LIGHT-DUTY
ENGINES & VEHICLES

EXECUTIVE SUMMARY

There are many technologies that have the potential to both incrementally and significantly improve the fuel economy of liquid fueled light-duty (LD) vehicles. The primary issues are the cost and time to bring them to market. There is no single technology that can deliver significant improvements. Multiple technologies will need to be developed and deployed as systems. Friction reduction, advanced valving, electrifying accessories, direct injection, reduced rolling resistance, and improved aerodynamics each provide incremental fuel economy improvements in the area of 1–6%. Smaller displacement turbocharged engines and advanced transmissions yield 2–15% each, and start-stop technology can provide 2–8% improvement. The most significant fuel economy improvements come from hybridization (25–55% improvement) and mass reduction (30% reduction may yield up to 28% fuel economy improvement). These estimates are according to the literature surveyed for the chapter. However, there are large differences, even among comprehensive, high-quality studies, in estimates of the incremental retail price equivalent of technology that achieves major reductions in vehicle fuel consumption. Data from these studies were used in this chapter to establish upper and lower bound technology price ranges corresponding to various levels of fuel economy improvement. These ranges were used for an initial analysis in this chapter and as input for the integrated LD vehicle modeling analysis (see Chapter Two, "Light-Duty Vehicles").

Many of the vehicle and propulsion system fuel economy improvement technologies considered for the liquid internal combustion engine (ICE) fuel-vehicle system are applicable to other fuel-vehicle systems. Advances in vehicle-level technologies such as improved aerodynamics, reduced rolling resistance, and lightweighting apply to all fuel-vehicle systems. Advances in ICE vehicle technologies are applicable to both liquid and compressed natural gas fueled engines.

The principal barrier to achieving significant fuel economy improvement in liquid fueled LD vehicles is achieving cost levels that provide an attractive value proposition to consumers. Incremental ICE improvements such as stratified charge/lean burn, homogeneous compressed charge ignition, clean diesel, exhaust heat recovery, and fuel flexibility require cost reduction to become attractive to consumers and be used more widely on new vehicles. Achieving the maximum potential of fuel economy increase from downsizing and turbocharging requires an increase in the minimum octane number of U.S. gasoline, or vehicles dedicated to the use of high concentration alcohol-gasoline blends. The use of advanced lightweight materials yields more fuel economy improvement, but requires significant reduction of material and manufacturing costs for mass-market applications. Hybridization, including batteries, motors, controllers, and regenerative braking, is more expensive and faces significant cost barriers.

This chapter also examines greenhouse gas (GHG) emissions. The analysis finds that even with full implementation throughout the LD fleet of technologies that double fuel economy, GHG emissions in 2050 would only be about 12% lower than those in 2005, due to increased vehicle miles traveled (VMT). Reduction in the carbon footprint of liquid transportation fuels, incorporation of alternative vehicle and fuel technologies into the fleet, and/or reduction of VMT will be required to

achieve greater reductions. More advanced break-throughs such as intelligent transportation systems, ultra-lightweight materials, and electric propulsion could enable new types of vehicles that are inherently simpler, cheaper, lighter, safer, smaller, and more efficient.

While there are many powertrain, vehicle, and fuel technologies that can improve liquid fueled LD vehicle fuel economy, it will likely take many years for some of them to achieve material penetration in the overall U.S. LD vehicle fleet due to combined effects of economics, long development lead times and vehicle life cycles, and slow turnover of the vehicle fleet.

INTRODUCTION

The overall scope of this chapter addresses technologies to reduce fuel energy consumption of LD vehicles. Fuel consumption reduction technologies and their related costs for a complete range of vehicle and liquid fueled powertrain types are assessed. These include spark and compression ignition engine technologies, improved drivelines, hybridization, low rolling resistance tires, improved aerodynamics, and mass reduction. Plug-in electric vehicles, hydrogen fuel cell electric vehicles, and natural gas fueled vehicles are addressed in other chapters. The impacts of changes in driving behavior and other advanced vehicle technologies such as smart, connected, autonomous vehicles are addressed briefly, but not quantified.

The Engines and Vehicles Subgroup concentrated on new components and technologies that impact vehicle fuel economy and fuel flexibility of LD vehicles. These technologies focus on minimizing energy losses in the engine, transmission, driveline, body, and chassis. Technologies can be combined to achieve substantial reductions in fuel consumption.

The Subgroup based its analyses on recently published studies by the National Research Council (NRC), the Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA), and others. The analysis in this chapter focuses on technologies described in the literature that are proven and expected to be available in the next 10 to 15 years. The potential fuel efficiency impact of fundamental clean-sheet approaches to

product development, supply, and manufacturing is also discussed.

AUTOMOBILE INDUSTRY OVERVIEW

Today's auto industry is global in scope. It is dominated by a small number of high-volume vehicle manufacturers/groups. In 2010, there were approximately 75 million new light- and heavy-duty vehicles sold around the world. Total production capacity, however, was about 86 million.[1] Six company groups (Toyota, GM, Volkswagen, Hyundai, Ford, and Renault-Nissan) sold over 5 million vehicles each and collectively accounted for approximately 55% of global vehicle unit sales. Another seven company groups (Fiat/Chrysler, Honda, Peugeot, Suzuki, Mazda, Daimler, and BMW) sold between 1.5 and 4.0 million vehicles each in 2010, and accounted for 17.8 million sales in total, or about 25% of global sales. Numerous small and/or country specific manufacturers account for the remaining 20% of the market. The U.S. auto market, at about 12 million units, represented about 16% of the world's total in 2010. According to the Energy Information Administration's (EIA) Annual Energy Outlook 2010 (AEO2010), the global LD vehicle fleet (or "parc" in industry parlance) is approximately 830 million.[2] The U.S. fleet is about 230 million.

The basic business model is very similar for most of the world's large auto manufacturers. Companies sell their products through many different brands and channels, usually trying to create unique images and price points. However, the cost-effective high volume production of LD vehicles relies on maximizing the use of globally common components, designs, and processes. So, for mass-market original equipment manufacturers (OEMs), multiple vehicle brands and body-style derivatives are produced from common vehicle and powertrain platforms (a term generally used to describe the fundamental design, systems, physical dimensions, performance, and manufacturing process bandwidths or parameters), which ideally have annual production volumes of many hundreds of thousands. These platforms are typically designed and engineered at product development and engineering centers, and are built in plants around the world

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1 Mathew Dolan, "Auto Industry Has Room to Shrink Further," *Wall Street Journal,* November 16, 2009.

2 Energy Information Administration, *Annual Energy Outlook 2010 – With Projections to 2035,* April 2010.

to align capacity and supply with expected demand. Significant amounts of engineering and capital dollars are required for each vehicle and powertrain platform and each specific vehicle brand and model. These resources are expended years in advance of start of production and revenue generation.

LD vehicle development lead time, life cycle, and longevity are very similar across the world's auto manufacturers.[3] It can take two to four years to conceptualize and develop a vehicle. Mild updating and refreshing takes the least amount of lead time, while all new platforms and vehicle models take the most time. Powertrain development lead times are typically longer than those for a vehicle. While the definition and execution of vehicle platform varies among manufacturers, it is often expected that core platforms will spawn at least two life cycles of vehicle models and derivatives. A vehicle model is typically in the market for 4–6 years (with light cosmetic and technical refreshes occurring mid-cycle), so a core platform is usually designed and intended to remain in production for 8–12 years. OEMs typically manage their product portfolios with a five to ten year horizon, and cadence the development and launch of vehicles to address their best assessment of market demand and to balance workload, engineering and capital spending, and showroom freshness. The longevity of vehicles in a country's operating vehicle fleet varies. The expected *median* lifetime for a 1990 model year automobile is 16.9 years.[4] However, the age distribution of vehicles has a long tail, according to AEO2010, so average lifetime is shorter than median lifetime. Analysis of AEO vehicle survival as a function of age indicates the *average* mileage-weighted lifetime of cars is 13 years and light trucks is 14 years.

Auto manufacturers rely on a global network of suppliers with which they design and develop systems and components for vehicles. Vehicle components such as fuel pumps, fuel injectors, tires, and batteries, are produced by "Tier 1" suppliers for multiple manufacturers. More complicated component systems are often OEM specific. Tier 2, 3, and 4 suppliers operate farther up the supply chain and provide everything from raw materials to basic subcomponents that are assembled by the Tier 1 systems suppliers. The supply "footprint" generally mirrors the auto manufacturers' vehicle assembly footprint—meaning systems and major component supply capacity is usually near vehicle assembly capacity and is managed globally. In this integrated global business model, manufacturing and assembly processes are, to varying degrees, standardized by each manufacturer and are integrated with product development and supply processes.

New vehicle programs are rarely done as pure "clean sheet" programs. Existing platforms, systems, and components are highly leveraged to minimize new engineering expense, capital investment, and development time. Most programs consciously avoid expectation of "invention" on the critical path, to maintain program timetables and reduce overall risk. New and advanced technology developed by the manufacturers and/or suppliers is typically done with high risk and investment, and deployed gradually in brands and vehicle models according to expected market demand and consumer willingness to pay. This also allows for cycles of technology learning during volume ramp-up to lower cost and improve performance. To keep invention off the critical path, the lead time for development of new technology precedes vehicle program timing. Synchronizing new technology development timetables with vehicle program timetables can be difficult. Vetting new technologies for performance, scale manufacturability, and cost can run into inevitable obstacles, while vehicle program timing is often fixed by the larger product portfolio plan cadence. A new technology that misses the development window for an initial vehicle application may have to wait until the next appropriate vehicle program. It is not unusual for the burden of a new technology's development costs to be borne by the first vehicle program application, though some OEMs spread costs over a broader range of applications over time. As new technologies evolve and improve in terms of performance and cost, wider applications in a manufacturer's vehicle portfolio are common, assuming market demand. Since a large manufacturer with many brands and models cadences its product development and launch plan over time, it can take many years to deploy new technology throughout a manufacturer's full portfolio of products, and a decade or more to significantly penetrate the operating vehicle fleet due to the longevity of vehicles in operation.

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3 Center for Automotive Research, *How Automakers Plan Their Products: A Primer for Policymakers on Automotive Industry Business Planning,* July 2007.

4 Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 29,* June 2010.

ENGINE AND VEHICLE TECHNOLOGY

The Current State

Energy Flows and Losses in a Vehicle

Before describing technologies available for improving vehicle fuel economy, it is useful to describe the energy flows and losses for a vehicle operating on a specific driving cycle. Full vehicle simulation models are used to analyze vehicle energy flows while the vehicle operates over a specific simulated driving cycle. Sovran and Blaser[5] discussed the concepts of tractive force and tractive energy to help understand the role of vehicle mass, rolling resistance, and aerodynamic drag. The tractive force, the force at the wheels required to propel a vehicle, is a function of rolling resistance, aerodynamic drag, vehicle mass, rotational inertia of the wheels, road incline, and the change in speed.

Tractive energy for a specific time step is calculated by multiplying tractive force times velocity times the time step ($dE=FdS=F*dS/dt*dt=F*Vdt$). The sum of tractive energy for each time step in which the tractive force is greater than zero (cruises and accelerations) is called total tractive energy. When tractive force is negative, during decelerations, braking force is normally required to slow down the vehicle. The sum of tractive energy during decelerations is summed to achieve braking energy. Given specific vehicle characteristics, such as mass, drag coefficient, frontal area, and tire rolling resistance coefficient, vehicle simulation models can be used to estimate tractive energy for a specific cycle, and the portion of tractive energy consumed by aerodynamics, rolling resistance, and braking. For a given driveline efficiency, fuel consumption is proportional to tractive energy.

The NRC,[6] in its LD vehicle fuel economy report, highlighted a specific vehicle simulation conducted by Ricardo[7] for a 2007 Toyota Camry. The energy distribution for various driving schedules is shown in Table 9-1. For the urban cycle, the total tractive energy was 1.25 kilowatt-hours (kWh). Of this total, 0.44 kWh was needed to overcome rolling resistance, 0.31 kWh was required to overcome aerodynamic drag, and 0.50 kWh was lost as heat generated during braking. The high speeds of the highway cycle required higher tractive energy despite the lower braking energy losses on the highway cycle. The US06 cycle, the cycle with highest speeds and highest acceleration and deceleration, had higher tractive energy than the other two cycles.

The vehicle simulation models, given transmission and driveline characteristics and engine fuel consumption maps as a function of speed and load, predict the total amount of fuel energy required to complete the cycle. The fuel energy required to drive the cycle is much higher than the tractive energy because of losses due to accessories, idling, transmission/driveline, and losses in the engine due to friction, cooling, and exhaust. Figure 9-1 shows the simulated energy flows for a 2007 Toyota Camry on the city, highway, and US06 cycles.

Figure 9-1 shows that a small fraction of total fuel energy is delivered to the wheels as tractive energy. The ratio of tractive energy to fuel energy, representing efficiency of the powertrain and final drive, was 14%, 21%, and 24% for the urban,

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5 G. Sovran and D. Blaser, *Quantifying the Potential Impacts of Regenerative Braking on a Vehicle's Tractive-Fuel Consumption for the U.S., European, and Japanese Driving Schedules,* SAE Paper 2006-01-0664, 2006.

6 National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles,* June 2011 (NRC 2011).
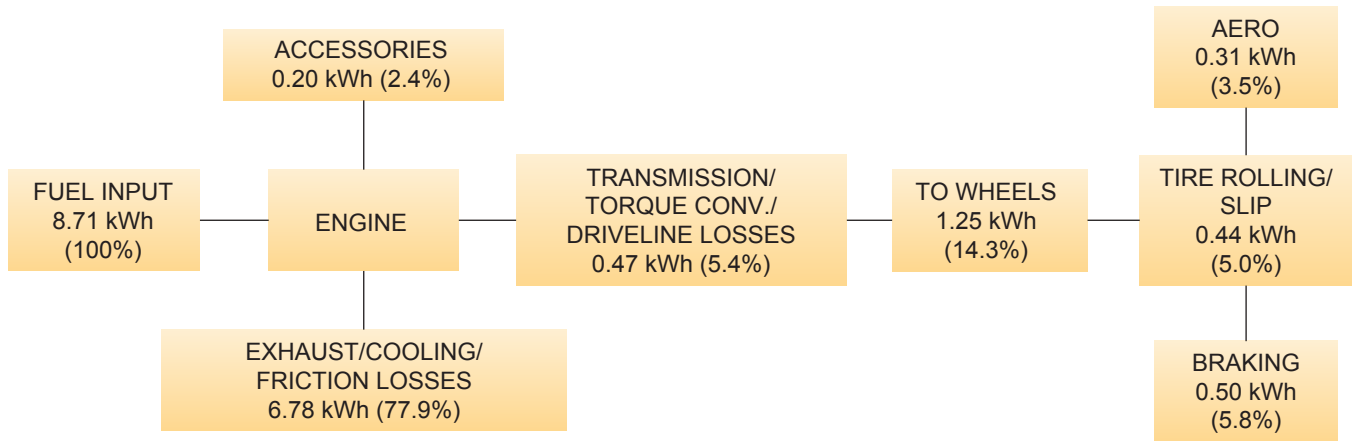
7 Mark J. Christie, Nicholas Fortino, and Hakan Yilmaz, *Parameter Optimization of a Turbo Charged Direct Injection Flex Fuel SI Engine,* SAE Paper 2009-01-0238, 2009.

