Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy: Letter Report

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February 14, 2008

The Honorable Nicole Nason
Administrator
National Highway Traffic Safety Administration
U.S. Department of Transportation
1200 New Jersey Avenue, S.E., West Building
Washington, D.C. 20590

Dear Administrator Nason:

The National Highway Traffic Safety Administration requested that the National Academies provide an objective and independent update of the 2001 National Research Council report *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards* and add to its assessment other technologies that have emerged since that report was prepared. The National Research Council has therefore formed the Committee on Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy, and the committee has begun its review of vehicle technologies. In this letter, the committee provides, as called for in its task statement (Appendix C), its interim assessment of the technologies to be analyzed in the final report and of the computational models that will be used in its analysis.

The committee presents this letter as its preliminary assessment of technologies and potential fuel-economy benefits. The estimated fuel-economy benefits, typically reported as the benefits that would be realized according to the procedure used to certify vehicles with respect to federal fuel-economy standards, reflect those that have been presented in the literature and have been presented to the committee. They represent the preliminary judgment of the committee based on those sources. The committee will continue to revise the list of technologies and fuel-economy benefits as it completes its study and writes its final report, to be provided in late spring of 2008.

MOTIVATION AND PURPOSE OF INTERIM REPORT

In the wake of the 1973 oil crisis, Congress passed the Energy Policy and Conservation Act in 1975 as a means of reducing the country's dependence on imported oil. The act established the Corporate Average Fuel Economy (CAFE) program, which required automobile manufacturers to increase the average fuel economy of passenger and nonpassenger vehicles sold in the United States to standards of 27.5 miles per gallon (mpg) for passenger cars and 22.5 mpg for light trucks. The standards are administered by the U.S. Department of Transportation (DOT) on the basis of the U.S. Environmental Protection Agency (EPA) city-highway dynamometer test procedure. In 2000, Congress called on the National Academies to conduct a study of the impact and effectiveness of CAFE standards, looking both historically and to the future. The study resulted in the 2001 National Research Council report, which included a chapter focused on the potential of various technologies to improve the fuel economy of light-duty vehicles.

The rapid rise in gasoline and diesel fuel prices experienced during 2005-2007 because of large increases in global demands and Middle East oil producers' policies on oil production continues to make vehicle fuel economy an important policy issue, and growing recognition of the climate-change issue has drawn more attention to fuel economy. The recently passed Energy Independence and Security Act of 2007 requires DOT to raise vehicle fuel-economy standards, starting with model year 2011, until they achieve a combined average fuel economy of at least 35 mpg for model year 2020. A recent Supreme Court decision also requires EPA to regulate greenhouse-gas emissions from new light-duty vehicles under its Clean Air Act authority.[1] DOT, through NHTSA, has continued to review estimates of the potential for various technologies to improve fuel economy. And a number of other investigations have been conducted to assess fuel economy or greenhouse-gas reduction potential, especially for California's recent initiative to reduce greenhouse-gas emissions in the state.

NHTSA would like to keep up to date on the potential for technologic improvements as it moves into planned regulatory activities. It was as part of its technologic assessment that NHTSA asked the National Academies to update the 2001 National Research Council report and add to its assessment other technologies that have emerged since that report was prepared. The task statement directs the committee to estimate the efficacy, cost, and applicability of technologies that might be used over the next 15 years. The list of technologies includes diesel and hybrid electric powertrains, which were not considered in the 2001 assessment. Weight and power reductions also are to be included. Updating the fuel economy-cost curves for different vehicle size classes that are in Chapter 3 of the 2001 report is central to the request. The current study focuses on technology and will not consider CAFE issues related to safety, economic effects on industry, or the structure of fuel-economy standards; these issues were addressed in the earlier report. It will look at lowering fuel consumption by reducing power requirements through such measures as reduced vehicle weight, lower tire rolling resistance, or improved vehicle aerodynamics and accessories; by reducing the amount of fuel needed to produce the required power through improved engine and transmission technologies; by recovering some of the exhaust thermal energy with turbochargers and other technologies; and by improving engine performance and recovering energy through regenerative braking in hybrid vehicles.

This letter constitutes the interim report called for in the task statement. It discusses the technologies to be analyzed in the final report, the types of vehicles that may use them, the estimated improvements in fuel economy that may result, and the computational models that will be used in analysis. In producing this interim report, the committee met four times and received presentations from automobile manufacturers, suppliers of technologies to the automobile industry, federal agencies, and researchers in universities and government laboratories. The agendas for the committee's public sessions are shown in Appendix D and demonstrate the committee's commitment to hearing from diverse experts.

There are two primary ways to show the effectiveness with which fuel is used in vehicles: fuel economy and fuel consumption. Both are used in this report. Fuel-economy standards are expressed as miles driven per gallon of fuel consumed. Fuel consumption is the inverse measure: the amount of fuel consumed in driving a given distance, such as gallons consumed per 100 miles traveled. Fuel consumption is a fundamental engineering measure and is useful because it is related directly to the goal of decreasing the amount of fuel required to travel a given distance.[2] Figure 1 shows how the two measures—miles per gallon and gallons per 100 miles—are related to one another: an increase in fuel economy from 25 mpg to 40 mpg is a 60% improvement in fuel economy and a 38% improvement in fuel consumption. Note that the curve is relatively flat beyond 35 mpg. Although this report describes changes primarily in terms of fuel consumption, in many cases it also expresses them in terms of fuel economy.

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[1] See *Massachusetts et al. v. Environmental Protection Agency et al.* EPA can avoid promulgating regulations only if it determines that greenhouse gases do not contribute to climate change or if it provides some reasonable explanation as to why it cannot or will not exercise its discretion to determine whether they do. Such an explanation must be grounded in the provisions of the Clean Air Act, not based on policy or other grounds.

[2] Furthermore, the "average" in CAFE standards is determined as the sales-weighted average of fuel consumption converted into fuel economy.

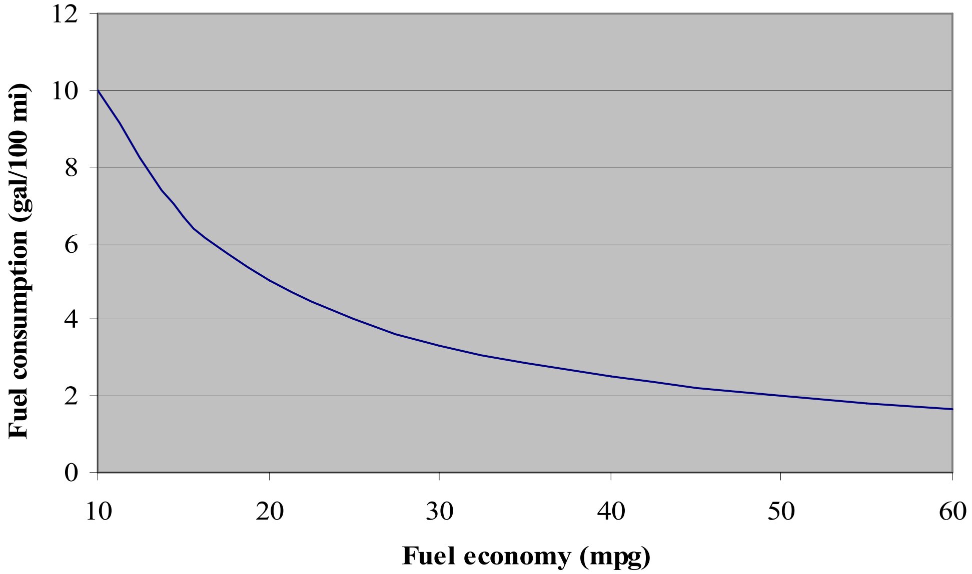

FIGURE 1 Relationship of fuel consumption to fuel economy.

FUEL-ECONOMY TECHNOLOGIES

On the basis of a preliminary analysis of sales information on light-duty vehicles, the committee selected the vehicle classes shown in Table 1 for use in assessing the costs and fuel-economy benefits of engine, transmission, and vehicle technologies. Individual vehicles in those classes will be used for the modeling efforts described later.

Fuel-Economy Technologies for Spark-Ignition Engines

Although new vehicle powertrain systems, such as those relying on hybrid electric and diesel technologies, have begun penetrating into the U.S. light-duty vehicle fleet, the vast majority of vehicles that make up the fleet are powered solely by conventional gasoline-powered spark-ignition engines. Thus, any discussion of fuel-economy-improvement technologies for light-duty vehicles must focus extensively on such engines. Table 2 lists some of the techniques and technologies that will be considered in the committee's final report. It is important to note that engine layouts and base powertrain configurations affect the types of improvements possible and their costs and benefits. Those issues will be discussed more extensively in the final report.

