the low end.

2.3.3.3 Dual (Independent) Camshaft Phasing (DCP)

The most flexible VVT design is dual cam phasing, where the intake and exhaust valve opening and closing events are controlled independently. This design allows the option of controlling valve overlap, which can be used as an internal exhaust gas recirculation (EGR) strategy. EPA estimates that DCP designs may enable a 2-4% reduction in CO_2 emissions compared to fixed-valve engines, similar to estimates for CCP. [3]

2.3.4 Engine Cylinder Deactivation

In implementing cylinder deactivation, some (usually half) of the cylinders are “shut down” during light load operation – the valves are kept closed, and no fuel is injected – as a result, the trapped air within the deactivated cylinders is simply compressed and expanded as an air spring, with reduced friction and heat losses. The active cylinders combust at almost double the load required if all of the cylinders were operating. Pumping losses are significantly reduced as long as the engine is operated in this “part-cylinder” mode. The theoretical engine operating region for cylinder deactivation is limited to no more than roughly 50% of peak power at any given engine speed. In practice, however, cylinder deactivation is employed primarily at lower engine cruising loads and speeds, where the transitions in and out of deactivation mode are less apparent to the operator and where the noise and vibration (NVH) associated with fewer firing cylinders may be less of an issue. Manufacturers are exploring the possibilities of increasing the amount of time that part-cylinder mode might be suitable to a vehicle with more refined powertrain and NVH treatment strategies.

Cylinder deactivation has seen a recent resurgence thanks to better valvetrain designs and engine controls (it was first offered in the 1980s on the Cadillac 8-6-4, but was discontinued because of reliability problems). General Motors and Chrysler Group have incorporated cylinder deactivation across a substantial portion of their V8-powered lineups. Honda (Odyssey, Pilot) and General Motors (Impala, Monte Carlo) offer V6 models with cylinder deactivation.

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

On its own accord, cylinder deactivation can reduce CO_2 emissions by 6%, at minimum, for applicable vehicles – those with engines of 6 or more cylinders (with vehicles with higher engine displacement-to-weight ratios seeing more of a potential improvement). This number is supported by official fuel economy test data on a model year 2005 V6 Honda Odyssey with cylinder deactivation compared to the same vehicle (and engine displacement) without cylinder deactivation.

2.3.5 Variable Valve Lift Systems

Controlling the lift height of the valves provides additional flexibility and potential for further reduction in CO_2 emissions. By reducing the valve lift, engines can decrease the volumetric flow at lower operating loads, improving fuel-air mixing and in-cylinder mixture motion which results in improved thermodynamic efficiency and also potentially reduced overall valvetrain friction. Also, by moving the throttling losses further downstream of the throttle valve, the heat transfer losses that occur from the throttling process are directed into the fresh charge-air mixture just prior to compression, delaying the onset of knock-limited combustion processes. At the same time, such systems may also incur increased parasitic losses associated with their actuation mechanisms. A number of manufacturers have already implemented VVLT into their fleets (Toyota, Honda, BMW) but overall this technology is still available for most of the fleet. There are two major classifications of variable valve lift, described below:

2.3.5.1 Discrete Variable Valve Lift

Discrete variable valve lift (DVVL) is a method in which the valvetrain switches between multiple cam profiles, usually 2 or 3, for each valve. These cam profiles consist of a low and a high-lift lobe, and may include an inert or blank lobe to incorporate cylinder deactivation (in the case of a 3-step DVVL system). DVVL is estimated to provide an additional 4% CO_2 emissions reduction above that realized by VVT systems (with the exception of minivans at 3%, due to their traditionally lower power-to-weight ratios).[2]

2.3.5.2 Continuous Variable Valve Lift

Continuous variable valve lift (CVVL) valvetrains are mechanically more complicated than DVVL designs. Currently, only BMW has implemented this type of system (in its Valvetronic engines, which also incorporates fully flexible valve timing), in which an extra set of rocker arms are used to vary the valve lift height. This design is limited to overhead cam engines. The contribution of CVVL, independent of any improvement of a VVT system, has been estimated to potentially reduce CO_2 emissions by 4% (minivans) up to 6% (large cars) over VVT systems according to simulation results in the NESCCAF report.[2]

2.3.6 Camless Valve Actuation Systems

Camless valve actuation relies on electromechanical actuators instead of camshafts to open and close the cylinder valves. An engine valvetrain that operates independently of any mechanical means provides the ultimate in flexibility for intake and exhaust timing and lift optimization. With it comes infinite valve overlap variability, the rapid response required to change between combustion modes (such as HCCI and spark ignition), intake valve throttling, cylinder deactivation, and elimination of the camshafts (reduced friction). Camless valvetrains have been under research for many decades due to the design flexibility and the attractive fuel economy improvement potential they might provide.

Despite the promising features of camless valvetrains, significant challenges remain. High costs and design complexity have reduced manufacturers' enthusiasm for camless engines in light of other competing valvetrain technologies. The advances in VVT, VVLT, and cylinder deactivation systems demonstrated in recent years have reduced the potential efficiency advantage of camless valvetrains.

There is a broad range of opinion on the potential CO_2 emissions reduction advantage of camless systems, depending on the level of parasitic loads required to operate the actuators. EPA projects that the potential net CO_2 emissions reductions might range from 5-15% (over a fixed cam-driven valvetrain) depending on the integration and optimization of a future camless system.[4] We are projecting the camless valve systems will not be widely available in high volume light-duty vehicles within the next 10 years.

2.3.7 Stoichiometric Gasoline Direct Injection Technology

Gasoline direct injection (GDI, or SIDI) engines inject fuel at high pressure directly into the combustion chamber (rather than the intake port in port fuel injection). Direct injection improves cooling of the air/fuel charge within the cylinder, which allows for higher compression ratios and increased thermodynamic efficiency. Injector design advances and increases in fuel pressure have promoted better mixing of the air and fuel, enhancing combustion rates, increasing exhaust gas tolerance and improving cold start emissions. GDI engines achieve higher power density and match well with other technologies, such as boosting and variable valvetrain designs.

Several manufacturers have recently released GDI engines: besides Audi’s lineup of GDI engines, Volkswagen and BMW have GDI offerings; Toyota (Lexus IS 350) and General Motors (Chevy Impala 3.6L) are already in production or about to be introduced. In addition, BMW and GM have announced their plans to dramatically increase the number of GDI engines in their portfolios.

On its own, stoichiometric GDI does not bring with it the promise of CO_2 emissions reductions much beyond 2%, but combined with other technologies (boosting, downsizing) it could enable a significant reduction in consumption compared to engines of similar power output (as discussed in Section 2.3.10). Confidential data from multiple manufacturers agree with this CO_2 reduction estimate.

2.3.8 Lean-Burn Gasoline Direct Injection Technology

Direct injection, especially with diesel-like “spray-guided” injection systems, enables operation with excess air in a stratified or partially-stratified fuel-air mixture, as a way of reducing the amount of intake throttling. Also, with higher-pressure fuel injection systems, the fuel may be added late enough during the compression stroke so as to delay the onset of autoignition, even with higher engine compression ratios. Taken together, an optimized “lean-burn” direct injection gasoline engine may achieve high engine thermal efficiency. European gasoline direct-injection engines have achieved some success with this concept, although at far higher NOx emissions levels than are allowed at today’s Tier 2 emissions standards. To date, no manufacturers have sold a light-duty lean-burn GDI engine in the US market due to the higher cost of lean NOx catalyst systems relative to three-way catalysts, coupled with the corresponding need for low-sulfur gasoline.

However, several injector suppliers are optimistic about the potential of lean-burn GDI engines in the near future. Fuel system improvements, changes in combustion chamber design, and repositioning of the injectors have allowed for better air/fuel mixing and combustion efficiency. There is currently a shift from wall-guided injection to spray guided injection, which improves injection precision and targeting towards the spark plug, increasing lean combustion stability. The increased combustion stability allows for recirculated exhaust gas (EGR) rates of up to 40% which can significantly reduce in-cylinder NOx emissions. Combined with advances in NOx aftertreatment (commensurate with diesel progress), lean-burn GDI engines may be a possibility in North America.

As noted above, a key technical requirement for lean-burn GDI engines to meet Tier 2 NOx emissions levels is the availability of gasoline with sulfur levels commensurate with ultra-low sulfur diesel, for durability of the lean NOx catalyst systems. Without the availability of ultra low sulfur gasoline, it does not appear that lean-burn GDI engines can be expected to penetrate the light-duty market anytime soon.

The most recent CO_2 reduction estimates for lean-burn GDI engines range from 8-10% for small cars to 10-14% for large trucks, compared to a port-fueled (stoichiometric) engine. These estimates are based on the 2004 NESCCAF report and are supported by confidential manufacturer and supplier estimates.

2.3.9 Gasoline Homogeneous Charge Compression Ignition

Gasoline homogeneous charge compression ignition (HCCI), also referred to as controlled autoignition (CAI), is an alternate engine operating mode that does not rely on a spark event to initiate combustion. The principles are more closely aligned with a diesel combustion cycle, in which the compressed charge exceeds a temperature and pressure necessary for spontaneous autoignition. The subsequent combustion event is much shorter in duration with higher thermal efficiency.

An HCCI engine has inherent advantages in its overall efficiency for two main reasons:

- The engine is operated with a higher compression ratio, and with a shorter combustion duration, resulting in a higher thermodynamic efficiency, and
- The engine can be operated virtually unthrottled, even at light loads,

Combined, these effects have shown an increase in engine brake efficiency (typically 25-28%) to greater than 35% at the high end of the HCCI operating range.[5]

Criteria pollutant emissions are very favorable during HCCI operation. Lower peak in-cylinder temperatures (due to high dilution) keep engine-out NOx emissions to a minimum – realistically below Tier 2 levels without aftertreatment – and particulates are low due to the homogeneous nature of the premixed charge.

Due to the inherent difficulty in maintaining combustion stability without encountering engine knock, HCCI is difficult to control, requiring feedback from in-cylinder pressure sensors and rapid engine control logic to optimize combustion timing, especially considering the transient nature of operating conditions seen in a vehicle. Due to the highly lean and/or dilute conditions under which HCCI combustion is stable, the range of engine loads achievable in a naturally-aspirated engine is somewhat limited. Because of this, it is likely that any commercial application would operate in a "dual-mode" strategy between HCCI and spark ignition combustion modes, in which HCCI would be utilized for best efficiency at light engine loads and spark ignition would be used at higher loads and at idle. This type of dual-mode strategy has already been employed in a few *diesel*-HCCI engines in Europe and Asia (notably the Toyota Avensis D-Cat and the Nissan light-duty “MK” combustion diesels).

Until recently, gasoline-HCCI technology was considered to still be in the research phase. However, most manufacturers have made public statements about the viability of incorporating HCCI into light-duty passenger vehicles, and have significant vehicle demonstration programs aimed at producing a viable product within the next 5-10 years.

There is widespread opinion as to the CO_2 reduction potential for HCCI in the literature. Based on confidential manufacturer information, EPA believes that a gasoline HCCI / GDI dual-mode engine might achieve 10-12% reduction in CO_2, compared to a comparable SI engine. Despite its promise, application of HCCI in light duty vehicles is not yet ready for the market, and will remain so for at least a few more years. It is not anticipated to be seen in volume for at least the next 5-10 years, which is concurrent with many manufacturers’ public estimates.

2.3.10 Gasoline Turbocharging and Downsizing

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

Almost every major manufacturer currently markets a vehicle with some form of boosting. While boosting has been a common practice for increasing performance for several decades, it has considerable fuel economy potential when the engine displacement is reduced. Specific power levels for a boosted engine often exceed 100 hp/L - compared to average naturally aspirated engine power densities of roughly 70 hp/L. As a result, engines can conservatively be downsized roughly 30% to achieve similar peak output levels.

In the last decade, improvements to turbocharger turbine and compressor design have improved their reliability and performance across the entire engine operating range. New variable geometry turbines and ball-bearing center cartridges allow faster turbocharger spool-up (virtually eliminating the once-common “turbo lag”) while maintaining high flow rates for increased boost at high speeds.

The 2002 NAS report suggests that a downsized turbocharged engine at equivalent performance levels would offer (CO_2) reductions of 5 to 7%, which is supported by confidential manufacturer data. EPA considers this 5 to 7% reduction achievable over a naturally-aspirated stoichiometric GDI engine of comparable performance. This technology is available today.

2.3.11 Diesel Engine

Diesel engines have several characteristics that give them superior fuel efficiency to conventional gasoline, spark-ignited engines:

- Pumping losses are greatly reduced due to lack of (or greatly reduced) throttling.

- The diesel combustion cycle operates at a higher compression ratio, with a very lean overall air/fuel mixture, both of which contribute to higher thermal efficiency.
- Turbocharged light-duty diesels typically achieve much higher torque levels at lower engine speeds than equivalent-displacement naturally-aspirated gasoline engines.

Additionally, diesel fuel has a higher energy content per gallon; all of these effects combine for dramatically lower CO_2 emissions. However, diesel engines have emissions characteristics that present challenges very different from gasoline engines to meet Tier 2 emissions.

Criteria pollutant emissions compliance strategies are expected to include a combination of combustion improvements and aftertreatment. Several key advances in diesel technology have made it possible to reduce emissions coming from the engine (prior to aftertreatment). These technologies include:

- Improved fuel systems (higher pressures and more responsive injectors)
- Advanced controls and sensors to optimize combustion and emissions performance
- Higher EGR levels to reduce NOx
- Lower compression ratios (still much higher than gasoline SI engines)
- Advanced turbocharging systems

For aftertreatment, the traditional 3-way catalyst found on gasoline-powered vehicles is ineffective due to the lean-burn combustion of a diesel. All diesels will require a particulate filter, an oxidation catalyst, and a NOx reduction strategy to comply with Tier 2 emissions standards. The NOx reduction strategies most common are outlined below:

2.3.11.1 Lean NOx Trap Catalyst aftertreatment

A lean NOx trap (LNT) operates, in principle, by storing NOx (NO and NO_2) when the engine is running in its normal (lean) state. When the control system determines (via a predictive model or an NOx sensor) that the trap is saturated with NOx, it switches to a rich operating mode. This rich mode produces excess hydrocarbons that act as a reducing agent to convert the stored NOx to N2 and water, thereby “regenerating” the LNT and opening up more locations for NOx to be stored. LNTs are sensitive to sulfur deposits which can reduce catalytic performance, but periodically undergo a desulfation engine operating mode to clean it of sulfur buildup. Tailpipe CO_2 reduction estimates for an LNT-based diesel car range from 15 to 32 percent compared to a fixed valvetrain, port-fueled gasoline engine. This estimate translates into a corresponding tailpipe fuel consumption reduction estimate of 25 to 40 percent. These estimates are based on the RIA supporting NHTSA’s Light Truck CAFE Rule.

While there is already evidence of LNT-based diesels in production worldwide, they are all certified at higher NOx emission levels than U.S. Tier 2 Bin 5 levels. However, EPA projects that T2B5 LNT-based diesel engines will be available in the US within the next year or two, based on announcements from Mercedes, Volkswagen, and Honda.

2.3.11.2 Selective Catalytic Reduction NOx Aftertreatment

SCR uses a reductant (typically, ammonia derived from urea) continuously injected into the exhaust stream ahead of the SCR catalyst. Ammonia combines with NO_x in the SCR catalyst to form N_2 and water. The hardware configuration for an SCR system is more complicated that that of an LNT, due to the onboard urea storage and delivery system (which requires a urea pump and injector into the exhaust stream). While there is no required rich engine operating mode prescribed for NO_x reduction, the urea is typically injected at a rate 3-4% that of fuel consumed. Manufacturers designing SCR systems are intending to align urea tank refills with standard maintenance practices such as oil changes. CO_2 reduction estimates for diesel engines with an SCR system range from 21 to 32 percent over conventional, port-fueled gasoline engines (which translates to a fuel consumption reduction of approximately 30 to 40 percent).

As is the case with LNT-based diesels, EPA projects that SCR-based diesel engines will be available within the next couple of years. Mercedes-Benz has recently announced two new vehicles which have received US EPA certificates for Model Year 2009, the Mercedes Benz R320 and GL320, both of which achieved Tier 2, Bin 5 emissions. Based on public announcements from several other companies, we expect a large number of product offerings from multiple companies over the next few years.

2.3.12 E20-E30 Optimized Ethanol Engines

Ethanol has many favorable combustion qualities that increase knock tolerance, provide for more stable and faster combustion, and cool the charge air down much more than gasoline; taken together, these properties may be leveraged in such a manner as to increase the engine's thermal efficiency. For example, ethanol's high octane number permits an engine's compression ratio to be increased, while still allowing spark advance to be further optimized. Moreover, its faster rate of combustion allows for a higher rate of exhaust gas recirculation, thereby reducing pumping losses.

Based on internal EPA work, we estimate that optimizing an engine to operate on E20 to E30 could increase fuel efficiency and reduce tailpipe CO_2 emissions by 7-10% relative to a port-fueled, fixed cam gasoline engine. However, this EPA work has not been peer reviewed or published, and therefore we consider this estimate to be preliminary. For this reason, we have not included this preliminary estimate in the summary tables in Section 2.2. Note that this technology would be applicable for a vehicle specifically optimized for E20-E30.

2.4 Transmission Technologies

2.4.1 Automatic 5-speed Transmissions

As automatic transmissions have been developed, more forward speeds have been added to improve fuel efficiency, performance, and to improve a vehicle's market position. Increasing the number of available ratios provides the opportunity to operate an engine at more optimized conditions over a wider variety of vehicle speeds and load conditions. Also, additional ratios can allow greater overdrive (where the output shaft of the transmission is turning at a higher speed than the input shaft) which can lower the engine speed at a given road speed (provided the engine has sufficient torque reserve at the lower rpm point) to reduce pumping losses. However, in some cases, additional gears can add weight, rotating mass, and friction providing some offset to the efficiency advantage. Nevertheless, manufacturers are increasingly adding 5-speed automatic transmissions to replace 3-, and 4-speed automatics.

Some 4-speed automatic transmission designs are capable of offering five (or more) ratios by modifying the hydraulic control system (valvebody) and the electronic controls. This is much less expensive than developing a new transmission, but the available ratios may not be ideally spaced for optimizing fuel economy.

We estimate a 5-speed automatic transmission offers a CO_2 reduction of 2.5% (relative to a 4-speed automatic transmission). This estimate is based on the 2002 NAS report. The effectiveness of this technology was well understood at the time of the NAS report and the 2.5% value is also confirmed by CBI information from manufacturers. A 5-speed automatic transmission is applicable to all vehicle types.

2.4.2 Aggressive Shift Logic

During vehicle operation, an automatic transmission's controller decides when to upshift or downshift based on a variety of inputs such as vehicle speed and throttle position according to programmed logic. This logic can be biased towards maximizing fuel efficiency by upshifting earlier and inhibiting downshifts under some conditions. Additional adaptive algorithms can be employed to maintain performance feel while improving fuel economy under most driving conditions.

The 2002 NAS report states that aggressive shift logic can reduce fuel consumption by 1-3% in a 5-speed automatic transmission. The 2004 NESCCAF report states that the benefit is 1.5%. Information from manufacturers suggests that the benefit is in the lower end of the NAS range, so we estimate the benefit to be between 1% and 2%. Aggressive shift logic is applicable to all vehicle types with automatic transmissions, and since in most cases it would require no significant hardware modifications, it can be adopted during vehicle redesign or refresh or even in the middle of a vehicle's product cycle. The application of this technology does, however, require a manufacturer to confirm that driveability, durability, and noise, vibration, and harshness (NVH) are not significantly degraded.

2.4.3 Early Torque Converter Lockup

A torque converter is a fluid coupling located between the engine and transmission in vehicles with automatic transmissions and continuously-variable transmissions (CVT). This fluid coupling allows for slip so the engine can run while the vehicle is idling in gear (as at a stop light), provides for smoothness of the powertrain, and also provides for torque multiplication during acceleration, and especially launch. During light acceleration and cruising, the inherent slip in a torque converter causes increased fuel consumption, so modern automatic transmissions utilize a clutch in the torque converter to lock it and prevent this slippage. Fuel consumption can be further reduced by locking up the torque converter at lower vehicle speeds, provided there is sufficient power to propel the vehicle, and noise and vibration are not excessive. If the torque converter cannot be fully locked up for maximum efficiency, a partial lockup strategy can be employed to reduce slippage.

The 2002 NAS report did not address this particular technology, but the 2004 NESCCAF report used a number of literature sources to determine that early lockup can provide a 0.5% CO_2

benefit. NESCCAF states that this estimate is conservative in order to protect shift quality and driveability. This value is within the range of CBI information submitted by manufacturers, so we believe 0.5% is an appropriate estimate for this technology.

Early torque converter lockup is applicable to all vehicle types with automatic transmissions. Some torque converters will require upgraded clutch materials to withstand additional loading and the slipping conditions during partial lock-up. As with aggressive shift logic, confirmation of acceptable driveability, performance, durability and NVH characteristics is required to successfully implement this technology.

2.4.4 Automatic 6-, 7- and 8-speed Transmissions

In addition to 5-speed automatic transmissions, manufacturers can also choose to utilize 6-, 7-, or 8-speed automatic transmissions. Additional ratios allow for further optimization of engine operation over a wider range of conditions, but this is subject to diminishing returns as the number of speeds increases. As additional planetary gearsets are added (which may be necessary in some cases to achieve the higher number of ratios), additional weight and friction are introduced. Also, the additional shifting of such a transmission can be perceived as bothersome to some consumers, so manufacturers need to develop strategies for smooth shifts. Some manufacturers are replacing 4-speed automatics with 6-speed automatics, and 7-, and 8-speed automatics have also entered production, albeit in lower-volume applications in luxury cars.

The 2002 NAS report states that relative to a 4 speed automatic, a 6 speed automatic can reduce fuel consumption by 3% to 5%. At the time of the NAS report, 6-speed automatics were not in use, although some were in development. More current knowledge and information provided by manufacturers suggests that the CO_2 reduction potential of 6-speed automatics is more like 4.5% to 6.5% which is the range of effectiveness we believe is appropriate. 7-speed and 8-speed automatics are just entering production in small numbers, so there is not a lot of experience with them. Although they may be slightly more efficient than 6-speed automatics, we group them together with 6-speeds. As more data becomes available and more manufacturers gain experience with these transmissions, their effectiveness can be independently estimated. 6-, 7-, and 8-speed automatic transmissions are applicable to all vehicle types.