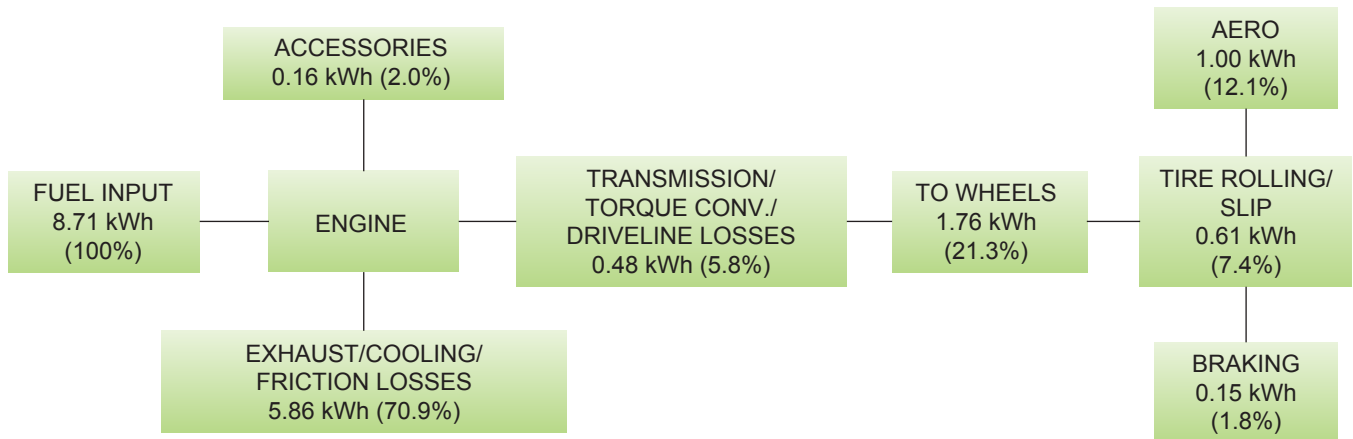|	Total Tractive Energy	Total Rolling	Total Aero	Braking Energy	Braking/ Tractive (%)
Urban	1.25	0.44	0.31	0.50	40.00
Highway	1.76	0.61	1.00	0.15	8.52
US06	2.39	0.66	1.17	0.56	23.43

Source: National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles,* June 2011.

Table 9-1. *Energy Distribution for Various Schedules for a 2007 Toyota Camry (Energy in Kilowatt-Hours)*
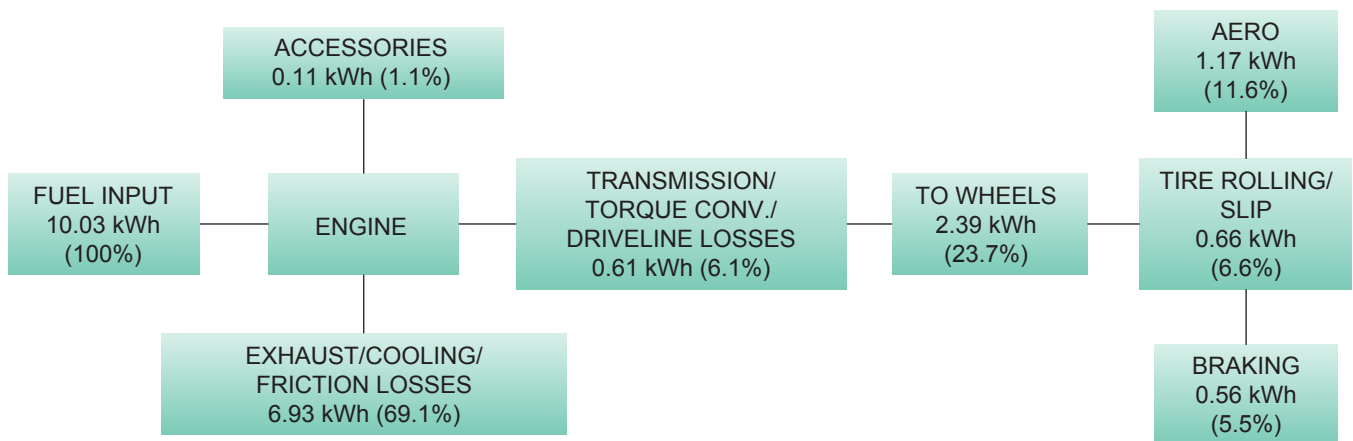
URBAN CYCLE:


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                    ACCESSORIES                                           AERO
                    0.20 kWh (2.4%)                                       0.31 kWh
                                                                          (3.5%)

                                    TRANSMISSION/                         TIRE ROLLING/
FUEL INPUT                          TORQUE CONV./          TO WHEELS      SLIP
8.71 kWh          ENGINE            DRIVELINE LOSSES       1.25 kWh       0.44 kWh
(100%)                              0.47 kWh (5.4%)        (14.3%)        (5.0%)

                    EXHAUST/COOLING/                                      BRAKING
                    FRICTION LOSSES                                       0.50 kWh
                    6.78 kWh (77.9%)                                      (5.8%)
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HIGHWAY CYCLE:

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                    ACCESSORIES                                           AERO
                    0.16 kWh (2.0%)                                       1.00 kWh
                                                                          (12.1%)

                                    TRANSMISSION/                         TIRE ROLLING/
FUEL INPUT                          TORQUE CONV./          TO WHEELS      SLIP
8.71 kWh          ENGINE            DRIVELINE LOSSES       1.76 kWh       0.61 kWh
(100%)                              0.48 kWh (5.8%)        (21.3%)        (7.4%)

                    EXHAUST/COOLING/                                      BRAKING
                    FRICTION LOSSES                                       0.15 kWh
                    5.86 kWh (70.9%)                                      (1.8%)
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US06 CYCLE:

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                    ACCESSORIES                                           AERO
                    0.11 kWh (1.1%)                                       1.17 kWh
                                                                          (11.6%)

                                    TRANSMISSION/                         TIRE ROLLING/
FUEL INPUT                          TORQUE CONV./          TO WHEELS      SLIP
10.03 kWh         ENGINE            DRIVELINE LOSSES       2.39 kWh       0.66 kWh
(100%)                              0.61 kWh (6.1%)        (23.7%)        (6.6%)

                    EXHAUST/COOLING/                                      BRAKING
                    FRICTION LOSSES                                       0.56 kWh
                    6.93 kWh (69.1%)                                      (5.5%)
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Source: National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles,* 2011.

Figure 9-1. *Energy Distribution for a 2007 Toyota Camry on Various Driving Cycles*

highway, and US06 cycles, respectively. Although fuel economy (miles/gallon) was lowest on the US06 cycle, powertrain efficiency on the US06 is highest because spark ignition engines operate most efficiently at high load. The largest share of energy is lost to heat that is removed by the coolant and exhaust. In addition 1–2% of fuel energy is used to power accessories and 5–6% of energy is lost in the driveline.

Aerodynamic losses are only 4% of fuel energy on the urban cycle, but increase to 12% of fuel energy for the higher speed highway and US06 cycles. Tire rolling resistance and slip account for 5–7% of fuel energy. The proportion of fuel energy lost in braking was 6% for the urban and US06 cycles but only 2% for the highway cycle, which has relatively mild decelerations.

The values in Table 9-1 and Figure 9-1 provide an indication of technology opportunities for reducing fuel consumption. For the urban cycle, for example, losses due to braking provide a clear opportunity for regenerative braking systems of hybrid electric vehicles that recapture some of this braking energy in the battery. Conversely, regenerative braking systems will provide little benefit on the highway cycle because braking is only about 2% of fuel energy. Although braking energy on the US06 cycle is high, hybrid systems typically do not have the capacity to recapture all of it. Hybrid vehicle systems also allow the engine to be shut off at idle, where all of the fuel energy is lost in the powertrain. The transmission losses shown in Figure 9-1 indicate significant opportunities for designs that eliminate losses in the torque converter, but new transmissions with more gear ratios can also help eliminate energy losses in the engine by keeping the engine operating at more efficient speeds.

Since losses to the coolant, exhaust, and friction in the engine comprise such a large share of fuel energy losses, more detailed discussion of the engine is warranted. Energy losses in the engine can be classified as thermodynamic losses, gas pumping losses, frictional losses, and parasitic losses. Thermodynamic losses occur when fuel combustion occurs at other than the ideal point in the cycle, when compression and expansion ratios are lower than ideal, and when thermodynamic properties of the gases are less than ideal (exhaust gas rather than air used as diluents to enable emissions control). Compression ratios

are lower than ideal to avoid knock with U.S. gasoline octane, which is lower than much of the rest of the world.

Well-known thermodynamic limits of heat engines prevent all thermodynamic losses from ever being eliminated. Pumping losses are primarily a result of throttling air flow to the intake system to control instantaneous power of spark ignition engines. Engine frictional losses occur primarily at the piston ring-cylinder interface and the crankshaft bearings. Parasitic losses in the engine include oil and coolant pumps, power steering, alternator, and balance shafts.

These vehicle energy loss mechanisms have been well understood for a number of years, and research continues on technologies to minimize losses and improve fuel economy. Over the years, a number of solutions that work under ideal laboratory conditions were identified that did not have practical benefit over the complete operating cycle of a vehicle. Recently, with the introduction of improved electronic control mechanisms, many solutions are appearing in production. A later section discusses various technologies, what energy losses they address, and a range of potential impact on reducing fuel consumption. As will be discussed later, tailpipe emissions limits can also constrain approaches to minimize energy losses during combustion.

U.S. Automobile Market Trends

The automobile market, much like the electronics market, incorporates new technology as it responds to the consumers' demand for more features. This is illustrated in the historical data compiled by EPA[8] and shown in Figure 9-2. The green curve shows combined laboratory fuel economy for cars and trucks. There was a sharp increase from 1975 to 1980 in response to fuel economy standards, high oil prices, and waiting lines at refueling stations. Since 1980, due in part to reduced oil prices, combined laboratory fuel economy has remained relatively constant until the last few years. Vehicle mass dropped as vehicles were downsized in the 1970s, but has largely increased since 1980.

The drop in mass during the 1970s resulted largely from segment downsizing and changing of

8   U.S. Environmental Protection Agency, *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2011,* March 2012.
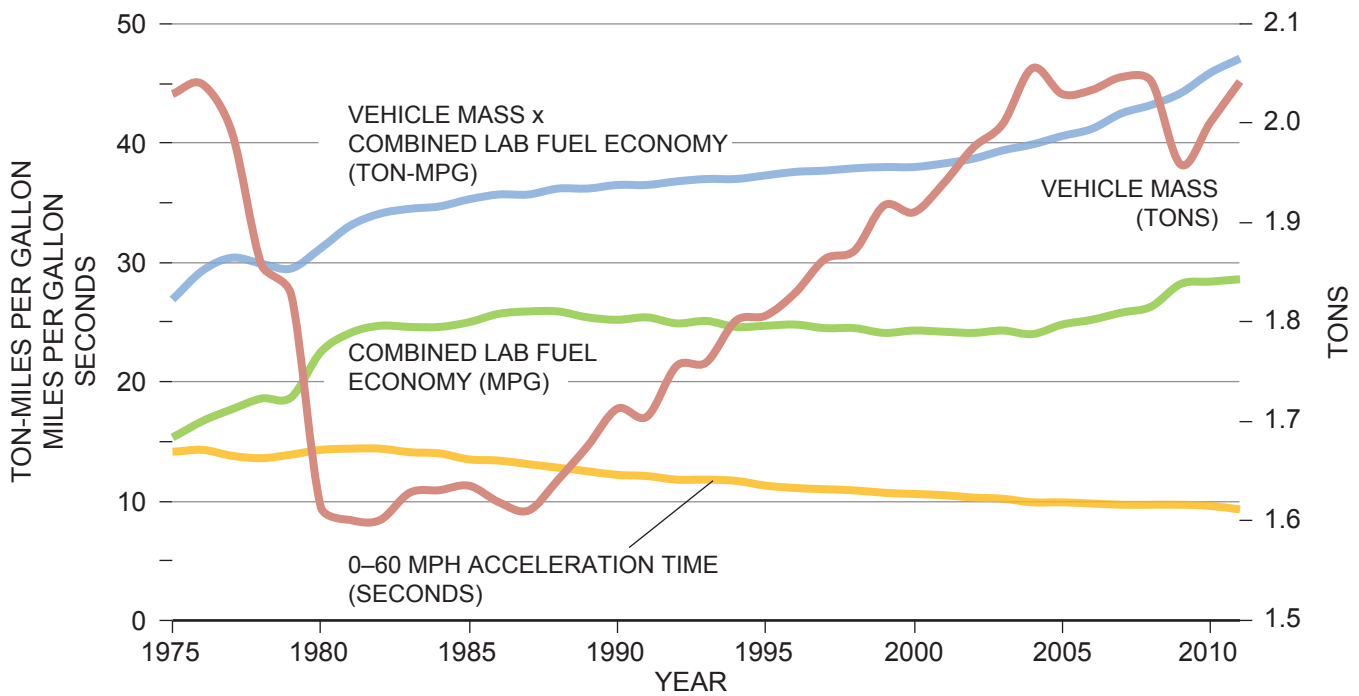
Source: U.S. Environmental Protection Agency, *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2011*, March 2012.

Figure 9-2. *Trends in Car and Light-Duty Truck Average Attributes Showing Changes in Customer Preference*

passenger car platforms from body-on-frame to unibody design. (Body-on-frame carries the structure in an H shaped steel subframe upon which the largely non-structural vehicle body is bolted. Unibody design carries the structure in an integrated welded steel floorplan, engine cradle, door, and roof frames.) The increase in mass since 1980 resulted from consumer demand for vans and sport utilities, increased safety equipment, content, and features. During this same period of time, the market preference for increased performance is illustrated by the decrease in 0–60 mph acceleration times. The remaining curve on Figure 9-2 is obtained by multiplying the combined laboratory fuel economy by the vehicle mass in tons. According to EPA, this ton-mpg parameter is a measure of powertrain/driveline efficiency. Ton-mpg (Figure 9-2) has increased at a cumulative annual growth rate of 1%/year since 1983.

Consumers have a vast array of options available to them when they purchase a vehicle. The trends in Figure 9-2 would look much different if consumers had selected the subcompact over the sport utility or the 4-cylinder compact instead of the V-6. Improved safety has been an important trend as illustrated in Figure 9-3.[9] In an earlier review, the Congressional Budget Office found:

Vehicles' current level of fuel efficiency most likely reflects consumers' trade-offs between fuel economy and other characteristics that drivers want, such as vehicle size, horsepower, and safety. The same technologies that can be used to boost fuel economy can also be used to hold fuel economy constant while increasing the vehicles' weight, size, or power. Thus, the fact that producers have done the latter rather than the former in recent years suggests that they have responded to buyers' preferences by targeting available technologies toward other features that consumers desire.[10]

9   National Highway Traffic Safety Administration, *2008 Traffic Safety Annual Assessment,* DOT HS 811 172, June 2009.

10 Congressional Budget Office, "Page 10" in *Reducing Gasoline Consumption: Three Policy Options,* November 2002.
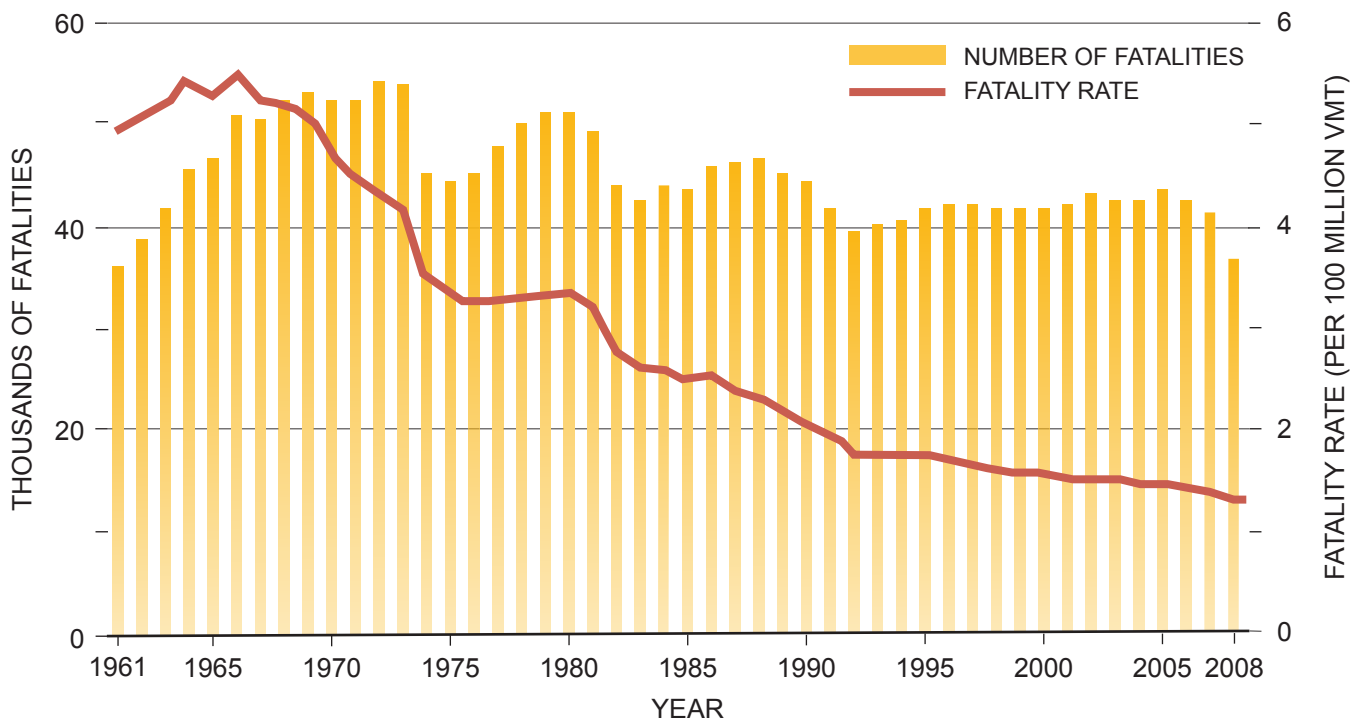
Source: National Highway Traffic Safety Administration, *2008 Traffic Safety Annual Assessment*, June 2009.