Some well-developed techniques involve fast-burn combustion systems combined with strategic use of exhaust-gas recirculation (EGR) at part load. Those techniques were introduced in the 1980s and have traditionally afforded a fuel-economy improvement of 3-5% over vehicles not using these techniques. All comparisons that use other fuel-economy enhancements should refer to that base condition because it is used in the vast majority of light-duty vehicles. Typical implementation of fast-burn combustion involves the creation of large-scale in-cylinder flows that are degraded into small-scale turbulence just before combustion. When this fluid-mechanical approach is impractical, fast-burn combustion can be implemented with multiple spark plugs (not common but used occasionally in automotive applications). EGR, which reduces energy losses when the engine is operating under partial load conditions, then is introduced up to the combustion-stability limit. Typically, fast-burn combustion and EGR enable a compression-ratio increase of about 0.5, the maximum possible without increasing engine knock to an unacceptable level. A higher compression ratio generally allows increased thermodynamic efficiency.

TABLE 1 Possible Classes of Light-Duty Vehicles for Analysis

Vehicle Class	Representative Models	Type of Vehicle
Compact car	Honda Civic, Ford Focus, Toyota Corolla	Passenger car
Midsize car	Toyota Camry, GM Malibu, Nissan Altima	Passenger car
Luxury car	GM Cadillac CTS, Mercedes E350, Nissan G35	Passenger car
Minivan	Chrysler Town and Country, GM Uplander, Toyota Sienna	Light truck
Small sports utility vehicle (SUV), 2WD	Honda CR-V, Ford Escape, Toyota RAV 4	Light truck
Large SUV, 2WD	Ford Expedition, Chevrolet Tahoe, Dodge Durango	Light truck
Crossover vehicle	Toyota Highlander, Honda Pilot, Ford Edge	Light truck
Medium SUV	Ford Explorer, Chevrolet Trailblazer, Toyota 4 Runner	Light truck
Large pickup, 2WD	Ford F150, Dodge RAM 1500, Chevrolet Silverado	Light truck

Cylinder deactivation is an attractive and cost-effective option for increasing fuel economy when applied to overhead-valve engines. This technique essentially turns a six-cylinder (V6) or eight-cylinder (V8) engine into a three- or four-cylinder engine at light engine loads, improving fuel economy by increasing the load on the active cylinders and creating higher intake manifold pressures, thereby reducing pumping losses. It is most beneficial when applied to vehicles with higher power-to-weight ratios. Although cylinder deactivation may increase noise, vibration, and harshness (NVH), active engine mounts or active noise-cancellation techniques can moderate these effects and enable aggressive use of the strategy.

Another technology, direct injection, offers the potential to increase both fuel economy and engine power output. As the fuel is forced to vaporize in the cylinder (as opposed to the intake port), an increase in the knock-limited compression ratio is possible. The technique can also increase the volumetric efficiency of the engine. Direct-injection gasoline engines have been studied for many years, but their application to mass-produced vehicles has been limited largely by injector deposit problems associated with hot shutdowns. Improvements in injector design, control strategies, and fuels, such as locating the fuel injector in the coolest part of the cylinder head, appear to be alleviating such problems.

Turbocharging with downsizing is another technique for raising fuel economy. The improved size-to-output efficiency of a turbocharged engine allows a smaller displacement engine to be used for the same power output and thus reduces fuel consumption. Fuel consumption in a given vehicle is lower in smaller engines primarily because of higher manifold pressure (reduced pumping losses) and smaller contact area of moving surfaces (reduced friction losses). Turbocharging is most beneficial when it is applied to vehicles subjected to highly diverse driving conditions and if it permits the use of a smaller-displacement engine, although the effects of and remedies for potential launch-performance shortfall need to be investigated.

Valve-event manipulation (VEM) technologies can also improve fuel economy. They come in many forms with many names (such as variable valve timing and variable valve lift). They can improve fuel economy by improving volumetric efficiency and reducing pumping losses. Their desirability tends to be related to the engine architecture and other characteristics of a vehicle. There is functional overlap among many VEM technologies. Spark-ignition engines used in any light-duty vehicle can benefit from some use of VEM, although some of the benefits may be achieved by other means, such as use of variable-geometry intake manifolds.

TABLE 2 Technologies for Reducing Fuel Consumption in Spark-Ignition Engines[a]

Item	Fuel-Consumption Reduction	Comments
Fast combustion with high dilution tolerance	3-5% vs. engines not specifically optimized with respect to this item	This is the 2007 datum against which other items should be referenced, in that the vast majority of today's vehicles already use these techniques
Cylinder deactivation	3-8% depending on power-to-weight ratio	Most cost-effective when applied to overhead-valve V6 and V8 engines NVH and drivability issues
Direct injection	1-3% for constant-displacement engine	Need for high-pressure fuel pump can increase parasitic loss, and increased volumetric efficiency increases pumping loss
Turbocharging and downsizing	3-7% for equal performance at 0-60 mph	Piston-oil squirters, oil coolers, and intercoolers will contribute to system merits About 1% increase in fuel consumption without engine downsizing
Valve-event manipulation		
Intake-valve closing	1-7% based on pumping-loss reduction at part load	Implementation methods include cam phasers and two-step-lift cams; timing is important, and lift is merely consequence of duration Small performance gains at wide-open throttle Benefit varies, depending on degree of engine downsizing; effects on different vehicle-performance measures need further analysis
Valve-overlap control	0.5-1.5% above conventional EGR system	Implementation includes exhaust-only and dual-cam phasers Reduces pumping losses
Intake-valve "throttling"; implementations include analogue or stepwise control (an alternative to conventional pressure throttling)	3-8% owing to (net) pumping-loss reduction	Goal is to shorten intake-valve-lift duration; short durations may reduce pumping losses; reduced valve lift is simply a consequence of shorter durations Manufacturing tolerance control is critical As intake-manifold vacuum decreases, alternative means must be found to implement power brakes and positive crankcase-ventilation valves Benefit will vary with engine size
Other valve events: exhaust-valve closing, exhaust-valve opening, intake-valve opening	Independently, relatively small effects outside the aforementioned	Timing of exhaust-valve closing is important for maintaining peak power
Friction reduction	0.3-1% owing to reduced-viscosity lubricants; other approaches require further investigation	Roller-follower valve trains and piston-kit friction-reduction measures were nearly universally implemented in the middle 1980s
Parasitic-loss reduction		
Electric coolant pump	To be determined	
Camless valve actuation	To be determined	
Variable charge motion	To be determined	
Homogeneous-charge compression ignition	To be determined	

[a] Improvements are over a 2007 naturally aspirated gasoline vehicle engine of similar performance characteristics.

Other techniques for improving fuel economy include reducing internal friction and reducing parasitic losses. Major friction-reducing options, such as roller-follower valve trains and technologies that apply to the piston assembly, were implemented in the 1980s, but there still remain opportunities to increase fuel economy by reducing friction. The replacement of hydraulic water pumps with electric coolant pumps and replacing the thermostat with electronic coolant flow control could also improve fuel economy, although they may cause higher parasitic losses through the electric system than they relieve through mechanical decoupling; this issue will be explored in the final report.

Three other technologies that could enhance fuel economy—variable compression ratios, camless valve trains, and homogeneous-charge compression ignition engines—have undergone substantial research efforts over decades. The committee will discuss them and their potential for improving fuel economy over the next 15 years in its final report.

Fuel Economy Technologies for Compression-Ignition Engines

The earlier NRC report did not consider diesel-powered, compression-ignition engines. At the time of that report, the technology available could not overcome the tradeoff between NO_x and particulate emissions typical of light-duty diesel engines. The motivation for including light-duty diesel technology in the new report stems from the fact that the light-duty diesel vehicles in production and in widespread use in Europe have already demonstrated a 30-40% reduction in fuel consumption, depending on engine size, compared with 2007 model-year gasoline engines. In addition, the emissions performance of diesel vehicles has improved.

In the United States, diesel technology holds the potential to improve fuel economy (compared with conventional gasoline vehicles on the market in the United States) while improving some aspects of vehicle performance. Performance advantages include higher low-end torque and possibly greater durability. U.S. manufacturers have committed to offering diesel technology as a higher-performance alternative to large V8 gasoline engines that also enables the downsizing of vehicle engines. Some of the technologies for reducing fuel consumption in diesel engines that the committee is assessing are shown in Table 3.