2.4.5 Automated (shift) Manual Transmissions

An Automated Manual Transmission (AMT) is mechanically similar to a conventional manual transmission, but shifting and launch functions are controlled by the vehicle. There are two basic types of AMTs, single-clutch and dual-clutch. A single-clutch AMT is essentially a manual transmission with automated clutch and shifting. Because there are some shift quality issues with single-clutch designs, dual clutch AMTs will likely be far more common in the U.S. and are the basis of our estimates. A dual-clutch AMT uses separate clutches (and separate gear shafts) for the even number gears and odd-numbered gears. In this way, the next expected gear is pre-selected which allows for faster and smoother shifting. For example, if the vehicle is accelerating in third gear, the shaft with gears one, three and five has gear three engaged and is transmitting power. The shaft with gears two, four, and six is idle, but has gear four engaged. When it comes time to shift, the controller disengages the odd-gear clutch while simultaneously engaging the even-gear clutch, thus affecting a smooth shift. If, on the other hand, the driver slows down instead of continuing to accelerate, the transmission will have to change to second gear on the idling shaft to anticipate a downshift. This shift can be made quickly on the idling shaft since there is no torque being transferred on it.

Overall, AMTs likely offer the greatest potential for CO_2 reduction among the various transmission options presented in this report because they offer the inherently lower losses of a manual transmission with the efficiency and shift quality advantages of computer control. The lower losses stem from the elimination of the conventional lock-up torque converter, and a greatly reduced need for high pressure hydraulic circuits to hold clutches to maintain gear ratios (in automatic transmissions) or hold pulleys in position to maintain gear ratio (in Continuously Variable Transmissions). However, the lack of a torque converter will affect how the vehicle launches from rest, so an AMT will most likely be paired with an engine that offers enough torque in the low-RPM range to allow for adequate launch performance.

The 2002 NAS report listed automated manual transmissions under emerging transmission technologies and assigned a fuel consumption reduction potential of 3%-5% over a 4-speed automatic. As these transmissions have entered production, it has become clear that the benefits are larger. We estimate these transmissions offer a CO_2 reduction potential of 9.5%-14.5% over a 4-speed automatic transmission. This estimate was developed from an aggregation of information from auto manufacturers and suppliers. AMTs can be used in all vehicle types.

2.4.6 Continuously Variable Transmissions

A Continuously Variable Transmission (CVT) is unique in that it does not use gears to provide ratios for operation. Instead, the most common CVT design uses two V-shaped pulleys connected by a metal belt. Each pulley is split in half and a hydraulic actuator moves the pulley halves together or apart. This causes the belt to ride on either a larger or smaller diameter section of the pulley which changes the effective ratio of the input to the output shafts.

Advantages of the CVT are that the engine can operate at its most efficient speed-load point more of the time, since there are no fixed ratios. Also, CVTs often have a wider range of ratios compared to conventional automatic transmissions which can provide for more options in engine optimization. While CVTs by definition are fully continuous, some automakers choose to emulate conventional stepped automatic operation because some drivers are not used to the sensation of the engine speed operating independently of vehicle speed.

The 2002 NAS report shows a relatively wide range of fuel consumption reduction of 3-8% compared to a 5-speed automatic. The 2004 NESCCAF report’s estimate is much lower at 3-4% better than a four-speed automatic. Based on an aggregation of manufacturers’ information, we estimate a CVT benefit of about 6% over a 4-speed automatic. This is above the NESCCAF value, but in the range of NAS. We assume that it is only practical to apply CVTs to small cars, large cars, and minivans because they are currently used mainly in lower-torque applications. While a high-torque CVT could be developed for small trucks and large trucks, it would likely have to be treated separately in terms of effectiveness. We do not see development in the area of high-torque CVTs and therefore did not include this type in our analysis.

2.4.7 Manual (clutch shifted) 6-, 7-, and 8-speed Transmissions

As with automatic transmissions, increasing the number of available ratios in a manual transmission can improve fuel economy by allowing the driver to select a ratio that optimizes engine operation at a given speed. Typically, this is achieved through adding additional overdrive ratios to reduce engine speed (which saves fuel through reduced pumping losses) Six-speed manual transmissions have already achieved significant market penetration, but for those vehicles with five-speed manual transmissions, an upgrade to a six-speed offers a benefit of 0.5% according to an aggregation of manufacturer-supplied information. 6-speed manual transmissions were not addressed in either the NAS or NESCCAF reports. These transmissions are applicable to all vehicle types with manual transmissions.

2.5 Hybrid Vehicle Technologies

A Hybrid is a vehicle that combines two or more sources of propulsion energy, where one uses a consumable fuel (like gasoline), and one is rechargeable (during operation, or by another energy source). Hybrid technology is established in the U.S. market and more manufacturers are adding hybrid models to their lineups. Hybrids reduce fuel consumption through three major mechanisms:

- The internal combustion engine can be optimized (through downsizing, modifying the operating cycle, or other control techniques) to operate at or near its most efficient point more of the time. Power loss from engine downsizing can be mitigated by employing power assist from the secondary power source.
- Some of the energy normally lost as heat while braking can be captured and stored in the energy storage system for later use.
- The engine is turned off when it is not needed, such as when the vehicle is coasting or when stopped.

Hybrid vehicles utilize some combination of the three above mechanisms to reduce CO_2 emissions. The effectiveness of CO_2 reduction depends on the utilization of the above mechanisms and how aggressively they are pursued. One area where this variation is particularly prevalent is in the choice of engine size and its effect on balancing fuel economy and performance. Some manufacturers choose to not downsize the engine when applying hybrid technologies. In these cases, performance is vastly improved, while fuel efficiency improves significantly less than if the engine was downsized to maintain the same performance as the conventional version. While this approach has been used in cars such as the Honda Accord Hybrid (now discontinued), it is more likely to be used for vehicles like trucks where towing and/or hauling is a integral part of their performance envelope. In these cases, the battery can be quickly drained during a long hill climb with a heavy load, leaving only a downsized engine to carry the entire load. Because towing capability is currently a heavily-marketed truck attribute, manufacturers are hesitant to offer a vehicle with significantly diminished towing performance with a low battery.

Different hybrid concepts utilize these mechanisms differently, so they are treated separately for the purposes of this analysis. Below is a discussion of the major hybrid concepts judged to be available in the near term.

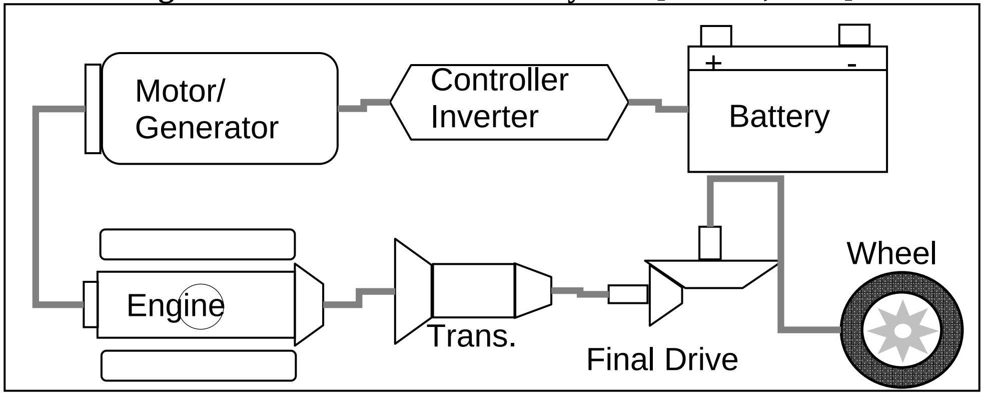
2.5.1 Integrated Starter Generator w/ Idle-Off

Integrated Starter-Generator (ISG) systems are the most basic of hybrid systems and offer mainly idle-stop capability. They offer the least power assist and regeneration capability of the hybrid approaches, but their low cost and easy adaptability to existing powertrains and platforms can make them attractive for some applications. ISG systems generally operate at around 42 volts and so have smaller electric motors and less battery capacity than other HEV designs because of their lower power demand.

Most ISG systems replace the conventional belt-driven alternator with a belt-driven, higher power starter-alternator (see Figure 2.5-1). The starter-alternator starts the engine during idle-stop operation, but often a conventional 12V gear-reduction starter is retained to ensure cold-weather startability. Also, during idle-stop, some functions such as power steering and automatic transmission hydraulic pressure are lost with conventional arrangements, so electric power steering and an auxiliary transmission pump are added. These components are similar to those that would be used in other hybrid designs. An ISG system could be capable of providing some launch assist, but it would be limited in comparison to other hybrid concepts.

The 2002 NAS report states that the potential fuel consumption reduction of an ISG system with idle-stop-only functionality is 4%-7%. Adding some regeneration and power assist can yield a total of 5%-10% fuel consumption reduction. The 2004 NESCCAF report states a 4%-10% benefit is possible. We chose 7.5% as the benefit based on the midrange of the NESCCAF estimate and the fact that ISG systems in production today in the Saturn Vue and Aura do offer some regeneration and power assist capability.

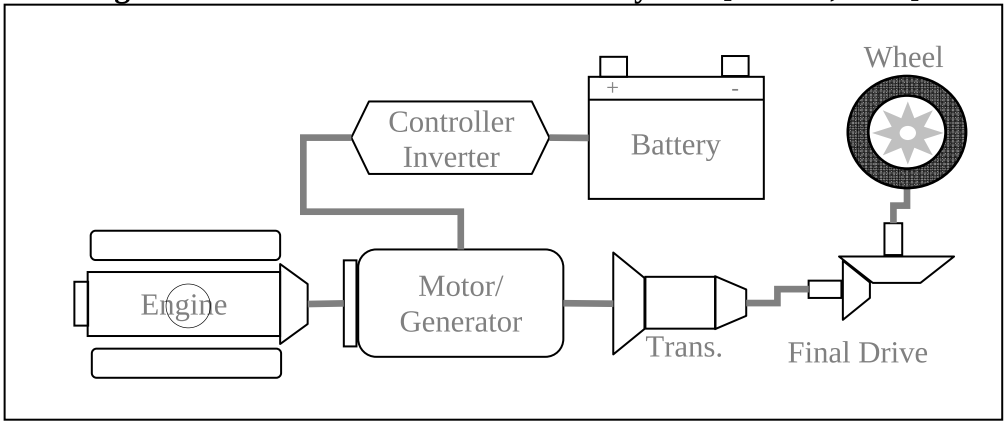
Figure 2.5-1 Schematic of ISG System [Husted, 2003]



2.5.2 Integrated Motor Assist (IMA)/Integrated Starter-Alternator-Dampener (ISAD) Hybrid

Integrated Motor Assist (IMA) and Integrated Starter-Alternator-Dampener (ISAD) are similar systems developed and marketed by Honda and Continental, respectively. Honda's Integrated Motor Assist (IMA) utilizes a thin axial electric motor bolted to the engine's crankshaft and connected to the transmission through a torque converter or clutch (see Figure 2.5-2). This electric motor acts as both a motor for helping to launch the vehicle and a generator for recovering energy while slowing down. It also acts as the starter for the engine and the electrical system's main generator. Since it is rigidly fixed to the engine, if the motor turns, the engine must turn also, but combustion does not necessarily need to occur. The Civic Hybrid uses cylinder deactivation on all four cylinders for decelerations and some cruise conditions. The Accord Hybrid also has cylinder deactivation, but it is on one bank of the V-6 engine and activates during cruise conditions as well as decelerations. This system does not launch the vehicle electric power alone, although on the Civic, the vehicle can cruise on electric power during some conditions.

Figure 2.5-2 Schematic of Honda IMA System [Husted, 2003]



Another application of this type of technology has been developed by Daimler for hybrid and plug-in hybrid versions of the Sprinter delivery van. The major driveline difference between Honda's IMA system and the Daimler system is a clutch between the engine and electric motor on the Daimler system. (This is largely enabled by the longitudinal arrangement of the powertrain in the Sprinter vs. the transverse arrangement in the front-wheel-drive Hondas.) The clutch allows for some extra efficiency by completely decoupling the engine from the electric motor and driveline under conditions where the engine is not running.

Since hybrids in general were relatively new technology at the time of the 2002 NAS report, we relied on a combination of certification data (comparing vehicles available with and without a hybrid system and backing out other components where appropriate--see Tables 2.5-1 and 2.5-2). and manufacturer-supplied information to determine that the effectiveness of these systems in terms of CO_2 reduction is 30% for small cars, 25% for large cars, and 20% for minivans and small trucks, This effectiveness for small cars assumes engine downsizing to maintain approximately equivalent performance. The large car, minivan, and small truck effectiveness values assume less engine downsizing in order to improve vehicle performance and/or maintain towing and hauling performance.

Table 2.5-1 Small Car IMA Certification Data

	Tailpipe CO_2		
	City	**Hwy**	**55/45 comb.**
Civic Sedan 1.8L 5-auto	296	222	269
Civic HEV 1.3L CVT	181	174	178
Raw % difference	-39%	-22%	-34%
CVT (on HEV only)			3.5%
Net difference			-29%

Table 2.5-2 Large Car IMA Certification Data

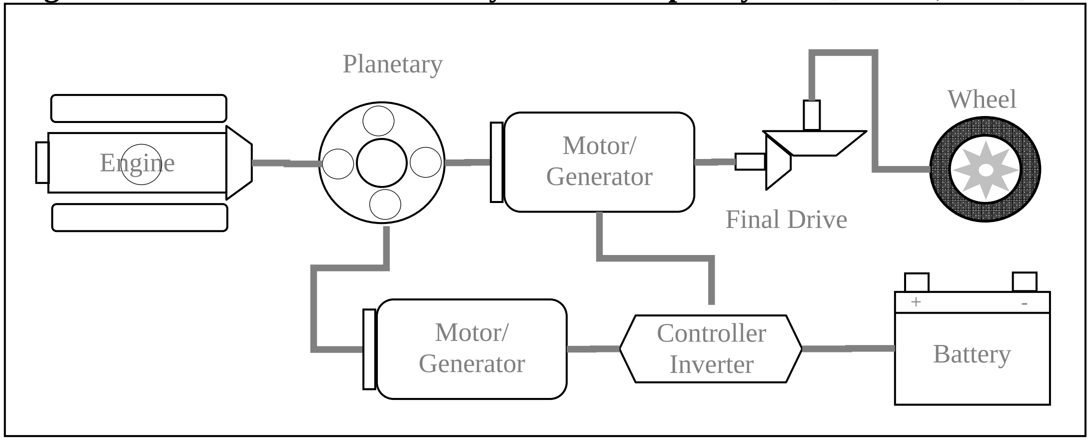
	Tailpipe CO_2		
	City	**Hwy**	**55/45 comb.**
Accord Sedan 3.0L 5-auto	444	306	386
Accord HEV 3.0L, cyl. deac, 5-auto	317	254	286
Net % difference			-26%

For large trucks, there is no certification data to use for analysis, however there have been several concept versions of Sprinter van hybrid and plug-in hybrid conversions that use this type of hybrid drive system. Published reports from these hybrid concepts indicates that these vehicles can achieve a 10% to 50% decrease in fuel consumption.[6] Although the Sprinter is capable of hauling loads similar to other large trucks sold in the U.S., it is not a directly comparable vehicle due to its different construction. The Sprinter does not have the same towing capacity of other large trucks sold in the U.S., and it is not designed for off-road use. Nevertheless, we estimate that an IMA-type hybrid system in a large truck can yield a CO_2 reduction of 20% based on the published Daimler information and the known performance of this type of system in the other vehicle classes.

2.5.3 Power-Split Hybrids

Power-Split hybrids are currently marketed by Ford, Nissan, and Toyota. They are significantly different than other hybrid designs because they do not use a conventional transmission. The Power Split system replaces the vehicle’s transmission with a single planetary gear and a motor/generator. A second, more powerful motor/generator is permanently connected to the vehicle’s final drive and always turns with the wheels (see Figure 2.5-3). The planetary gear splits the engine’s torque between the first motor/generator and the drive motor. The first motor/generator uses its torque input to either charge the battery or supply additional power to the drive motor. The speed of the first motor-generator determines the relative speed of the engine to the wheels. In this way, the planetary gear allows the engine to operate completely independently of vehicle speed, much like a CVT.

Figure 2.5-3 Schematic of Aisin/Toyota Power Split System [Husted, 2003]



The Power Split system allows for outstanding fuel economy in city driving. The vehicle also avoids the cost of a conventional transmission, replacing it with a much simpler single planetary and motor/generator. However, its highway efficiency is not optimized due to the requirement that the first motor/generator must be constantly spinning at a relatively high speed to maintain the correct ratio of engine speed to final drive speed. Also, load capacity is limited to the first motor/generator's capacity to resist the reaction torque of the drive train. Newer-generation Power Split systems, however, are reducing these limitations.

We believe Power Split hybrids will be used mainly on small cars, large cars, minivans, and small trucks. We did not analyze the Power Split system on large trucks because of a lack of certification data to extract an effectiveness and the fact that there does not seem to be any real movement by manufacturers to introduce this particular technology on large trucks (although this technology is scalable to large trucks). We used a combination of manufacturer-supplied information and a comparison of vehicles available with and without a hybrid system from EPA's fuel economy test data to determine that the effectiveness is 35% for the classes to which it is applied. (See Table 2.5-3 and Table 2.5-4) Future generations of this technology will certainly significantly improve on this technology to achieve greater CO_2 reductions, but this analysis does not take these into account. We did not rely on NAS or NESCCAF because NAS did not cover the technology in depth and NESCCAF used a comparison of certification data as well.

Table 2.5-3 Large Car Power Split Certification Data

	Tailpipe CO_2		
	City	**Hwy**	**55/45 comb.**
Nissan Altima			
3.5L CVT	444	306	386
HEV 2.5L PS	317	254	286
Net % difference			-26%
Toyota Camry			
3.0L 5-auto	404	286	355
HEV 2.4L PS	222	234	228
Net % difference			-36%
Lexus GS			
4.3L 6-auto	493	355	423
HEV 3.5L PS	355	317	341
Net % difference			-19%

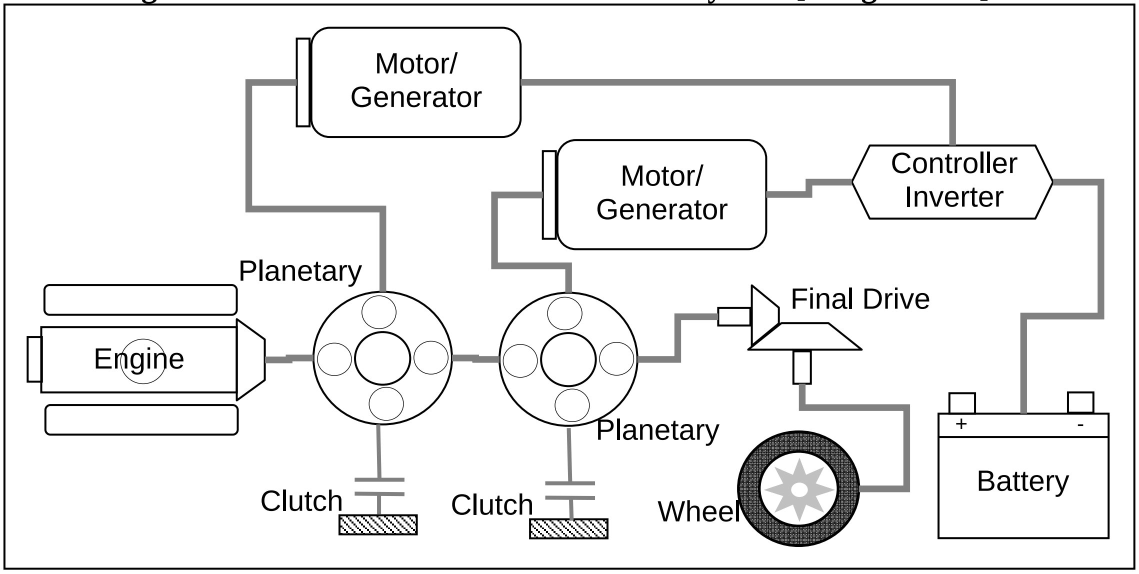
Table 2.5-4 Small Truck Power Split Certification Data

	Tailpipe CO_2		
	City	**Hwy**	**55/45 comb.**
Ford Escape 4X4			
3.0L 4-auto	467	386	423
HEV 2.3L PS	277	306	286
Net % difference			-32%
Ford Escape 4X2			
3.0L 4-auto	444	370	404
HEV 2.3L PS	247	286	261
Net % difference			-35%
Toyota Highlander 4X4			
3.3L 5-auto	493	370	423
HEV 3.3L PS	286	329	306
Net % difference			-28%

2.5.4 Two-Mode Hybrids

GM , Chrylser, Daimler and BMW have formed a joint venture to develop a new HEV system based on HEV transmission technology originally developed by GM's Allison Transmission Division for heavy-duty vehicles like city buses. This technology uses an adaptation of a conventional stepped-ratio automatic transmission by replacing some of the transmission clutches with two electric motors, which makes the transmission act like a CVT. Like Toyota's Power Split design, these motors control the ratio of engine speed to vehicle speed. But unlike the Power Split system, clutches allow the motors to be bypassed, which improves both the transmission's torque capacity for heavy-duty applications and fuel economy at highway speeds. (See Figure 2.5-4)

Figure 2.5-4 Schematic of GM-DCX HEV System [Hargitt 2002]



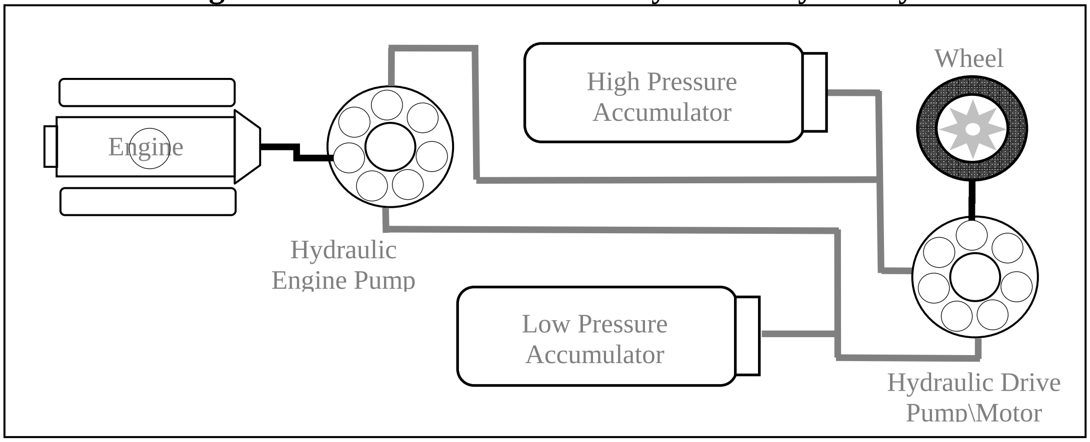
There is considerably less information about the effectiveness of Two-Mode hybrid systems than for Power-Split systems; however it is expected that the effectiveness will be slightly higher than Power-Split because of the higher efficiency on the highway. We assume this technology is not applicable to small cars, but on large cars, minivans and small trucks, the effectiveness is 40%.