Figure 9-3. *Fatalities and Fatality Rates per 100 Million Vehicle Miles Traveled from 1961–2008*

Speculation on the possibility of future changes in desires of consumers is beyond the scope of this chapter.

One of the factors driving the increased mass in Figure 9-2 is vehicle content that improves crash safety. Safety content includes items such as strengthened front and rear structures, door beams, roof pillars, airbags, and improved bumpers. As shown in Figure 9-3, the fatality rate reduced substantially during this period.

Incremental Technology Pathways for Fuel Consumption Reduction

A variety of technologies is available to reduce many of the energy losses described in the previous section. Substantial reductions in fuel consumption will not be achieved with a single technology, but will require appropriate technology combinations. Estimating the benefits of technology combinations requires care because multiple technologies are available to address one specific source of energy loss. For example, turbocharging/downsizing, valve

event modulation, and lean burn combustion all work in part by reducing pumping or gas exchange losses in a spark ignition engine. The benefits of adding one of these technologies will vary based on whether other of the technologies has already been added. Engine and vehicle system modeling is required to properly assess the impact.

Several recently published studies by the NRC[11] and EPA/NHTSA[12,13] provide a review and analysis of technology opportunities for reducing LD vehicle fuel consumption. The most useful studies of fuel consumption reduction potential include use of full vehicle simulation to quantify the technology

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11 NRC 2011 (see footnote 6).

12 U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, *Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standard and Corporate Average Fuel Economy Standards,* Joint Technical Support Document, Report EPA-420-R-10-901, April 2010 (EPA/NHTSA 2010a).

13 U.S. Environmental Protection Agency, National Highway Traffic Safety Administration, and California Air Resources Board, *Interim Joint Technical Assessment Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025,* September 2010 (EPA/NHTSA 2010b).

impacts on the appropriate driving cycles and avoid double counting of competing technologies that address one specific vehicle energy loss mechanism.

Vehicle-Level Technologies

This section will first describe pathways for fuel consumption reduction that could be applied, independently of the propulsion system. The technologies and their impact are summarized in Table 9-2. Improvements in tire design reduce rolling resistance but continued technology improvements are required to avoid compromises in stopping performance and ride. Fuel consumption reduction estimates range from 1–3% with the upper range representing an impressive reduction of half of the baseline energy losses (see Figure 9-1)

Technology	Description	Fuel Consumption Reduction	
		NRC 2011	EPA/NHTSA 2010a and 2010b
Reduced rolling resistance	Optimize tire materials, shape, tread design, inflation without compromising performance	1–3%	1–2%
Improved aerodynamics 1	Improved design, covers in underbody and wheels achieves 5–10% reduction in drag	1–2%	2–3%
Improved aerodynamics 2	Active grille shutters, rear visors, and larger under body panels (EPA/NHTSA 2010b)		2%
5% mass reduction	Moderate substitution of materials with resized powertrain	3–3.5%	
10% mass reduction	Aggressive substitution of materials with resized powertrain	6–7%	
15% mass reduction	Details confidential; includes material substitution, smart design, and mass reduction compounding (EPA/NHTSA 2010b)		*
20% mass reduction	Redesigned body with aluminum and composite intensive structures with resized powertrain	11–13%	*
30% mass reduction	Details confidential; includes material substitution, smart design, and mass reduction compounding (EPA/NHTSA 2010b)		*
Cumulative		**11–15%** (20% mass reduction)	**16–22%** (30% mass reduction)

* EPA/NHTSA 2010a and EPA/NHTSA 2010b did not provide estimates of impact of mass reduction on fuel consumption; for every 10% reduction in vehicle mass, a 4–6% reduction in fuel consumption was assumed in this study.

Sources: National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles,* June 2011 (NRC 2011).

U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, *Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standard and Corporate Average Fuel Economy Standards,* Joint Technical Support Document, Report EPA-420-R-10-901, April 2010 (EPA/NHTSA 2010a).

U.S. Environmental Protection Agency, National Highway Traffic Safety Administration, and California Air Resources Board, *Interim Joint Technical Assessment Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025,* September 2010 (EPA/NHTSA 2010b).

Table 9-2. *Vehicle Level Fuel Consumption Reduction Technologies*

due to rolling and slip. Low cost changes to reduce aerodynamic drag can achieve 1–2% reduction in fuel consumption. More aggressive and expensive options include grille shutters, rear visors instead of mirrors, and larger under body panels.[14] The NRC examined 2%, 5%, 10%, and 20% mass reduction, while the EPA and NHTSA considered 15%, 20%, and 30% mass reduction. Table 9-2 describes the technology for the mass reduction assumptions by NRC. EPA/NHTSA did not provide fuel consumption results for mass reduction technology alone; instead the impact of mass reduction was combined with other technologies as part of their vehicle modeling. Based on the EPA/NHTSA assumptions, the total cumulative reduction in fuel consumption for vehicle technologies is about 20%.

Another topic to consider with mass reduction is what has been called mass decompounding.[15] Introduction of clean sheet vehicle designs are required to take full advantage of mass decompounding. If components or subsystems can be lightweighted early in the vehicle development process, then other vehicle systems can be lightweighted, and the resulting vehicle performance and fuel economy can be improved, giving rise to the concept of mass decompounding. With mass decompounding, primary weight reduction permits secondary mass reduction to be achieved. Estimates of the magnitude of the impact of mass compounding vary across the literature. Based on the results of Malen, Verbrugge[16] estimates that for every 1 kg of primary mass removed early in the vehicle design, an additional 1 kg of secondary mass can also be removed. NRC estimated secondary benefits of up to an additional 30% of primary mass reduction, based on a report by IBIS Associates.[17] EPA/NHTSA, based on MIT studies,[18,19]

used a value of 1.5, the value adopted for this study. The impact of mass decompounding is significant because it impacts both the cost and the fuel consumption benefits of mass reduction.

Opportunities for mass reduction include changing vehicle design to use less material and substituting lighter materials for traditional materials. Figures 9-4 and 9-5 show vehicle mass distribution by subsystem and material. Mass reduction solutions can depend on whether the component has strength or stiffness as a design limit. When strength is the design limit, steel components can be substituted with thinner components of high strength steel, reducing mass while maintaining strength. Traditionally, forming high strength steel has been a limitation, but major progress has been made. When stiffness is a design limit, such as in structural components, technology employing layered material, with a lighter material sandwiched between outer layers of steel, can be used. This sandwich technology is expensive and difficult to join.

As discussed earlier, most high volume vehicles in production today are unibody designs. Aluminum

Note: Subsystem mass as a percentage of curb mass, average of selected 2002–2007 sedans.

Source: Mark Verbrugge et al., "Mass Decompounding and Vehicle Lightweighting," *Materials Science Forum* 618-619 (2009).

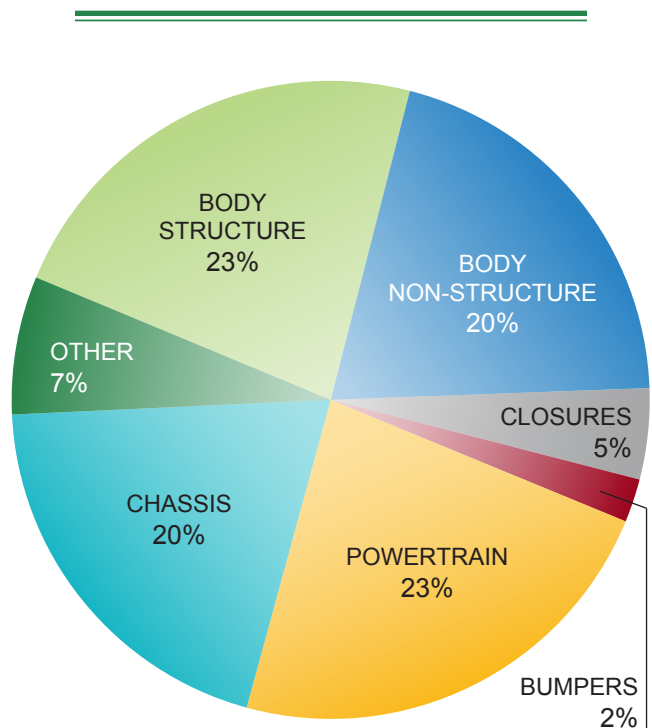**Figure 9-4.** *Typical Mass Distribution by Vehicle Subsystem*

14 Ibid.

15 D. E. Malen and K. Reddy, *Preliminary Vehicle Mass Estimation Using Empirical Subsystem Influence Coefficients,* May 2007 (Revised June 26, 2007).

16 Mark Verbrugge, Theresa Lee, Paul Krajewski, Anil Sachdev, Catarina Bjelkengren, Richard Roth, and Randy Kirchain, "Mass Decompounding and Vehicle Lightweighting," *Materials Science Forum* 618-619 (2009), pages 411-418.

17 IBIS Associates, *Benefit Analysis: Use of Aluminum Structures in Conjunction with Alternative Power Train Technologies in Automobiles,* Waltham, MA, 2008.

18 Catarina Bjelkengren, "The Impact of Mass Decompounding on Assessing the Value of Vehicle Lightweighting," Masters Thesis, Massachusetts Institutes of Technology, June 2008.
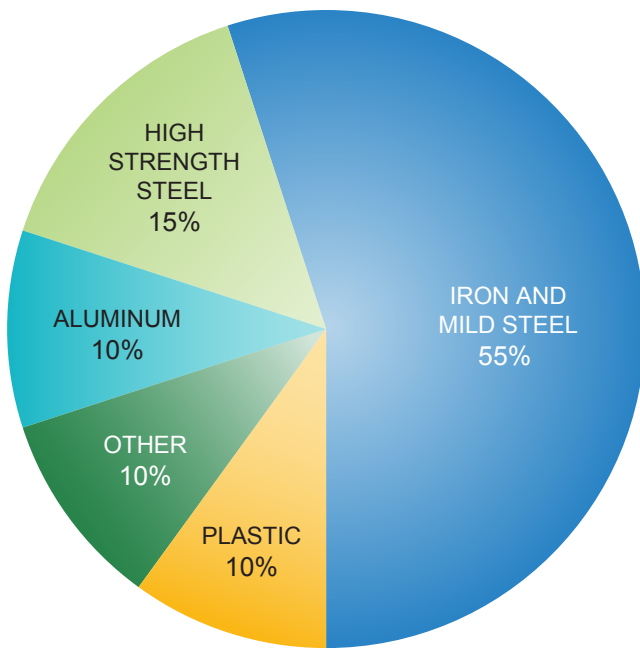
19 Matthew A. Kromer and John B. Heywood, *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet,* Laboratory for Energy and the Environment, LFEE 2007-03 RP, May 2007.

Note: Material shares in a typical 2009 midsize sedan, mass%.
Source: National Research Council of the National Academies,
Assessment of Fuel Economy Technologies for Light-Duty Vehicles, June 2011.

Figure 9-5. *Typical Mass Distribution by Material*

can substitute for steel in a unibody design. However, due to its other attributes, aluminum body structures can also be based on a space frame design, one in which extruded aluminum components are joined at their ends. Aluminum space frame designs, which have lower manufacturing investment costs but higher material costs, are economically suited to vehicle designs with low production volumes, which tend to be premium applications with premium pricing. However, since not all body panels contribute to structure in space frames, weight efficiency is compromised.

Magnesium is even lighter than aluminum. However, its properties may make it unsuitable for use in space frames or other structural materials. Because magnesium is brittle, crash energy management is difficult. Work is underway to develop higher toughness magnesium alloys.

The Minerals, Metals, and Materials Society (TMS), in a recent publication,[20] identified light-

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20 The Minerals, Metals, and Materials Society, *Linking Transformational Materials and Processing for an Energy-Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization*, February 2011. http://energy.tms.org/docs/pdfs/Opportunity_Analysis_for_MSE.pdf.

weight materials, such as aluminum, magnesium, titanium, and polymer-based materials as key to reducing weight in transportation body and structural applications. However, according to TMS, today's use of such materials is limited by high cost, corrosion issues, forming and assembly challenges, and end of life materials management challenges. Gaps and limitations for these materials, identified by TMS include:

- Poor corrosion and wear resistance

- Lack of technology for integrating dissimilar materials into automobile body structures

- Lack of synthesis, processing, and manufacturing technologies for titanium, magnesium, and composites that meet targeted costs and properties

- Inability to detect crash damage to low-cost, light materials in situ.

TMS identified top-priority research areas to overcome these limitations. Commercialization of these new technologies is expected in 5–20 years.

Polymer matrix composites (PMC), polymers reinforced with glass, natural, or carbon fibers, are having increasing application in vehicle production. Carbon fiber PMC is of major interest for mass reduction because its strength and stiffness exceed that of steel. Following is a quote from EPA/NHTSA on magnesium and carbon fiber PMC:

A number of firms also discussed the more advanced light-weight materials such as carbon fiber and magnesium. While these materials can offer very significant mass reduction, in general these materials are only used on more exotic luxury or high performance vehicles. There are, of course, examples of vehicles today which use carbon fiber, but they tend to be very expensive, ultra-high performance vehicles (such as the limited edition Ferrari Enzo, or the Mercedes SLR MacLaren) or in other cases the amount of carbon fiber in the vehicle is for a few select components (such as in the high performance Corvette ZR1 or the high performance Lexus ISF). A number of automotive firms are exploring the ability to produce a less expensive automotive grade carbon fiber, but in general companies did not see carbon fiber, or for that matter

magnesium, as playing a major role in the 2017-2025 time frame.[21]

TMS also identified carbon fiber PMC as a promising automotive material, not only because it is lightweight, but also because it consumes less energy in manufacturing than metals and because it is corrosion resistant. However, TMS highlights the need for research to overcome the following gaps and limitations:

- Processes to produce complex geometries are expensive and energy intensive

- Manufacturing of layered/hybrid material systems for damage tolerance and corrosion resistance is only possible at high costs

- Fiber-substrate adhesion limits the strength of composites.