Recent developments in NO_x after-treatment systems further improve the prospects for diesel light-duty vehicles. Production vehicles using improved after-treatment systems have proved able to meet U.S. emissions regulations. Work on new technologies for controlling particulate and NO_x emissions is continuing; most of it is in the proprietary development phase. Little detail is available in the open literature on the cost or effectiveness of these technologies. Assessments of the devices will need to consider any fuel-economy penalties associated with flow restrictions and the use of fuel or reagent for device regeneration, although developments to date appear to have minimized such penalties.

It should be noted that part of the fuel-economy benefit of diesel engines stems from the differences in energy content between gasoline and diesel fuels. On the average, the energy content of gasoline and diesel fuel per unit mass (MJ/kg) are similar, but diesel fuel's specific gravity is typically 0.82-0.85 and that of gasoline 0.72-0.78, so the energy content of a gallon of diesel fuel (MJ/gal) is about 11% higher than that of a gallon of gasoline. Moreover, the carbon content of a gallon of diesel fuel is about 14.7% higher than that of a gallon of gasoline. If carbon dioxide emissions are the concern rather than fuel economy, the higher energy density and carbon content of diesel fuel will have to be taken into account.

Transmission Technologies for Improving Fuel Economy

Transmission technologies that can improve fuel economy involve increasing electronic controls, continuing to reduce the mechanical losses in transmissions, and improving the mating of transmission operations with engines. Table 4 lists some of the technologies. In both automatic and manual transmissions, increasing the number of gear ratios can allow the engine to operate closer to its efficient optimum at a wider variety of speeds and thus allow improvements in fuel economy. Many manual

TABLE 3 Technologies for Reducing Fuel Consumption in Compression-Ignition Engines[a]

Technology	Fuel-Consumption Reduction	Comments
Turbocharged diesel (current standard diesel technology for light-duty vehicles)	20-40%	
2000 bar piezoelectric injectors	To be determined	Technology allows improved emission control, which has indirect effect on fuel economy
Engine shut-off during idle	2% for city cycle	Baseline diesel-similar performance characteristics
Ceramic glow plugs	To be determined	Decreased fuel sensitivity, improved cold start
Two-stage turbocharging	To be determined	Performance enhancement
Improved particulate control	To be determined	Required for emissions certification
Improved particulate and NO_x after-treatment	To be determined	Required for emissions certification
Improved starter-alternator	To be determined	Required for idle-stop operation
Lean NO_x trap	To be determined	Candidate after-treatment for NO_x
Urea selective catalytic reduction	To be determined	Candidate after-treatment for NO_x
Hydrogen-rich reactant to reduce NO_x	To be determined	Candidate after-treatment for NO_x
Homogeneous-charge compression ignition combustion	To be determined	Exploration to reduce after treatment cost
Diesel hybrid	5-15%	Improvement is over a diesel vehicle of similar performance characteristics

[a] Improvements are over a 2007 naturally aspirated gasoline vehicle engine of similar performance characteristics.

TABLE 4 Transmission Technologies for Reducing Fuel Consumption[a]

Technology	Fuel-Consumption Reduction	Comments
Five-speed automatic transmissions	2-3%	Technology can also improve vehicle performance
Six-speed automatic transmissions	3-5%	
Seven-speed automatic transmissions	5-7%	
Eight-speed automatic transmissions	6-8%	
Automated manual transmissions (six-speed)	6-8%	
Continuously variable transmissions	1-8%	Some issues related to differences in feel and engine noise; improvements depend on engine size
Early torque converter lockup	0.5%	NVH issues
Aggressive shift logic	1-5%[b]	Potential effects on drivability

[a] Improvements are over a 2007 naturally aspirated gasoline vehicle engine of similar performance characteristics.
[b] Potential benefits of aggressive shift logic can vary even more widely depending on how aggressively it is implemented and the baseline against which fuel-economy benefits are estimated.

transmissions today have four or five speeds, sometimes referred to as overdrive gearing. With the lower gear ratios, the engine is actually turning slower than the drive shaft and rear axle. The low gear ratios and lower engine speeds permit substantial improvements in fuel economy.

The five-speed automatic transmission is already a standard for many vehicles; six-, seven-, and eight-speed automatic transmissions have been available on luxury cars and are penetrating into the mainstream market. Another technology is the automated manual transmission (AMT), which attempts to combine the efficiency of a manual transmission with the seamless shifting of an automatic transmission. The AMT does not require the driver to actuate the clutch or manually shift gears; instead, these functions are carried out with a hydraulic system or an electronically controlled electric motor.

Most current transmissions feature a discrete number of gear ratios that determines the ratio of engine speed to vehicle speed. In contrast, a continuously variable transmission (CVT) offers a seemingly infinite choice of ratios between fixed limits, which allows engine operating conditions to be optimized for fuel economy. CVT technology has tended to be used in lower-horsepower vehicles because of materials limitations. Other fuel-economy improvements can be implemented through electronic transmission control (ETC), which is part of an automatic transmission. Electronic sensors monitor vehicle speed, gear-position selection, and throttle opening and send this information to the electronic control unit (ECU). The ECU controls the operation of the transmission. Two measures that can improve fuel economy, early lock-up and aggressive shift logic, can be implemented by the ETC through the ECU; both measures can also increase NVH and affect drivability.

Vehicle Technologies for Improving Fuel Economy

Vehicle technologies focus on nonpowertrain methods of reducing fuel consumption. The committee considers car-body design (aerodynamics and mass), vehicle interior materials (mass), tires, and vehicle accessories (power steering and heating, ventilation, and air-conditioning [HVAC] systems) to offer the greatest opportunity for achieving near-term, cost-effective reductions in fuel consumption. Those technologies are summarized in Table 5.

The U.S. Council for Automotive Research and the U.S. Department of Energy continue to research ways to reduce body mass by substituting new materials—such as high-strength steel, advanced high-strength steel, aluminum, magnesium, and composites—for current materials. The materials industries also conduct research to advance new materials (for example, through the Auto-Steel Partnership, the Aluminum Association, and the American Chemistry Council). Increased costs for lighter and stronger materials result from higher material costs and higher costs of component fabrication and joining. Estimates of the body-mass reduction that can be achieved in the near term vary from 10% (with mostly conventional and high-strength steels) to 50% (with a mostly aluminum structure). Even greater reductions are feasible, but they require expensive composite structures that involve such materials as carbon fiber.

A midsize-car body with closure panels (no trim or glass) can weigh roughly 800 lb (about 25% of the vehicle curb weight). Vehicle testing has confirmed the reductions in fuel consumption associated with reductions in vehicle mass. (See, for example, Pagerit et al., 2006 and U.S. EPA, 2006). For example, vehicles powered by internal-combustion engines (ICEs) can reduce fuel consumption by about 0.1 gal/100 miles driven for each decrease of 190 lb in mass. Potential improvements are smaller for hybrid vehicles because some of the increase in kinetic energy is captured by regenerative braking. If the total mass reduction is significant, a secondary benefit can accrue from reducing the size of the needed powertrain, braking systems, and crash-management structures; the secondary benefit is difficult to estimate but potentially can approach an additional 30% reduction in mass.

Vehicle interiors also offer opportunities to reduce vehicle mass. Some changes can be implemented for little cost, and others high cost. For example, composite-intensive instrument panels, recycled seating materials, and lighter-weight trim panels can reduce mass by tens of pounds at virtually no cost. However, those options tend to affect vehicle character, and additional costs may be incurred in offsetting negative aesthetics.

TABLE 5 Vehicle Technologies for Reducing Fuel Consumption[a]

Technology	Fuel-Consumption Reduction	Comments
Mass reduction: body structure, closure panels, bumpers	3-7%	Applicable to all sizes of vehicles; high-strength steel, aluminum, magnesium, and composites offer advantages, but generally at higher costs
Mass reduction: interior body and trim (seating, trim, instrument panel, glass)	1-4%	May incur adverse effects on aesthetics and vehicle character; material substitution and design tradeoffs; polycarbonate substitution for glass may be feasible
Improved aerodynamics (coefficient of drag, C_d)	1-2%	Affected significantly by vehicle design; affects vehicle character; varies with vehicle size
Reduced tire rolling resistance	1-3%	Need to investigate tradeoffs with tire wear and NVH
Electric accessory technologies: power steering, power brakes, HVAC, thermoelectric materials	2-7%	Opportunities for electrification and performance optimization of HVAC and power steering systems

[a] Improvements are over a 2007 naturally aspirated gasoline vehicle engine of similar performance characteristics.