Large trucks, on the other hand, are being developed by GM and Chrysler. During its development GM stated that they expected at least a 25% fuel economy increase (20% CO_2 decrease) from this system on a large SUV. This lower value compared to the other vehicle classes is due mainly to the lack of engine downsizing in a large truck in order to maintain full towing capability even in situations with low battery charge. It is difficult to directly compare data for the Tahoe Hybrid to a conventional version, but preliminary data suggests that a 25% fuel consumption reduction is appropriate. We therefore chose a value of 25% CO_2 decrease for the Two Mode system in a large truck.

2.5.5 Full-Series Hydraulic Hybrids

A Full Series Hydraulic Hybrid Vehicle (HHV) is somewhat similar in concept to a full-series electric hybrid vehicle, except that the energy is stored in the form of compressed nitrogen gas and the power is transmitted in the form of hydraulic fluid (See Figure 2.5-5).

Figure 2.5-5 Schematic of Series Hydraulic Hybrid System



Series HHV technology currently under development by EPA is capable of a 40% decrease in tailpipe CO_2 emissions in the small car, large car, minivan, and small truck classes. In the large truck class, a 30% CO_2 reduction is possible. The large truck benefit is somewhat lower than the other classes because it is assumed that a large truck requires a larger engine to maintain towing and hauling performance after the energy in the high pressure hydraulic accumulator is exhausted. This technology is still under development and not yet commercialized, however there are technology demonstration vehicles in service with UPS in daily package delivery service.

2.5.6 Plug-in Hybrid Electric Vehicles

Plug-In Hybrid Electric Vehicles (PHEVs) are very similar to Hybrid Electric Vehicles, but with three significant functional differences. The first is the addition of a means to charge the battery pack from an outside source of electricity (usually the electric grid). Second, a PHEV would have a larger battery pack with more energy storage, and a greater capability to be discharged. Finally, a PHEV would have a control system that allows the battery pack to be significantly depleted during normal operation.

Table 2.5-5 below, illustrates how PHEVs compare functionally to both hybrid electric vehicles (HEV) and battery electric vehicles (BEV). These characteristics can change significantly within each class, so this is simply meant as an illustration of the general characteristics. In reality, the design options are so varied that all these vehicles exist on a continuum with conventional vehicles on one end and pure electric vehicles on the other.

Table 2.5-5 Conventional, HEVs, PHEVs, and BEVs Compared

Increasing Electrification →

Attribute	Conventional	HEV	PHEV	BEV
Drive Power	**Engine**	**Blended Engine/Electric**	**Blended Engine/Electric**	**Electric**
Engine Size	**Full Size**	**Full Size or Smaller**	**Smaller or Much Smaller**	**No Engine**
Electric Range	**None**	**None to Very Short**	**Short to Medium**	**Medium to Long**
Battery Charging	**None**	**On-Board**	**Grid/On-Board**	**Grid Only**

Deriving some of their propulsion energy from the electric grid provides several advantages for PHEVs. PHEVs offer a significant opportunity to replace petroleum used for transportation energy with domestically-produced electricity. The reduction in petroleum usage does, of course, depend on the amount of electric drive the vehicle is capable of under its duty cycle.[B] PHEVs also provide electric utilities the possibility to increase electric generation during "off-peak" periods overnight when there is excess generation capacity and electricity prices are lower. Utilities like to increase this "base load" because it increases overall system efficiency and lowers average costs. PHEVs can lower localized emissions of criteria pollutants and air toxics especially in urban areas by operating on electric power. The emissions from the power generation occur outside the urban area at the power generation plant which provides health benefits for residents of the more densely populated urban areas. Unlike most other alternative fuel technologies, PHEVs can use existing infrastructure for fueling with gasoline and electricity so large investments in fueling infrastructure are not required.

In analyzing the impacts of grid-connected vehicles like PHEVs and EVs, the emissions from the electrical generation can be accounted for if a full upstream and downstream analysis is desired. While EPA is studying this issue on an on-going basis, upstream CO_2 emissions are not unique to grid-connected technologies and so are not included in this analysis of tailpipe CO_2 emissions.

PHEVs will be considerably more costly than conventional vehicles and some other advanced technologies. To take advantage of their capability, consumers would have to be willing to charge the vehicles nightly, and would need access to electric power where they park their vehicles. For many urban dwellers who may park on the street, or in private or public lots or garages, charging may not be practical. Charging may be possible at an owner's place of work, but that would increase grid loading during peak hours, which would eliminate some of the benefits to utilities of off-peak charging vs. on-peak (although the oil savings will still be the same in this case assuming the vehicle can be charged fully).

[B] For PHEVs herein, we define electric range as the sum of all the electrified miles in charge-depleting mode (before the battery reaches a minimum state-of-charge and the vehicle reverts to charge-sustaining mode). Charge-depleting mode may be interrupted by periods of engine-on operation, but is not necessarily ended by the engine turning on.

The CO_2 reduction potential of PHEVs depends on many factors, the most important being the electrical capacity designed into the battery pack. To estimate the tailpipe CO_2 reduction potential of PHEVs, EPA has developed an in-house vehicle energy model (PEREGRIN) to estimate the CO_2 emissions reductions of PHEVs. This model is based on the PERE (Physical Emission Rate Estimator) physics-based model used as a fuel consumption input for EPA's MOVES mobile source emissions model[C].

We modeled the PHEV small car, large car, minivan and small trucks using parameters from a midsize car similar to today's hybrids and scaled to each vehicle's weight. The large truck PHEV was modeled separately assuming no engine downsizing. We designed each PHEV with enough battery capacity for a 20-mile-equivalent all-electric range and a power requirement to provide similar performance to a hybrid vehicle. 20 miles was selected because it offers a good compromise for vehicle performance, weight, battery packaging and cost. Given expected near-term battery capability, a 20 mile range represents the likely capability that will be seen in PHEVs in the near-to-mid term.[D]

To calculate the total energy use of a PHEV, the PHEV can be thought of as operating in two distinct modes, electric (EV) mode, and hybrid (HEV) mode. At the tailpipe, the CO_2 emissions during EV operation are zero. The EV mode fuel economy can then be combined with the HEV mode fuel economy using the Utility Factor calculation in SAE J1711 to determine a total MPG value for the vehicle. (See Table 2.5-6)

Table 2.5-6 Sample Calculation of PHEV Gasoline-Equivalent CO_2 Reduction

	Midsize Car	**Large Truck**
EV energy comb (0.55 city / 0.45 hwy)	0.252 kwh/mi	0.429 kwh/mi
EV range (from PEREGRIN)	20 miles	20 miles
SAE J1711 utility factor	0.30	0.30
HEV mode comb FE (0.55 city / 0.45 hwy)	49.1 mpg	25.6 mpg
Total UF-adjusted FE ($UF*FC_{EV} + (1-UF)*FC_{HEV}$)	70.1 mpg	36.6 mpg
Baseline FE	29.3 mpg	19.2 mpg
Percent FE gain	139%	90%
Percent CO_2 reduction	-58%	-47%

Calculating a total tailpipe CO_2 reduction based on model outputs and the Utility Factor calculations, results in a 58% CO_2 reduction for small cars, large cars, minivans, and small trucks. For large trucks, the result is a 47% reduction. The lower improvement is due to less engine downsizing in the large truck class.

2.6 Full Electric Vehicles

The recent intense interest in Hybrid vehicles and the development of Hybrid vehicle battery and motor technology has helped make Electric Vehicle technology more viable than it has ever been. Electric Vehicles require much larger batteries than either HEVs or PHEVs, but the

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[C] PERE can be downloaded at http://www.epa.gov/otaq/models/ngm/pere.zip

[D] General Motors is developing one of their PHEVs, the Volt, to have a 40 mile range. This vehicle uses a series hybrid arrangement with the electric drive as the primary motive source and is of a very different design than the PHEV concept studied in this report.

batteries must be of a high-energy and lower-power design to deliver an appropriate amount of power over the useful charge of the battery. These high-energy batteries are generally less expensive per kilowatt-hour than high-power batteries required for hybrids, but the size of the battery pack still incurs a considerable cost.

Electric motor and power electronics designs are very similar to HEV and PHEV designs, but they must be larger, more powerful, and more robust since they provide the only motive power for the vehicle. On the other hand, the internal combustion engine, fuel system, and possibly the transmission can all be removed for significant weight, complexity and cost savings.

As for PHEVs, we modeled two full electric vehicles, a small car and a large car using the same model (PEREGRIN) and similar assumptions. Full EVs are only considered for these two classes because the larger, heavier vehicles would require too much battery capacity to be practical in the short-to-mid term and we do not see any serious development activities in these vehicle types in the market.

We chose to model the full EVs with a range of 150 miles on the urban driving cycle because this range offers a good compromise in capability and battery cost, weight and size with expected technology in the near- to mid-term. Using the same methodology as used for PHEVs to calculate gasoline-equivalent fuel consumption, we obtained the results shown in Table 2.6-1, below.

Table 2.6-1 Full Electric Vehicle Gasoline-Equivalent CO_2 Reduction

	Small Car	**Large Car**
EV energy comb (0.55 city / 0.45 hwy)	0.202 kwh/mi	0.244 kwh/mi
City cycle EV range	150 miles	150 miles
Highway cycle EV range	166 miles	162 miles
Baseline FE	35.5	25.3 mpg
Tailpipe CO_2 reduction	100%	100%

2.7 Vehicle Accessories

2.7.1 Electric Accessories and High Efficiency Alternator

The accessories on an engine – for example, the alternator, coolant and oil pumps - are traditionally driven by the accessory belt, or directly off of the crankshaft. Direct benefit may be obtained by improving their efficiency, or by driving them electrically (12V) only when needed ("on-demand"), and thereby reducing the accessory load relative to mechanically-driven systems. Examples would be electric water or oil pumps, and mechanical fans on some large trucks. Indirect benefit may be obtained by reducing the flow from the water pump electrically during the engine warmup period, allowing the engine to heat more rapidly and thereby reducing the fuel enrichment needed during cold starting of the engine. Further benefit may be obtained when electrification is combined with an improved, higher efficiency engine alternator.

The estimated CO_2 reduction for combined accessory improvements is between 1 and 2 percent based on the NAS report. This estimate is also supported by confidential manufacturer information. Air conditioning and power steering are other candidates for accessory load reduction, but they are addressed separately below and not included in this efficiency estimate. Improved accessories as described above are available today.

2.7.2 Electric Power Steering for 12V and 42V systems

Electric power steering (EPS) is advantageous over hydraulic steering in that it only draws power when the wheels are being turned, which is only a small percentage of a vehicle's operating time. This eliminates the parasitics associated with belt-driven power steering pumps in open-center steering systems, which consistently draw load from the engine to pump hydraulic fluid through the steering actuation systems, even when the wheels are not being turned. EPS may be implemented on many vehicles with a standard 12V system; however for heavier vehicles, a 42V system may be required for compactness and reliability (which adds cost and complexity). CO_2 reduction estimates for EPS range from 1.5 to 2 percent over a hydraulically driven power steering system based on the 2002 NAS report. This range is in agreement with the estimates provided by manufacturers. Electric power steering is available today.

2.7.3 Upgrade Electrical Systems to 42V

Most vehicles today (aside from hybrids) operate on 12 V electrical systems. At higher voltages, the power density of motors, solenoids, and other electrical components increases to the point that new and more efficient systems, such as electric A/C compressors and electric power steering (for heavier trucks) and may be feasible. A 42-volt system also acts as an enabler for an integrated starter generator. In addition to enabling other technologies, greater CO_2 reductions are possible for improved accessories on a 42V system, of 1 to 2 percent incrementally (over 12V improved accessories) based on the higher voltage alone. When combined with 12-volt improved accessories, these estimates are consistent with the NAS report.

2.8 Other Vehicle Technologies

2.8.1 Aerodynamic Drag Force Reduction

A vehicle's size and shape determine the amount of power needed to push the vehicle through the air at different speeds. Changes in vehicle shape or frontal area can therefore reduce CO_2 emissions. Areas for potential aerodynamic drag improvements include skirts, air dams, underbody covers, and more aerodynamic side view mirrors. EPA estimates a fleet average of 20% total aerodynamic drag reduction is attainable for passenger cars, whereas a fleet average of 10% reduction is more realistic for trucks (with a caveat for "high-performance" vehicles, described below). These drag reductions equate to CO_2 reductions of 2% and 3% for trucks and cars, respectively. These numbers are in agreement with the technical literature and supported by confidential manufacturer information.

Aerodynamic drag reduction technologies are readily available today, although the phase-in time required to distribute over a manufacturer's fleet is relatively long (6 years or so).

2.8.2 Low Rolling Resistance Tires

Tire characteristics (e.g., materials, construction, and tread design) influence durability, traction control, vehicle handling, and comfort. They also influence rolling resistance – the frictional losses associated mainly with the energy dissipated in the deformation of the tires under load – and therefore, CO_2 emissions. This technology is applicable to all vehicles, except for body-on-frame light trucks and performance vehicles (described in the next section).

Based on a 2006 NAS/NRC report, a 10% rolling resistance reduction would provide a CO_2 emissions reduction of 1 to 2 percent – and at this level the tires would maintain similar traction and handling characteristics. Lower rolling resistance tires are widely available today.

2.8.3 Low Drag Brakes

Low drag brakes reduce the sliding friction of disc brake pads on rotors when the brakes are not engaged because the brake shoes are pulled away from the rotating disc. While most passenger cars have already adopted this technology, there are indications that this technology is still available for body-on-frame trucks. Manufacturers have indicated that low drag brakes could reduce CO_2 emissions up to 1 percent for these trucks. Low drag brakes are available today.

2.8.4 Secondary Axle Disconnect (front axle for ladder frame and rear axle for unibody frame)

To provide shift-on-the-fly capabilities, many part-time four-wheel drive systems use some type of front axle disconnect. The front axle disconnect is normally part of the front differential assembly. As part of a shift-on-the-fly four-wheel drive system, the front axle disconnect serves two basic purposes. First, in two-wheel-drive mode, it disengages the front axle from the front driveline so the front wheels do not turn the front driveline at road speed, saving wear and tear. Second, when shifting from two- to four-wheel drive "on the fly" (while moving), the front axle disconnect couples the front axle to the front differential side gear only when the transfer case's synchronizing mechanism has spun the front driveshaft up to the same speed as the rear driveshaft. Four-wheel drive systems that have a front axle disconnect typically do not have either manual- or automatic-locking hubs. To isolate the front wheels from the rest of the front driveline, front axle disconnects use a sliding sleeve to connect or disconnect an axle shaft from the front differential side gear. Confidential manufacturer information suggests that front axle disconnect for 4WD vehicles can reduce CO_2 emissions by 1.5 percent.

We are not aware of any manufacturer offering this technology in the US today on unibody frame vehicles; however, we see no reasons why this technology could not be introduced by manufacturers within the next one to two years.

2.8.5 Weight Reduction

While certainly an effective option for reducing CO_2 emissions, reducing the weight of vehicles is a controversial topic. In the past, conventional wisdom held that a heavier vehicle is more safe than a light one. Recently, however, some studies have challenged the weight-safety connection, notably a June 2007 ICCT study, *Sipping Fuel and Saving Lives: Increasing Fuel Economy Without Sacrificing Safety* (available at http://www.theicct.org/reports_live.cfm). Also, during the public comment period for NHTSA's 2006 light truck CAFE rule, some auto manufacturers, notably Volkswagen and Honda challenged the traditional weight-safety connection. This traditional position was also challenged by the Aluminum Association which said that a 10% weight reduction is possible without affecting safety.[7]

The most promising way to reduce the weight of vehicles while maintaining vehicle size and performance is through material substitution. Examples of materials substitution include using higher-strength steel alloys, or even aluminum, magnesium or other light metals, in place of conventional steel structural components. Additionally, other materials can be replaced with lower density materials in other vehicle components, such as replacing plastics with lighter weight plastics.

In addition to materials substitution, components and systems can be redesigned to reduce weight, even while improving performance and reliability and lowering cost. An example would be redesigning a subsystem replacing multiple components and mounting hardware with a simpler system using advanced materials and a more integrated design.

Although EPA is not in a position today to provide estimates of the effectiveness or costs of materials or strategies to reduce vehicle weight, we believe they will play an increasingly important role in future efforts to reduce CO_2 emissions. Because of the importance of this emerging field, EPA intends to study weight reduction technologies in depth in the near future.

3 Synergistic Effects of Combining Multiple CO_2 Reducing Technologies

In Section 2 of this report, we present CO_2 reduction effectiveness estimates for a large number of individual technologies. When considering a combination of technologies to reduce CO_2 emissions, for the reasons discussed below, simply adding up the individual effectiveness values of a package of technologies will lead to an incorrect result, which in most cases will be an over prediction of the benefit of the combined technologies.

In estimating the aggregate effectiveness of combinations of multiple technologies, it is important to recognize technologies that address the same categories of efficiency losses, such that their combined effectiveness is appropriately accounted for, as opposed to using a simple sum or product of their individual benefits. For example, a variable valvetrain system and a six-speed automatic transmission both act to shift the engine operating points to a portion of the engine speed/load map where pumping losses are less significant, and it is therefore reasonable to anticipate a negative synergy, or dis-synergy, between such technologies. On the other hand, a vehicle technology that reduces road loads at highway speeds (e.g., lower aerodynamic drag or low rolling resistance tires) may extend the vehicle operating range over which cylinder deactivation may be employed, and so such a combination may be expected to have a slightly positive synergy. As the complexity of the technology combinations is increased, and the number of interacting technologies grows accordingly, it becomes increasingly important to account for these synergies.

There are two methods EPA has used in order to account for the impact of combining multiple technologies: lumped-parameter analysis, and full-scale vehicle simulation modeling. In this Section, we discuss both of these techniques and how they can account for the impact of combining multiple technologies into a “package” and the associated synergistic impacts between technologies. We also discuss how full-scale vehicle simulation modeling, which while generally more robust is also more resource intensive, can be used to validate results from the lumped-parameter approach.

Full-scale vehicle simulation modeling is one of the most accurate and robust means for determining synergies between technologies. In order to assess these synergies, EPA commissioned rigorous, detailed vehicle simulation work with Ricardo, Inc. Ricardo is a global leader in automotive design, engineering and simulation, and their software is used by the automotive industry in the design of engines, transmissions and vehicles. The results of their simulation work were analyzed and used to validate synergy estimates generated from a first-order “lumped parameter” analysis. The lumped parameter analysis was a tool used by EPA for the purpose of estimating technology synergies, and is based upon vehicle efficiency characteristics published in the technical literature. The lumped parameter analysis method (Section 3.1) and the Ricardo vehicle simulation modeling (Section 3.2) are described below. Section 3.3 discusses a comparison between the two methods, and finally Section 3.4 describes how the lumped parameter analysis can be used to estimate synergy pairs when technologies are applied in a pre-defined flow path order.

3.1 EPA's Lumped Parameter Approach for Determining Effectiveness Synergies

EPA engineers reviewed existing tools that could be used to develop estimates of the technology synergies, including the NEMS model[8]. However, the synergies in the NEMS model depend heavily upon an assumed technology application flow path; those technologies that the model would apply first would be expected to have fewer synergies than those applied later on. For this reason, and because this report includes many new technologies not available in NEMS, it was necessary for EPA to develop its own set of estimates. EPA used a well-documented engineering approach known as a lumped-parameter technique to determine values for synergies. At the same time, however, EPA recognized the availability of more robust methods for determining the synergistic impacts of multiple technologies on vehicle CO_2 emissions than the lumped-parameter approach, particularly with regard to applying synergy effects differentiated across different vehicle classes, and therefore augmented this approach with the detailed vehicle simulation modeling described in Section 3.2.