BMW has announced plans for producing two new models in 2013 that incorporate advanced lightweighting technologies. To reduce vehicle structure and body mass, according to BMW:

An aluminum chassis houses the powertrain, and the passenger cell consists of high-strength but extremely lightweight carbon reinforced plastic (CFRP).[22]

The smaller of the two vehicles, i3, is a battery electric urban vehicle in which the vehicle mass reduction offsets the mass increase of the batteries. The larger performance vehicle, i8, is a plug-in hybrid. With these vehicles, BMW appears to be working on a near "clean sheet" effort in which new materials, suppliers (including significant equity interest in the carbon fiber supplier), vehicle design and engineering, propulsion systems, manufacturing processes, and branding are all being attempted at the same time. Other manufacturers of premium and mass-market vehicles are also thought to be experimenting with expanded use of carbon fiber to varying degrees. Table 9-2 summarizes the NRC analyses on three levels of mass reduction. The NRC assessment of the impacts of mass reduction on fuel consumption was based on a Ricardo, Inc. study,[23]

which included the impact of engine resizing, but did not include the impact of decompounding on redesign of other vehicle components. According to NRC, 5% vehicle mass reduction could be achieved with moderate substitution of materials, aggressive substitution of materials could achieve 10% vehicle mass reduction, and redesigned aluminum and composite-intensive structures could achieve 20% mass reduction, although NRC found 20% mass reduction to not be cost effective. As vehicle mass is reduced, powertrain size could also be reduced because tractive energy requirements are reduced. Including the impact of powertrain resizing, 5%, 10%, and 20% vehicle mass reduction could reduce fuel consumption by about 3%, 6%, and 12%, respectively, in vehicles without regenerative braking and 2%, 4%, and 8%, respectively, in vehicles with regenerative braking.

Greater potential for mass reduction was identified in EPA/NHTSA than that of NRC. The primary resource used by EPA/NHTSA was a study by Lotus Engineering.[24] In their study, Lotus tore down and analyzed all of the non-powertrain parts in a Toyota Venza. Considering both proven and emerging technologies, Lotus conducted an analysis to assess mass reduction potential. Lotus eliminated some parts and replaced others with lightweight materials such as high strength steel, aluminum, magnesium, and composites. In what Lotus called the High Development Concept, with technologies estimated to be feasible for 2020 production, mass savings of 38% for the vehicle, not including the powertrain, were estimated. The scope of the Lotus study did not include a full validation of whether their concepts would pass typical tests to validate compliance with customer requirements, durability, or manufacturability that the automobile industry would complete before putting these technology concepts into production.

EPA/NHTSA analyzed pathways with three different levels of vehicle mass reduction: 15%, 20%, and 30%. As of the completion of their report, safety assessment of these mass reduction options are planned but had not been conducted. In addition EPA and NHTSA along with other U.S. government agencies plan a peer review of the Lotus study. Lutsey of UC Davis reviewed studies and concept

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21 EPA/NHTSA 2010b (see footnote 13).

22 BMW, "Revolutionary Vehicle Concepts," press release issued February 21, 2011.

23 Ricardo, Inc., *Impact of Vehicle Weight Reduction on Fuel Economy for Various Vehicle Architectures,* Research Report, prepared for the Aluminum Association, Inc., 2007.

24 Lotus Engineering Inc., *An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program*, March 2010.

vehicles demonstrating mass reduction technologies.[25] Lutsey concluded that 20–35% vehicle mass reduction was feasible.

The studies from EPA/NHTSA, Lotus Engineering, and Nicholas Lutsey also found mass reduction to be less expensive than in the NRC study. This difference will be explored more in a later section. However, all of these studies found that the cost of mass reduction increases as an exponential function of the percentage of mass reduced.

The Rocky Mountain Institute sees even greater opportunity for vehicle mass reduction.[26] Their Revolution concept car emphasized a design based on achieving low mass. The structure was carbon fiber intensive. Mechanical vehicle dynamic components were replaced with electronics. The Revolution concept had an overall 50% mass reduction compared to a benchmark. More recent concept cars making extensive use of carbon fiber include the BMW vehicles mentioned above and the Toyota 1X concept vehicle.

Although the preceding discussion involves mass reduction, it should be noted that most alternative propulsion systems can increase vehicle mass due to fuel storage systems for gaseous fuels or batteries in hybrid and electric vehicles. Vehicle mass increases can also be caused by consumer demand and/or regulatory requirements for added features and content. In these cases, the vehicle mass reduction technologies may be needed just to offset the increased mass of energy storage and other added content. It should also be mentioned that increases in gross vehicle weight (GVW) due to increased number and/or mass of passengers and gear onboard has a real-world impact on fuel economy of any given vehicle.

Spark Ignition Engine Powertrain Technologies

This section shows options for reducing spark ignition engine energy losses that were shown in Figure 9-1. Table 9-3 lists and quantifies technologies to reduce fuel consumption of spark ignition engines. Included in Table 9-3 are technologies that reduce energy losses in the engine, transmission, and accessories. The first two items address energy losses due to friction. Dual cam phasing, continuously variable valve lift, and turbocharging/downsizing all reduce engine pumping losses. Gasoline direct injection improves combustion thermodynamics by allowing the engine to operate at a higher compression ratio. Improved accessories and electric power steering reduce losses due to accessory loads.

For most technologies, the NRC[27] and EPA/NHTSA[28] assumptions for fuel consumption reduction of specific technologies agree pretty well. Exceptions are the dual clutch transmission and downsizing and turbocharging technologies, where the EPA/NHTSA benefit assumptions are substantially greater than those of NRC. Cumulative fuel consumption reductions for these technologies ranged from 13–28% for NRC and 30–38% for EPA/NHTSA.

A major factor in the higher cumulative fuel consumption reduction for EPA/NHTSA is the assumption of 15% fuel consumption reduction using a combination of turbocharging, downsizing, and dual cam phasers. One potential explanation for the discrepancy compared to NRC is a difference in assumptions about how much boost can be provided by the turbocharger. Higher boost levels provide opportunity for greater magnitudes of downsizing. Engine boost is limited by engine knock, and is therefore impacted by fuel octane. The NRC analysis specifically limited the benefits to that which could be achieved with regular gasoline because otherwise the benefit could not be solely attributed to turbocharging and downsizing.

Engine knock, and therefore boost levels, are also limited by temperatures of the gas charge delivered to the engine. Exhaust gas recirculation (EGR), which is used in many engines for emissions and efficiency, increases charge temperatures. Adding technology to cool EGR has the potential for increasing the benefits of turbocharging and downsizing. EPA/NHTSA[29] estimates that gasoline direct injection, dual cam phasers, and turbocharging/downsizing with cooled EGR can reduce fuel consumption

25 Nicholas Lutsey, *Review of technical literature and trends related to automobile mass-reduction technology,* UCD-ITS-RR-10-10, prepared for California Air Resources Board, May 2010.

26 Amory Lovins and David Cramer, "Hypercars, hydrogen, and the automotive transition," *International Journal of Vehicle Design* 35, no. 1–2 (2004): pages 50-85.

27 NRC 2011 (see footnote 6).

28 EPA/NHTSA 2010b (see footnote 13).

29 EPA/NHTSA 2010b (see footnote 13).

Technology	Description	Fuel Consumption Reduction	
		NRC 2011	EPA/NHTSA 2010a and 2010b
Low friction lubricants	Formulations that reduce engine friction	0.5%	0.5%
Engine friction reduction	Engine design and materials that reduce engine friction	0.5–2%	1–3%
Dual cam phasing	Valve event modulation that dynamically varies intake and exhaust valve overlap	1.5–3%	2–4%
Continuously variable valve lift	Valve event modulation that allows valve lift to continuously vary with operating conditions	3.5–6.5%	4–6%
Turbocharging and downsizing	Downsizing an engine combined with turbocharging to maintain power; EPA/NHTSA 2010b includes more aggressive downsizing and cooled EGR	2–5%	11–13%
Gasoline direct injection	Gasoline injection directly into combustion chamber enables increased compression ratio	1.5–3%	1–2%
Dual clutch 6-/7-speed transmission	Eliminates energy losses in transmission torque converter. When replacing 4-speed transmission provides more efficient engine operation	3–9%	8–13%
Electric power steering	Power steering provided by electricity rather than hydraulics	1–3%	1.5–2%
Improved accessories	Engine accessories with improved efficiency	0.5–1.5%	1–2%
Cumulative		**13–28%**	**27–38%**

Sources: National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles,* June 2011 (NRC 2011).

U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, *Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standard and Corporate Average Fuel Economy Standards,* Joint Technical Support Document, Report EPA-420-R-10-901, April 2010 (EPA/NHTSA 2010a).

U.S. Environmental Protection Agency, National Highway Traffic Safety Administration, and California Air Resources Board, *Interim Joint Technical Assessment Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025,* September 2010 (EPA/NHTSA 2010b).

Table 9-3. *Gasoline Spark Ignition Engine Technologies and Benefits*

20% relative to a typical 2008 engine. Following is a quote from NRC on cooled EGR:

> The fuel consumption benefits of this feature are highly dependent upon the base engine to which it is applied and the engine's operating map in a particular vehicle. As the heat exchanger must be equipped with a diverter valve to accommodate heat-exchanger bypass for lighter-load operation, the sequences of carbonaceous deposit formation in the heat exchanger, in the diverter and control valves and in the turbine are among the real-world factors that can compromise the overall performance of this feature.[30]

Higher octane gasoline would enhance the fuel consumption reduction that could be achieved with turbocharging/downsizing technology. Although

30 NRC 2011 (see footnote 6).

premium fuel is available, not all customers pay the extra cost of premium even in a vehicle designed for premium. Increasing the minimum U.S. octane would enable increased vehicle fuel economy, but would require increased investment and energy usage in the refinery or additional high octane components such as ethanol. Clearly, the potential benefits of turbocharging technology could be enhanced by increasing the minimum octane of gasoline in the United States or by engines dedicated to the use of E85 or other high ethanol blends. The impacts of octane and E85 on benefits of turbocharging and downsizing are discussed in a later section.

Hybridization Technologies

To reduce fuel consumption, hybrid electric vehicles incorporate electric energy storage, at least one motor to convert the stored energy into motion, and an internal combustion engine. Several of the energy losses discussed above are addressed by hybridization. Hybrid systems incorporate means to avoid wasting fuel while the vehicle is temporarily stopped, for example at a red traffic light or while the vehicle is moving slowly on a congested roadway (low-speed electric-only mode). Also, hybrid systems can store and reuse some of the energy lost during braking. Furthermore, hybrid systems can enable more efficient operation of the powertrain because, as was shown in Figure 9-1, relative magnitudes of the energy losses vary with driving cycle.

As is shown in Table 9-4, there is a range of technologies, and associated benefits, to propulsion systems that have been called hybrid. The most fundamental micro hybrid design, which is called belt-driven alternator starter (BAS), may not meet the technical definition of a hybrid because stored electricity is only used to start the engine, not propel the vehicle. This mode of operation has also been called "start-stop" or "idle-stop." When used with an automatic transmission, a system to maintain hydraulic pressure in the transmission is necessary for a smooth and rapid vehicle launch. Fuel consumption benefits are modest, and are greater for urban driving and greater for spark ignition engines that have not been downsized and do not have valve event modulation.

Full hybrid designs have sufficient electrical energy storage and large enough motor(s) to provide very low speed all-electric driving, acceleration assist, and regeneration during braking. Typi-

cally the battery charge is sustained over a very narrow state of charge, to prolong battery life, and the engine operates over a relatively narrow speed-load range to maximize efficiency. Three different strong hybrid architectures are generally in use: integrated starter/generator, power split, and two-mode.

In the integrated starter/generator design, a large electric motor between the engine and transmission replaces the starter and generator of a conventional engine. The battery has higher storage capacity and higher voltage (up to 140V) than in the BAS system. The motor/generator and battery are powerful enough to launch the vehicle and provide some all-electric travel. The Honda Civic hybrid is the best-known example of this design, which provides a fuel consumption reduction of roughly 35%.

Another hybrid architecture is called the power split. In this design, the engine, motor/generator, and driveshaft are connected by a differential gear set. With this design, the wheels can be powered by both the engine and the motor, allowing the engine to be optimized for low fuel consumption. Excess power generates electricity that is stored in the battery. Stored electricity can be used by the electric motor to launch the vehicle, operate all electric at low speeds, and provide power assist. This design also incorporates regenerative braking and engine stop at idle. Examples of vehicles using the power split architecture are the Toyota Prius, Ford Escape, and Nissan Altima hybrid models. Fuel consumption reduction for the power split hybrid is nearly 40%.

A variation on the power split concept, called two-mode, was first developed for urban transit buses. The two-mode design uses more clutches and gears than the power-split design to match power supply to demand. This minimizes electrical efficiency losses in the generator and motor and provides benefits at high speed and while towing. This design, which has been used in the Chevrolet Tahoe and Saturn Vue, has fuel economy reduction potential of up to 45%.

The hybridization architectures described above provide a guideline for the options available and their benefits. However, future systems are likely to be made using combinations of these concepts, providing a continuum of options. For example,

Technology	Description	Fuel Consumption Reduction	
		NRC 2011	EPA/NHTSA 2010a and 2010b
12V Belt-Driven Alternator Starter (start-stop)	Allows the engine to be stopped at idle and quickly started for acceleration; system voltage remains 12V	2–4%	
42V Belt-Driven Alternator Starter (start-stop)	Allows the engine to be stopped at idle and quickly started for acceleration; system voltage increases to 42V		7.5%
Integrated Starter/ Generator	Recovers energy from regenerative braking in addition and provides all-electric launch	29–39%	20–30%
P2 Hybrid	Electric drive motor coupled to the engine crankshaft via a clutch, making the engine and the drive motor mechanically independent		30%
Power Split Hybrid	Differential gearset allows wheels to be powered by engine, motor, or combination	24–50%	35%
Two-Mode Hybrid	Differential gearset with additional clutches and gears to increase torque capability and reduce electrical losses	25–45%	25–40%

Sources: National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles,* June 2011 (NRC 2011).

U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, *Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standard and Corporate Average Fuel Economy Standards,* Joint Technical Support Document, Report EPA-420-R-10-901, April 2010 (EPA/NHTSA 2010a).

U.S. Environmental Protection Agency, National Highway Traffic Safety Administration, and California Air Resources Board, *Interim Joint Technical Assessment Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025,* September 2010 (EPA/NHTSA 2010b).

Table 9-4. Hybrid Technologies for Spark Ignition Engines

EPA/NHTSA[31] use a concept called a P2 hybrid as their model hybrid architecture. A P2 hybrid is a concept in which a motor is connected to the engine crankshaft through a clutch. This is more complicated than the integrated starter/generator system, but adds a clutch, larger motors, and larger batteries. EPA/NHTSA estimate the fuel consumption reduction for P2 hybrid at 30%, similar to the reduction assumed by NRC for the integrated starter/generator hybrid. Full system simulation of the P2 concept by Ricardo[32] for EPA found 18–22% fuel consumption reduction on the urban cycle and no benefit on the highway cycle.

Series hybrids and other plug-in technologies are addressed in Chapter Thirteen, "Electric."

Diesel Technologies

Compression ignition diesel engines offer reduced fuel energy consumption because combustion uses lean fuel-air mixtures, throttling losses are avoided, and compression ratios are higher than those for gasoline engines. In addition, on a volume basis, fuel consumption is reduced because diesel fuel has a higher volumetric heating value than gasoline. Technologies and benefits for a diesel engine powertrain package are given in Table 9-5 based on assumptions in NRC. The first four technologies listed are the same as those for gasoline engines. Cumulative reduction in fuel consumption ranged from 23–51% on a volume basis or 20–44% on an energy basis. Lack of suitable solutions for diesel aftertreatment led EPA/NHTSA to leave diesel

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31 EPA/NHTSA 2010b (see footnote 13).

32 Ricardo, Inc. and Systems Research and Applications Corporation, *Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe,* Report EPA-420-R-11-020, prepared for the U.S. Environmental Protection Agency, December 2011.

engines out of their analysis, so the last column in Table 9-5 is blank.