The aerodynamic performance of a vehicle (represented by the coefficient of drag, C_d, which typically ranges from about 0.25 to 0.38 on production vehicles) depends on several factors. The primary influences are vehicle shape and height, but smaller influences come from, for example, external mirrors, rear spoilers, frontal inlet areas, wheel-well covers, and the vehicle underside. Vehicles with a high C_d may be able to reduce it by 5% or so (up to 10%) at low cost. The associated effect on fuel consumption and fuel economy could be 1-2%.

A report on tires and fuel economy estimates that a 10% reduction in rolling resistance will improve fuel economy by 1-2% (NRC, 2006). The opportunity to improve fuel economy may differ between original-equipment tires and consumer-replaced tires because typical values of the coefficient of rolling resistance (C_r) associated with them differ. The total opportunity is defined by the fraction of the tires on the road that falls into each category. Tires with low rolling resistance do not appear to compromise traction but may wear faster than conventional tires. The incremental cost of low-resistance tires may not be great, but the cost-benefit tradeoff with increased wear and possibly NVH may be important to the consumer.

Some automakers are beginning to introduce electric devices (such as motors) that can reduce the load on the engine, reduce weight, and optimize performance; the result is reduced fuel consumption. There may be an opportunity to decrease fuel consumption 3-4% with a variable-stroke HVAC compressor and better control of the amount of cooling and heating used to reduce humidity. Further reductions can be achieved by decreasing air-conditioner load through the use of low-transmissivity glazing, reflective “cool” paint, and cabin ventilation while parked. Electric power steering or electrohydraulic power steering might yield a decrease in fuel consumption of 3-5%; however, the benefits of electric or electrohydraulic power steering and greater efficiency in air-conditioning are not credited by current EPA fuel-economy tests (neither operates during the test), and they add cost, so manufacturers are reluctant to implement them. Recent improvements in thermoelectric materials for HVAC and exhaust-energy recovery appear promising with respect to the 15-year horizon and will be investigated further in the committee’s final report.

Hybrid and Other Advanced Powertrain Fuel-Economy Technologies

Hybrid electric vehicles achieve improved fuel economy by incorporating both an electric motor and an ICE in the drive train. In its most effective implementation, this permits the ICE to shut down when the vehicle is stopped, permits brake energy to be recovered, permits the ICE to be downsized, and permits the ICE to function at more efficient operating points. As shown in Table 6, those operational characteristics in combination can result in a decrease in fuel consumption of 17-30%, depending on the vehicle class. Hybrid vehicles are the fastest-growing segment of the light-duty vehicle market, although they still make up less than 2% of the market in the United States.

For purposes of this report, hybrid vehicles are defined as having one or more electric motors or generators and an ICE. There are four categories of hybrids, according to the size and function of the motor or generator:

- **Type I—microhybrids.** The starter and generator of a conventional vehicle are usually replaced with a single larger machine, still belt-driven and capable of both starting the engine and generating electric power. (Some microhybrid designs retain the starter for cold starts.) Fuel consumption is reduced by turning off and decoupling the engine at idle and during deceleration and by regenerating a small amount of braking energy (in some models). That reduces fuel consumption by about 6-9 %.
- **Type II—integrated starter-generator (ISG).** The starter and generator are replaced with a larger machine connected between the engine and transmission. That enables some energy recovery through regenerative braking, which results in a reduction in fuel consumption of 11-17% in the city driving cycle. Generally, these vehicles use a larger battery (such as a 42-V battery) and a higher voltage than gasoline or microhybrid vehicles.
- **Type III—parallel hybrids.** These generally involve two electric machines coupled to each other, the engine, and the vehicle wheels through a series of planetary gears and possibly clutches. Power flows to the wheels in parallel paths, directly through the mechanical gears or by conversion to electric power and back to mechanical power. Parallel hybrids allow a wide range of sizes of electric machinery and batteries. Typically, a much larger battery than in type I and type II hybrids is used (capacity, 1-2 kWh) at a voltage of 200-400 V. These hybrids often launch with electric power. The engine operates over a narrower speed and load range to improve efficiency and uses regeneration to recover braking energy. The reduction in fuel consumption is hard to estimate because all the systems discussed in the literature (such as the Prius, the Escape, and General Motors' two-mode hybrid) involve changes in both the vehicle and the engine that contribute to their outstanding results. Reductions in fuel consumption can range from 17-30%.
- **Type IV—plug-in hybrids.** These optimally have a series configuration with the engine driving a generator that provides electric power to charge the battery. The wheels are driven by a large motor that gets its power from the battery through electronics. Because there is no mechanical connection between the engine and the wheels, the motor and the battery must be sized for the full torque and power needed by the vehicle. The potential advantages of this configuration are that a smaller engine may be used because it does not need to provide the full power needed for acceleration, the engine may be operated at its best efficiency point, and, with a larger battery, the vehicle can operate as a purely electric vehicle over a limited range (10-40 miles). The engine is used to recharge the battery. The battery can also be charged from the electric grid, in which case these vehicles are also known as plug-in hybrids. Such hybrids represent future technology and require a much larger battery than other hybrids (capacity, 4-20 kWh),[3] depending on the desired electric-only range. General Motors has announced plans for such a vehicle for 2010 provided that a suitable battery is developed. Plug-in hybrids can also use a parallel configuration. For example, Toyota has announced plans for a plug-in hybrid for 2010 that will be built on a parallel hybrid architecture.

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[3] The Energy Independence and Security Act of 2007 defines a plug-in hybrid as a light-, medium-, or heavy-duty vehicle that draws motive power from a battery with a capacity of at least 4 kWh that can be recharged from an external source of electricity.

TABLE 6 Reductions in Fuel Consumption of Hybrid Technologies[a]

Technology	Fuel-Consumption Reduction (Combined City-Highway Cycle)	Comments
Type I—microhybrids, belt-driven starter-alternator (S/A)	6-9%	In production
Type II—integrated S/A (ISG)	10-17%	In production
Type III—parallel hybrid, NiMH battery	17-30%	In production
Type III—parallel hybrid, Li-ion battery	17%- (to be determined)	Not in production; if successful, Li-ion batteries should be lighter and less expensive than NiMH batteries and have higher energy capacity
Type IV—plug-in hybrid	To be determined	Highly dependent on battery developments, particularly Li-ion

[a] Improvements are over a 2007 naturally aspirated gasoline vehicle engine of similar performance characteristics.

Type I hybrids (microhybrids) use advanced lead-acid batteries designed for deeper and more frequent cycling than the conventional lead-acid batteries used for starting, lighting, and ignition in current vehicles. Type II hybrids (ISG) use either advanced lead-acid or nickel metal hydride (NiMH) batteries, depending on the required power and control philosophy. Type III hybrids of large commercial volume all use NiMH batteries; this technology is benefiting from improvements in cell packaging and cooling. There are no commercial type IV hybrids. Any type IV vehicles in use are conversions from type III. The current lithium-ion battery offers the promise of substantial improvements in both energy and power density relative to NiMH batteries. Several newer chemical formulations are showing promise because of their stability and performance at extreme temperatures; their cycle life expectancy and volume production costs are yet to be determined.

For its final report, the committee will select hybrid vehicles for detailed analysis of the effect of hybridization on performance. Information from manufacturers, to the extent available, will be used to infer the performance improvements from hybridization that can be expected in the near term. Separately, the question of battery technology, a critical component of performance improvement, will be explored to determine the likely viability of batteries now being developed. Of particular importance is the prospect for the newer lithium-ion batteries, which, it is predicted, will substantially reduce safety problems and have longer cycle lives and considerably higher energy densities than the NiMH batteries now installed in all type III hybrids.

Both all-electric and fuel-cell vehicles have the potential to reduce energy use and emissions (depending on how electricity and hydrogen are produced) and U.S. dependence on imported oil over the long term. The prospect of widespread introduction of all-electric vehicles is a function of the battery technologies discussed above. The commercial viability of the vehicles depends on a battery breakthrough. In the period of this study (15 years), all-electric vehicles probably will be limited to vehicles with less than full performance.

In spite of the investment of hundreds of millions of dollars on the development of fuel cells by vehicle builders, equipment suppliers, and government organizations, serious problems requiring technical and economic resolution remain, including

- The higher cost of fuel cells than of other energy converters.
- The lack of a hydrogen-distribution infrastructure.