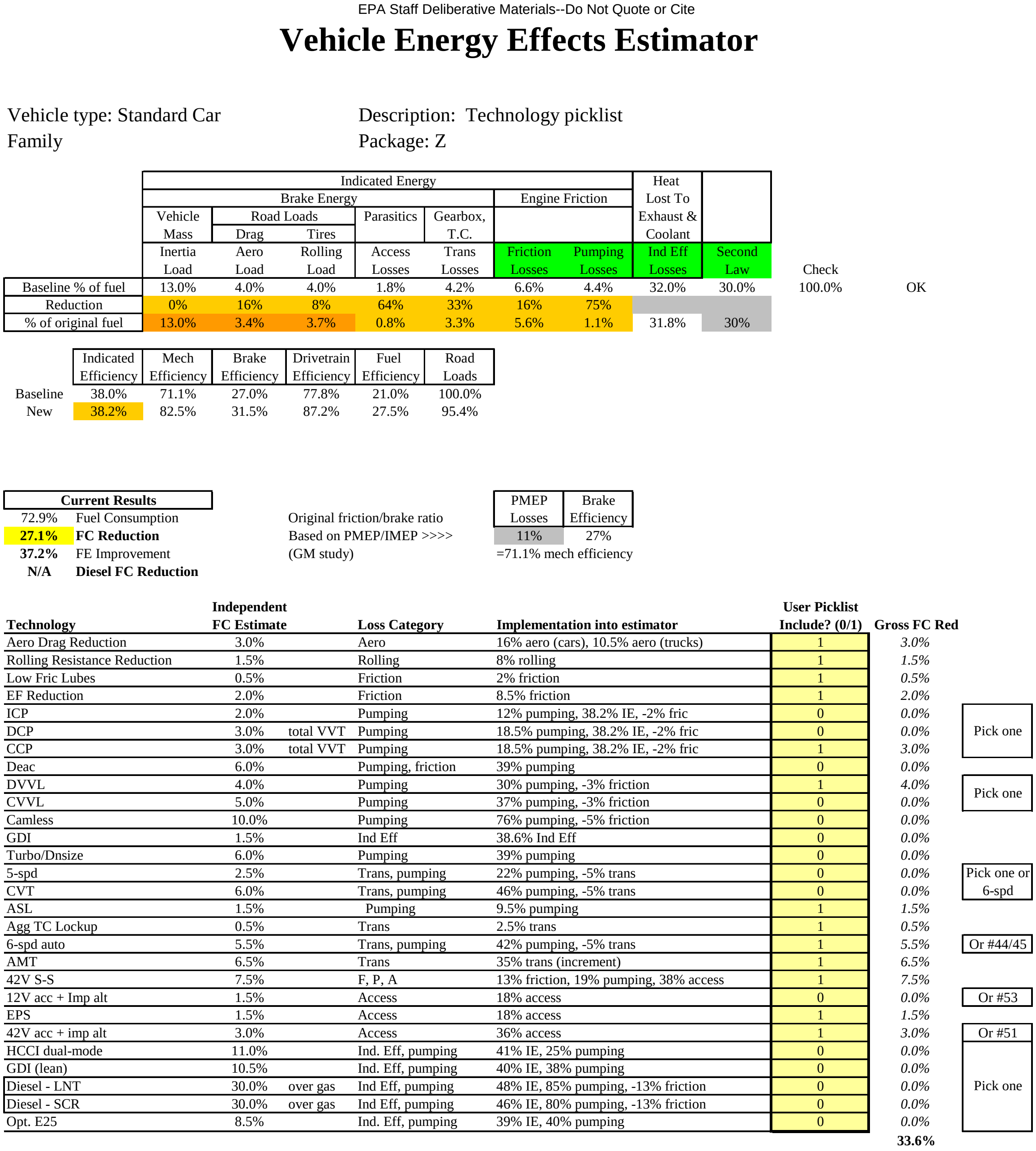
The basis for EPA's lumped parameter analysis is a first-principles energy balance that estimates the manner in which the chemical energy of the fuel is converted into various forms of thermal and mechanical energy on the vehicle. The analysis accounts for the dissipation of energy into the different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

- Second law losses (thermodynamic losses inherent in the combustion of fuel),
- Heat lost from the combustion process to the exhaust and coolant,
- Pumping losses, i.e., work performed by the engine during the intake and exhaust strokes,
- Friction losses in the engine,
- Transmission losses, associated with friction and other parasitic losses,
- Accessory losses, related directly to the parasitics associated with the engine accessories and indirectly to the fuel efficiency losses related to engine warmup,
- Vehicle road load (tire and aerodynamic) losses;

with the remaining energy available to propel the vehicle. It is assumed that the baseline vehicle has a fixed percentage of fuel lost to each category.

Each technology is categorized into the major types of engine losses it reduces, so that interactions between multiple technologies applied to the vehicle may be determined. When a technology is applied, its effects are estimated by modifying the appropriate loss categories by a given percentage. Then, each subsequent technology that reduces the losses in an already improved category has less of a potential impact than it would if applied on its own. Figure 3.1-1 below is an example spreadsheet used by EPA to estimate the synergistic impacts of a technology package for a standard-size car.

Figure 3.1-1. Sample Lumped Parameter Spreadsheet



EPA Staff Deliberative Materials--Do Not Quote or Cite

Vehicle Energy Effects Estimator

Vehicle type: Standard Car Family

Description: Technology picklist

Package: Z

	Indicated Energy							Heat Lost To Exhaust & Coolant			
	Brake Energy					Engine Friction					
	Vehicle Mass	Road Loads		Parasitics	Gearbox, T.C.						
		Drag	Tires								
	Inertia Load	Aero Load	Rolling Load	Access Losses	Trans Losses	Friction Losses	Pumping Losses	Ind Eff Losses	Second Law	Check	
Baseline % of fuel	13.0%	4.0%	4.0%	1.8%	4.2%	6.6%	4.4%	32.0%	30.0%	100.0%	OK
Reduction	0%	16%	8%	64%	33%	16%	75%				
% of original fuel	13.0%	3.4%	3.7%	0.8%	3.3%	5.6%	1.1%	31.8%	30%		

	Indicated Efficiency	Mech Efficiency	Brake Efficiency	Drivetrain Efficiency	Fuel Efficiency	Road Loads
Baseline	38.0%	71.1%	27.0%	77.8%	21.0%	100.0%
New	38.2%	82.5%	31.5%	87.2%	27.5%	95.4%

Current Results	
72.9%	Fuel Consumption
27.1%	**FC Reduction**
37.2%	FE Improvement
N/A	**Diesel FC Reduction**

Original friction/brake ratio
Based on PMEP/IMEP >>>>
(GM study)

PMEP Losses	Brake Efficiency
11%	27%

=71.1% mech efficiency

Technology	**Independent FC Estimate**		**Loss Category**	**Implementation into estimator**	**User Picklist Include? (0/1)**	**Gross FC Red**	
Aero Drag Reduction	3.0%		Aero	16% aero (cars), 10.5% aero (trucks)	1	*3.0%*	
Rolling Resistance Reduction	1.5%		Rolling	8% rolling	1	*1.5%*	
Low Fric Lubes	0.5%		Friction	2% friction	1	*0.5%*	
EF Reduction	2.0%		Friction	8.5% friction	1	*2.0%*	
ICP	2.0%		Pumping	12% pumping, 38.2% IE, -2% fric	0	*0.0%*	Pick one
DCP	3.0%	total VVT	Pumping	18.5% pumping, 38.2% IE, -2% fric	0	*0.0%*	
CCP	3.0%	total VVT	Pumping	18.5% pumping, 38.2% IE, -2% fric	1	*3.0%*	
Deac	6.0%		Pumping, friction	39% pumping	0	*0.0%*	
DVVL	4.0%		Pumping	30% pumping, -3% friction	1	*4.0%*	Pick one
CVVL	5.0%		Pumping	37% pumping, -3% friction	0	*0.0%*	
Camless	10.0%		Pumping	76% pumping, -5% friction	0	*0.0%*	
GDI	1.5%		Ind Eff	38.6% Ind Eff	0	*0.0%*	
Turbo/Dnsize	6.0%		Pumping	39% pumping	0	*0.0%*	
5-spd	2.5%		Trans, pumping	22% pumping, -5% trans	0	*0.0%*	Pick one or 6-spd
CVT	6.0%		Trans, pumping	46% pumping, -5% trans	0	*0.0%*	
ASL	1.5%		Pumping	9.5% pumping	1	*1.5%*	
Agg TC Lockup	0.5%		Trans	2.5% trans	1	*0.5%*	
6-spd auto	5.5%		Trans, pumping	42% pumping, -5% trans	1	*5.5%*	Or #44/45
AMT	6.5%		Trans	35% trans (increment)	1	*6.5%*	
42V S-S	7.5%		F, P, A	13% friction, 19% pumping, 38% access	1	*7.5%*	
12V acc + Imp alt	1.5%		Access	18% access	0	*0.0%*	Or #53
EPS	1.5%		Access	18% access	1	*1.5%*	
42V acc + imp alt	3.0%		Access	36% access	1	*3.0%*	Or #51
HCCI dual-mode	11.0%		Ind. Eff, pumping	41% IE, 25% pumping	0	*0.0%*	Pick one
GDI (lean)	10.5%		Ind. Eff, pumping	40% IE, 38% pumping	0	*0.0%*	
Diesel - LNT	30.0%	over gas	Ind Eff, pumping	48% IE, 85% pumping, -13% friction	0	*0.0%*	
Diesel - SCR	30.0%	over gas	Ind Eff, pumping	46% IE, 80% pumping, -13% friction	0	*0.0%*	
Opt. E25	8.5%		Ind. Eff, pumping	39% IE, 40% pumping	0	*0.0%*	
						33.6%	

Table 3.1-1 below lists the technologies considered in this example, their corresponding individual technology effectiveness values, and a comparison of the gross combined package CO_2 reduction (i.e. disregarding synergies) to the lumped parameter results. The difference is the implied synergistic effects of these technologies combined on a package.

Table 3.1-1 Comparison of Lumped Parameter Analysis with Standard Car Package

Technology	Individual CO_2 Reduction	Cumulative CO_2 Reduction
Aero Drag Reduction	3.0%	3.0%
Rolling Resistance Reduction	1.5%	4.5%
Low Friction Lubricants	0.5%	4.9%
Engine Friction Reduction	2.0%	6.8%
VVT - coordinated cam phasing	3.0%	9.6%
VVL – discrete variable lift	4.0%	13.2%
Aggressive shift logic	1.5%	14.5%
Early torque converter lockup	0.5%	15.0%
6-speed automatic trans	5.5%	19.6%
AMT (6-speed)	6.5%	24.9%
Stop-Start with 42 volt system	7.5%	30.5%
Electric power steering	1.5%	31.5%
42V acc + improved alternator	3.0%	33.6%
Gross combined effectiveness	33.6%	
Lumped parameter estimate	27.1%	
Estimated synergistic effects	**-6.5%**	

The synergy estimates obtained using the lumped parameter technique were subsequently compared to the results from the vehicle simulation work. EPA will continue to use the lumped parameter approach as an analytical tool, and (using the output data from the vehicle simulation as a basis) may adjust the synergies as necessary in the future.

3.2 Ricardo's Vehicle Simulation

Vehicle simulation modeling was performed by Ricardo, Inc. The simulation work addressed gaps in existing synergy modeling tools, and served to both supplement and update the earlier vehicle simulation work published by NESCCAF. Using a physics-based, second-by-second model of each individual technology applied to various baseline vehicles, the Ricardo model was able to estimate the effectiveness of the technologies acting either individually or in combination. This information could then be used to estimate the synergies of these technology combinations, and also to differentiate the synergies across different vehicle classes.

In total, Ricardo modeled five baseline vehicles and twenty-six distinct technology combinations, covering the full range of gasoline and diesel powertrain technologies used in the Volpe model, with the exception of the powersplit, plug-in and two-mode hybrid vehicle technologies. The five generalized vehicle classes modeled were a standard car, a full-size car, a small multi-purpose vehicle (MPV), a large MPV and a large truck. The complete list of vehicles and technology packages is given below in this section, along with a detailed explanation of the selection criteria.

Each technology package was modeled under a constraint of "equivalent performance" to the baseline vehicle. To quantify the performance, a reasonably comprehensive, objective set of vehicle performance criteria were used as a basis to compare with the baseline vehicle, characterizing the launch acceleration, passing performance and grade capability that a vehicle buyer might expect when considering a technology package. The main metrics used to compare vehicle performance are listed below in Table 3.2-1.

Table 3.2-1 Performance Metrics Used as Basis for "Equivalent Performance"

Characteristic	Performance Metric
Overall Performance	Time to accelerate from 0-60 mph*
Launch Acceleration	Time to accelerate from 0-30 mph
	Vehicle speed and distance after a 3-second acceleration from rest
Passing Performance	Time to accelerate from 30 to 50 mph
	Time to accelerate from 50 to 70 mph
Grade Capability	Maximum % grade at 70 mph (standard car, large car, small MPV and large MPV)
	Maximum % grade at 60 mph at GCVWR (large truck)*

Notes:
All accelerations are assumes at WOT (wide-open throttle) condition
GCVWR = EPA Gross Combined Vehicle Weight Rating

A summary of the vehicle simulation results is given below in Section 3.2.1.5, including the CO_2 emissions reduction effectiveness for each technology package. The full Ricardo vehicle simulation results, including the acceleration performance data, may be found in Ricardo's final report posted publicly at EPA's website.[9]

3.2.1 Description of Ricardo's Report

In this section, the structure, methodology and results from the Ricardo vehicle simulation report are summarized. EPA worked closely with Ricardo to develop baseline models of five generalized vehicle classes that could be validated against EPA certification data, and then used as a platform upon which to add various technology packages. The vehicle simulation modeling results generated by Ricardo consist of the following:

- Baseline vehicle characterization, to determine the baseline fuel consumption and CO_2 emissions over the EPA combined cycle federal test procedure (FTP) for five baseline vehicles, for validation with EPA certification data.
- Simulation of the vehicle technology combinations (applied to the baseline vehicles)
- Incremental technology effectiveness estimates, to examine the effect of adding technologies one-by-one. These could then be used more directly to validate synergies estimated using the lumped parameter method.

This section describes the selection process for each of the baseline vehicles and the technology packages, and summarizes the results of the vehicle simulation.

3.2.1.1 Determination of representative vehicle classes

In an effort to establish a reasonable scope for the vehicle simulation work and to update the earlier simulation done by NESCCAF, EPA chose five representative vehicle classes as the basis for evaluating technology benefits and synergies, representing the vehicle attributes of the projected highest-volume light-duty car and truck sales segments. These five classes covered a broad range of powertrain and vehicle characteristics, over which the effectiveness and synergies of each of the technologies could be evaluated. The main distinguishing attributes of the five vehicle classes considered by EPA and Ricardo are given below in Table 3.2-2.

Table 3.2-2 Attributes of the Five Generalized Vehicle Classes Considered by Ricardo

Vehicle Class	**Standard Car**	**Large Car**	**Small MPV**	**Large MPV**	**Large Truck**
EPA Vehicle Types Included	Compact, Mid-size	Large car	Small SUV, Small Pickup	Minivans, Mid-SUVs	Large SUVs, Large Pickups
Curb Weight Range	2800-3600 lbs	>3600 lbs	3600-4200 lbs	4200-4800 lbs	>4800 lbs
Engine Type	I4	V6	I4	V6	V8
Drivetrain	FWD	RWD/AWD	FWD	FWD/AWD	4WD
Body Type	Unibody	Unibody	Unibody	Unibody	Ladder Frame
Towing Capability	None	None	Partial	Partial	Full
Example Vehicles	Toyota Camry, Chevy Malibu, Honda Accord	Chrysler 300, Ford 500 / Taurus	Saturn VUE, Ford Escape, Honda CR-V	Dodge Grand Caravan, GMC Acadia, Ford Flex	Ford F-150, Chevy Silverado 1500, Dodge Ram

EPA then selected representative vehicle models for each of these classes, based on three main criteria:

- The vehicle should possess major attributes and technology characteristics that are near the average of its class, including engine type and displacement, transmission type, body type, weight rating, footprint size and fuel economy rating.
- It should be among the sales volume leaders in its class, or where there is not a clearly-established volume leader, the model should share attributes consistent with major sellers.
- The vehicle should have undergone a recent update or redesign, such that the technology in the baseline model could be considered representative of vehicles sold at the beginning of the proposed regulatory timeframe.

Consideration was also given to include the sales-leading vehicle manufacturers among the baseline models. Hence, the U. S. domestic manufacturers account for four of the five models (Chrysler 300, GM/Saturn Vue, Chrysler/Dodge Caravan, and the Ford F-150), while import manufacturers are represented in their strongest sales segment, the standard car class, by the Toyota Camry.

3.2.1.2 Description of Baseline Vehicle Models

The baseline vehicles selected to represent their respective vehicle classes are described below in Table 3.2-3, listed with the critical attributes that EPA used as selection criteria. While each attribute for these baseline vehicles does not match the precise average for its class, each of these baselines is an actual vehicle platform that allows validation of the simulation data with "real world" certification data.

Table 3.2-3 Description of Baseline Vehicles

Vehicle Class		**Standard Car**	**Full Size Car**	**Small MPV**	**Large MPV**	**Large Truck**
Baseline Vehicle		Toyota Camry	Chrysler 300	Saturn VUE	Dodge Grand Caravan	Ford F-150
CO2 Emissions* (g/mi)		327	409	415	435	575
Vehicle Attributes	**Base Engine**	DOHC I4	SOHC V6	DOHC I4	OHV V6	SOHC V8
	Displacement (L)	2.4	3.5	2.4	3.8	5.4
	Rated Power (HP)	154	250	169	205	300
	Torque (ft-lbs)	160	250	161	240	365
	Valvetrain Type	VVT (DCP)	Fixed	VVT (DCP)	Fixed	VVT (CCP)
	Valves per Cyl	4	4	4	2	3
	Drivetrain	FWD	RWD	FWD	FWD	4WD
	Transmission	Auto	Auto	Auto	Auto	Auto
	Number of Forward Speeds	5	5	4	4	4
	Curb Wt (lbs)	3108	3721	3825	4279	5004
	ETW (lbs)	3500	4000	4000	4500	6000
	GVWR (lbs)	--	--	4300	5700	6800
	GCWR (lbs)	--	--	--	--	14000
	Front Track Width (in.)	62	63	61.4	63	67
	Wheelbase (in.)	109.3	120	106.6	119.3	144.5
Performance Characteristics	**Displacement / Weight Ratio (L/ton)**	1.54	1.88	1.25	1.78	2.16
	Power / Weight Ratio (HP/ton)	99.1	134.4	88.4	95.8	119.9

*-Estimated CO_2 equivalent, taken from EPA adjusted combined fuel economy ratings.

3.2.1.3 Technologies Considered by EPA and Ricardo in the Vehicle Simulation

A number of advanced gasoline and diesel technologies were considered in the Ricardo study, comprising the majority of the technologies used in the Volpe model, with the exception of the hybrid electric vehicle technologies. In developing a comprehensive list of technologies to be modeled, EPA surveyed numerous powertrain and vehicle technologies and technology trends, in order to assess their potential feasibility in the next one to ten years. The list of technologies considered therefore includes those that are available today (e.g., variable valve timing, six-speed automatic transmissions) as well as some that may not be ready for five to ten years (e.g., camless valve actuation and HCCI engines). Table 3.2-4 below lists the technologies that Ricardo included in the vehicle simulation models.

Table 3.2-4. Technologies Included in the Ricardo Vehicle Simulation

Engine Technologies	
Abbrev.	**Description**
DOHC	Dual Overhead Camshaft
SOHC	Single Overhead Camshaft
OHV	Overhead Valve (pushrod)
CCP	Coordinated cam phasing
DCP	Dual (independent) cam phasing
DVVL	Discrete (two-step) Variable Valve Lift
CVVL	Continuous Variable Valve Lift
Deac	Cylinder Deactivation
CVA	Camless Valve Actuation (full)
Turbo	Turbocharging with engine downsizing
GDI	Gasoline Direct Injection
Diesel	Diesel with advanced aftertreatment
HCCI	Homogeneous Charge Compression Ignition (gasoline)
LUB	Low-friction engine lubricants
EFR	Engine friction reduction

Transmission Technologies	
Abbrev.	**Description**
L4	Lockup 4-speed automatic transmission
L5	Lockup 5-speed automatic transmission
L6	Lockup 6-speed automatic transmission
DCT6	6-speed dual clutch automated manual transmission
CVT	Continuously variable transmission
ASL	Aggressive shift logic
TORQ	Early torque converter lockup

Accessory Technologies	
Abbrev.	**Description**
ISG (42V)	42V Integrated Starter-Generator
EPS	Electric Power Steering
EACC	Electric Accessories (water pump, oil pump, fans)
HEA	High-Efficiency Alternator

Vehicle Technologies	
Abbrev.	**Description**
AERO	Aerodynamic drag reduction (10%-20%)
ROLL	Tire rolling resistance reduction (10%)

3.2.1.4 Choice of Technology Packages

EPA chose a number of technology packages representing a range of options that manufacturers might pursue. In determining these technology combinations, EPA considered available cost and effectiveness numbers from the literature, and applied engineering judgment to match technologies that were compatible with each other and with each vehicle platform. Also, where appropriate, we applied the same technologies to multiple vehicle classes, to determine where specific vehicle attributes might affect their benefits and synergies. These technologies represent most of those listed in Section 2 of this report. Table 3.2-5 below describes in detail the technology content in each technology package simulated by Ricardo.

Table 3.2-5 Description of the Vehicle Technology Packages Modeled by Ricardo

Vehicle	Technology Package	Engine	Valvetrain	Transmission	Accessories
Standard car	**baseline**	**2.4-Liter I4**	**DOHC, DCP**	**L5**	
	Z	2.4L I4, PFI	CCP, DVVL	DCT6	ISG (42V), EPS, EACC
	1	2.4L I4, GDI	DCP, DVVL	CVT	EPS, EACC, HEA
	2	2.4L I4, GDI	DCP	L6	ISG (42V), EPS, EACC
Small MPV	**baseline**	**2.4-Liter I4**	**DOHC, DCP**	**L4**	**EPS**
	Z	2.4L I4, PFI	CCP, DVVL	DCT6	ISG (42V), EPS, EACC
	1	2.4L I4, GDI	DCP, DVVL	CVT	EPS, EACC, HEA
	2	2.4L I4, GDI	DCP	L6	ISG (42V), EPS, EACC
	15	1.5L I4, GDI, Turbo	DCP	DCT6	EPS, EACC, HEA
	15a	2.4L I4, GDI	CVA	DCT6	EPS, EACC, HEA
	15b	2.4L I4, GDI, HCCI	DCP, CVVL	DCT6	EPS, EACC, HEA
	5	1.9L I4, Diesel	DOHC	DCT6	EPS, EACC, HEA
Full Size car	**baseline**	**3.5-Liter V6**	**SOHC**	**L5**	
	4	2.2L I4, GDI, Turbo	DCP	L6	EPS, EACC, HEA
	5	2.8L I4, Diesel	DOHC	DCT6	EPS, EACC, HEA
	Y1	3.5L V6, GDI	CVA	DCT6	EPS, EACC, HEA
	Y2	3.5L V6, GDI, HCCI	DCP, CVVL	DCT6	EPS, EACC, HEA
	6a	3.0L V6, GDI	DCP, CVVL	DCT6	EPS, EACC, HEA
	16	3.5L V6, GDI	CCP, Deac	L6	ISG (42V), EPS, EACC
Large MPV	**baseline**	**3.8-Liter, V6**	**OHV**	**L4**	
	4	2.1L I4, GDI, Turbo	DCP	L6	EPS, EACC, HEA
	6b	3.0L V6, GDI	CCP, Deac	DCT6	EPS, EACC, HEA
	16	3.8L V6, GDI	CCP, Deac	L6	ISG (42V), EPS, EACC
Large Truck	**baseline**	**5.4-Liter V8**	**SOHC, CCP**	**L4**	
	9	5.4L V8, GDI	CCP, Deac	DCT6	ISG (42V), EPS, EACC
	10	3.6L V6, GDI, Turbo	DCP	DCT6	EPS, EACC, HEA
	11	4.8L V8, Diesel	DOHC	DCT6	EPS, EACC, HEA
	12	5.4L V8, GDI	CCP, Deac	L6	ISG (42V), EPS, EACC
	17	5.4L V8, GDI	DCP, DVVL	L6	EPS, EACC, HEA
	X1	5.4L V8, GDI	CVA	DCT6	EPS, EACC, HEA
	X2	5.4L V8, GDI, HCCI	DCP, CVVL	DCT6	EPS, EACC, HEA

Other:

20% Aerodynamic drag reduction, 10% tire rolling resistance reduction assumed for all vehicles, except Large Truck

10% Aerodynamic drag reduction assumed for Large Truck

Low-friction lubricants and moderate engine friction reductions are assumed for all vehicles

Aggressive shift logic and early torque converter lockup strategies are assumed for all vehicles, where applicable.