Potential Future Combustion Technologies

Gasoline Lean Burn Combustion Technologies

The spark ignition powertrain technologies described above all operate at a stoichiometric or chemically balanced air fuel ratio, allowing the exhaust aftertreatment system to simultaneously oxidize hydrocarbon and carbon monoxide emissions and reduce nitrogen oxide (NOx) emissions. However, it is well known that stoichiometric combustion of gasoline delivers less than peak efficiency. A review paper describes two promising lean gasoline combustion technologies, direct injection spark ignition stratified charge (DISC) and homogenous charge compression ignition (HCCI).[33] Lean combus-

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[33] Alex C. Alkidas, "Combustion Advancements in Gasoline Engines," *Energy Conversion and Management* 48, no. 11 (2007): pages 2751–2761.

tion reduces pumping losses and heat transfer losses, and the cycle efficiency is improved because of the improved thermodynamic gas properties. To maximize fuel economy, both technologies require expensive spray-guided direct injection systems, whereas essentially all stoichiometric direct injection systems in production are lower cost wall-guided injection systems. Variable valve and combustion sensing systems are also required as enablers.

The DISC system is designed to provide richer fuel-air mixtures near the spark plug than in the remainder of the combustion chamber. Ignition occurs in richer portion of the stratified charge and then propagates through the remainder of the fuel-air mixture. The primary disadvantage of the DISC system is the requirement for an aftertreatment system that reduces NOx in lean exhaust, is expensive, and compromises the fuel economy benefit.

The HCCI system is designed to provide a homogeneous lean mixture throughout the combustion

Technology	Description	Fuel Consumption Reduction	
		NRC 2011	EPA/NHTSA 2010b
Low friction lubricants	Formulations that reduce engine friction	0.5%	
Dual clutch 6/7 speed transmission	Eliminates energy losses in transmission torque converter. When replacing 4-speed transmission provides more efficient engine operation	3–9%	
Electric power steering	Power steering provided by electricity rather than hydraulics	1–3%	
Improved accessories	Engine accessories with improved efficiency	0.5–1.5%	
Conventional diesel	Direct-injected, turbocharged, compression ignition engine reduces fuel consumption due to lean mixtures, no throttling, and higher compression ratio	15–35%	
Advanced diesel	Diesels with downsizing, 2-stage turbochargers, down-speeding, friction reduction, combustion improvement, and improved transmissions	7–13%*	
Cumulative		**23–51%**	

*Relative to conventional diesel.

Sources: National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles,* June 2011 (NRC 2011).

U.S. Environmental Protection Agency, National Highway Traffic Safety Administration, and California Air Resources Board, *Interim Joint Technical Assessment Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025,* September 2010 (EPA/NHTSA 2010b).

Table 9-5. *Diesel Engine Technologies and Benefits*

chamber. This mixture is generally too lean to ignite with a spark plug, but is instead ignited by the temperature achieved during compression. HCCI systems are designed to operate at a lean enough fuel-air ratio to eliminate the need for lean NOx aftertreatment. Since gasoline fuels are resistant to compression ignition, means to increase the charge temperature higher than those in a spark ignition engine are required. In addition, gasoline HCCI engines require techniques to control the phasing of combustion for optimum efficiency. Techniques that have been used for heating and combustion control include intake charge preheating, high compression ratio, external EGR, internal EGR, direct injection during compression with both valves closed (negative valve overlap), and spark-assisted ignition.

Both DISC and HCCI combustion systems provide lean combustion during only a portion of the engine speed load range.[34] At very low and high speeds and loads, conventional stoichiometric combustion is required for combustion stability and power density. Consequently, these combustion systems require fuels of octane similar to those for conventional stoichiometric engines. Alkidas estimates a 15% fuel economy benefit (13% reduction in fuel consumption) compared to a conventional port fuel injection (PFI) engine. For the stoichiometric spark ignition engine technologies listed in Table 9-3 (gasoline direct injection, dual cam phasing, and continuously variable valve lift), cumulative reductions in fuel consumption range from 6 to 11%. Therefore, these lean burn systems offer approximately an additional 2–7% reduction in fuel consumption compared to that in Table 9-3. EPA/NHTSA[35] estimate the benefits of DISC and HCCI, relative to a non-turbocharged stoichiometric GDI, at 10–12%. Since DISC and HCCI achieve efficiencies by reducing pumping losses at light load, benefits are likely to be smaller when compared to that achievable with turbocharged and downsized engines.

Although there has been limited production of DISC spray-guided systems in Europe, DISC and HCCI are primarily still in a research and development stage. Consequently, none of the available references provide estimates of the expected price of these technologies. They are, however, technolo-gies that can provide some incremental fuel consumption benefit in the future.

Scuderi Split-Cycle Engines

A recently developed novel engine concept is called a Scuderi Split Cycle, named for the inventor, Carmelo Scuderi.[36] This engine concept, recently reviewed by Southwest Research Institute:

> . . . divides the four strokes of a conventional combustion engine cycle over two paired cylinders. The first cylinder, referred to as the 'compressor', provides intake and compression strokes. The second cylinder, referred to as the 'expander', provides power and exhaust strokes. The two cylinders are connected by a 'crossover port', through which the high pressure gas is transferred from the compressor cylinder to the expander cylinder between the compression and power strokes.[37]

Splitting the strokes into different cylinders allows independent optimization of each process and design. Although it is too early in the research and development phase for reliable predictions of efficiency or cost, the concept is interesting and deserves further work.

Other Designs

There are a number of other automotive engine designs that have been considered over the years. These include linear engine, opposed-piston engine, Stirling engine, and gas turbine engine. Improvements in electronics, fuel injection systems, turbocharging, and hybridization systems and the potential future role of engines as range-extending battery chargers for series plug-in hybrid electric vehicles could provide opportunities for one or more of these alternative concepts to find applications in future electric vehicles. The main development challenges include emissions, durability, cost, and production at high volumes.

Fuel Impacts

Fuel properties are known to impact engine efficiency and merit some discussion. In particular, the

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34 Ibid.

35 EPA/NHTSA 2010a (see footnote 12).

36 C. J. Scuderi, "Split Four Stroke Cycle Internal Combustion Engine," International Patent WO 03/008785A1, January 30, 2003.

37 Ford Phillips, Ian Gilbert, Jean-Pierre Pirault, and Marc Megel, *Scuderi Split Cycle Research Engine: Overview, Architecture and Operation,* SAE Paper 2011-01-0403, 2011.

following paragraphs discuss the impact of gasoline octane or ethanol blending on engine efficiency. Also, flexible-fuel vehicle (FFV) design considerations will be discussed.

Octane and Alcohol Impacts on Engine Efficiency

MIT reviewed the history of vehicle demand for octane in the United States.[38] Increasing gasoline octane from 1930 to 1960 enabled increased compression ratios and improved efficiency of U.S. vehicles. MIT also discussed the two laboratory measurements of octane, called motor octane and research octane, and how U.S. engines were historically more sensitive to motor octane, but now have become sensitive almost exclusively to research octane. Sensitivity of recent production engines to research octane and insensitivity to motor octane has been confirmed in recent auto/oil company cooperative research (Coordinating Research Council). Gasoline refueling pumps in the United States are labeled with an average of research and motor octane.

Of the fuel economy improvement technologies discussed previously, the one that is most sensitive to research octane number is turbocharging and downsizing. Even using 98 research octane gasoline, highly turbocharged/downsized engines can have efficiency limited by engine knock.[39] Studies by Toyota[40] and BP[41] found an increase in engine efficiency of 5 to 15% as research octane increased from 92 to 100.

Research octane numbers in the United States are typically about 97 for premium grade and for regular grade average about 92, but can be as low as 89 in mountain states. Although small-volume premium and performance cars can be designed exclusively for premium gasoline, regular gasoline must be used in engines intended for high volume

applications. In the United States, octane number (about 89 minimum) limits the fuel economy benefits achievable by turbocharging/downsizing technology. Increased research octane would be an enabler for increased fuel economy of gasoline vehicles.

A number of studies have found high concentrations of ethanol to be well-suited for turbocharged/downsized engines.[42,43,44,45,46] The studies have shown benefits result from ethanol's high research octane and ethanol's high heat of vaporization, which leads to charge cooling. High concentrations of methanol, which has similar research octane but an even higher heat of vaporization, are also well suited for downsized turbocharged engines. Topic Paper #4, "Alcohol Boosted Turbo Gasoline Engines," prepared as part of this study and found on the NPC website, presents technology in which a separate small tank of alcohol (ethanol or methanol) could be used to enable turbocharging/downsizing and improve engine efficiency.

As discussed above, high concentration alcohol fuels, such as E85, are an enabler to some fuel economy technologies. This benefit will be lost if gasoline-like hydrocarbon (drop-in) biofuels are used instead of ethanol. Even with conventional powertrain technology, FFVs operated on E85 have been found to have about a 3% increase in miles per gasoline gallon equivalent when compared to operation on gasoline.[47] The improved efficiency on ethanol is likely a result of reduced heat rejection and an improvement in ratio of specific heats of the product gases.

38 Vikram Mittal and John B. Heywood, *The Shift in Relevance of Fuel RON and MON to Knock Onset in Modern SI Engines Over the Last 70 Years,* SAE Paper 2009-01-2622, 2009.

39 William P. Attard, Elisa Toulson, Ferenc Hamori, and Harry C. Watson, *Combustion System Development and Analysis of a Downsized Highly Turbocharged PFI Small Engine,* SAE Paper 2010-32-0093, 2010.

40 Koichi Nakata, Daisuke Uchida, Atsuharu Ota, Shintaro Utsumi, and Katsunori Kawatake, *The Impact of RON on SI Engine Thermal Efficiency,* SAE Paper 2007-01-2007, 2007.

41 John Williams, Nozomi Yokoo, Koichi Nakata, Rana Ali, Walter Bunting, and Kenichi Ishiwa, *The Impact of Fuel Composition on the Combustion and Emissions of a Prototype Lean-Boosted PFI Engine,* SAE Paper 2010-01-2094, 2010.

42 James Szybist, Matthew Foster, Wayne Moore, Keith Confer, Adam Youngquist, and Robert Wagner, *Investigation of Knock Limited Compression Ratio of Ethanol Gasoline Blends,* SAE Paper 2010-01-0619, 2010.

43 Jean Milpied, Nicolas Jeuland, Gabriel Plassat, Sabine Guichaous, Nathalie Dioc, Alexandre Marchal, and Pierre Schmelzle, *Impact of Fuel Properties on the Performances and Knock Behaviour of a Downsized Turbocharged DI SI Engine – Focus on Octane Numbers and Latent Heat of Vaporization,* SAE Paper 2009-01-0324, 2009.

44 J. W. G. Turner, R. J. Pearson, B. Holland, and R. Peck, *Alcohol-Based Fuels in High Performance Engines,* SAE Paper 2007-01-0056, 2007.

45 Mark J. Christie, Nicholas Fortino, and Hakan Yilmaz, *Parameter Optimization of a Turbo Charged Direct Injection Flex Fuel SI Engine,* SAE Paper 2009-01-0238, 2009.

46 Wayne Moore, Matthew Foster, and Kevin Hoyer, *Engine Efficiency Improvements Enabled by Ethanol Fuel Blends in a GDi VVA Flex Fuel Engine,* SAE Paper 2011-01-0900, 2011.

47 Brian H. West, Alberto J. López, Timothy J. Theiss, Ronald L. Graves, John M. Storey, and Samuel A. Lewis, *Fuel Economy and Emissions of the Ethanol-Optimized Saab 9-5 Biopower,* SAE Paper 2007-01-3994, 2007.

Flexible-Fuel Vehicle Design and Cost

Flexible-fuel vehicles on the road today have a number of design changes to accommodate ethanol concentrations up to 85% in the United States or up to 100% in Brazil. The most important design change is to increase fuel flow to accommodate the higher stoichiometric fuel-air ratio of ethanol. Delivering the appropriate fuel-air ratio requires increased flow fuel pumps, increased flow fuel injectors, and a means to sense the current ethanol content of the fuel. Ethanol sensing has been accomplished with either an onboard sensor or a "virtual" sensor, using the engine's closed-loop fuel control system. Materials changes in the engine and fuel system are required to accommodate the chemical properties of ethanol and ethanol-gasoline blends. Additional issues arise as exhaust and evaporative emissions standards become more stringent. Due to its low volatility, high heat of evaporation, and high stoichiometric fuel-air ratio, controlling cold start emissions can be a challenge for E85, driving the need for additional emissions control hardware. In addition, low concentration ethanol-gasoline blends, because of their increased vapor pressure and tendency to permeate through plastics, require new technologies for meeting the most stringent evaporative emissions standards. FFV technology was developed in the United States in the 1980s and early 1990s for compatibility with methanol-gasoline blends rather than ethanol-gasoline blends. As the interest in methanol-gasoline blends decreased and interest in ethanol-gasoline blends increased, FFV technology was applied to ethanol-gasoline blends using similar technology. Lately, there has been an increase in dialogue about FFVs operating on methanol-gasoline blends.[48,49] Methanol FFVs must accommodate a wider range of fuel flow than ethanol FFVs and must accommodate more aggressive chemical and physical properties. However, the greatest challenge of methanol FFV design is accommodating the high vapor pressure and low boiling point of low concentration methanol-gasoline blends. Meeting stringent evaporative emissions with methanol FFVs is likely to drive the vehicle cost significantly higher than that of ethanol flexible-fueled vehicles.

Gasoline-Like Fuels in Diesel Engines

As is discussed in Chapter Eleven, "Hydrocarbon Liquids," one of the issues in U.S. refining is a decline in the demand for gasoline relative to diesel. This creates a potential imbalance between the mix of fuels that U.S. refineries can make and the mix of fuels that the vehicle fleet requires.

One of the key challenges for future diesel engines is the lack of technologies that allow ultra-low emissions at reasonable cost. One of the promising technologies that has been explored and implemented to some extent is low temperature combustion. Low temperature combustion uses a partially premixed fuel-air mixture to avoid soot emissions and high dilution to avoid NOx emissions during combustion. Low temperature combustion has been enabled by improved boosting systems and improved fuel injection systems. Recently, researchers have found that introducing gasoline-like fuels into the diesel engine can improve the range of engine conditions under which low temperature combustion is possible.[50,51] Although not ready for commercialization, this work shows the possibility of addressing both the diesel/gasoline demand imbalance and the costs of diesel emissions control.

Emissions of Hydrocarbons, NOx, Particulates, and Carbon Monoxide

In the discussions above of diesels, lean-burn engines, and FFVs, it is clear that meeting future near-zero emissions standards for LD vehicles provides a challenge for many of the concepts that have the capability to reduce petroleum consumption and GHG emissions. Over the past 30 years, U.S. vehicles have almost exclusively used gasoline engines in which the fuel-air mixture is tightly controlled at the stoichiometric ratio. Stoichiometric mixtures are used because they allow exhaust

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48 George A. Olah, Alain Goeppert, and G. K. Surya Prakash, *Beyond Oil and Gas: The Methanol Economy*, Wiley-VCH, March 23, 2006.

49 L. Bromberg and W. K. Cheng, *Methanol as an alternative transportation fuel in the US: Options for sustainable and/or energy-secure transportation,* prepared by the Sloan Automotive Laboratory, Massachusetts Institute of Technology, November 2010.

50 Scott Curran, Vitaly Prikhodko, Kukwon Cho, Charles Sluder, James Parks, Robert Wagner, Sage Kokjohn, and Rolf Reitz, *In-Cylinder Fuel Blending of Gasoline/Diesel for Improved Efficiency and Lowest Possible Emissions on a Multi-Cylinder Light-Duty Diesel Engine,* SAE Paper SAE-2010-01-2206, 2010.

51 Fan Zhang, Hongming Xu, Jun Zhang, Guohong Tian, and Gautam Kalghatgi, *Investigation into Light Duty Dieseline Fuelled Partially-Premixed Compression Ignition Engine,* SAE Paper 2011-01-1411, 2011.

aftertreatment systems to simultaneously control hydrocarbons, NOx, and carbon monoxide at the tailpipe. These systems have also provided low levels of particulate emissions. It is well known that stoichiometric combustion does not provide optimum combustion efficiency, but the need for low tailpipe emissions at sustainable costs have required stoichiometric combustion.

During this same period of time, there has been an abundance of research on aftertreatment systems for lean-burn engines. More recently, particulate emissions of these systems have gained a lot of attention. This work continues to be of importance as a key enabler for the introduction of engine concepts that provide increased efficiency.