- The need for a low-carbon source of hydrogen (biomass or water electrolysis using electricity produced with low emissions).
- The need to demonstrate acceptable durability and reliability.

The committee does not expect commercialization of fuel-cell vehicles or widespread marketing of all-electric vehicles before 2020 and therefore will not devote substantial resources to the assessment of these vehicles.

MODELING OF FUEL-ECONOMY TECHNOLOGIES

The 2001 National Research Council report was criticized by some in the automobile industry for its method of estimating fuel-economy improvements. In particular, it was claimed that stepwise application of technologies, the method used to estimate incremental improvements, could overestimate fuel-economy benefits. The committee that produced the 2001 report revisited the methodology in a public meeting, and a letter report released in 2002 reaffirmed the committee's approach and general results. The issues have been revisited by the current committee, and it elected to review the attributes of several of the modeling approaches available.

Modeling Approaches

During the committee's information-gathering, it has focused on two principal methods for assessing fuel-economy technologies for light-duty vehicles:

- Full-system simulation modeling (FSS).
- Partial discrete approximation (PDA).

The committee has deliberated on the characteristics of the two approaches and how each might contribute to the study.

The FSS approach attempts to capture the physics of the vehicle and powertrain system to some level of fidelity in the governing equations that are in the models, including the interactions of the various components in the vehicle (an "inside-out" approach). With the ability to simulate the interactions of vehicle subsystems directly, this approach has the potential to provide useful information about applying combinations of technologies to a given vehicle, to account for the nonlinear effects on overall vehicle performance that can result from the combinations, and to evaluate whether the estimated benefits of the individual technologies applied to vehicle subsystems are realized at the vehicle system level when technologies are combined. The approach may also provide useful information regarding potential fuel-economy improvements associated with new technologies or combinations of technologies when experimental data are sparse or unavailable. However, given the large number of simulations that would be needed, it will not be possible to use the FSS approach to develop the curves of cost *vs.* potential fuel-economy improvement called for in the study charge.

The challenges related to implementing the FSS approach lie in obtaining sufficient specific data about the physical processes that are to be captured in the model equations, determining whether the data are of the appropriate type for the simulation (steady-state *vs*. transient data), balancing the fidelity of various component models within the vehicle system, and estimating how the modeling errors from each component accrue in the overall vehicle system simulation. Obtaining the data needed for FSS is often hampered by the fact that the owners of information consider it to be proprietary. Without valid models of the key components affecting fuel economy, FSS would not be able to predict either fuel-economy effects or synergies accurately. Not only must models of key components be accurate, but control strategies, such as transmission shift points and control of fuel injection and ignition timing, must be known. Such details also are generally considered proprietary by vehicle manufacturers. Lacking that information, numerous engineering assumptions must be made at the subsystem model level, and these assumptions can significantly influence predictions.

The PDA approach gathers data from a variety of sources on a wide array of proven technologies and uses lumped-parameter modeling to account for first-order interactions among technologies. The information used in the PDA approach includes vehicle-certification data collected by EPA (EPA, 2007), data from the literature, and data from manufacturers. As a general rule, the PDA method is limited to "proven" technologies, that is, technologies that have already been implemented by motor-vehicle manufacturers on some mass-produced vehicle that is available somewhere in the world. The method uses the available estimates of the effects of individual technologies and their synergies to estimate the expected fuel-economy improvement afforded by the technologies when combined in other vehicles (an "outside-in" approach). When possible, the approach can be informed by observation of the synergies that occur when subsystem technologies are combined in mass-produced vehicles. Expert judgment must also be used in combining technologies to avoid engineering incompatibilities. An advantage of the PDA method is that it has the potential to estimate the effects of fuel-economy technologies in a broad array of vehicle types. It allows assessment of fuel-economy technologies for a class of vehicles composed of many vehicle models without the need to simulate each model within the class separately.

There are different ways to implement the PDA approach. In one, multiplication or addition is used to aggregate technologies, and engineering judgment and vehicle-testing are relied on to capture interactions of multiple technologies. Another is the energy consumption-balance PDA model developed by Energy and Environmental Associates, Inc. (EEA), which uses the computation methods outlined by Sovran and Bohn (1981). The EEA method is used to estimate the interactions among technologies and to ensure that pumping and friction losses are not reduced to below zero. It does not calculate absolute fuel economy, but only the changes from a given measured baseline vehicle. Although the EEA method still relies on data from proven technologies, it is able to provide an energy-balance accounting for system losses. It has been evaluated through comparisons with independent vehicle data and with results from FSS models, which have shown that results from energy consumption-balance PDAs are consistent with measured FSS values (Duleep, 2007). The committee will evaluate the EEA approach further as part of its work.

The challenges related to the PDA approach lie in the difficulty of inferring specific details about the synergies among subsystem technologies from the input data used to generate the summary. As opposed to the FSS approach, in which these interactions are represented in the formulation of the model, in the PDA approach synergies are approximated by using simple lumped-parameter models, are embedded in the available vehicle data, or are introduced by means of engineering judgment. The PDA approach is generally not used for estimating the fuel-economy effects of novel vehicle systems on which there are no observed data, partly because of the difficulty of estimating synergistic effects among components. The effects of technologies applied to vehicle subsystems can be nonlinear, so the principle of superposition (whereby the effects of multiple technologies can be obtained by summing the effects of the individual technologies) may not represent the potential synergies of new systems.

Applications of the FSS and PDA Approaches

Each approach has its own strengths and weaknesses, so it is important to use each in a manner that capitalizes on its strengths to maximize the usefulness and accuracy of the committee's conclusions. The committee's analysis must also draw on and augment recently completed and current assessments of the effects of vehicle technologies on fuel economy or greenhouse-gas emissions.[4] Both methods must be anchored by comparing with vehicle data.

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[4] For example, NSCCAF (2004) details FSS modeling of greenhouse-gas emissions reductions from a variety of vehicle technologies. And in response to a May 14, 2007, executive order to develop regulations that would cut gasoline consumption and emission of greenhouse gases by motor vehicles, EPA and NHTSA are using both FSS

It is proposed to use the PDA approach to assess a large dataset on current vehicles and to estimate the contribution of each technology to potential fuel-economy improvements in broad classes of vehicles. Examples of the approach and various assessments of technology contributions to overall vehicle fuel economy have already been presented to the committee. One important modification of the final results from the PDA examples that have been presented will be the inclusion of estimates of the range and accuracy associated with the approach. For example, it might be estimated that a given technology would improve fuel economy by 1.3%, but an assessment of the variability of this result (perhaps in the form of a range) should also be included; this will require an evaluation of model accuracy through a comparison of model estimates with vehicle data and FSS results.

The addition of ranges and the comparison of estimates with other data and results will be important for interpreting the results of the PDA approach and assessing it for possible use by NHTSA. Given that the PDA approach depends on experimental data showing the effects of technologies on vehicles, its use to extrapolate potential fuel-economy effects to new technologies on which such data are not available should be limited.

It is proposed to use the FSS approach in two ways: to assess incremental changes in fuel economy that result from adding individual technologies to or removing them from a base vehicle system, and to provide a comparison with the results obtained with the PDA approach. A few base vehicles that span a significant range of the classes of vehicles of interest will be chosen. They will be limited to two to four vehicles, depending on the resources available to the committee for this modeling activity. For each vehicle, a set of appropriate technologies, to be chosen by the committee, will be added to the base vehicle incrementally, and the incremental fuel-economy improvement associated with each technology will be assessed. The technologies included in the modeling should include combinations not currently available or an extrapolation beyond the dataset used in the PDA approach.

The rationale for assessing vehicle technologies incrementally is that when the fuel economy of a particular vehicle is estimated with the FSS approach, the probability that the final estimate will be consistent with the actual value is reduced because of the accumulation of modeling errors for each component in the system. Often, the modeling errors are multiplicative; even if the component models represent the physics of the process accurately, the multiplicative effect at the system level can produce large estimation errors. However, if the models are used to assess *incremental* fuel-economy improvements rather than absolute fuel economy, the effects of small component modeling errors on the final result will usually be much smaller. That is, the sensitivity of the final result to component modeling errors is usually substantially reduced. Assessment of such incremental fuel-economy improvements is also what NHTSA has asked the committee to provide.