3.2.1.5 Simulation Results

The CO_2 emissions results from the vehicle simulation are summarized below in Table 3.2-6 (for cars) and Table 3.2.7 (for light-duty trucks). The CO_2 estimates are given for the combined city and highway test cycles, according to the EPA Federal Test Procedure (FTP), with the technology package results compared with the baseline vehicle as shown.

It is important to reiterate that each of the technology package results were obtained with performance determined to be equivalent to the baseline vehicle. No attempt was made to project trends in performance during the proposed regulatory period, nor did we downgrade performance to give improved fuel efficiency. A full comparison of vehicle acceleration performance is given in the Ricardo final report.

Table 3.2-6. CO_2 Emissions Estimates Obtained from Vehicle Simulation (Cars)

Vehicle	Technology Package	Major Features*	CO_2 City	CO_2 Hwy	CO_2 Combined	CO_2 Reduction
			g/mi	g/mi	g/mi	%
Standard car	**baseline**	**2.4L I4, DCP, L5**	**338**	**217**	**284**	**x**
	Z	CCP, DVVL, DCT, ISG	250	170	214	24.7%
	1	GDI, DCP, DVVL, CVT	294	198	251	11.5%
	2	GDI, DCP, L6, ISG	277	180	233	17.8%
Full Size car	**baseline**	**3.5L V6, L5**	**420**	**279**	**356**	**x**
	4	2.2L I4, GDI, Turbo, DCP, L6	346	236	296	16.9%
	5	2.8L I4 Diesel, DCT	315	221	273	23.5%
	Y1	GDI, CVA, DCT	278	199	242	32.0%
	Y2	GDI, HCCI, DCT	290	197	248	30.4%
	6a	GDI, DCP, CVVL, DCT	331	235	288	19.2%
	16	GDI, CCP, Deac, L6, ISG	301	205	257	27.7%

*-Please refer to Table 3.2-4 for a full description of the vehicle technologies

Table 3.2-7. CO_2 Emissions Estimates Obtained from Vehicle Simulation (Light-Duty Trucks)

Vehicle	Technology Package	Major Features*	CO_2 City	CO_2 Hwy	CO_2 Combined	CO_2 Reduction
			g/mi	g/mi	g/mi	%
Small MPV	**baseline**	**2.4L I4, DCP, EPS**	**367**	**253**	**316**	**x**
	Z	CCP, DVVL, DCT, ISG	272	208	243	23.0%
	1	GDI, DCP, DVVL, CVT	310	227	272	13.7%
	2	GDI, DCP, L6, ISG	291	211	255	19.3%
	15	1.5L I4, GDI, Turbo, DCP, DCT	272	212	245	22.5%
	15a	GDI, CVA, DCT	262	193	231	26.8%
	15b	GDI, HCCI, DCT	270	197	237	24.8%
	5	1.9L I4 Diesel, DCT	282	205	247	21.8%
Large MPV	**baseline**	**3.8L V6**	**458**	**313**	**393**	**x**
	4	2.1L I4, GDI, Turbo, DCP, L6	357	256	312	20.6%
	6b	GDI, CCP, Deac, DCT	333	248	295	24.9%
	16	GDI, CCP, Deac, L6, ISG	325	225	280	28.7%
Large Truck	**baseline**	**5.4L V8, CCP**	**612**	**402**	**517**	**x**
	9	GDI, CCP, Deac, DCT, ISG	432	315	379	26.7%
	10	3.6L V6, GDI, Turbo, DCP, DCT	404	319	366	29.3%
	11	4.8L V8 Diesel, DCT	444	326	391	24.4%
	12	GDI, CCP, Deac, L6, ISG	459	328	400	22.6%
	17	GDI, DCP, DVVL, L6	492	333	420	18.8%
	X1	GDI, CVA, DCT	422	314	374	27.8%
	X2	GDI, HCCI, DCT	425	311	374	27.7%

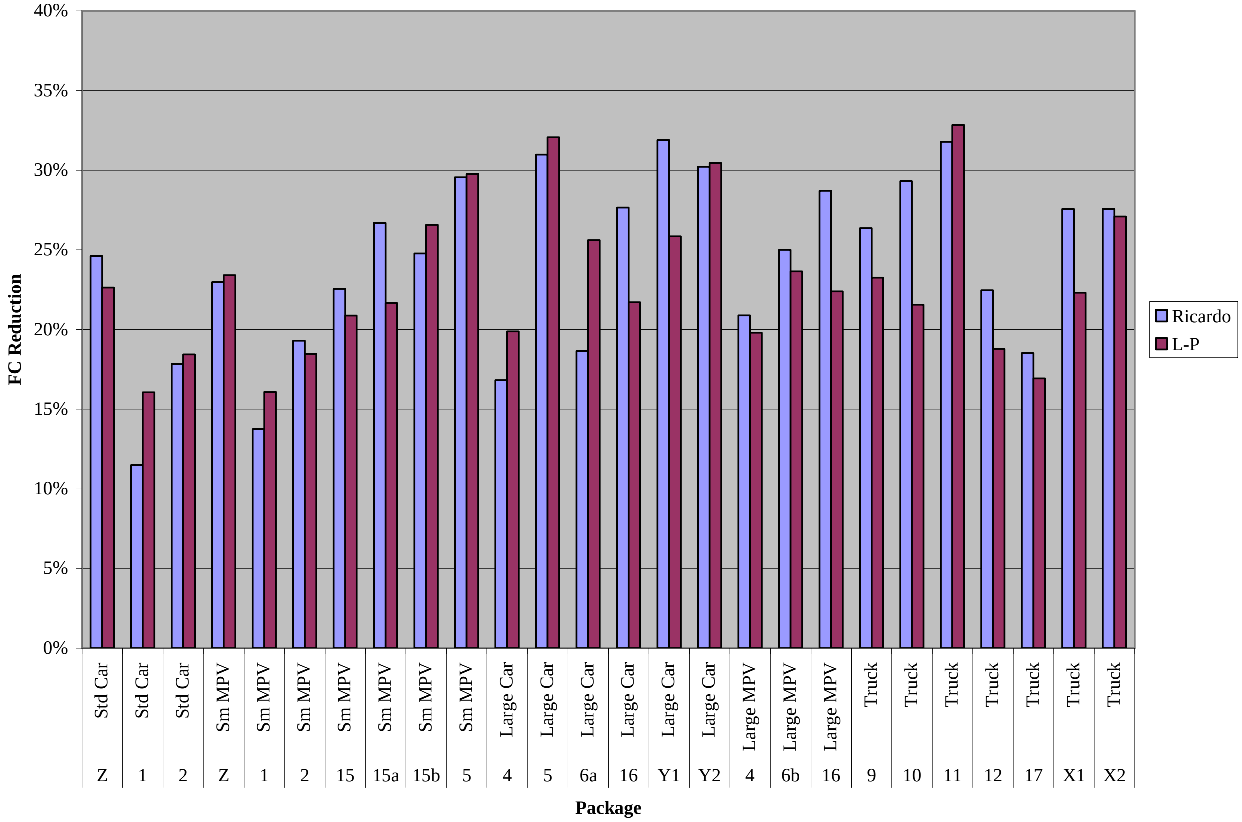
*-Please refer to Table 3.2-4 for a full description of the vehicle technologies

3.3 Comparison of Lumped-Parameter Results to Modeling Results

Considering the following:

1) EPA's lumped-parameter package estimates are comparable with those obtained from the detailed Ricardo simulations. This is illustrated in Figure 3.3-1 below.
2) EPA is confident in the plausibility of the individual technology effectiveness estimates in Table 2.2-1 through Table 2.2-5, based on the sources from which that information was assimilated, as detailed in Section 2 of this report.
3) Additionally, EPA expresses confidence in the overall Ricardo package results due to our knowledge of the robust methodology used in building the models and generating the results.

Figure 3.3-1. Comparison of Ricardo package results to equivalent lumped parameter package results



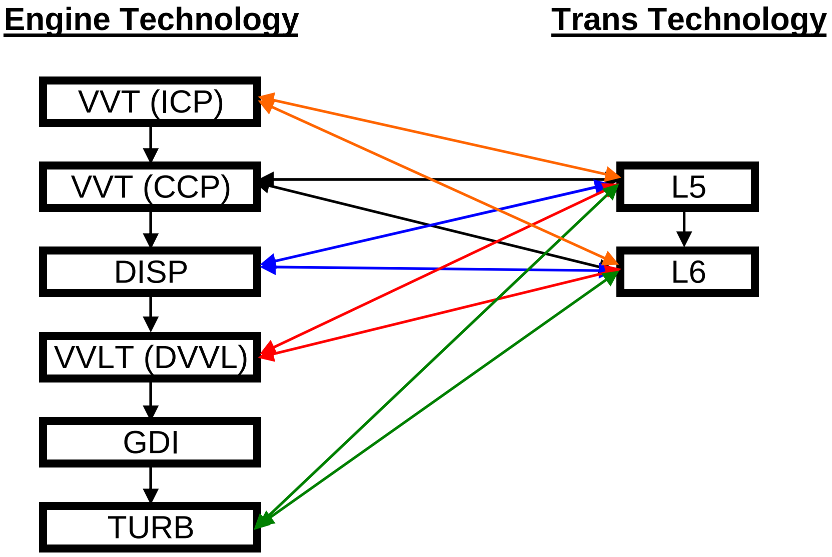
Based on this, EPA concludes that the synergies derived from the lumped parameter approach are generally plausible (with a few packages that garner additional investigation). EPA will continue to analyze this data, focusing on those packages where the differences between the two approaches are large.

The simulation results may present opportunities to improve the fidelity of the lumped-parameter approach by identifying differences between different platforms or important vehicle traits (such as displacement-to-weight ratio, e.g.). There might also be opportunity to infer (through detailed analysis) the individual effectiveness values for some technologies by comparing and isolating Ricardo package results across different vehicle platforms.

3.4 Using the Lumped-Parameter Technique to Determine Synergies in a Technology Application Flowpath (Identifying "Technology Pairs" to account for synergies)

In order to account for the real world synergies of combining of two or more technologies, the product of their individual effectiveness values must be adjusted based on known interactions, as noted above. When using an approach in which technologies are added sequentially in a pre-determined application path to each individual vehicle model, as used in NHTSA's 2006 fuel economy rule for light trucks[10], these interactions may be accounted for by considering a series of interacting technology pairs. EPA believes that a lumped parameter approach can be used as a means to estimate and account for synergies for such a technology application method. When using a sequential technology application approach which applies more than one technology, it is necessary to separately account for the interaction of each unique technology pair. Moreover, if the sequential technology application approach applies a technology that supersedes another, for example, where a VVLT system is substituted in place of a cylinder deactivation system, its incremental effectiveness must be reduced by the sum of the synergies of that technology with each individual technology that was previously applied, regardless of whether any of them have also been superseded. Figure 3.4-1 below provides an example of how technology pairs are identified for a specific technology application path similar to one used by NHTSA. In this example, an interaction is identified between each of the engine technologies (except GDI) with each of the transmission technologies. So, in this example, were the model to couple a turbocharged and downsized GDI engine with a 6-speed transmission, it would apply a series of many synergy pairs to the combined individual effectiveness values to arrive at the overall effectiveness.

Figure 3.4-1 Illustration of technology pairings for a specific technology application path



(Lines indicate potential synergies)

4 Costs for Technologies

4.1 Methodology for Estimating Variable Piece Costs

This section describes the costs associated with the new vehicle technologies described in Section 2. The costs described here represent the piece costs for an individual piece of hardware or system, e.g., an intake cam phaser to provide variable valve timing. To estimate piece costs, we relied upon a number of sources for cost related information. Our objective was to use those sources of information that we considered to be most credible for projecting the costs of individual vehicle technologies. These sources included: the 2002 NAS report on the effectiveness and impact of CAFE standards;[11] the 2004 study done by NESCCAF;[12] the recent California Air Resources Board (CARB) Initial Statement of Reasons in support of their carbon rulemaking;[13] a 2006 study done by Energy and Environmental Analysis (EEA) for the Department of Energy;[14] and our own vehicle fuel economy certification data. We also considered confidential data submitted by vehicle manufacturers in response to NHTSA's request for product plan information,[15] and confidential information shared by automotive industry component suppliers in meetings with EPA and NHTSA staff held during the second half of the 2007 calendar year. These sources of data do not present their values in terms of 2006 dollars as was desired for this analysis. To adjust to 2006 dollars, we have used the appropriate Producer Price Index as determined by the Department of Labor's Bureau of Labor Statistics, and we present our methodology for these adjustments in Appendix 4.A to this report. Where estimates differ between sources, we have used engineering judgment to arrive at what we believe to be the best cost estimate available today, and explained the basis for that exercise of judgment. The following discussion summarizes our piece cost estimates and how we used these data sources to arrive at our best estimate of piece costs.

4.2 Piece Costs Assigned to CO_2 Reduction technologies

Table 4.2-1 presents our estimated costs associated with the technologies we believe will be used to reduce carbon dioxide emissions from passenger cars and light trucks. Following the table is a detailed description of how each of these costs was developed. The costs are meant to represent the incremental compliance costs for each technology. As such, these costs account for both the direct manufacturing costs and the indirect costs. These indirect costs include production-related costs (research, development, and other engineering), business-related costs (salaries, pensions), or retail-sales-related costs (dealer support, marketing), and profits.[16] For this analysis, we first developed piece cost estimates for each technology or system at the auto manufacturer level, i.e., the price paid by the manufacturer to a Tier 1 component supplier.[E] To these costs, we then added an indirect cost markup factor of 50 percent to generate the compliance costs presented in the table.[F] We believe that this indirect cost markup overstates the incremental indirect costs because it is based on studies that include cost elements—such as

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[E] A Tier 1 supplier is one that sells its products directly to the automobile manufacturer, or any original equipment manufacturer (OEM) that sells its products at the consumer retail level. A Tier 2 supplier would be one that sells its products to a Tier 1 supplier, and so on.

[F] We have a more detailed discussion of markup factors and what cost elements they capture in section 4.3 of this report.

funding of pensions—which we believe are unlikely to change as a result of the introduction of new technology. Consequently, the incremental compliance costs we have developed should not be understood as estimated price increases for vehicles, but rather an estimate of the incremental cost of the technology at the retail level which accounts (conservatively) for all direct and indirect OEM costs.[G] We have a detailed discussion of markup factors in Section 4.3 of this report.

Note that throughout this discussion we compare our estimated compliance costs to manufacturer costs (i.e., costs without any indirect cost markup) and retail price equivalents (i.e., costs with indirect cost markups) from other studies. These comparisons are sometimes necessarily imprecise given different markups and/or lack of markups among the estimates. In addition, please note that the 2002 NAS study and the NESCCAF study used a markup of 40 percent to arrive at their retail price equivalent (RPE) estimates. Also please be aware that the EEA study referred to throughout this discussion applied no markups, presenting only the manufacturer's direct costs. Lastly, the CBI submittals reported RPEs but contained no information as to how those RPEs were calculated (i.e., no information showing the direct cost versus indirect cost portions).

[G] We differentiate between cost and price where cost is meant to capture the concept of what it costs entity A to produce and make available a product that can be purchased by entity B, while price is meant to capture the concept of what entity B actually pays to entity A for the product. The price is generally higher than the cost but can also be lower since so many factors impact the price. The incremental compliance costs we have developed are meant only to capture all of the incremental business expenses that entity A – the original equipment auto manufacturer – would incur.

Table 4.2-1 Incremental Compliance Costs for Technologies (2006 Dollars per Vehicle)

Technology	Incremental to	Vehicle Class				
		Small Car	Large Car	Minivan	Small Truck	Large Truck
Engine Technologies						
Low friction lubricants	Base engine	3	3	3	3	3
Engine friction reduction	Base engine	0-84	0-126	0-126	0-126	0-168
Overhead Cam Engines						
VVT – intake cam phasing	Base engine	59	119	119	119	119
VVT – coupled cam phasing	Base engine	59	119	119	119	119
VVT – dual cam phasing	Base engine	89	209	209	209	209
Cylinder deactivation	Base engine	n.a.	203	203	203	229
Discrete VVLT	Base engine	169	246	246	246	322
Continuous VVLT	Base engine	254	466	466	466	508
Overhead Valve Engines						
Cylinder deactivation	Base engine	n.a.	203	203	203	229
VVT – coupled cam phasing	Base engine	59	59	59	59	59
Discrete VVLT	Base engine	169	246	246	246	322
Continuous VVLT (includes conversion to Overhead Cam)	Base engine w/ VVT-coupled	599	1262	1262	1262	1380
Camless valvetrain (electromagnetic)	Base engine	336-673	336-673	336-673	336-673	336-673
GDI – stoichiometric	Base engine	122-420	204-525	204-525	204-525	228-525
GDI – lean burn	GDI - stoich	750	750	750	750	750
Gasoline HCCI dual-mode	GDI - stoich	263	390	390	390	685
Turbocharge+downsize	Base engine	690	120	120	120	810
Diesel – Lean NOx trap	Base gasoline engine	2790				
Diesel – urea SCR	Base gasoline engine		3045	3120	3405	4065
Optimized E20-E30	Base gasoline engine	713	143	143	143	833
Transmission Technologies						
Aggressive shift logic	Base trans	38	38	38	38	38
Early torque converter lockup	Base trans	30	30	30	30	30
5-speed automatic	4-speed auto	76-167	76-167	76-167	76-167	76-167
6-speed automatic	4-speed auto	76-167	76-167	76-167	76-167	76-167
6-speed AMT	6-speed auto	141	141	141	141	141
6-speed manual	5-speed man	107	107	107	107	107
CVT	4-speed auto	231	270	270	n.a.	n.a.
Hybrid Technologies						
Stop-Start with 42 volt system	Base engine w/ upgraded 42V accessories & base trans	563	600	600	600	600
IMA/ISA/BSG (includes engine downsize)	Base engine & trans	2477	3153	n.a	n.a	n.a
2-Mode hybrid electric vehicle	Base engine & trans		4655	4655	4655	6006
Power-split hybrid electric vehicle (P-S HEV)	Base engine & trans	3754				
Full-Series hydraulic hybrid	Base engine & trans	750	825	825	900	1200
Plug-in hybrid electric vehicle (PHEV)	Base engine & trans	4500	6750	6750	6750	10200
Full electric vehicle (EV)	Base engine & trans	12000	15000			
Accessory Technologies						
Improved high efficiency alternator & electrification of accessories (12 volt)	Base accessories	89-119	89-119	89-119	89-119	89-119
Electric power steering (12 or 42 volt)	Base accessories	118-197	118-197	118-197	118-197	118-197
Improved high efficiency alternator & electrification of accessories (42 volt)	Improved high efficiency alternator & electrification of accessories (12 volt)	89-119	89-119	89-119	89-119	89-119
Vehicle Technologies						
Aero drag reduction (20% on cars, 10% on trucks)	Base vehicle	0-75	0-75	0-75	0-75	0-75
Low rolling resistance tires (10%)	Base vehicle	6	6	6	6	
Low drag brakes (ladder frame only)	Base vehicle				87	87
Secondary axle disconnect (unibody only)	Base vehicle	676	676	676	676	
Front axle disconnect (ladder frame only)	Base vehicle				114	114

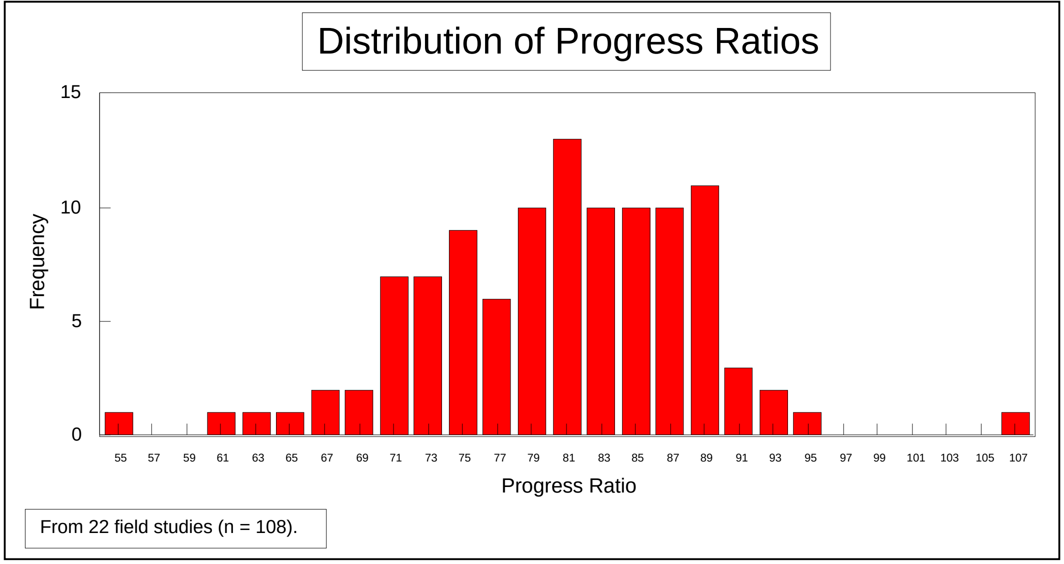
For some of the technologies presented in Table 4.2-1, we believe that learning effects would reduce future costs from the levels shown.[H] The "learning curve" or "experience curve" describes the reduction in unit production costs as a function of accumulated production volume. In theory, the cost behavior it describes applies to cumulative production volume measured at the level of an individual manufacturer, although it is often assumed—as EPA has often done in past regulatory analyses—to apply at the industry-wide level particularly in industries that utilize many common technologies and component supply sources.[17] We believe there are factors that cause hardware costs to decrease over time. Research in the costs of manufacturing has consistently shown that as manufacturers gain experience in production, they are able to apply innovations to simplify machining and assembly operations, use lower cost materials, and reduce the number or complexity of component parts, all of which allows them to lower the per-unit cost of production (i.e., the manufacturing learning curve).[18]

The learning curve is a well documented phenomenon. The general concept is that unit costs decrease as cumulative production increases. Learning curves are often characterized in terms of a progress ratio, where each doubling of cumulative production leads to a reduction in unit cost to a percentage "p" of its former value (referred to as a "p cycle"). Organizational learning, which brings about a reduction in total cost, is caused by improvements in several areas. Areas involving direct labor and material are usually the source of the greatest savings. Examples include, but are not limited to, a reduction in the number or complexity of component parts, improved component production, improved assembly speed and processes, reduced error rates, and improved manufacturing process. These all result in higher overall production, less scrappage of materials and products, and better overall quality. As each successive p cycle takes longer to complete, production proficiency generally reaches a relatively stable plateau, beyond which increased production does not necessarily lead to markedly decreased costs.