Impact of Fuel Economy Technology on Vehicle Price

This section addresses the Retail Price Equivalent (RPE) of the fuel consumption reduction technologies. RPE or similar methodologies have been used by most researchers.[52] RPE is intended to reflect long-run, substantially learned, industry-average production costs that incorporate rates of profit and overhead expenses. In other words, RPE represents the consumer's cost, the average additional price consumers would pay for fuel economy technology.

All fuel economy values discussed in this section are urban/highway combined test results used for fuel economy compliance. Vehicle label/on-road values are roughly 20% lower.

Literature sources for consumer cost-benefit analysis are summarized in Table 9-6. Although other sources are available, most have been incorporated into these studies. In consolidating the findings of these studies, one concern is the wide range of focus years. This is important because it is well recognized that technology prices decrease with time due to scale and learning. Another issue

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52 NRC 2011 (see footnote 6), EPA/NHTSA 2010b (see footnote 13), and EIA AEO2010.

Reference	Focus Year	Vehicle Segmentation Used in Results
AEO2010*	2010 through 2035	12 car and truck classes
EPA/NHTSAa†	2016	Car and truck average only
EPA/NHTSAb‡	2025	Car and truck average only
MIT2008§	2010 and 2035	Car and truck average only
NRC2011¶	2015	5 car and truck classes
Sierra#	2015	Car and truck average only
Sierra**	2015	Car and truck average only

Sources:

* Energy Information Administration, *Annual Energy Outlook 2010 – With Projections to 2035,* 2010.

† U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, *Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standard and Corporate Average Fuel Economy Standards,* Joint Technical Support Document, Report EPA-420-R-10-901, April 2010.

‡ U.S. Environmental Protection Agency, National Highway Traffic Safety Administration, and California Air Resources Board, *Interim Joint Technical Assessment Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025,* September 2010.

§ Laboratory for Energy and the Environment, Massachusetts Institute of Technology, *On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions,* July 2008.

¶ National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles,* June 2011.

\# Sierra Research, *Basic analysis of the cost and long-term impact of the energy independence and security act fuel economy standards,* Report No. SR2008-04-01, May 2008.
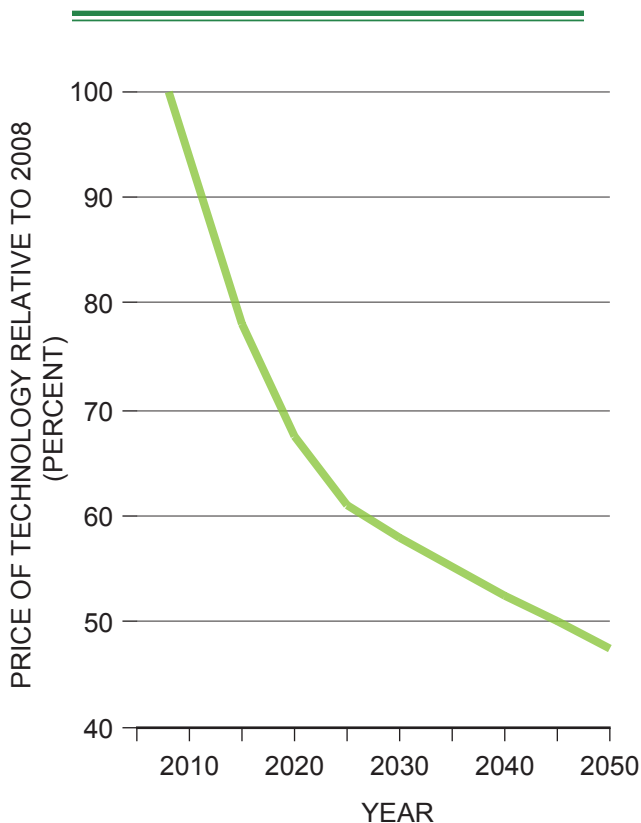
** Sierra Research, *Attachments to the Comments Regarding NHTSA Proposal for Average Fuel Economy Standards for Passenger Cars and Light Trucks Model Years 2011-2015,* Docket No. NHTSA-2008-0089, June 2008.

Table 9-6. *Literature Sources for Fuel Economy Technology Price Analysis*

in consolidating these studies is the differences in vehicle segmentation.

The first step in consolidating these studies was to develop a technique to adjust technology prices to a common focus year. EPA/NHTSA[53] used a rule of thumb that a given technology, once at commercial volume, decreases in price 3% per year in the first 5 years, 2% per year in the next 5 years, and 1% per year thereafter. Rules of thumb such as this should be applied to individual technologies. However, keeping track of the implementation timing for individual technologies requires a sophisticated model that was beyond the scope of this analysis. Instead, the EPA/NHTSA rule of thumb was applied to packages of technologies selected in each of the references. This would tend to overestimate the learning impacts of technologies that have been in production, but this is not expected to provide serious errors for this analysis.

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53 EPA/NHTSA 2010b (see footnote 13).

Based on the EPA/NHTSA rule of thumb, technology prices relative to 2008 were calculated and are shown in Figure 9-6. This relationship was used to convert all technology price focus years to 2015. For example, to convert a technology focus year from 2025 to 2015, the price is multiplied by 0.78 then divided by 0.61.

This analysis of fuel economy technology prices was applied in the integration portion of this study. During integration, the 12 car and truck classes from AEO2010 were consolidated into 2 car and 3 truck classes (see Table 9-7). This required inputs on the price of fuel economy technology for each of the 5 vehicle classes. A methodology was required to adjust the literature vehicle technology prices for each vehicle class. This adjustment was based on the AEO2010 fuel economy and retail price results by vehicle class.

The first step in this process was to calculate weighted average fuel economy and vehicle price for each of the five consolidated vehicle classes using the output of AEO2010. Next the weighted average

Figure 9-6. *Assumed Technology Prices Relative to 2008; Used to Adjust Varying Reference Focus Years to a Common Basis*

AEO Classes	NPC Study Light-Duty Classes	VISION Light-Duty Classes
Two-Seater Cars	Small Car	Car
Minicompact Cars		
Subcompact Cars		
Compact Cars		
Midsize Cars	Large Car	
Large Cars		
Small Van	Small Utility	Truck
Small Utility		
Large Utility	Large Utility	
Large Van		
Small Pickup	Pickup	
Large Pickup		
Commercial Light Trucks*		

* Commercial light trucks are not considered a light-duty vehicle class in AEO but were added in this analysis for consistency with the VISION model.

Table 9-7. *Consolidation of AEO2010 Vehicle Classes into Five Vehicle Classes for Integration*
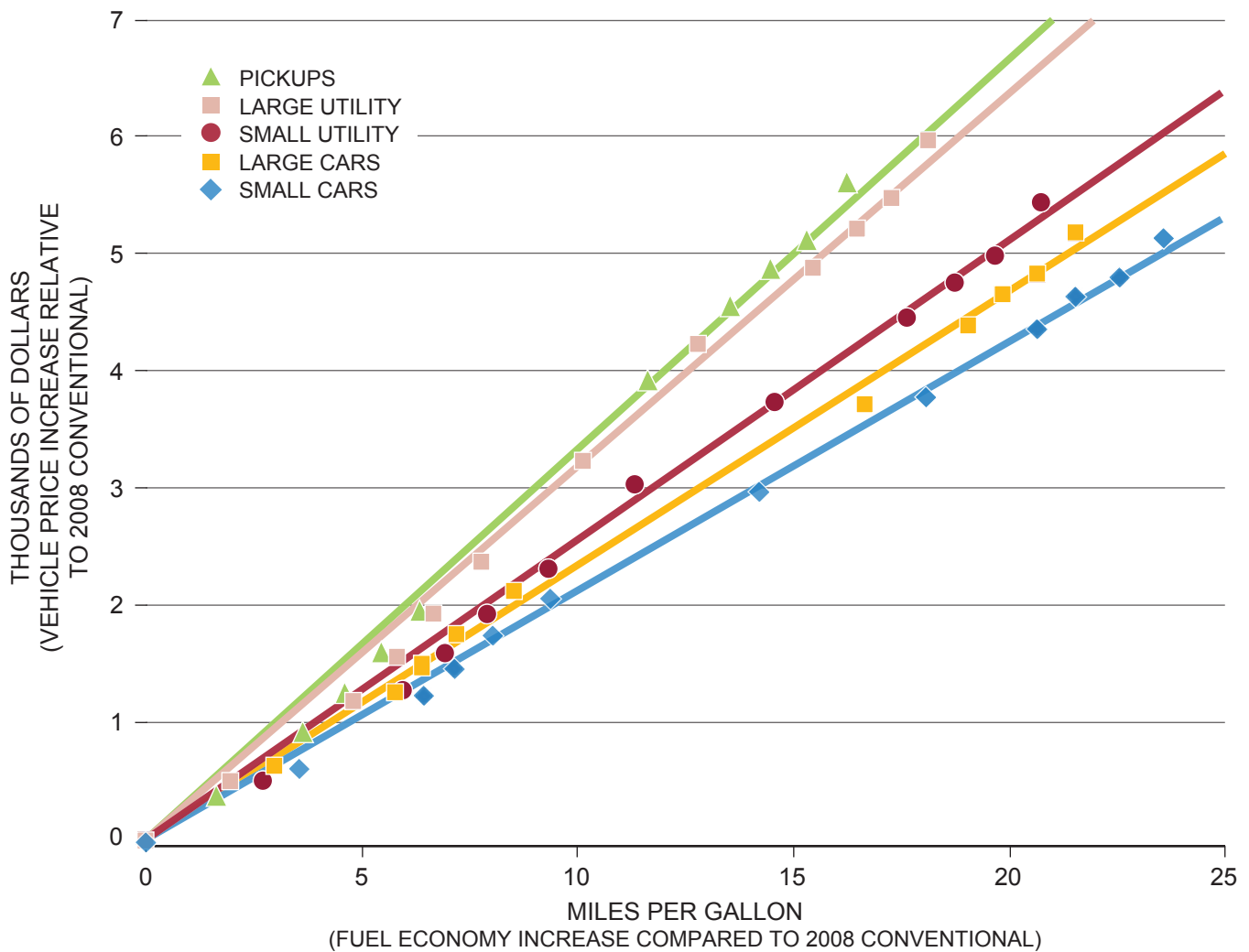
Note: AEO2010 results for conventional and gasoline hybrid electric vehicles, adjusted to 2015 technology price.
Source: Energy Information Administration, *Annual Energy Outlook 2010*, 2010.

Figure 9-7. *Fuel Economy Technology Price by Vehicle Segment –*
Adjusted to 2015

vehicle prices were adjusted to a common technology year using the rule of thumb from Figure 9-6. For example, the 2035 vehicle prices were multiplied by 0.78, then divided by 0.55 to adjust them to year 2015. Incremental vehicle prices are plotted versus incremental fuel economy by vehicle class in Figure 9-7. The highest slope is for pickups ($334/mpg) and the lowest is for small cars ($213/mpg). These slopes were used to derive multipliers to change car average prices to prices for the car classes or to change truck average prices to prices for the truck classes. These multipliers were calculated according to Equation 9-1, where slope$_{class}$ is $/mpg from Figure 9-7 and share$_{class}$ is the market share proportion of each class within all cars or all trucks.

Equation 9-1:

$$\text{RPE Multiplier} = \frac{\text{Slope}_{class}}{\sum_{class}\text{Slope}_{class} * \text{Share}_{class}}$$

Gasoline Powertrain and Vehicle Technologies Combined

The first step in this process was to take a look at what the studies listed in Table 9-6 found for the price impact of improving fuel economy using both propulsion and vehicle technologies. Results of each study were adjusted to 2015 technology prices and the five vehicle classes, as discussed earlier. For each study finding, price increase was

computed relative to 2008 conventional vehicles, and fuel economy was computed as a ratio to 2008 conventional vehicle fuel economy. Results for the small car class are shown in Figure 9-8.

The AEO2010 points in Figure 9-8 were developed as follows. The points (green circles) represent the weighted average of the vehicle price increase (adjusted to 2015) and fuel economy ratio relative to 2008 conventional of the AEO2010 classes that were combined into small car for conventional and gasoline hybrids. AEO2010 hybrid results are shown with the "+" sign on top of the green circle. Starting from the lower left and progressing to the upper right, the six points in the conventional and hybrid groups are AEO2010 results for 2008, 2010, 2015, 2020, 2025, 2030, and 2035, respectively.

The NRC2011 results for conventional propulsion (red squares without the "+" sign) are results of the NRC small car pathway with reanalysis to include vehicle mass reductions up to 20% (maximum mass reduction for which assumptions were available in this study).[54] Starting from the lower left, the technologies represented by these points are improved rolling resistance, improved aerodynamics, improved lubrication, engine friction reduc-

tion, electric power steering, improved accessories, high voltage alternator, dual clutch transmission, dual cam phasers, continuously variable valve lift, turbocharging and downsizing, 5% mass reduction, 10% mass reduction, and 20% mass reduction. The lower left hybrid point is power split hybrid with 10% mass reduction and the upper point is power split hybrid with 20% mass reduction. Since the NRC published results by vehicle segment and for focus year of 2015, no adjustment was required.

The lower left green square was derived from EPA/NHTSA 2010a (see footnote 12) and the other green squares are from EPA/NHTSA 2010b (see footnote 13). Neglecting the A/C credit, EPA/NHTSA 2010a found a car fleet average fuel economy of 37.8 mpg (ratio of 1.17 to EIA AEO2010 car average for 2008) at a price of $870 relative to 2011 ($870+$63=$933 relative to 2008). Applying the 0.95 RPE multiplier for small cars gives $884 at a fuel economy ratio of 1.17. The remaining green squares are results from the 16 cases (3, 4, 5, 6 %/year GHG stringency increases, 4 technology paths) of EPA/NHTSA 2010b. The lower left of the 16 points is the 3%/year, Path A scenario, which produced a car average of 51.2 mpg equivalent, which after subtracting the A/C CO_2 credit becomes 47.1 mpg (1.46 ratio to 2008 AEO2010 car average). The car average RPE

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54 NRC 2011 (see footnote 6).
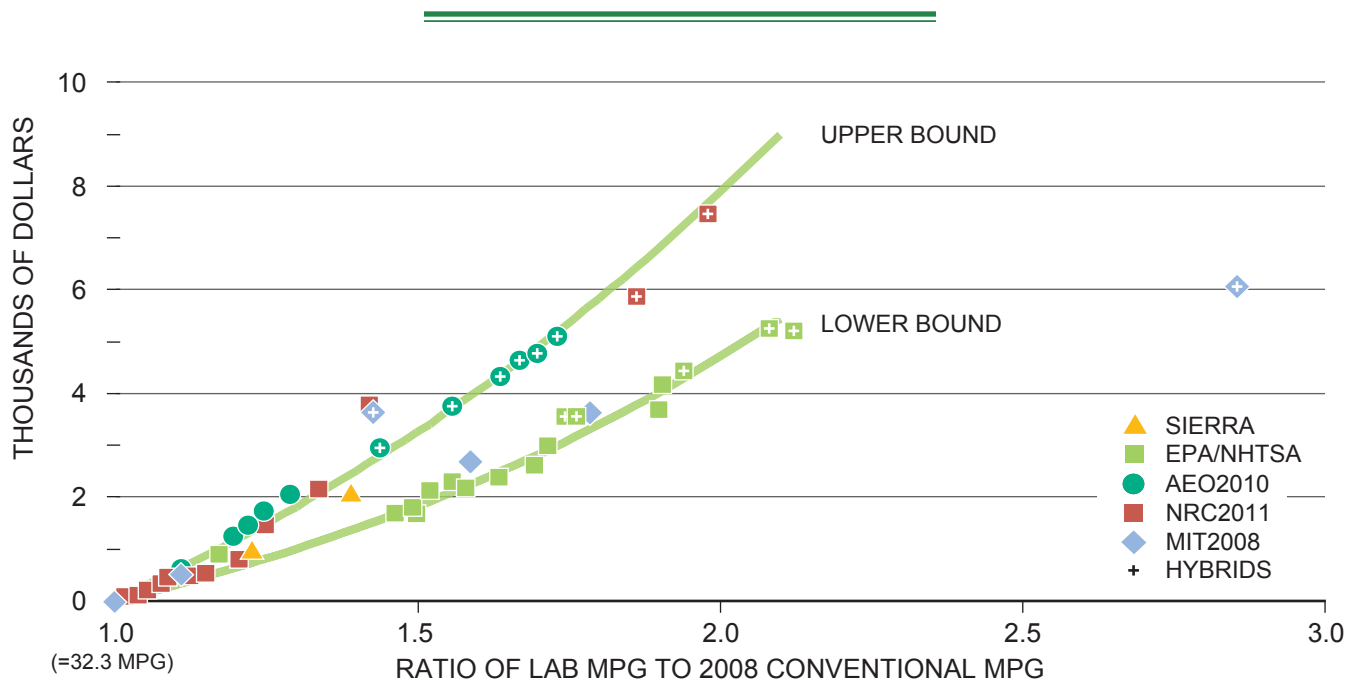
Figure 9-8. *Incremental Retail Price Equivalent as a Function of Fuel Economy Increase – Gasoline Engines in Small Cars in 2015*

for this case was $659 incremental to 2016, which becomes $659*0.95=$624 for small cars. The final step was to adjust the RPE from incremental to 2016 to incremental to 2008, the baseline for this analysis. As indicated above, the RPE for 2016 incremental to 2008 was $884, but this is at a 2015 technology price whereas EPA/NHTSA 2010b is at a 2025 technology price. The first step is to adjust the $884 to 2025 technology price, making it $689. The 3%/year Path A case, at 2025 technology price, relative to 2008 becomes $624+$689=$1,313. Finally, after adjusting from 2025 to 2015 technology price (multiplying by 0.78 and dividing by 0.61) the incremental RPE for small cars becomes $1,686. The other 15 cases were handled in the same way and plotted in Figure 9-8. Cases in which gasoline hybrid technology penetration were greater than 50% are marked with the "+".