The FSS approach can be compared with a similar analysis that uses a PDA method to assess the importance of synergies among the technologies; the synergies are represented directly in the FSS approach and inferred in the PDA approach. Results of both approaches must be compared with vehicle data. That will allow the committee to assess the adequacy of the PDA approach for producing the set of cost and potential-efficiency-improvement curves called for in the committee's charge and to determine whether the inability of the PDA approach to capture such synergies implies that the FSS approach is required to assess the benefits of fuel-economy technologies. If the committee is satisfied that the PDA approach is sufficient for representing potential fuel-economy improvements in different classes of vehicles, it will undertake such analysis for the classes of vehicles listed in Table 1.

Thermodynamics-Based Modeling Analysis

In addition to modeling fuel economy with the FSS and PDA approaches, the committee proposes to do cycle simulations based on the second law of thermodynamics. Such simulations could demonstrate how changes in thermodynamic losses (changes in dissipative or irreversible processes) change vehicle

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and PDA methods to assess fuel-economy improvements and reductions in greenhouse-gas emissions that result from new vehicle technologies.

fuel economy. The simulations would be conducted under conditions that are typical during the EPA city-highway dynamometer test for fuel economy (for example, 2.4-bar brake mean effective pressure and 1800-2000 revolutions per minute).

From a fundamental point of view, the fuel in a vehicle's fuel tank supplies "available energy," the potential for doing useful work, to the engine. The fuel's chemical energy is changed by the combustion process into a form that can do work that powers the vehicle. A thermodynamic analysis involves tracking what is occurring in the engine that makes some of the energy unavailable to do useful work. For example, some energy is lost to the cooling system, and some flows out of the engine as thermal energy and as chemical energy in the unburned fuel components of the hot exhaust gases. Some energy is dissipated as mechanical friction in the engine.

Those types of thermodynamic losses occur in all vehicle components and subsystems. Once the flows of available energy in a vehicle engine have been described mathematically, data and software packages can be used to simulate the changes in thermodynamic losses caused by fuel-economy technologies.

This approach should lead to a much clearer understanding of the benefits of the more complicated changes in individual subsystems and of changes that affect multiple subsystems at the same time. For example, the addition of exhaust-gas recirculation (EGR) reduces thermodynamic losses that are affected by gas temperatures and pressures and thus reduces engine fuel consumption. Such effects would be highlighted directly by analysis based on the second law of thermodynamics. Not all technologic system changes would be subjected to that kind of analysis. Rather, it would be applied only to combinations of changes that are most complex and difficult to simulate. If the analysis does not yield a clearer understanding of the effects of such changes, it will not be included in the committee's final report.

PLAN AND INFORMATION NEEDS FOR FINAL REPORT

The committee's task statement calls for it to estimate, in its final report, the efficacy, cost, and applicability to different vehicle classes of fuel-economy technologies that might be used in the next 15 years. That will require the committee to move from its preliminary list of fuel-economy technologies and its preliminary assessment of the fuel-economy effects of the technologies, as contained in this interim report, to final decisions concerning the technologies and their effects. It will also require the committee to move from its assessment of the attributes of models that are used to project vehicle fuel economy to the application of the models. The committee's immediate next steps will be to select one PDA model and one FSS model to use in its analysis. The committee will select a set of appropriate technologies to use in assessing the ability of both models to simulate actual vehicle fuel economy and in assessing the importance of synergies among technologies; this will be done during and after the committee's January 2008 meeting.

The committee will continue to collect information for use in its analysis during the coming months. As noted earlier, a May 14, 2007, executive order called for EPA and NHTSA to jointly develop a proposal for improving fuel economy and reducing greenhouse-gas emissions. The two agencies are developing data on costs and fuel-economy potential and are conducting analyses with both FSS and PDA methods. The draft rule, which will be accompanied by the release of the NHTSA and EPA information, will be a critical source of information for the committee. It is the committee's understanding that the rule is scheduled to be released at the end of 2007. However, the recently passed Energy Independence and Security Act of 2007 has caused NHTSA and EPA to delay release of the rule.

The need for additional information is especially acute with respect to costs. Although the costs of fuel-economy technologies are central to the committee's final report, the task statement did not call for costs to be part of the interim report. The committee notes that the information provided to it by automobile manufacturers and technology suppliers was insufficient to allow a discussion of costs in this report. Preliminary cost information has been supplied in a consultant's report commissioned by the committee (EEA, 2007), and NHTSA has informed the committee that it has held extensive discussions with automobile manufacturers and technology suppliers concerning costs. The committee concludes that obtaining cost information from NHTSA, from which proprietary information has been removed, will be important in accomplishing its task.

Sincerely,

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

Appendix A
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Appendix B
Committee Biographies

Trevor O. Jones (NAE) ***(Chair)*** is chairman and CEO of ElectroSonics Medical, Inc. Earlier, he was founder, chairman, and CEO of Biomec Incorporated, a biomedical-device company. He had also been chairman of the board of Echlin, Incorporated, a supplier of automotive components primarily to the after-market. Mr. Jones is chairman and CEO of International Development Corporation, a private management-consulting company that advises on strategy and technology. He was chair, president, and CEO of Libbey-Owens-Ford Company, a major manufacturer of glass for automotive and construction applications. Before that, he was an officer of TRW, Incorporated, serving as vice president of engineering in the company's Automotive Worldwide Sector and group vice president, Transportation Electronics Group. Before joining TRW, he was employed by General Motors (GM) in many aerospace and automotive executive positions, including director of GM Proving Grounds; director of the Delco Electronics Division, Automotive Electronic and Safety Systems; and director of GM Advanced Product Engineering Group. He received the U.S. Department of Transportation Safety Award for Engineering Excellence in 1978 and the H. H. Bliss Award from the Center for Study of Responsive Law in 1991; both awards recognized his pioneering contributions to the development of automotive inflatable occupant-restraint systems. Mr. Jones was appointed to the National Motor Vehicle Safety Advisory Council by Secretary of Transportation John Volpe in 1971 and was appointed vice chairman of the council in 1972. In 1975, President Ford appointed him to a 3-year term on the National Highway Safety Advisory Committee. In 1976, he was appointed the first nongovernment chairman of the committee. Mr. Jones is a life fellow of the American Institute of Electrical and Electronics Engineers and has been cited for "leadership in the application of electronics to the automobile". He is also a fellow of the American Society of Automotive Engineers, a fellow of the British Institution of Electrical Engineers, an honorary fellow of the Institution of Mechanical Engineers, a fellow of the Engineering Society of Detroit, a registered professional engineer in Wisconsin, and a chartered engineer in the United Kingdom. He holds many patents and has lectured and written on automotive safety and electronics. He was a member of the National Research Council Commission on Engineering and Technical Systems. Mr. Jones has served on several other National Research Council committees, including the Committee for a Strategic Transportation Research Study on Highway Safety; chaired the NAE Steering Committee on the Impact of Products Liability Law on Innovation; and for 7 years chaired the Committee on Review of the Research Program of the Partnership for a New Generation of Vehicles for six reviews. He currently serves on the Committee for the Small Business Innovative Research study. He holds a Higher National Certificate in electrical engineering from Aston Technical College and an Ordinary National Certificate in mechanical engineering from Liverpool Technical College. He was awarded an honorary doctor of science degree by Cleveland State University and was recognized for outstanding developments in fuel cells and biomedical devices.

Thomas W. Asmus (NAE) is retired senior research executive of DaimlerChrysler Corporation. He has also held positions at Mead Corporation and was an adjunct faculty member of mechanical engineering at the University of Michigan and a professor of physical chemistry at the University of Guadalajara, Mexico. He has over 30 years of experience and has played a leadership role in nearly all aspects of internal-combustion engine and fuels research and development, focusing mainly on fuel-consumption and exhaust-emissions reduction. His entry into this field was based on a background in combustion and emissions-formation mechanisms for both gasoline and diesel engines; with time and circumstances, his activities have expanded to include gas-exchange processes, controls, lubrication, many types of fault diagnoses, and heat management. He is a fellow of the Society of Automotive Engineers and a recipient of the Soichiro Honda Lecture Award for 1999. He has a BS in paper science and engineering and an MS and PhD in physical chemistry from Western Michigan University.

Rodica Baranescu (NAE) is a professor in the Department of Mechanical and Industrial Engineering of the College of Engineering of the University of Illinois at Chicago. Previously, she was manager of the Fuels and Lubricants and Engine Group of the International Truck and Engine Corporation in Melrose Park, IL. She is an internationally sought-after public speaker on technical issues related to mobility technology, environmental control, fuels, and energy. She has extensive expertise in diesel-engine technology and was elected to the National Academy of Engineering in 2001 “for research leading to effective and environmentally sensitive diesel and alternative-fuel engines and leadership in automotive engineering”. She is a fellow of the Society of Automotive Engineers International, of which she was president in 2000. In 2003, she received the American Society of Mechanical Engineers Internal Combustion Engine Award. Dr. Baranescu received her MS and PhD in mechanical engineering in 1961 and 1970, respectively, from Politehnica University in Bucharest, Romania, where she also served as assistant professor (1964-1968), lecturer (1970-1974), and associate professor (1974-1978).