Companies and industry sectors learn differently. In a 1984 publication, Dutton and Thomas reviewed the progress ratios for 108 manufactured items from 22 separate field studies representing a variety of products and services.[19] The distribution of these progress ratios is shown in Figure 4.2-1. Except for one company that saw increasing costs as production continued, every study showed cost savings of at least five percent for every doubling of production volume. The average progress ratio for the whole data set falls between 81 and 82 percent. Other studies (Alchian 1963, Argote and Epple 1990, Benkard 1999) appear to support the commonly used p value of 80 percent, i.e., each doubling of cumulative production reduces the former cost level by 20 percent.

[H] During the development of our cost estimates, EPA technical staff had several discussions and shared drafts of technical write-ups with colleagues at the Department of Transportation's Volpe Center regarding the learning curve. While the final write-up presented here on the theory and application of the learning curve was not reviewed by DOT, it benefited greatly from the input and many suggested additions from technical staff at the Volpe Center.

Figure 4.2-1 Distribution of Progress Ratios (Dutton and Thomas 1984)



The learning curve is not the same in all industries. For example, the effect of the learning curve seems to be less in the chemical industry and the nuclear power industry where a doubling of cumulative output is associated with 11 percent decrease in cost (Lieberman 1984, Zimmerman 1982). The effect of learning is more difficult to decipher in the computer chip industry (Gruber 1992).

A typical experience curve can be described by three parameters: (1) the initial production volume that must be reached before cost reductions begin to be realized (referred to as the "threshold volume"); (2) the percentage at which costs are reduced with increases in cumulative production beyond this initial volume (usually referred to as the "learning rate"); and (3) the production volume after which costs reach a "floor," and further cost reductions no longer occur. As such, a typical cost curve can be expressed by the following set of equations where $Cost_t$ is the current cost and $Cost_0$ is the original cost.

$$Cost_t = Cost_0 * (1 - decay)^{lVol_t}$$

$$lVol_t = \max\left(0, \log_2\left(mVol_t / seedV\right)\right)$$

$$mVol_t = \min(cVol_t, a * kD * seedV)$$

$$cVol_t = \sum_{i=1}^{i=t} Volume$$

$$kD = 2$$

where,

a = the number of stages of learning-related cost reductions. Setting a=2 results in two full learning stages.

$decay$ = the learning rate.

$lVol$ = zero until the threshold volume, $seedV$, is reached.

mVol = the cumulative volume, *cVol*, until the volume floor, *a*kD*seedV* is reached. The volume floor, *a*kD*seedV* represents the volume at which learning effects cease.

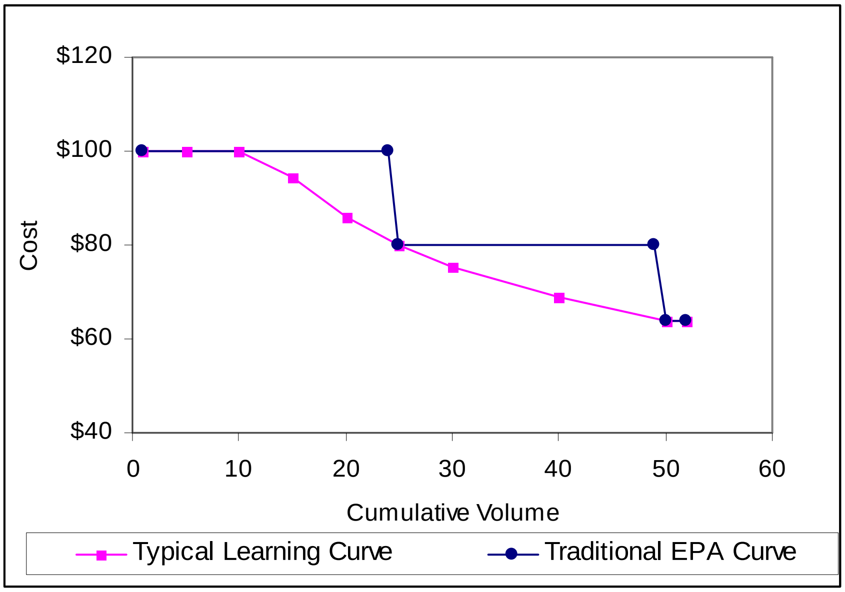
kD = the volume factor which defines the volume floor. Setting *kD*=2 and *a*=2 would result in a volume floor of four times the threshold volume, *seedV*.

seedV = the threshold volume at which learning effects begin to occur.

Figure 4.2-2 illustrates an experience curve for a vehicle technology with an initial average unit cost, $Cost_0$, of $100 and a learning rate, *decay*, of 20 percent. In this hypothetical example—illustrated by the curve, $Cost_t$, named "Typical Learning Curve"—the initial production volume, or threshold volume, before cost reductions begin to be realized is set at 12,500 units and *kD* is set at 2 (i.e., the volume floor is set at 50,000 units). As shown in the figure, costs remain constant until the threshold volume, *seedV*, of 12,500 is reached at which point learning begins to decrease the part cost. Upon a doubling of the threshold volume, the learning curve effect has resulted in a 20 percent reduction in part costs (i.e., *mVol*=25,000 so that *lVol*=1 and then $Cost_t$ = $100*(1-0.2)). Another doubling of volume at 50,000 units results in another 20 percent reduction in costs. Since a cumulative volume of 50,000 units represents the volume floor, costs then stabilize and no further learning occurs.

Figure 4.2-2 also shows a "Traditional EPA Curve." As discussed more below, EPA has traditionally used a simple approach to applying the learning curve by ignoring the threshold volume and assuming that learning occurs in a step-wise fashion. We have traditionally applied two learning steps to our initial costs which would result in the same final cost as the approach described above while simplifying the analysis. Further, while the more detailed approach described above more closely approximates reality, our traditional approach has slightly underestimated the learning impacts (i.e., our approach has not accounted for the cost reductions represented by the area between the "typical" curve and the "EPA" curve).

Figure 4.2-2 Typical Experience Curve



Most studies of the effect of experience or learning on production costs appear to assume that cost reductions begin only after some initial volume threshold has been reached, but not all of these studies specify this threshold volume. The rate at which costs decline beyond the initial threshold is usually expressed as the percent reduction in average unit cost that results from each successive doubling of cumulative production volume, sometimes referred to as the learning rate. Many estimates of experience curves do not specify a cumulative production volume beyond which cost reductions no longer occur, instead depending on the asymptotic behavior of the effect for learning rates below 100 percent to establish a floor on costs. Table Table 4.2-2 summarizes estimates of learning rates derived from studies of production costs for various products.

Table 4.2-2 Estimated Learning Rates and Associated Volumes for Various Products

Product(s)	Costs Affected	Threshold Volume	Learning Rate
Photovoltaic cells	Total costs	Not reported	20%
Wind turbines	Total costs	100 MW	20%
Gas turbines	Total costs	100 MW	10%
Semiconductors	Total costs	Not reported	13-24%
Automobile assembly	Assembly labor	Not reported	16%
Truck manufacturing	Total costs	Not reported	10%
Battery-electric LDV	Total costs	10,000 units	10%
Fuel cell hybrid LDV	Total costs	10,000 units	16%
Fuel cell LDV powertrain	Total costs	10,000 units	19%

In past rulemaking analyses, as noted above, EPA has used a learning curve factor of 20 percent for each doubling of production volume. In those analyses, we simplified our approach by using a time based learning progression rather than a pure production volume progression (i.e., after two years of production we have assumed that production volumes have doubled and, therefore, costs are reduced by 20 percent). This approach has served the Agency well, especially considering that those rulemaking analyses have reflected programs in which every new engine or vehicle beginning in year one of implementation would be equipped with the newly required piece of technology.

We believe that a 20 percent learning factor has been appropriate for all newly applied technologies in past EPA rules, and we believe it is appropriate in the future for most carbon dioxide reducing technologies. One exception is learning applied to diesel technologies where we believe that a 10 percent factor is more applicable going forward because those costs build on past EPA estimates and consider already at least two learning steps (resulting from the Tier 2 highway and 2007 heavy-duty highway rules). That said, we believe there is still room for more learning on diesel technologies since so few light-duty diesels with aftertreatment devices exist in the United States and because General Motors has made announcements recently about potential cost savings associated with their new 4.5 liter Duramax diesel V8 engine.

For each of the technologies presented in Table 4.2-1, we have considered whether we could project future cost reductions due to manufacturer learning. In making this determination, we considered whether or not the technology was in wide-spread use today or expected to be by the model year 2011-2012 time frame, in which case estimating future learning may not be appropriate because the technology is already in wide-spread production by the automotive industry today, e.g., on the order of multi-millions of units per year. Savings from learning are thus already reflected in our estimates. (Examples of these include 5-speed automatic transmissions and intake-cam phasing variable valve timing. These technologies have been in production for light-duty vehicles for more than 10 years.) In addition, we carefully considered the underlying source data for our cost estimate. If the source data specifically stated that manufacturer cost reduction from future learning would occur, we took that information into account in determining whether we would apply manufacturer learning in our cost projections. Thus, for many of the technologies, we do not believe it would be appropriate to consider any learning curve cost reductions during the timeframe of consideration.

However, there are a number of technologies that are not yet in mass production for which we believe the initial cost would be reduced in the time frame of consideration due to manufacturer production learning. As indicated in Table 4.2-3, we believe that application of learning effects for some technologies would be appropriate beginning today while for others the learning effects should not be considered for another four to six years. The distinction between the application of learning in the near term versus its application in the longer term is due to the source data for our cost estimates. For those technologies where the source of our cost estimate did not take into account manufacturer learning, we believe that learning effects are applicable in the near term.

Table 4.2-3 Technologies Expected to See Cost Reductions due to Learning Effects Cost Reductions Measured Relative to Costs Shown in Table 4.2-1

Technology	Learning curve cost reductions upon doubling of production starting in the given time frame [a]	
	Year	Learning Factor
Cylinder deactivation – overhead cam	longer term	20%
Continuous VVLT – overhead cam	longer term	20%
Camless valvetrain (electromagnetic)	near term	20%
GDI – lean burn	near term	20%
Gasoline HCCI dual-mode	near term	20%
Turbo+downsize	longer term	20%
Diesel – Lean NOx trap	near term	10%
Diesel – urea SCR	near term	10%
6-speed AMT	near term	20%
Stop-Start with 42 volt system	longer term	20%
IMA/ISA/BSG (includes engine downsize)	longer term	20%
2-Mode hybrid electric vehicle	longer term	20%
Power-split hybrid electric vehicle (P-S HEV)	longer term	20%
Plug-in hybrid electric vehicle (PHEV)	near term	20%
Improved high efficiency alternator & electrification of accessories (42 volt)	near term	20%
Secondary axle disconnect (unibody only)	near term	20%

[a] Cost reductions would occur at the first doubling of production for production beginning in the time frame shown (near term or longer term). Cost reductions would occur again at the second doubling of production. Note that the time frame designation—near term or longer term—is not meant to be an absolute measure, but rather a relative measure tied only to this analysis. Please refer to the text for detail on the meaning of these terms within the context of this report. The learning factor represents the level of cost reduction that would occur at each step. Technologies not shown may experience cost reductions from our estimated levels, but we believe those reductions would not occur during the timeframe of consideration.

Certain other technologies are based on a source that we understand to have taken into account manufacturer learning and, therefore, we believe that the cost estimates we present for those technologies should not have any learning applied to them in the near term. The technologies for which we believe that longer term learning is more appropriate, we have used as our primary source the 2004 NESCCAF study, for which the sub-contractor was The Martec Group. In the work done for the 2004 NESCCAF report, Martec relied upon actual price quotes from Tier 1 automotive suppliers to develop automotive manufacturer cost estimates. During the process of developing the cost estimates for this proposal, EPA staff met directly with representatives from Martec to better understand how their cost estimation methodology was developed. Based on this information, we understand that the Martec cost estimates already incorporate some element of manufacturer learning. Martec informed us that the Tier 1 suppliers were specifically requested to provide price quotes which would be valid for three years (2009-2011), and that for some components the Tier 1 supplier included cost reductions in years two and three which the supplier anticipated could occur, and which they anticipated would be necessary in order for their quote to be competitive with other suppliers. Therefore, for this analysis, we believe that some learning effects are already reflected in the Martec-sourced costs and additional learning effects should not be applied to those costs for several years, at least until after 2013. However, the theory of manufacturer learning is that it is a continuous process, though the rate of improvement decreases as the number of units produced increases. While we were not able to gain access to the detailed submissions from Tier 1 suppliers upon which Martec relied for their estimates, we do believe that additional cost reductions will occur in the future for a number of the technologies for which we relied upon the Martec cost estimates. Those technologies are noted in Table 4.2-3 with learning curve effects being applicable in the longer term.

4.2.1 Piece Costs Associated with Engine Technologies

The technologies listed here are discussed in detail in Section 2 of this report.

4.2.1.1 Low-Friction Lubricants

A change in lubricant, whether engine oil or transmission fluid, usually requires some durability testing to ensure that durability is not compromised. It may also require some bearing changes, but we suspect these to be minimal. The 2002 NAS study estimated the low friction lubricant RPE at $8 to $11 using a 40 percent markup, the NESCCAF study showed an RPE of $5 to $15 with a 40 percent markup, and the EEA report to DOE showed manufacturer costs of $10 to $20. By contrast, many of the manufacturer CBI submittals had lower or even no costs associated with low friction lubricants. We believe these manufacturer estimates are more accurate (among other things, it is in manufacturers' interests to use higher cost estimates), but also believe that a change in any lubricant would involve some level of verification and durability testing and have estimated the incremental compliance cost at $3. We believe that this estimate is independent of vehicle class since the engineering work required should apply to any engine size.

4.2.1.2 Engine Friction Reduction

Several friction reduction opportunities (piston surfaces and rings, crankshaft design, improved material coatings, etc.) have been identified that are still available to a significant number of engine designs. Additionally, as computer-aided modeling software continues to improve, more opportunities for evolutionary friction reduction might become apparent. The 2002 NAS study estimated the engine friction reduction RPE at $35 to $140 (40 percent markup); NESCCAF showed an RPE of $5 to $15 (40 percent markup); the EEA report to DOE showed manufacturer costs of $10 to $55. The CBI submittals suggest that these ranges are reasonable, although they contained values ranging from $0 to $140. For this analysis, we have estimated the incremental compliance cost to range from $0 to $84 for small cars, $0 to $168 for large trucks, and $0 to $126 for applications in between. We have estimated such a wide range here because there are so many friction reduction opportunities – piston surfaces and rings, crankshaft design, improved material coatings, low-tension piston rings, roller cam followers, material substitution, more optimal thermal management, piston surface treatments, as well as lubricant friction reduction – and manufacturers may do anywhere from none to many or all of them.

4.2.1.3 Variable Valve Timing Systems

Manufacturers are currently using many different types of variable valve timing, which have a variety of different names and methods. The major types of VVT are listed below.

a. Intake Camshaft Phasing (ICP)

Valvetrains with VVT-ICP, which is the simplest of the cam phasing technologies, can modify the timing of the intake valve while the exhaust valve timing remains fixed. This requires the addition of a cam phaser for each bank of intake valves on the engine. An in-line 4-cylinder engine has one bank of intake valves, while V-configured engines would have two banks of intake valves. In our efforts to understand the estimates presented in the 2002 NAS study, we believed that they estimated the cam phaser RPE at $35 (40% markup),[I] while the EEA report showed a manufacturer cost (rather than an RPE) of $35. The NESCCAF study showed a manufacturer cost of $35 which would mean an RPE of $49 (40% markup). Consistent with the EEA report and NESCCAF study, we have used this $35 manufacturer cost to arrive at our PPI-adjusted incremental compliance cost of $59 per cam phaser or $59 for an in-line 4 cylinder and $119 for a V-type engine. We have developed an estimate for VVT-ICP associated with overhead cam engines only. For overhead valve engines we do not expect use of VVT-ICP since they typically use a form of VVT called coupled cam phasing, described below.

b. Coupled Camshaft Phasing (CCP)

Coupled (or coordinated) cam phasing is a design in which both the intake and exhaust valve timing are varied using the same cam phaser. For an overhead cam engine, the same phaser added for VVT-ICP would be used for VVT-CCP control. As a result, its costs are identical to those for VVT-ICP. For an overhead valve engine, only one phaser would be required for both 4-cylinder and V-configured engines since only one camshaft exits. Therefore, for overhead valve engines, the incremental compliance cost is estimated at $59 regardless of engine configuration, for the reasons given in the previous sub-section.

[I] The 2002 NAS study estimated the lower end of the RPE range for variable valve timing at $35 and for variable valve lift and timing at $70. VVT requires one cam phaser while VVLT requires two.

c. Dual (Independent) Camshaft Phasing (DCP)

The most flexible VVT design is dual cam phasing, where the intake and exhaust valve opening and closing events are controlled independently. This design allows the option of controlling valve overlap, which can be used as an internal EGR strategy. Our estimated incremental compliance cost for this technology is built upon that for VVT-ICP where an additional cam phaser is added to control each bank of exhaust valves less the cost to the manufacturer of the removed EGR valve. For example, the incremental compliance cost for a V6 engine would be $59 for each bank of intake valves (i.e., 2 banks times $59/bank = $119), $59 for each bank of exhaust valves (i.e., another $119), less $29 incremental compliance cost for the removed EGR valve; the total incremental compliance cost being $209.[J] Note that we do not anticipate VVT-DCP being used on overhead valve engines and, hence, do not have a cost associated with VVT-DCP on overhead valve engines.

4.2.1.4 Engine Cylinder Deactivation

Cylinder deactivation allows for some (usually half) of the cylinders to be "shut down" during light load operation. Noise and vibration issues reduce the operating range to which cylinder deactivation is allowed, although manufacturers are exploring the possibility of increasing the amount of time that cylinder deactivation might be suitable. The 2002 NAS study estimated the RPE to range from $112 to $252 (40% markup) while the NESCCAF study estimated the RPE at $161 to $210 (40% markup). The EEA report showed manufacturer costs of $105 to $135 (no markup), depending on vehicle class. In reviewing all our sources, we have attempted to determine the cost associated with individual components needed to employ cylinder deactivation. This way, we can use a "bottom-up" approach to estimate costs. Doing this, we have estimated the cost for individual components of these systems at $15 per cylinder being deactivated, $15 per engine for controls, and $60 per engine for engine mounts to address noise and vibration. Adjusting to 2006 dollars this results in incremental compliance costs of $203 for a V6 engine and $229 for a V8 engine, as shown in Table 4.2-1. These incremental compliance costs are consistent with the NAS Report and the NESCCAF study as well as with the CBI submissions from manufacturers. Note that 4-cylinder engines are not expected to add this technology because noise and vibration problems become very difficult to control.

4.2.1.5 Variable Valve Lift Systems

Controlling the lift height of the valves provides additional flexibility and potential for further reduction in pumping losses. There are two major classifications of variable valve lift, described below.

a. Discrete Variable Valve Lift

[J] Note that rounding may impact the totals presented throughout this discussion. For example, $59.30 is stated in the text as $59 for clarity, while 2 x $59.30 is stated as $119.

The 2002 NAS study shows DVVL system RPEs to range from $70 to $210 (40% markup) depending on engine size. The NESCCAF study shows a RPE range of $105 to $210 (40% markup) for electro-hydraulic DVVL systems depending on engine size and overhead cam versus overhead valve engines. We have used the NESCCAF values and added to those a $25 cost to the manufacturer for controls and associated oil supply needs (costs not reflected in the NESCCAF study). We have also estimated that a single valve lifter could control valve pairs, so engines with dual intake and/or dual exhaust valves would require one lifter per pair of valves being controlled. As a result, our estimates for overhead cam and overhead valve engines are the same. The end result, including PPI adjustments, is an incremental compliance cost of $169, $246, and $322 depending on vehicle class.

b. Continuous Variable Valve Lift

Continuous variable valve lift (CVVL) typically employs a mechanism that varies the pivot point in the rocker arm. The NESCCAF study showed estimated RPEs from $210 to $420 (40% markup), depending on vehicle class. The EEA report showed manufacturer costs of $180 to $350 (no markup), depending on vehicle class and assuming presence of overhead cams. Consistent with NESCCAF, we estimated the PPI-adjusted incremental compliance cost for these systems on overhead cam engines at $254, $466, and $508 for a 4-, 6-, and 8-cylinder engine, respectively.