Next the six MIT2008[55] points (blue diamonds) will be discussed. The points at mpg ratios of 1.0, 1.1, and 1.4 are the results for 2008: conventional gasoline, turbocharged gasoline, and gasoline hybrid. The points at mpg ratios of 1.6, 1.8, and 2.9 are the same propulsion systems in 2035. The mpg ratios for each point were computed from the fuel consumption values given in MIT2008 relative to conventional gasoline in 2008. Two examples of RPE calculation will be given. First is the 2008 gasoline turbo, which, in the study, has an incremental RPE of $700 for the average car. This is multiplied by 0.95, the RPE multiplier for small cars, and then adjusted from 2008 technology price to 2015 technology price (0.78/1) to give $519. The second example is the 2035 hybrid, which, in MIT2008, had an RPE of $3,500 for the average car. Multiplying by 0.95 for small cars and converting from 2035 to 2015 technology price (multiplying by 0.78/0.55) gives $6,050 at an mpg ratio of 2.9 (inverse of 0.35 fuel consumption ratio to 2008 conventional as reported by MIT2008). The MIT2008 point at a mpg ratio of 2.9 falls far to the right of the trend line from the balance of studies. One potential explanation of the high mpg in the 2035 hybrid is the relatively large (25%) reduction in rolling resistance and large (33%) reduction in aerodynamic drag assumed in 2035.[56]

Reduction in rolling resistance and drag contribute a larger proportion to energy losses in hybrids, than in conventional propulsion systems, because the regenerative braking systems of hybrids reduce the impact of inertial mass on tractive energy. Although other studies added costs for rolling resistance and aerodynamic reduction, MIT2008 assumes these are achieved through continuous improvement without cost increase. Clearly the method described above to adjust results to 2015 does not work well for the MIT2008 2035 hybrid.

Finally for the Sierra Research reports,[57,58] fuel economy ratio was calculated from the ratio of their 2015 car average to their 2006 car average (would be close to 2008 average). Sierra RPEs were multiplied by 0.95 to get small car values. Since the focus year was 2015, no correction for technology year was required.

There are two major observations from Figure 9-8. First, there is substantial technology potential for increasing fuel economy. Neglecting the 2035 MIT2008 hybrid, doubling of fuel economy is feasible. It is not clear why much larger benefits were seen with the MIT2008 hybrid case. Second, the literature shows a wide range of RPE required to achieve increases in fuel economy. Figure 9-8 shows nearly a bimodal distribution of RPE, with EIA, NRC, and Sierra at the high end and EPA and MIT2008 at the low end. Critical analysis of these differences is beyond the scope of the current study. However, the integration portion of the NPC study requires quantification of the impact of increases in fuel economy on retail price. To fulfill this need, upper and lower bound curves were constructed with the intent that these would be used for analyses of sensitivity to the price of technology.

The first decision that had to be made before constructing curves to describe the upper and lower bounds of the literature was the mathematical form of the equations to be used. The results in Figure 9-8 might be adequately described using straight lines. However, intuitively, straight lines are problematic because they imply that fuel economy could increase indefinitely at finite prices. To

55 Massachusetts Institute of Technology, Laboratory for Energy and the Environment, *On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions,* July 2008.

56 Emmanuel P. Kasseris and John B. Heywood, *Comparative Analysis of Automotive Powertrain Choices for the Next 25 Years,* SAE Paper 2007-01-1605, 2007.

57 Sierra Research, *Basic Analysis of the Cost and Long-Term Impact of the Energy Independence and Security Act Fuel Economy Standards,* Report No. SR2008-04-01, May 2008.

58 Sierra Research, *Attachments to the Comments Regarding NHTSA Proposal for Average Fuel Economy Standards for Passenger Cars and Light Trucks Model Years 2011-2015,* Docket No. NHTSA-2008-0089, June 2008.

show upward curvature, an exponential relationship was used for the slope of the curve (Equation 9-2, where *b* and *k* are adjustable coefficients). Integrating Equation 9-2 with the boundary condition that RPE=0 at a fuel economy ratio of 1, gives Equation 9-3.

**Equation 9-2:**

$$\frac{d\ RPE\$}{d\ mpg.ratio} = be^{k*mpg.ratio}$$

Equation 9-3:

$$Incremental\ RPE\ \$= \frac{b}{k}\ (e^{k*mpg.ratio} - e^{k})$$

The upper and lower bound curves were constructed using the form of Equation 9-3. The upper and lower bound *b* and *k* coefficients were selected such that 10% (±1%) of the points were at least $100 above the upper curve and 10% (±1%) of the points were at least $100 below the lower curve. The NRC point above the upper curve is for all non-hybrid technologies and 20% mass reduction. The MIT2008 point above the upper curve is the 2008 hybrid, whereas the MIT2008 point to the right of

the lower curve is the 2035 hybrid. This indicates that the MIT2008 study assumed a much greater rate of learning than that provided by the EPA rule of thumb used in this NPC analysis.

The analysis described above was repeated for the remaining four vehicle classes, and the results are shown in Figures 9-9 through 9-12. The large car results in Figure 9-9 look similar to those for small cars in Figure 9-8, except the equation coefficients are about 10% larger. The truck segment charts have some differences from the car segment charts, however. One difference is the relative location of the Sierra Research points. Although they fell between the lower and upper curve for cars, the Sierra Research points were above the upper curve for the trucks. This indicates that the Sierra Research study has a larger fuel economy technology price difference between trucks and cars than those of the other studies. On the other hand, the AEO2010 points are near the upper curve for cars, but are between the upper and lower curves for trucks. This indicates that the EIA assumption for the difference in fuel economy technology price for trucks versus cars is smaller than that of the other studies.
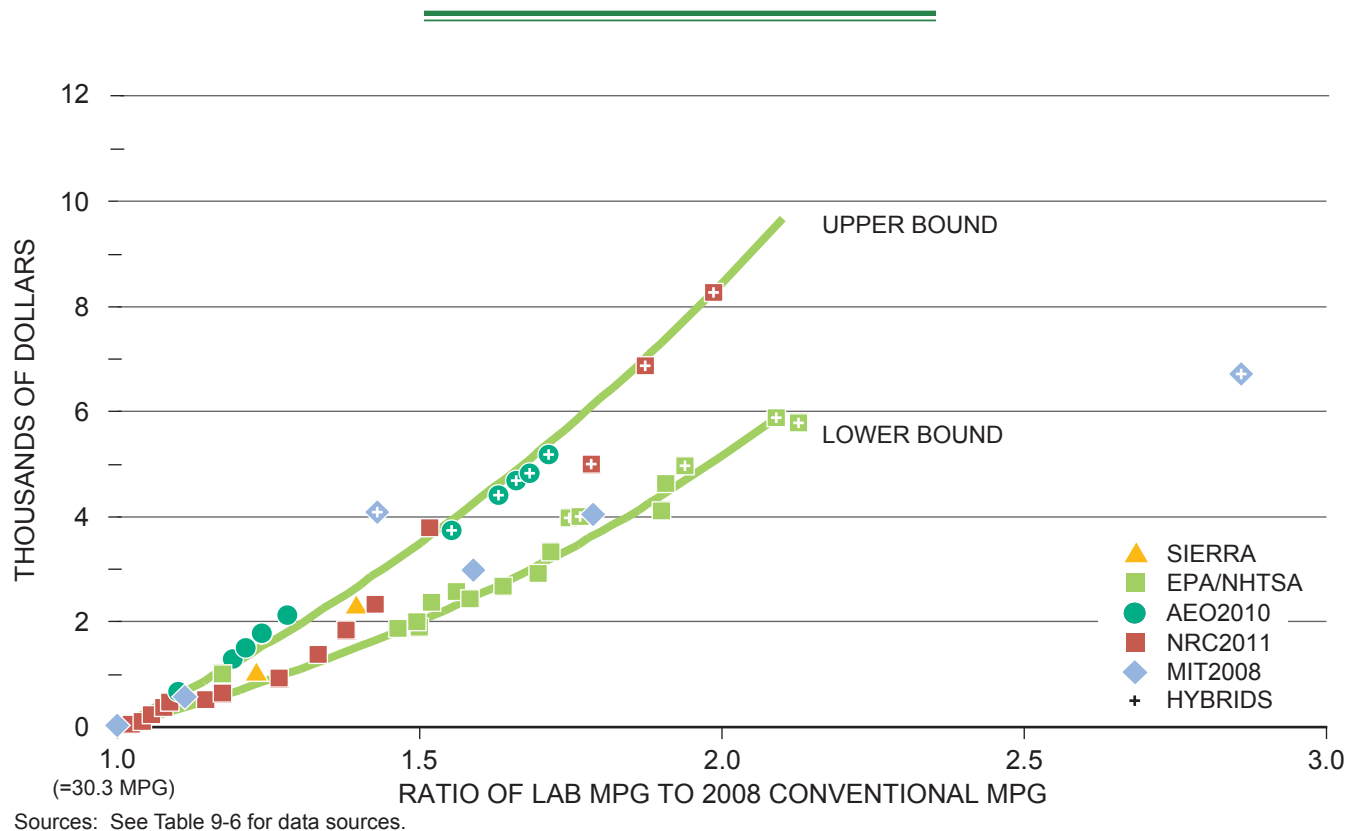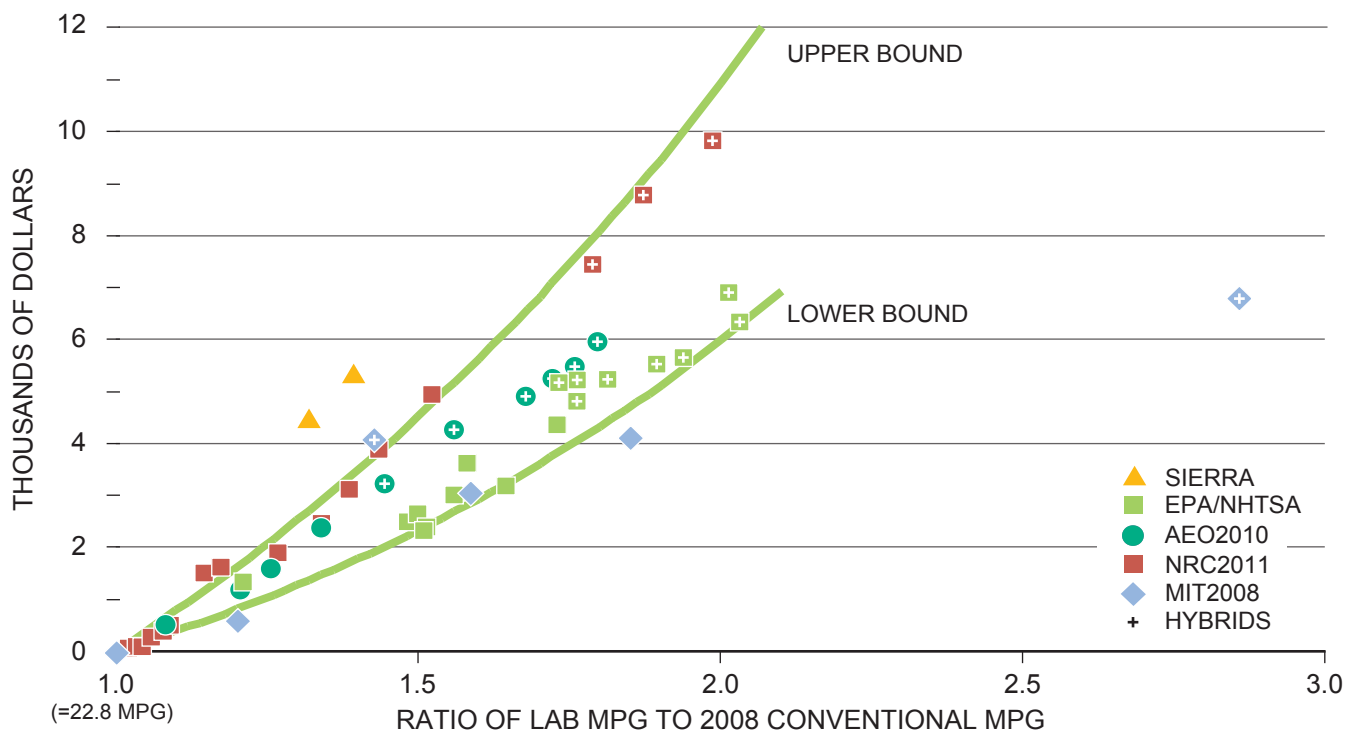