Jay Baron is president of the Center for Automotive Research (CAR) and director of CAR’s Manufacturing, Engineering and Technology Group. Dr. Baron’s recent research has focused on developing new methods for the analysis and validation of sheet-metal processes, including die-making, tool and die tryout, and sheet-metal assembly processes. He developed functional build procedures that result in lower tooling costs and shorter development lead times while improving quality—particularly of sheet-metal assemblies. He has been researching new technologies in the automotive industry, including looking at body-shop design and flexibility and evaluating the manufacturing capability of evolving technologies. He recently completed investigations on the state-of-the-art of tailor-welded blank technologies, the economics of weld-bond adhesives, and the analysis of car-door quality and construction methods. Before becoming Director of Manufacturing Systems at CAR and subsequently president, Dr. Baron was the manager of manufacturing systems at the Office for the Study of Automotive Transportation at the University of Michigan Transportation Research Institute. He also worked for Volkswagen of America in quality assurance and as staff engineer and project manager at the Industrial Technology Institute in Ann Arbor and the Rensselaer Polytechnic Institute’s Center for Manufacturing Productivity in Troy, NY. Dr. Baron holds a PhD and a master’s degree in industrial and operations engineering from the University of Michigan and an MBA from Rensselaer Polytechnic Institute.

Patrick F. Flynn (NAE) is retired vice president for research at Cummins Engine Company, Inc. Among other professional associations, Dr. Flynn was on the executive advisory board of the U.S. Army University Research Initiative and the advisory board for the Department of Energy’s combustion-research facility at Sandia National Laboratories. Dr. Flynn is a member of the Combustion Institute and a registered professional engineer in Indiana. He has served on a number of National Research Council boards and committees, including the Board on Army Science and Technology, the Committee on Portable Energy Sources for the Objective Force Warrior (of which he was chair), the Committee on the Future of Personal Transport in China, and the Committee on Army after Next Logistics. He has expertise in diesel-engine design, mechanical engineering, and integrated power systems. He received his bachelor and master’s degrees in agricultural engineering from the University of Minnesota, his MBA from Indiana University, and his PhD in mechanical engineering from the University of Wisconsin.

David Friedman is research director of the Clean Vehicles Program of the Union of Concerned Scientists (UCS), Washington, D.C. He is the author or coauthor of more than 30 technical papers and reports on advancements in conventional, fuel-cell, and hybrid electric vehicles and alternative energy sources with an emphasis on clean and efficient technologies. Before joining UCS in 2001, he worked for the University of California, Davis (UCD) in the Fuel Cell Vehicle Modeling Program, developing simulation tools to evaluate fuel-cell technology for automotive applications. He worked on the UCD FutureCar team to build a hybrid electric family car that doubled its fuel economy. He previously worked at Arthur D. Little, researching fuel-cell, battery electric, and hybrid electric vehicle technologies and photovoltaics. He was a member of the National Research Council Panel on the Benefits of Fuel Cell

R&D of the Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, Phase 1, and the Committee on National Tire Efficiency. He is a member of the National Research Council Committee on the Assessment of Resource Needs for Development of Fuel Cell and Hydrogen Technology. He earned a bachelor's degree in mechanical engineering from Worcester Polytechnic Institute and is a doctoral candidate in transportation technology and policy at UCD.

David Greene is a corporate fellow of Oak Ridge National Laboratory (ORNL). He has spent over 20 years researching transportation and energy policy issues. His research interests include energy-demand modeling, economic analysis of petroleum dependence, modeling of market responses to advanced transportation technologies and alternative fuels, economic analysis of policies to mitigate greenhouse-gas emissions from transportation, and theory and methods for measuring the sustainability of transportation systems. After joining ORNL in 1977, he founded the Transportation Energy Group in 1980 and later established the Transportation Research Section in 1987. Dr. Greene spent 1988-1989 in Washington, D.C., as a senior research analyst in the Office of Domestic and International Energy Policy of the Department of Energy. He has published over 150 articles in professional journals, contributions to books, and technical reports and has given congressional testimony on transportation and energy issues. From 1997 to 2000, Dr. Greene served as the first editor-in-chief of the *Journal of Transportation and Statistics*, the only scholarly periodical published by the Department of Transportation. He serves on the editorial boards of *Transportation Research Part D*, *Energy Policy*, *Transportation Quarterly* and the *Journal of Transportation and Statistics*. Active in the Transportation Research Board (TRB) and the National Research Council, Dr. Greene has served on several standing and ad hoc committees. He is past chair and member emeritus of TRB's Energy Committee, past chair of the Section on Environmental and Energy Concerns, and a recipient of TRB's Pyke Johnson Award. Dr. Greene received a BA from Columbia University in 1971, an MA from the University of Oregon in 1973, and a PhD in geography and environmental engineering from Johns Hopkins University in 1978.

Linos Jacovides recently retired as director of Delphi Research Labs, a position he held from 1998 to 2007. Dr. Jacovides joined General Motors Research and Development in 1967 and became department head of electrical engineering in 1985. His research was in the interactions between power electronics and electric machines in electric vehicles and locomotives. He later moved to Delphi with a group of researchers from GM to set up the Delphi Research Labs. He received a BS in electrical engineering and a master's degree in machine theory from the University of Glasgow, Scotland, in 1961 and 1962, respectively. He received his PhD in generator control systems from the Imperial College, University of London, in 1965. He is a fellow of the Institute of Electrical and Electronic Engineers (IEEE) and past president of the IEEE Industrial Applications Society.

John H. Johnson is a Presidential Professor Emeritus in the Department of Mechanical Engineering-Engineering Mechanics of Michigan Technological University (MTU) and a fellow of the Society of Automotive Engineers (SAE) and the American Society of Mechanical Engineers (ASME). His experience spans a wide array of analysis and experimental work related to advanced engine concepts, diesel and other internal-combustion engine emissions studies, fuel systems, and engine simulation. He was previously project engineer in the U.S. Army Tank Automotive Center and chief engineer in Applied Engine Research at the International Harvester Company before joining the MTU mechanical-engineering faculty. He served as chairman of the MTU mechanical engineering and engineering mechanics department from 1986 to 1993. He has served on many committees related to engine technology, engine emissions, and health effects—for example, committees of SAE, the National Research Council, the Combustion Institute, the Health Effects Institute, and the Environmental Protection Agency—and consults with a number of government and private-sector institutions. In particular, he served on the National Research Council Committee on Fuel Economy of Automobiles and Light Trucks and the Committee on the Impact and Effectiveness of Corporate Average Fuel Economy (CAFE) Standards and chaired the Committee on Review of DOE's Office of Heavy Vehicle Technologies. He is the chair of the

Committee to Review the DOE 21st Century Truck Program. In 2002, he was honored with the ASME Soichiro Honda Medal for advancing the understanding of vehicle cooling problems and research investigations into the origin of diesel-exhaust pollutants and their effects on human health. He received his PhD in mechanical engineering from the University of Wisconsin.

John G. Kassakian (NAE) is professor of electrical engineering and director of the Massachusetts Institute of Technology (MIT) Laboratory for Electromagnetic and Electronic Systems. His expertise is in the use of electronics for the control and conversion of electric energy, industrial and utility applications of power electronics, electronic manufacturing technologies, and automotive electric and electronic systems. Before joining the MIT faculty, he served in the U.S. Navy. Dr. Kassakian is on the boards of directors of a number of companies and has held numerous positions with the Institute of Electrical and Electronics Engineers (IEEE), including being founding president of the IEEE Power Electronics Society. He is a fellow of IEEE and a recipient of the IEEE William E. Newell Award for Outstanding Achievements in Power Electronics (1987), the IEEE Centennial Medal (1984), and the IEEE Power Electronics Society's Distinguished Service Award (1998). He has served on a number of National Research Council committees, including the Committee on Review of the Research Program of the Partnership for a New Generation of Vehicles and the Committee on Review of the FreedomCAR and Fuel Research Program. He has a ScD in electrical engineering from MIT.