We consider this technology to be limited to overhead cam engines. As a result, for an overhead valve engine to add CVVL, it would first have to be converted to an overhead cam engine. (The NESCCAF value of $420 for a V8 overhead valve engine did not include costs associated with conversion to overhead cam(s).) Such a conversion is not inexpensive, as it entails the addition of one to three camshafts, additional valves, and then addition of the CVVL costs just discussed. As shown in Table 4.2-1, we have estimated this PPI-adjusted incremental compliance cost at $599 to $1,380 depending on vehicle class.

4.2.1.6 Camless Valve Actuation Systems

Camless valve actuation relies on electromechanical actuators instead of camshafts to open and close the cylinder valves. Camless valvetrains have been under research for decades because it would allow for considerable fuel economy improvement potential and tremendous flexibility. In reviewing our sources for costs, we have determined that the values presented in the 2002 NAS study – $280 to $560 (40% markup), depending on vehicle class – represent the best available estimates. These are shown in Table 4.2-1, after applying our markup and PPI adjustments, as ranging from $336 to $673, independent of vehicle class. For comparison, the NESCCAF study showed RPE estimates ranging from $805 to $1,820 (40% markup), and the EEA report to DOE showed manufacturer costs ranging from $210 to $600 (no markup). The NESCCAF study shows considerably higher values than our estimates. Importantly, the NESCCAF study estimated the costs for camless valve actuation on both the intake and the exhaust valves. We believe that a more likely scenario would be using camless valve actuation on only the intake valves. Therefore, we believe that our lower estimates represent the more likely technology application.

4.2.1.7 Stoichiometric Gasoline Direct Injection Technology

Gasoline direct injection (GDI), also known as spark-ignition direct injection (SIDI), engines inject fuel at high pressure directly into the combustion chamber (rather than the intake port in port fuel injection). The stoichiometric GDI engine operates at stoichiometric conditions and uses a spark to initiate ignition, unlike a compression ignition engine. This requires injector design advances, new fuel pumps to deliver higher injection pressures, and new fuel rails to handle the higher fuel pressures. The NESCCAF study estimated the RPE for these systems at \$189 to \$294 (40% markup), depending on vehicle class. The EEA report to DOE shows a manufacturer cost range of \$77 to \$135. The CBI submittals from manufacturers suggest these ranges are low. For our analysis, we have estimated the costs of individual components of a GDI system and used a "bottom up" approach looking at incremental costs for injectors, fuel pumps, etc., to arrive at system incremental compliance costs ranging from \$122 to \$420 for small cars and up to \$228 to \$525 for large trucks. The lower end of the ranges represent our best estimate using a bottom up approach while the upper end of the ranges represent levels more consistent with the manufacturer CBI submittals.

4.2.1.8 Lean-Burn Gasoline Direct Injection Technology

One way to dramatically improve an engine's thermodynamic efficiency is by operating at a lean air-fuel mixture (excess air). Such operation presents difficult challenges for a gasoline fueled engine. To achieve such operation while meeting emissions standards requires everything mentioned above for stoichiometric GDI engines. In addition, some incremental costs would be likely for the aftertreatment system since NOx aftertreatment for lean-burn engines is generally more costly than for stoichiometric engines. The NESCCAF study estimated the RPE for lean-burn GDI aftertreatment to range from \$539 to \$1,260 (40% markup) depending on vehicle class. We do not believe that lean-burn GDI engines can be expected to penetrate the light-duty market anytime soon due to gasoline sulfur levels being slightly too high.[K] Nonetheless, we have estimated the incremental compliance cost for these systems at \$750, independent of vehicle class, and incremental to a stoichiometric GDI engine.

4.2.1.9 Homogeneous Charge Compression Ignition

Homogeneous charge compression ignition (HCCI), also referred to as controlled autoignition (CAI), is an alternative engine operating mode that does not rely on a spark event to initiate combustion. As the combustion is more closely aligned with diesel compression ignition combustion, the engine operates at the higher compression ratios and efficiencies typical of diesel engines. However, proper control of the combustion process is difficult to achieve and requires in-cylinder pressure sensors and very fast engine control logic to optimize combustion timing, especially considering the variable nature of operating conditions seen in a vehicle. The NESCCAF study estimated the RPE to range from \$560 to \$840 (40% markup), depending on vehicle class, including the costs for a stoichiometric GDI system and VVLT-DVVL. We have based our estimated incremental compliance cost on the NESCCAF estimates and, after applying our markup and adjusting to 2006 dollars, have arrived at \$263 to \$685, depending on vehicle

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[K] Note that gasoline lean-burn aftertreatment is essentially the same technology as diesel aftertreatment. We explain in detail in our 2007 Heavy-duty Highway and Nonroad Tier 4 rules that lean-burn aftertreatment works only if fuel sulfur is below 15 ppm. Current gasoline sulfur levels in the U.S. are, on average, 30 ppm with a maximum of 80 ppm.

class. Note that our estimated incremental compliance cost is incremental to a stoichiometric GDI engine.

4.2.1.10 Gasoline Turbocharging and Engine Downsizing

Turbocharging and supercharging (grouped together here as boosting) are two methods to increase the intake manifold and cylinder pressures above typical levels. Boosting increases the airflow into the engine, thus increasing the specific power level, and with it the ability to reduce engine size while maintaining performance. The technology considered here involves addition of a boost system, removal of two cylinders in most cases (from an 8-cylinder to a 6, or a 6 to a 4) and associated valves, and the addition of some form of cold start control system (e.g., air injection) to address possible cold start emission control. Consistent with NESCCAF, we have estimated the boost system incremental compliance cost at \$600. The incremental compliance cost for material associated with a cylinder we estimated at \$75, valves at \$15, and camshafts at \$150. An air injection pump incremental compliance cost was estimated at \$90. Using these values, we have estimated the incremental compliance cost for a boosted/downsized engine system at \$690 for small cars, \$810 for large trucks, and \$120 for other vehicle classes. The small car value is higher than the mid-range classes because it does not eliminate any cylinders so that there are no cost savings associated with that elimination. For the large trucks, the costs are higher than the mid-range classes because we have assumed an overhead valve engine as the baseline and an overhead cam engine once downsized. That results in the addition of camshafts, rather than removal of camshafts and associated costs, which outweighs the removal of cylinders and associated costs.

4.2.1.11 Diesel Systems

Diesel engines have several characteristics that give them superior fuel efficiency to conventional gasoline, spark-ignited engines. The diesel combustion cycle operates with fewer pumping losses, at a higher compression ratio, with a very lean air/fuel mixture, and typically at much higher torque levels than an equivalent-displacement gasoline engine. These features carry with them higher costs relative to gasoline engines. These higher costs result from:

- Improved fuel systems (higher pressures and more responsive injectors)
- Advanced controls and sensors to optimize combustion and emissions performance
- Higher compression ratios which require a more robust engine
- A turbocharger
- More costly aftertreatment systems

We have considered the costs for two types of diesel systems: one using a lean-NOx trap (LNT) along with a particulate filter; and one using a selective catalytic reduction (SCR) system along with a particulate filter. In our discussions with industry over the past couple of years – both auto manufacturers and aftertreatment device manufacturers – we have been repeatedly told that LNT systems would probably be used on smaller vehicles while the SCR systems would be used on larger vehicles and trucks. The primary reason given for this choice is the trade off between the rhodium needed for the LNT and the urea injection system needed for SCR. The breakeven point between these two cost factors appears, at present, to occur at roughly the 3.0 liter engine size – below that, LNT is less costly while above that SCR is less costly. Other factors impact a manufacturer's decision on which system to use, but we have used that rule-of-thumb for our analysis.

We have estimated the incremental compliance cost for diesel systems in a manner consistent with our recent clean diesel rulemakings (2007 Heavy-duty Highway and Nonroad Tier 4), building upon that approach by also considering the incrementally higher costs associated with the diesel engine relative to the gasoline engine. Our estimated incremental compliance costs range from $2,790 for the small car to $4,065 for the large truck. For comparison, the NESCCAF study showed RPEs of $2,100 to $2,730 (40% markup), although that analysis did not specify LNT versus SCR so direct comparisons are difficult to make.

4.2.1.12 E20-E30 Optimized Ethanol Engines

None of the other cost sources have directly addressed or considered engines optimized for ethanol use. For these systems, we believe that the only hardware cost required for optimization for ethanol use is to substitute some materials in the fuel system to accommodate the ethanol because ethanol reacts differently with materials than does gasoline. The cost to substitute affected materials should be low and we estimate them to be on the order of $15. However, for true optimization, the engine would also have to be boosted either using a turbo charger or supercharger. Further, we would expect such optimization to include engine downsizing to minimize fuel consumption. Neither of these costs is captured in the $15 material substitution cost. As a rough estimate of the incremental compliance costs, we have added the $15 material substitution cost, or $23 with markup, to our engine downsize and turbocharging costs presented in Section 4.2.1.10, to arrive at incremental compliance costs of $713 for small cars, $833 for large trucks, and $143 for other vehicle classes. These compliance costs would be incremental to a base gasoline engine (i.e., an engine that has not been downsized or turbocharged).

4.2.2 Piece Costs Associated with Transmission and Hybrid Technologies

4.2.2.1 Automatic 5-speed Transmissions

As automatic transmissions have been developed over the years, more forward speeds have been added to improve fuel efficiency, and performance. Increasing the number of available ratios provides the opportunity to optimize engine operation under a wider variety of vehicle speeds and load conditions. We have relied on the 2002 NAS study for our estimated incremental compliance costs associated with migrating from a 4-speed automatic transmission to a 5-speed automatic. Those RPEs range from $70 to $154 (40% markup) which becomes $76 to $167 for using our indirect cost markup and adjusting to 2006 dollars, independent of vehicle class. This range is consistent with the NESCCAF report which showed RPEs of $140 (40% markup), independent of vehicle class, while the EEA report showed a manufacturer cost estimate of $130.

4.2.2.2 Aggressive Shift Logic

In operation, an automatic transmission's controller decides when to upshift or downshift based on a variety of inputs such as vehicle speed, and throttle position according to programmed logic. This logic can be biased towards maximizing fuel efficiency by upshifting earlier and inhibiting downshifts under some conditions. Additional adaptive algorithms can be employed to maintain performance feel while improving fuel economy under most driving conditions. This technology consists of calibration of computer software as no hardware is required. We have estimated the incremental compliance cost for this calibration effort at $38 based on the 2002

NAS study which estimated the RPE of aggressive shift logic to range from $0 to $70 (40% markup).

4.2.2.3 Early Torque Converter Lockup

As with aggressive shift logic, early torque converter lockup requires no new hardware and is accomplished through calibration to force lockup earlier than done traditionally. The 2002 NAS study did not provide a RPE estimate for this technology. The NESCCAF study estimated the RPE to range from $0 to $10 (40% markup) and, in its 2006 report for the Department of Energy, EEA estimated the manufacturer cost at $5. Here, we have estimated the incremental compliance cost of this technology (i.e., the calibration effort) at $30 based in part on NESCCAF and the CBI submissions which were slightly higher than NESCCAF. We have used a higher value here than NESCCAF and EEA because we have tried to account for the engineering effort in addition to the hardware which we believe NESCCAF and EEA did not do.

4.2.2.4 Automatic 6-, 7- and 8-speed Transmissions

In addition to 5-speed automatic transmissions, manufacturers can also choose to utilize 6-, 7-, or 8-speed automatic transmissions. Additional gears allows for further optimization of engine operation over a wider range of conditions, but this is subject to diminishing returns as the number of speeds increases. According to EEA in its 2006 report for DOE, a Lepelletier gear set design provides for 6-speeds at the same cost as a 5-speed automatic. Based on that analysis, we have estimated the incremental compliance cost of a 6-speed automatic to be equivalent to that for a 5-speed automatic. We have not developed any estimate costs for 7- or 8-speed transmissions because of the diminishing returns in efficiency versus the costs for transmissions beyond 6-speeds.

4.2.2.5 Automated (shift) Manual Transmissions

An Automated Manual Transmission (AMT) is mechanically similar to a conventional manual transmission, but shifting and launch functions are controlled by the vehicle rather than the driver. A switch from a conventional automatic transmission with torque converter to an AMT incurs some costs but also allows for some cost savings. Savings can be realized through elimination of the torque converter which is a very costly part of a traditional automatic transmission, and through reduced need for high pressure hydraulic circuits to hold clutches (to maintain gear ratios in automatic transmissions) or hold pulleys (to maintain gear ratios in Continuously Variable Transmissions). Cost increases would be incurred in the form of calibration efforts since transmission calibrations would have to be redone, and the addition of a clutch assembly for launce and gear changes.

While AMTs are becoming more common in Europe, a primary concern with respect to this technology is the production capacity in the United States. Transmission manufacturing facilities in the United States are primarily for automatic transmissions. They are very costly and cannot be easily converted from producing traditional automatic transmissions to AMTs which are more like manual transmissions in design. However, as facilities are upgraded and transmission manufacturing equipment is replaced, existing facilities can be converted to AMT production at little to no additional cost relative to retooling for continued production of automatic transmissions. General Motors has made investments recently in manufacturing facilities geared toward production of traditional automatic transmissions so a widespread migration to AMTs would be very costly and unlikely for GM. In 2007, Getrag and Chrysler announced plans to build a new transmission plant in the U.S. to supply Chrysler with AMTs beginning as soon as 2009.

We believe that, overall, the hardware associated with an AMT, whether single clutch or dual clutch, is no more costly than that for a traditional automatic transmission given the savings associated with removal of the torque converter and high pressure hydraulic circuits. Nonetheless, given the need for engineering effort (e.g., calibration and vehicle integration work) when transitioning from a traditional automatic to an AMT, we have estimated the incremental compliance cost at $141, independent of vehicle class.

4.2.2.6 Continuously Variable Transmissions

A Continuously Variable Transmission (CVT) is unique in that it does not use gears to provide ratios for operation, but instead uses two V-shaped pulleys and a belt. The pullies are split in half and a hydraulic actuator moves the pulley halves together or apart which causes the belt to ride on either a larger or smaller diameter section of the pulley. This changes the effective ratio of the input to the output shafts providing for a very wide range of ratios. The 2002 NAS study estimated the RPE for this technology at $140 to $350 (40% markup) with the higher end of the range apparently meant for larger vehicles and trucks. The NESCCAF study estimated the RPE at $210 to $245 (40% markup) noting that the technology was not applicable to large trucks (i.e., V8 engines). For this analysis, we are consistent with the NESCCAF study and have estimated the incremental compliance cost at $231 to $270 in 2006 dollars, depending on vehicle class.

4.2.2.7 Manual (clutch shifted) 6-, 7-, and 8-speed Transmissions

As with automatic transmissions, increasing the number of available ratios in a manual transmission can improve fuel economy by allowing the driver to select a ratio that optimizes engine operation at a given speed. Typically, this is achieved through adding additional overdrive ratios to reduce engine speed (which saves fuel through reduced pumping losses). Six-speed manual transmissions have already achieved significant market penetration, so manufacturers have considerable experience with them and the associated costs. Based on CBI submissions, we have estimated the incremental compliance cost of a 6-speed manual relative to a 5-speed manual at $107, regardless of vehicle class.

4.2.2.8 Hybrid Systems

A hybrid is a vehicle that combines two or more sources of propulsion energy, where one uses a consumable fuel (like gasoline), and the other is rechargeable (during operation or by an external energy source). There are three primary ways to make use of hybrid technology to reduce fuel consumption as described in more detail in Section 2.5 of this report. The major hybrid concepts we have considered are listed below.

a. Integrated Starter-Generator with Idle-Off

Integrated Starter-Generator (ISG) systems are the most basic of hybrid systems and offer mainly idle-stop capability. The most common ISG systems replace the conventional belt-driven alternator with a belt-driven, higher power starter-alternator. In addition, when idle-off is used (i.e., the petroleum fuelled engine is shut off during idle operation), an electric power steering and auxiliary transmission pump are added to provide for functioning of these systems which, in a traditional vehicle, were powered by the petroleum engine. The 2002 NAS study estimated the RPE of these systems at $210 to $350 (40% markup) with a 12 volt electrical system and independent of vehicle class, while the NESCCAF study estimated the RPE for these systems at $280 (40% markup) with a 12 volt electrical system for a small car. We have estimated the incremental compliance cost of these systems, including the costs associated with upgrading to a 42 volt electrical system (discussed below in Section 4.2.3.3) and expressed in 2006 dollars, at $563 to $600, depending on vehicle class.

b. Integrated Motor Assist (IMA)/Integrated Starter-Alternator-Dampener (ISAD)

Honda's IMA system uses an electric motor bolted to the engine's crankshaft and connected to the transmission through a torque converter or clutch. This electric motor acts as both a motor for helping to launch the vehicle and a generator for recovering energy while slowing down. It also acts as the starter for the engine and the electrical system's main generator. The Continental ISAD system is similar to Honda's IMA and allows for idle-stop capability. The 2002 NAS study did not consider this technology while the NESCCAF study estimated the RPE for these systems at $2310 to $2940 (40% markup) for a small car and large car, respectively. We have used these estimates as the basis for our incremental compliance costs of $2477 for the small car and $3153 for the large car, expressed in 2006 dollars. We have not estimated incremental compliance costs for the other vehicle classes because we do not believe those classes would use this technology and would, instead, use the hybrid technologies discussed below.

c. 2-Mode Hybrids

This technology uses an adaptation of a conventional stepped-ratio automatic transmission by replacing some of the transmission clutches with two electric motors, which makes the transmission act like a CVT. The 2002 NAS study did not consider this technology, while the NESCCAF study estimated the RPE at $4340 to $5600 (40% markup), depending on vehicle class. We have used these estimates as the basis for our incremental compliance costs of $4655 to $6006 in 2006 dollars, depending on vehicle class. We have not estimated incremental compliance costs for small cars because we do not believe that this technology is well suited to small cars which would, instead use ISG or IMA/ISAD for a mild hybrid approach or power split for a more aggressive approach.

d. Power Split Hybrids

Power Split HEV systems are used currently by Toyota, Ford and Nissan. The Power Split system replaces the transmission with a single planetary gear and a motor/generator. A second, more powerful motor/generator is permanently connected to the vehicle's final drive and always turns with the wheels. This allows for removal of the conventional transmission, replacing it with a much simpler single planetary and motor/generator. Because load capacity is limited by the first motor/generator's capacity to resist the reaction torque of the drive train, this technology is best suited to low load applications (i.e., smaller vehicles), although recent advances have expanded Power Split system applicability. The 2002 NAS study did not consider this technology, while the NESCCAF study estimated the RPE at $3500 (40% markup) for a small car. Based on the NESCCAF study, we have estimated the incremental compliance cost at $3754 for a small car, expressed in 2006 dollars.

e. Full-Series Hydraulic Hybrids

A Full Series Hydraulic Hybrid Vehicle (HHV) is somewhat similar in concept to a full-series electric hybrid vehicle, except that the energy is stored in the form of compressed nitrogen gas and the power is transmitted in the form of hydraulic fluid. Series HHV technology is under development by EPA. We have estimated the incremental compliance cost for this technology at $771 to $1233 expressed in 2006 dollars, depending on vehicle class.[20] Because this technology is still under development and has not yet been commercialized, we believe that it would not be available until the second half of the next decade.

f. Plug-in Hybrids

Plug-In Hybrid Electric Vehicles (PHEVs) are very similar to Hybrid Electric Vehicles, but would have a larger battery pack with more energy storage and a greater capability to be discharged. A PHEV would also have a control system that allows the battery pack to be significantly depleted during normal operation. These changes mean that PHEVs are expected to be more costly than conventional vehicles and some other advanced technologies. Neither the 2002 NAS study nor the NESCCAF study considered this technology as manufacturers have only recently made statements about it being a technology for serious consideration. Based on our own work, we have estimated the incremental compliance cost at $4500 to $10200, depending on vehicle class. This incremental compliance cost assumes a 20 mile “all electric” range.

g. Full Electric Vehicles

The recent intense interest in hybrid vehicles and the development of hybrid vehicle battery and motor technology has helped make Electric Vehicle (EV) technology a more viable candidate for consideration. Electric vehicles require much larger batteries than either HEVs or PHEVs and the batteries must be of a high-energy and lower-power design to deliver an appropriate amount of power over the useful charge of the battery. While electric motor and power electronics designs are very similar to HEV and PHEV designs, they must be larger, more powerful, and more robust since they provide the only motive power for the vehicle. However, cost savings can be realized by removing the internal combustion engine, fuel system, and possibly the transmission. Neither the 2002 NAS nor the NESCCAF study considered this technology and, based on our own work, we have estimated the incremental compliance cost at $12000 for the small car and $15000 for the large car. We have not made estimates for other vehicle classes because we do not consider this to be a viable technology for vehicles larger than a large car.

4.2.3 Piece Costs Associated with Accessory Technologies

4.2.3.1 High Efficiency Alternators, electric water pumps and electrification of other accessories for 12 Volt systems

Replacing the traditionally belt-driven accessories – the alternator, coolant and oil pumps – with electrically controlled accessories, or simply improving the efficiency of the belt driven accessories would provide an opportunity to reduce the accessory loads on the engine. Some large trucks also employ mechanical fans, some of which could be improved or electrified as well. Additionally, there are now higher efficiency alternators which require less of an accessory load to achieve the same power flow to the battery. The 2002 NAS study estimated the RPE for this at \$84 to \$112 (40% markup), independent of vehicle class. The NESCCAF study estimated an RPE of \$56, but that estimate included only a high efficiency generator and did not include electrification of other accessories. We have used the NAS estimates to arrive at our incremental compliance costs of \$89 to 119 expressed in 2006 dollars, independent of vehicle class. Note that air conditioning and power steering are other candidates for accessory load reduction. We discuss those below and have not included them in this incremental compliance cost estimate.

4.2.3.2 Electric Power Steering for 12 Volt and 42 Volt systems

Electric power steering (EPS) is advantageous over hydraulic steering in that it only draws power as needed when the vehicle is cornering, which is only a small percentage of a vehicle's operating time. EPS may be implemented on many vehicles with a standard 12V system, but heavier vehicles may require a 42V system adding cost and complexity. The 2002 NAS study estimated the RPE for a 12V system to range from \$105 to \$150 (40% markup), independent of vehicle class. The NESCCAF study estimated the RPE to range from \$28 to \$56 (40% markup) for a 12V system, independent of vehicle class. We have estimated the incremental compliance cost to range from \$118 to \$197 for a 12V system expressed in 2006 dollars, independent of vehicle class.