John J. Moskwa is professor of mechanical engineering and founding director of the Powertrain Control Research Laboratory in the Department of Mechanical Engineering at the University of Wisconsin-Madison. He has more than 33 years of experience in the powertrain industry. In addition to 19 years on the faculty at Wisconsin, he has worked for Cummins Engine Company, General Motors Research Labs, the U.S. Army Tank-Automotive Command (Propulsion Division. and System Simulation and Technical Division), Ford Motor Company's R&E Centre in England, the City of Detroit Department of Transportation, and the Massachusetts Institute of Technology (MIT) Vehicle Dynamics Laboratory. Dr. Moskwa is a fellow in the American Society of Mechanic Engineers and the Society of Automotive Engineers. His academic background includes a PhD from MIT and an MSE and a BSE from the University of Michigan.

Gary W. Rogers is president, chief executive officer, and sole director of FEV Engine Technology, Inc. He is also president of FEV Test Systems, Inc. He has been director of the Power Plant Engineering Services Division and senior analytic engineer at Failure Analysis Associates, Inc., a design development engineer at Garrett Turbine Engine Company, and an exploration geophysicist at Shell Oil Company. He has extensive experience in research, design, and development of advanced engine and powertrain systems, including homogeneous and direct-injected gasoline engines, high-speed direct-injected passenger-car diesel engines, heavy-duty diesel engines, hybrid vehicle systems, gas turbines, pumps, and compressors. He provides corporate leadership for a multinational research, design, and development organization specializing in engines and energy systems. He is a member of the Society of Automotive Engineers, is an adviser to the Defense Advance Research Projects Agency on Heavy-Fuel Engines, and sits on the advisory board to the College of Engineering and Computer Science of Oakland University in Rochester, MI. He served as a member of the National Research Council Committee on Review of DOE's Office of Heavy Vehicle Technologies Program, Committee on the Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) standards, and Panel on Benefits of DOE's Light-Duty Hybrid Vehicle R&D Program. He also recently supported the Department of Transportation National Highway Traffic Safety Administration (NHTSA) by conducting a peer review of the NHTSA CAFE Model. He has a BSME from Northern Arizona University.

Robert F. Sawyer (NAE) is the Class of 1935 Professor of Energy Emeritus at the University of California, Berkeley (UCB). He recently served as chair of the California Air Resources Board (CARB). His previous positions include research engineer and chief, Liquid Systems Analysis, U.S. Air Force

Rocket Propulsion Laboratory; member of the research staff, Princeton University; member, CARB; and vice-chair for graduate studies of the Department of Mechanical Engineering and chair of the Energy and Resources Group at UCB. He also served as president of the Combustion Institute. He conducts research in engine combustion, pollutant formation and control, alternative fuels, and regulatory policy. Dr. Sawyer has served on numerous National Research Council committees, including the Committee for the Evaluation of the Congestion Mitigation and Air Quality Improvement Program, the Committee to Review EPA's Mobile Source Emissions Factor (MOBILE) Model, and the Committee on Adiabatic Diesel Technology. He holds a BS and an MS in mechanical engineering from Stanford University and an MA in aeronautical engineering and a PhD in aerospace science from Princeton University.

Appendix C
Statement of Task

The committee formed to carry out this study will provide updated estimates of the cost and potential efficiency improvements of technologies that might be employed over the next 15 years to increase the fuel economy of various light-duty vehicle classes. Specifically, the committee shall:

1. Reassess the technologies analyzed in Chapter 3 of the NRC report, *Impact and Effectiveness of Corporate Average Fuel Economy (CAFE) Standards* (2002) for efficacy, cost, and applicability to the classes of vehicles considered in that report. In addition, technologies that were noted but not analyzed in depth in that report, including direct injection engines, diesel engines, and hybrid electric vehicles, shall be assessed for efficacy, cost and applicability. Weight and power reductions also shall be included.
2. Estimate the efficacy, cost, and applicability of emerging fuel economy technologies that might be employed over the next 15 years. Promising engine, transmission and vehicle technologies shall be selected in light of factors that may motivate their market adoption such as economic impacts, oil imports, greenhouse gas emissions, increased market share for "light trucks" including sport utility vehicles (SUVs) and minivans, and the possible emergence of fuel cell, biofuel, and electric vehicles.
3. Identify and assess leading computer models for projecting vehicle fuel economy as a function of additional technology. These models would include both lumped-parameter types, where the input depends on engineering judgment as to how technologies will interact, and engine mapping models that analyze the interactions. Check the models against current, known fuel economy examples and select one of each type to perform the analyses of the effect of the technologies in 1 and 2 above.
4. Develop a set of cost/potential efficiency improvement curves, as in Chapter 3 of the 2002 NRC report, that is guided by the following question: "What is the estimated cost and potential fuel economy benefit of technologies that could be applied to improve the fuel economy of future passenger vehicles, given the constraints imposed by vehicle performance, functionality, safety and emission regulations? The ten vehicle classes considered in the 2002 report shall be analyzed, including important variants such as different engine sizes (e.g. 6 and 8 cylinders). Most analyses shall be with the engineering judgment model, but sufficient cases to ensure overall accuracy shall be checked with the engine mapping model.
5. Define and document the methodology(ies) used to estimate the costs and benefits of the fuel economy technologies chosen by the committee. Although methodologies vary, the committee's report should specify its calculation methodology(ies) to levels of specificity, clarity and completeness sufficient for implementation and integration into models that project the fuel economy capability of vehicles, fleets and manufacturers. The report should also provide and document estimates of all parameters and input data required for implementation of these methodologies.

The committee's analysis and methodologies will be documented in two NRC-approved reports. An interim report will discuss the technologies to be analyzed, the classes of vehicles which may employ them, the estimated improvement in fuel economy that may result, and the models that will be used for analysis. The final report will include the results of the modeling using the input from the interim report and any new information that is available.

Appendix D
Presentations at Public Committee Meetings

MEETING ONE, WASHINGTON, D.C.
SEPTEMBER 10-11, 2007

Julie Abraham, National Highway Traffic Safety Administration
Fuel Economy Technology Study

William Charmley, EPA Office of Transportation and Air Quality representative
Greenhouse Gases and Light-Duty Vehicles

Coralie Cooper, Northeast States for Coordinated Air Use Management
Technical Feasibility and Costs Associated with Reducing Passenger Car GHG Emissions

John German, USA Honda
Advanced Technologies, Diesels, and Hybrids

Dan Hancock, GM Powertrain
Assessing Powertrain Fuel Economy

John Heywood, Massachusetts Institute of Technology
Challenges in Estimating Future Vehicle Fuel Consumption

Aymeric Rousseau, Argonne National Laboratory
Designing Advanced Vehicle Powertrains Using PSAT

Wolfgang Stütz, BMW of North America
Fuel Economy of BMW Diesel Vehicles

MEETING TWO, WASHINGTON, D.C.
SEPTEMBER 27, 2007

K. G. Duleep, Energy and Environmental Analysis, Inc.
Approaches to Modeling Vehicle Fuel Economy

Kevin Green, The Volpe Center
CAFE Compliance and Effects Modeling System

Marc Wiseman, Ricardo Inc.
Potential Approaches to Modeling Fuel Economy Technologies: Engine Simulation Modeling Capabilities and Cost Analysis Capabilities

MEETING THREE, WASHINGTON, D.C.
OCTOBER 25-26, 2007

Manahem Anderman, Advanced Automotive Batteries
Lithium-Ion Batteries for Hybrid Electric Vehicles: Opportunities and Challenges

Mark Daroux, Stratum Technologies, Inc.
Lithium Ion Phosphate Batteries for Traction Application

Tien Duong, U.S. Department of Energy
Status of Electrical Energy Storage Technologies

Michel Forissier, Valeo
Fuel Economy Solutions

Bart Riley, A123 Systems
A123 Systems Battery Technologies

MEETING FOUR, WASHINGTON, D.C.
NOVEMBER 27-28, 2007

Khalil Amine, Argonne National Laboratory
Advanced High Power Chemistries for HEV Applications

Paul Blumberg, Ethanol Boosting Systems, LLC
Ethanol Turbo Boost for Gasoline Engines: Diesel and Hybrid Equivalent Efficiency at an Affordable Cost

Frank Fodal, Chrysler LLC
Fuel Economy/Fuels

Robert Wimmer and Shunsuke Fushiki, Toyota
Toyota Hybrid Program

David Geanacopoulos, Volkswagen of America, Inc.
Diesel Technology for VW

Johannes Ruger, Bosch
Increasing Fuel Economy: Contribution of Bosch to Reach Future Goals