4.2.3.3 Upgrade Electrical Systems to 42V

Most vehicles today (aside from hybrids) operate on 12 V electrical systems. At higher voltages, the power density of motors, solenoids, and other electrical components increases to the point that new and more efficient systems, such as electric A/C compressors and electric power steering (for heavier trucks) may be feasible. A 42V system also allows for smaller-gauge wiring and smaller, lighter electric motors and actuators. A 42V system also acts as an enabler for an integrated starter generator. The 2002 NAS study estimated the RPE for upgrading to 42V at \$70 to \$280 (40% markup), independent of vehicle class. We have estimated the incremental compliance cost at \$89 to \$119 in 2006 dollars, independent of vehicle class and exclusive of improvements to the efficiencies or electrification of 12V accessories.

4.2.4 Piece Costs Associated with Other Vehicle Technologies

4.2.4.1 Aerodynamic Drag Reduction through reduced drag coefficient and reduced frontal area

A vehicle's size and shape determine the amount of power needed to push the vehicle through the air at different speeds. Changes in vehicle shape or frontal area can therefore reduce CO_2 emissions. Areas for potential aerodynamic drag improvements include skirts, air dams, underbody covers, and more aerodynamic side view mirrors. The CBI submittals generally showed the RPE associated with these changes at less than $100. We have estimated the incremental compliance cost to range from $0 to $75, independent of vehicle class.

4.2.4.2 Low Rolling Resistance Tires

Tire characteristics (e.g., materials, construction, and tread design) influence durability, traction control, vehicle handling, and comfort. They also influence rolling resistance. This technology is applicable to all vehicles, with the exception of body-on-frame light trucks. We have based our estimates on a 2006 NAS/NRC report which showed a $1 per tire cost for low rolling resistance tires.[21] For four tires, our incremental compliance cost estimate is $6 per vehicle, independent of vehicle class, although not applicable to large trucks.

4.2.4.3 Low Drag Brakes

Low drag brakes reduce the sliding friction of disc brake pads on rotors when the brakes are not engaged because the brake shoes are pulled away from the rotating disc. While most passenger cars have already adopted this technology, there are indications that this technology is still available for body-on-frame trucks. Based on the recent NHTSA light-duty truck CAFE rule, we have estimated the incremental compliance cost for low drag brakes at $87 per truck.[22] As noted, this technology is already on most passenger cars so we have estimated the incremental compliance cost for trucks only.

4.2.4.4 Secondary Axle Disconnect (front axle for ladder frame and rear axle for unibody frame)

To provide shift-on-the-fly capabilities, many part-time four-wheel drive systems use some type of axle disconnect which, whether front or rear axle, reduces parasitic losses and fuel consumption. For front-axle disconnect systems, we have estimated the incremental compliance cost at $114 based on CBI submittals. This technology is considered applicable for light-duty ladder-on-frame trucks. For unibody vehicles and trucks, expected to use a secondary-axle disconnect system, the incremental compliance cost is estimated at $676, based again on CBI submittals.

4.3 Estimates of Indirect Costs and the Use of Markup Factors

Regulatory agencies, including EPA, have frequently relied upon multiplicative adjustment factors to account for the indirect costs associated with changes in direct manufacturing costs. (Indirect costs include research and development, salaries, pensions, marketing, and other expenses.) The resulting cost after applying the factor is often called the “Retail Price Equivalent” (RPE): thus these factors are frequently called “RPE factors” or “RPE multipliers.” Clearly the best approach to determining the impact of changes in direct manufacturing costs on a manufacturer’s indirect costs would be to actually estimate the cost impact on each indirect cost element. However, this is not always feasible within the constraints of an agency’s time or budget, or the necessary information to carry out such an analysis is simply unavailable. Given this, EPA has continued to rely on the use of an indirect cost multiplier for some of our regulatory cost analyses.

There is a history of what multiplier to use. In past mobile source regulatory actions, EPA has sometimes used an RPE factor of 1.26 to account for the indirect costs associated with the variable cost impacts of a regulation. This factor was originally derived in the late 1970’s and updated in a 1985 report by Jack Faucett Associates under contract to EPA.[23] In 2000, Argonne National Laboratory (ANL) published a technical memorandum comparing three different estimates of RPE multipliers for vehicle manufacturing.[24] In this memorandum, ANL compared their own estimates with those from Chrysler and Energy and Environmental Analysis, and found that the three estimates of indirect cost multipliers, when put on a comparable basis, were very similar. The ANL analysis made a distinction between components made by suppliers and components developed and manufactured by the vehicle manufacturer, reasoning that for outsourced components the outside vendor would incur some of the costs that would otherwise be borne by the vehicle manufacturer (i.e., indirect cost items such as warranty, research and development, and depreciation and amortization). The ANL analysis estimated retail price equivalent factors of 1.5 for outsourced components and 2.0 for products developed and manufactured internally. A more recent analysis commissioned by the automobile manufacturing industry and conducted by Sierra Research, Inc., suggested that the 1985 Faucett report contains "basic methodological errors that make it unreliable for use in a regulatory analysis."[25] The Sierra analysis concluded that a retail price equivalent factor for components manufactured internally should be about 2.0 to accurately account for the per-vehicle indirect costs.

In Section 4.2 above we applied a multiplicative adjustment factor of 1.5 to our estimates of the direct manufacturing costs to account for the incremental indirect costs associated with each CO_2-reducing technology. The derivation of this factor, which is consistent with the ANL analysis, is described below. As explained in Section 4.3.1 below, EPA believes that this factor is reasonable, if one utilizes the RPE methodology. However, EPA also believes that the RPE multiplier, as it has been traditionally derived, may not be entirely appropriate for the purpose of estimating the impacts on a manufacturer's indirect costs of a new EPA regulation, and may, in fact, overestimate the overall costs. For the reasons described below, EPA is initiating a new study that will evaluate the methodology's appropriateness for use in EPA cost analyses.

EPA has a fundamental concern with using an RPE factor, as they are currently derived, to estimate incremental indirect costs that result from a regulatory action. The RPE approach assumes that all costs rise in direct proportion to the incremental cost change of an individual cost element. We believe that many of the indirect cost elements that get marked up by the RPE factor do not in fact behave in this way. Including such elements in the development of an indirect cost markup factor would be clearly inappropriate, and could result in significantly overestimating the costs. Consider an illustrative example where the only direct cost is energy and all other costs are indirect. In this example, assume a company's energy costs are 10 percent of the manufacturer suggested retail price (MSRP), and an RPE factor is created relating MSRP to energy costs. The very nature of the RPE multiplier approach assumes that the 10:1 relationship of MSRP to energy costs remains constant, meaning that a doubling of energy costs would, using the RPE multiplier methodology, effectively result in a doubling of the MSRP. In the case of energy costs, we believe that a more likely and more realistic response would be that the indirect (i.e., non-energy) cost components of the MSRP would remain unchanged. In this case, the correct response to a doubling of an element that comprises 10 percent of the total MSRP would be a 10 percent increase in MSRP, not the 100 percent increase that results from uncritical application of the RPE multiplier.

A key question when using an indirect cost multiplier is which of the individual indirect cost elements increase in proportion to the direct cost elements (and if so, by what factor) and which remain relatively fixed. Unfortunately, the literature at our disposal does not address this issue specifically. EPA's study will consider each manufacturer cost element for the automotive industry and carefully evaluate whether or not each cost element should be included in a total indirect cost markup due to an EPA regulatory action. In a recent study NHTSA identified eight components of a manufacturer's indirect costs:

Maintenance and repairs;
Research and development;
Taxes other than income;
Selling, general, and administrative;
Depreciation of property, plant, and equipment;
Amortization of special tooling;
Pension expense; and
Other retirement benefits expense.

The new EPA study will analyze each of these, breaking them down in to sub-elements when possible, to determine the extent to which each cost element responds to an increase in direct costs resulting from an EPA regulation of the automotive industry. There may also be costs on the dealer side that do not scale in proportion to increases in variable costs, and EPA intends to evaluate these as well.

EPA also intends to evaluate the appropriateness of using an RPE multiplier to estimate price. EPA believes that using such a multiplier achieves results that are inconsistent market realities, and that a market model based on supply and demand elasticities would be a more appropriate method for estimating price. Standard microeconomic theory tells us that setting the MSRP based simply on an RPE multiplier will result in establishing a price that fails to maximize corporate profits, and we do not believe that automotive manufacturers behave in this way with respect to their pricing strategies.

4.3.1 Current Methodology

For this analysis, we have estimated direct costs for individual technologies based on input from existing published reports and information from automotive component suppliers and auto manufacturers. We provide estimates of the direct costs incurred by the auto manufacturer, or, in other words, what the auto manufacturer pays the component supplier for the component or system. To estimate the indirect costs to the auto manufacturer and auto dealer, we are relying on an indirect cost adjustment factor applied to the direct costs. This indirect cost factor is an empirically derived multiplier intended to account for all indirect costs, including auto manufacturer R&D, other engineering costs (primarily product integration), corporate overhead, pensions, marketing, dealer support and profits. For this analysis, we are using an adjustment factor of 1.5. As such, an indirect cost adjustment of 1.5 implies that direct manufacturing costs represent two-thirds of the total costs while indirect costs represent 1/3 of the total costs. The 1.5 ANL factor is consistent with our approach in that we estimated that most of the technology elements that we have considered are likely to be purchased from outside suppliers, rather than developed and produced internally by the auto manufacturer.

NHTSA developed the adjustment factor we are using in a report that analyzed the financial reports of the domestic three auto manufacturers for the years 1989 through 1997.[L] We have studied the NHTSA report and have considered the elements contained in the factor and the amounts associated with those elements. We believe that an indirect cost markup factor of 1.5 is a reasonable reflection of the cost structure typical in the auto industry. The relevant information from the report and its analysis are reproduced here in Table 4.3-1.

Table 4.3-1 Domestic Three Auto Manufacturers Weighted Average Marginal Analysis of Operating Results, 1989-1997 (Reproduced from Reference 6)

Chrysler, Ford, & GM	Average for 1989-1997	Adjustment Factor
Net sales	100%	
Variable Costs – Manufacturing	73.3%	1.00
Contribution Margin	26.7%	0.36
Fixed & Discretionary Costs		
Maintenance & Repairs	3.4%	0.046
Research & Development	4.7%	0.064
Selling, General, & Administrative	6.6%	0.090
Taxes Other than Income	2.6%	0.035
Pension Expense & Other Pension Related Benefits	1.9%	0.026
Depreciation	2.8%	0.038
Amortization, Tooling	2.2%	0.030
Provision for Plant Closing	0.3%	0.004
Amortization, Intangibles	0.1%	0.001
Subtotal	24.6%	0.34
Operating Margin	2.1%	0.028
Net Profit Margin	0.6%	0.008

For this analysis, we have first estimated the cost to the automobile manufacturer for a supplied part, or the price charged by the supplier to the manufacturer. That value would represent the direct cost of manufacturing in the table above (i.e., "Variable Costs – Manufacturing"). To estimate the markup that the manufacturer would apply to that value we use the contribution margin above which is meant to reflect the firm's ability to cover discretionary costs, fixed costs, interest expenses, taxes, and still leave a residual net profit. That markup factor can be calculated as:

Contribution Margin/Variable Costs = Markup on Variable Costs

or,

26.7%/73.3% = 0.36

[L] Bruce Spinney, Barbara Fagin, Noble Bowie, and Stephen Kratzke, "Advanced Air Bag Systems: Cost, Weight, and Lead Time Analysis: Summary Report," Contract No. DTNH22-96-0-12003, Task Orders 001, 003, and 005, National Highway Traffic Safety Administration.

In other words, we can estimate wholesale price by multiplying supplier price by a 1.36 factor. We can then estimate dealer price or retail price by accounting for dealer related costs. The NHTSA study does this by using an 11% markup factor which was determined by calculating a sales weighted comparison of suggested retail prices to wholesale prices for the domestic manufacturers. In the end, the markup from manufacturer cost to retail price equivalent is:

Retail price equivalent = Variable Cost x Markup on Variable Cost x Dealer Margin

or,

RPE = Variable Cost x 1.36 x 1.11 = Variable Cost x 1.5

4.3.2 Limitations and Uncertainties with Current Methodologies

As noted above, EPA is concerned that there are inherent limitations in an RPE approach which may lead to overly conservative cost estimates. EPA also believes that even if one uses an unqualified RPE approach, all of the work to date suffers from a number of limitations and uncertainties in addition to the broad concerns with the use of an RPE approach noted above. Consequently, in addition to the fundamental concerns with an RPE approach, EPA will attempt to address the following limitations and concerns in our upcoming study.

4.3.2.1 Outdated Research

While the Jack Faucett Associates paper served as a source for a multiplier for a number of EPA's regulatory actions, it is undeniable that the automotive industry has evolved in many ways since the mid-1980s. Although the various critiques have suggested improvements on the Faucett paper, EPA believes that it has been overtaken by time. EPA intends to use the most recent financial and engineering information available in our upcoming analytical work.

4.3.2.2 Studies Limited to U.S. Domestic Manufacturers

All of the research to date has been limited to analyses of the financial information from the U.S. domestic manufacturers. If, possible, it would be desirable to include financial information from other large manufacturers, such as Honda and Toyota, in the analysis. However, due to differences in accounting principles in different countries, past work has found it difficult to incorporate foreign manufacturers due to the difficulty of reconciling their financial statements with U.S. accounting methods. Nevertheless, these manufacturers represent a significant market share in the U.S., and EPA intends to further evaluate the possibility of incorporating other manufacturers in the analysis.

4.3.2.3 Treatment of Outsourced vs. Internally-Developed Technologies

As noted earlier, some of the more recent research has made a distinction between outsourced and in-house technology sources. Given the large quantity of vehicle components that are outsourced, EPA agrees that this distinction is one which should be drawn. It seems reasonable to assume that a given vehicle component costs the same amount to develop and manufacture, whether it is outsourced or produced in-house by the automobile manufacturer. For an outsourced part, however, many of the indirect costs associated with making the part are assumed by the supplier and are included in the price charged to the vehicle manufacturer for the component. If the part is developed and manufactured by the automobile manufacturer, then the manufacturer bears all of the indirect costs associated with producing the part. We believe that multiplying the cost charged by a supplier by an indirect cost multiplier should logically produce the same total cost as multiplying the direct costs to a manufacturer by an indirect cost multiplier. Given the assumption of some overhead costs by the supplier in the case of a supplier-sourced part, the indirect cost multiplier for supplier-sourced parts should be lower than the multiplier applied to a manufacturer's direct manufacturing costs if the same total RPE for the part is the expected result. This concept is consistent with the approach that we have used in our analysis described above and with the results of the ANL analysis. EPA's upcoming work will evaluate markup factors for both outsourced components and those developed in-house.

4.3.2.4 Short-term and Long-term Adjustment Factors

EPA believes that a two-stage indirect cost multiplier may more accurately reflect the cost impacts of a new regulation on auto manufacturers. The markup factor as it has traditionally been used results in incremental indirect costs that continue in perpetuity. In reality, however, we believe that a portion of the indirect costs included in the multiplier will not occur beyond the first few years of implementation of a new regulatory program. For example, we believe that manufacturers would continue to conduct research and development and would incur indirect costs, but after the new regulation is fully implemented those costs would no longer be attributed by a manufacturer to the regulation. Instead, indirect research and development costs would be redirected to performance improvements, drivability, entertainment features, new product development, etc. EPA expects our upcoming study to evaluate this issue and determine an appropriate long-term indirect cost multiplier and when it should apply relative to the implementation of a new regulation.

Appendix 4.A Producer Price Index Adjustments

Throughout this analysis, we have presented our incremental cost estimates in terms of 2006 dollars. However, some of the data sources upon which we have based many of our estimates presented costs in terms of dollars for other years. To convert the sourced estimates to 2006 dollars, we used the Producer Price Index (PPI) for the data series that most closely represented the technology of interest. Table 4.A-1 shows the PPI series we have used for this analysis.

Table 4.A-1 Producer Price Indexes Used in this Analysis

Series Name	Code	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Lubricating oil and greases	3241107	80.9	59.3	70.2	113.6	98.8	102.6	137.8	136.4	202.8	219.4
Passenger car pneumatic tires	3262111	92.1	89.5	88.1	88.1	89.3	90.6	93.1	97.7	103.7	111.9
Carburetors, new and rebuilt (All types) [see note a]	3363111	137.8	139.2	140.3	144.1	148.5	153.6	157.5	163.3	163.3	181.7
Valves (engine intake and exhaust) [see note a]	3363115	130.0	126.9	126.4	126.9	126.2	124.8	124.9	143.3	151.2	151.2
Gasoline engines and engine parts for motor vehicles, new	3363121	99.4	97.7	96.6	95.4	95.6	96.8	94.9	96.6	97.7	107.2
Battery charging alternators, generators, and regulators	3363223	129.8	128.7	127.4	126.6	128.5	128.8	126.8	126.1	126.2	126.9
Motor vehicle steering and suspension components, new	3363301	NA	NA	NA	99.7	99.8	100.0	99.8	101.3	103.8	104.9
Motor vehicle brake parts and assemblies, new	3363401	107.5	109.2	109.0	108.6	107.3	106.7	106.5	105.4	106.4	107.0
Motor vehicle drive train components except brakes and wheels, new	3363501	105.7	106.3	105.7	105.0	105.1	104.7	103.2	102.4	102.9	104.4
Original equipment automotive stampings	3363701	109.5	109.1	108.2	108.3	107.9	107.1	108.3	109.7	112.0	112.5
Parts for manual and automatic transmissions, new [see note b]	33635013	100.9	101.0	100.8	99.7	98.9	98.8	97.6	96.6	98.5	100.3

Source: Bureau of Labor Statistics, U.S. Department of Labor, http://data.bls.gov/PDQ/servlet/SurveyOutputServlet

a Data for years 2005 and 2006 are estimated due to incomplete monthly data for the year.

b Data for year 2006 is estimated based on data for December of 2005.

Table 4.A-2 shows the sources of data used in this analysis and our understanding of what year in which the costs are expressed for each. With that, we were able to calculate a PPI adjustment factor that could be applied to source estimates to express those source estimates in 2006 dollars. The resultant PPI adjustments are shown in Table 4.A-3, along with the PPI series we considered to be the most applicable.

Table 4.A-2 Data Sources and Base Year Dollars

Source	Base Year of Costs
NAS Study (Reference 11)	2001
NESCCAF Report (Reference 12)	2003
2006 EEA report to DOE (Reference 14)	2006
EPA Interim Technical Report (Reference 20)	2003
Transportation Research Board Special Report 286 (Reference 21)	2006
NHTSA Light-duty Truck Rule (Reference 22)	2003

Table 4.A-3 PPI Adjustments Used to Express Source Costs in 2006 Dollars

Technology	PPI Series	PPI Adjustment
Low friction lubricants	3241107	1.000
Engine friction reduction	3363121	1.121
Overhead Cam Engines		
VVT – intake cam phasing	3363121	1.130
VVT – coupled cam phasing	3363121	1.130
VVT – dual cam phasing	3363121	1.130
Cylinder deactivation	3363121	1.130
Discrete VVLT	3363121	1.130
Continuous VVLT	3363121	1.130
Overhead Valve Engines		
Cylinder deactivation	3363121	1.130
VVT – coupled cam phasing	3363121	1.130
Discrete VVLT	3363121	1.130
Continuous VVLT (includes conversion to Overhead Cam)	3363115	1.211
Camless valvetrain (electromagnetic)	3363121	1.121
GDI – stoichiometric	3363121	1.000
GDI – lean burn	3363121	1.000
Gasoline HCCI dual-mode	3363121	1.130
Turbocharge + engine downsize	3363121	1.000
Diesel – Lean NOx trap	3363121	1.000
Diesel – urea SCR	3363121	1.000
Optimized E20-E30	3363121	1.000
Aggressive shift logic	33635013	1.014
Early torque converter lockup	33635013	1.000
5-speed automatic	33635013	1.014
6-speed automatic	33635013	1.000
6-speed AMT	33635013	1.000
6-speed manual	33635013	1.000
CVT	33635013	1.028
Stop-Start with 42 volt system	3363223	1.001
IMA/ISA/BSG (includes engine downsize)	3363223	1.001
2-Mode hybrid electric vehicle	3363223	1.001
Power-split hybrid electric vehicle (P-S HEV)	3363223	1.001
Full-Series hydraulic hybrid	33635013	1.028
Plug-in hybrid electric vehicle (PHEV)	3363223	1.000
Full electric vehicle (EV)	3363223	1.000
Improved high efficiency alternator & electrification of accessories (12 volt)	3363223	0.988
Electric power steering (12 or 42 volt)	3363301	1.051
Improved high efficiency alternator & electrification of accessories (42 volt)	3363223	0.988
Aero drag reduction (20% on cars, 10% on trucks)	3363701	1.000
Low rolling resistance tires (10%)	3262111	1.000
Low drag brakes (ladder frame only)	3363401	1.005
Secondary axle disconnect (unibody only)	3363501	1.012
Front axle disconnect (ladder frame only)	3363501	1.012

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Attachment 1

THE NATIONAL ACADEMIES
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March 4, 2008

The Honorable Stephen L. Johnson
Administrator
United States Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Mail Code 1101A
Washington, DC 20460

Dear Administrator Johnson:

I am serving as the chair of the National Research Council's Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy. The committee is tasked with providing updated estimates of the cost and potential efficiency improvements of light-duty vehicle technologies that might be employed to improve fuel economy. Our group has received a great deal of cooperation from your staff, including presentations related to the agency's activities on control of vehicle greenhouse gas emissions. I am writing today to request that the Environmental Protection Agency provide to the committee its report, *Greenhouse Gas Vehicle Proposal*, which would become part of the committee's public record on the information used in its deliberations. It is my understanding that this report details much of the agency's analysis of the control of greenhouse gas emissions from light-duty vehicles. I believe the information would greatly aid the committee in its work. I look forward to your reply.

Sincerely,

Trevor O. Jones, Chair
Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy

cc: K. John Holmes, National Research Council

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