Figure 9-9. *Incremental Retail Price Equivalent as a Function of Fuel Economy Increase – Gasoline Engines in Large Cars in 2015*
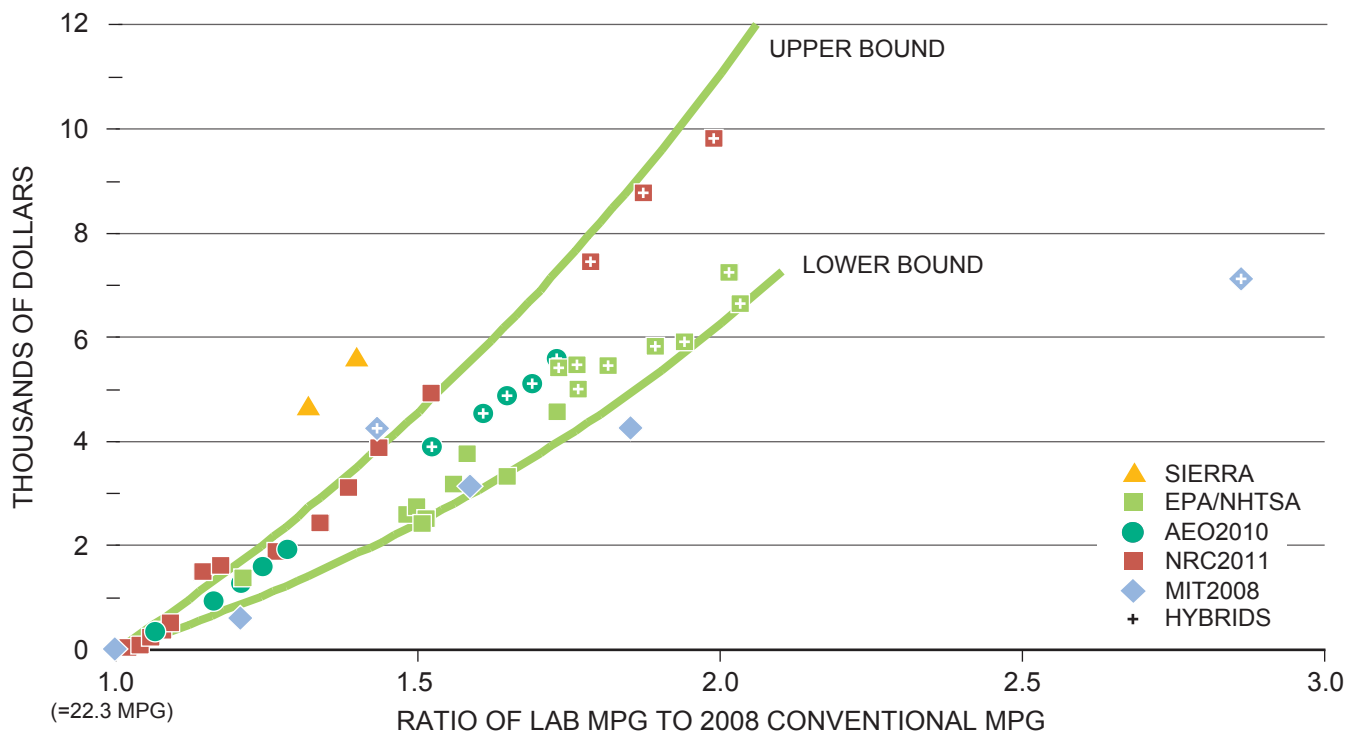
Figure 9-10. *Incremental Retail Price Equivalent as a Function of Fuel Economy Increase – Gasoline Engines in Pickups in 2015*
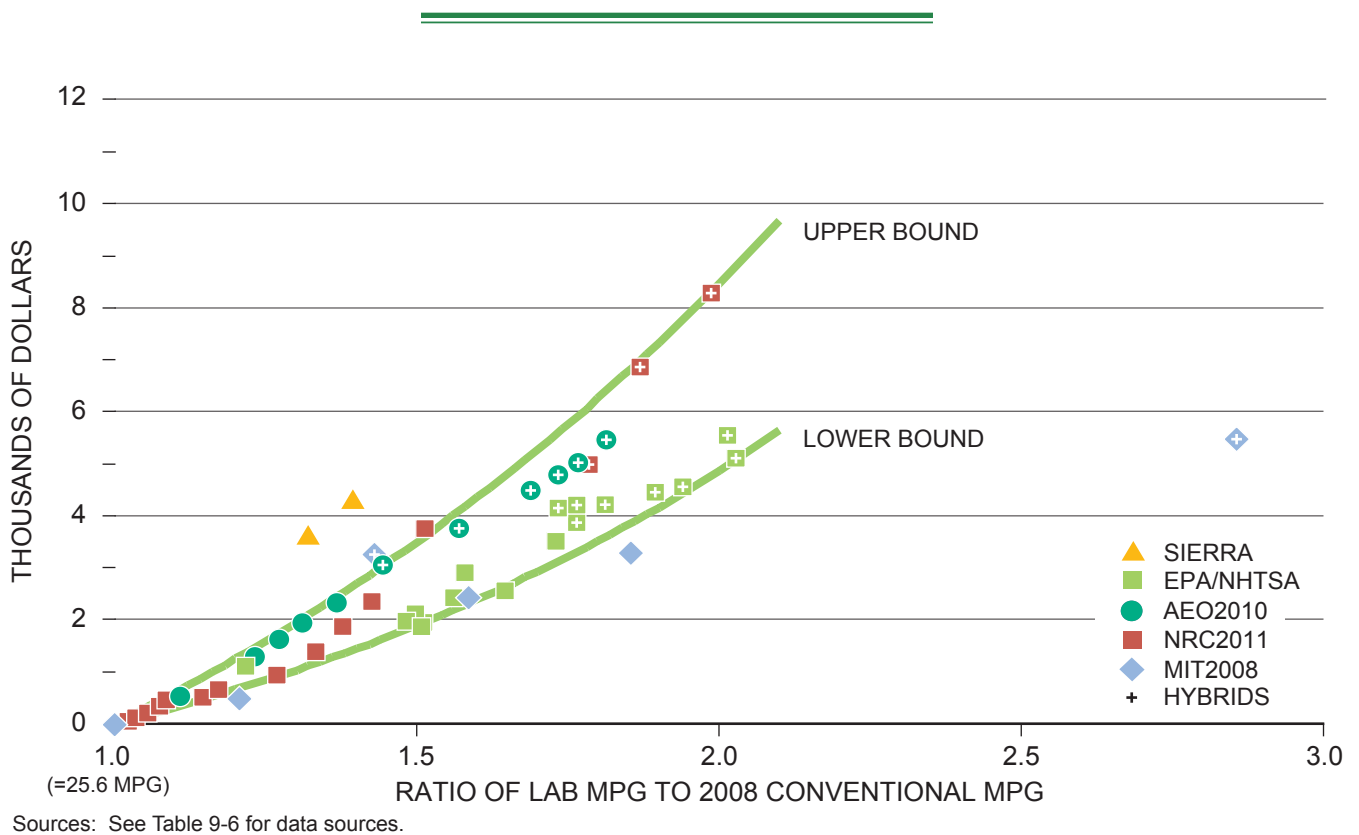
Figure 9-11. *Incremental Retail Price Equivalent as a Function of Fuel Economy Increase – Gasoline Engines in Small SUVs in 2015*

Figure 9-12. *Incremental Retail Price Equivalent as a Function of Fuel Economy Increase – Gasoline Engines in Large SUVs in 2015*

Using the vehicle segment sales shares from AEO2010, Figure 9-13 was constructed to show the fleet average incremental RPE as a function of mpg ratio. For the fleet, 50% increase in fuel economy (mpg ratio=1.5) has an increment RPE of about $2,000–$4,000.

Coefficients of Equation 9-3 used for the upper and lower bound curves for each vehicle segment are shown in Table 9-8 (adjusted to 2015). The k (curvature) coefficients were kept the same across classes, but were slightly larger for the lower bound than upper bound. The b coefficients (proportional to the slope) were largest for pickups and smallest for small cars.

Diesel Powertrain and Vehicle Technologies Combined

Analysis similar to that for gasoline above was attempted for LD diesel engines. Unfortunately diesel results are not available for EPA/NHTSA,[59] because EPA and NHTSA were not able to complete

their assessment of the cost of diesel aftertreatment. This creates a problem in creating upper and lower bound price curves for diesel that are directly comparable to those created in the previous section for gasoline.

Analyzing the references in a similar manner to that described for gasoline in the previous section gives the small car diesel results shown in Figure 9-14. For studies that gave diesel fuel economy results based on diesel gallons, corrections were

	Lower Bound		Upper Bound	
	b	*k*	*b*	*k*
Small Cars	1,180	0.9	2,800	0.7
Large Cars	1,290	0.9	3,080	0.7
Pickups	1,570	0.9	4,010	0.7
Small SUVs	1,220	0.9	2,970	0.7
Large SUVs	1,500	0.9	3,950	0.7

Table 9-8. *Equation 9-3 Coefficients – Powertrain and Vehicle Technology in 2015*
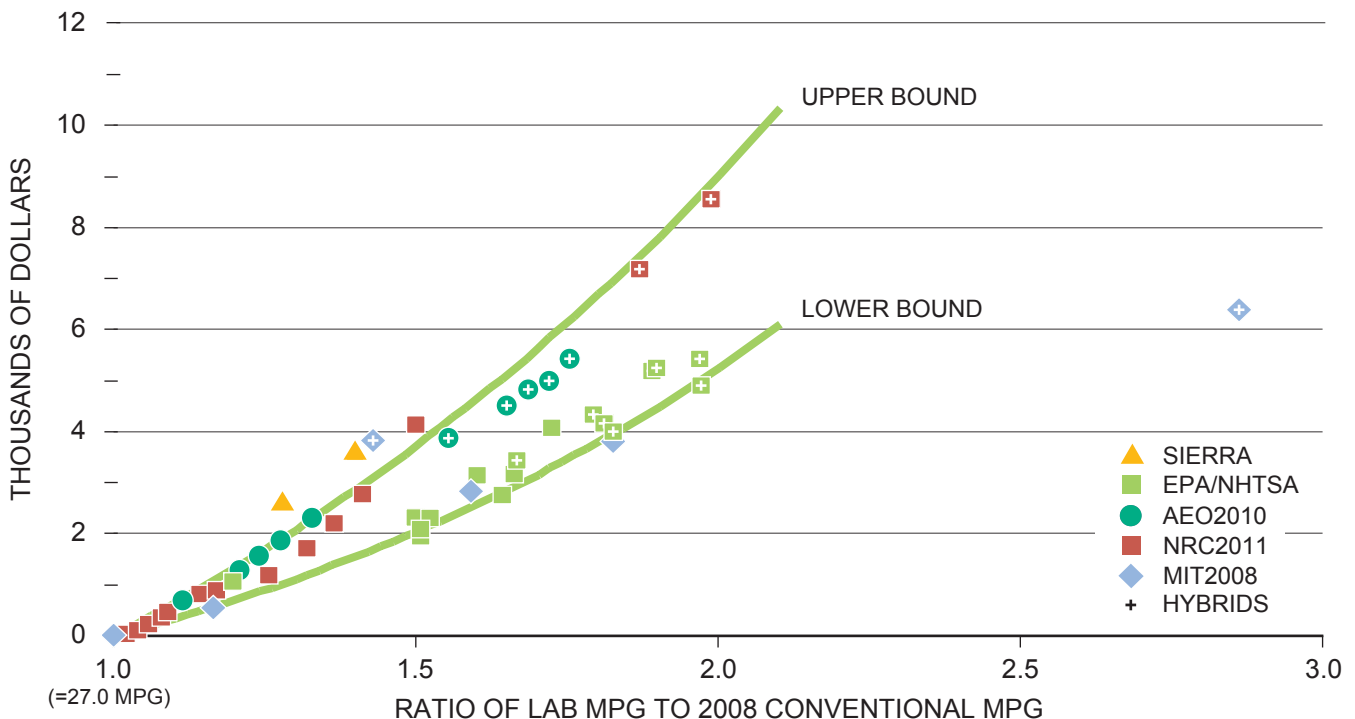
Sources: See Table 9-6 for data sources.

Figure 9-13. *Incremental Retail Price Equivalent as a Function of Fuel Economy Increase – 2015 Fleet Average*
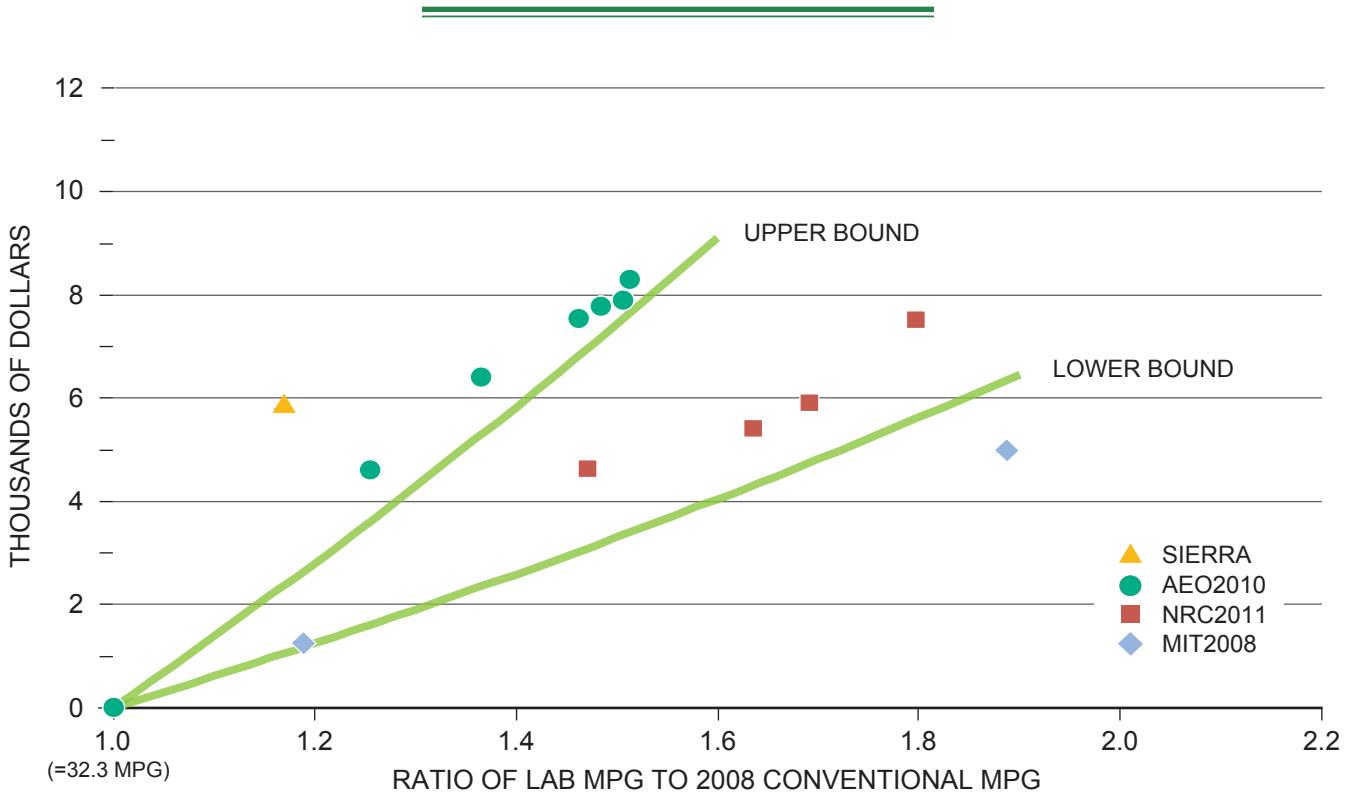
Sources: See Table 9-6 for data sources.

Figure 9-14. *Incremental Retail Price Equivalent as a Function of Gasoline-Equivalent Fuel Economy Increase – Diesel Engines in Small Cars in 2015*

made to provide miles per gallon of gasoline equivalent energy. The upper bound curve in Figure 9-14 was created in a manner similar to that described for Figure 9-8. The lower bound curve was created so that the ratio of lower bound/upper bound b and k coefficients for small car diesel was equal to that for small car gasoline. This choice for defining the lower bound curve was somewhat arbitrary, but intended primarily to provide the fairest comparison between the RPE of diesel technology to that for gasoline hybrids. As can be seen from Figure 9-14, this places the lower bound above the 2035 MIT2008 diesel point. This is consistent with Figure 9-8, where the lower bound curve falls above the MIT2008 gasoline hybrid point. For small cars, all diesel retail prices fell above the lower bound gasoline curve and all except the 2035 MIT2008 point fell above the upper bound gasoline curve, indicating that diesel is a more costly option for fuel economy improvement at the vehicle RPE level.

Figures 9-15 through 9-18 show diesel results for the other vehicle classes. As with small cars,

the lower bound b and k were calculated from the upper bound coefficients so that for each class, the ratio of lower to upper bound coefficients for diesel was equal to that for gasoline. Note that the upper bound curve for the large car diesel results is substantially above the AEO2010 points. The AEO2010 large car incremental prices for diesel are substantially below those for small car diesel. This appears to be an anomaly in the AEO2010 large car diesel results. Consequently, the coefficients for large car diesel in the upper bound curve were set equal to those for small car. As shown in Figures 9-15 through 9-18, pickups had the highest incremental prices. The coefficients for small utilities were the same as those for small and large cars.

Glider Technologies Only

The above RPE analysis for gasoline and diesel engines included both propulsion and "glider" technologies. (A glider refers to a fully functional vehicle minus its propulsion, fuel storage, and delivery related systems.) To provide glider technology input for the electric and fuel cell subgroups of the study, two of the literature sources were used to
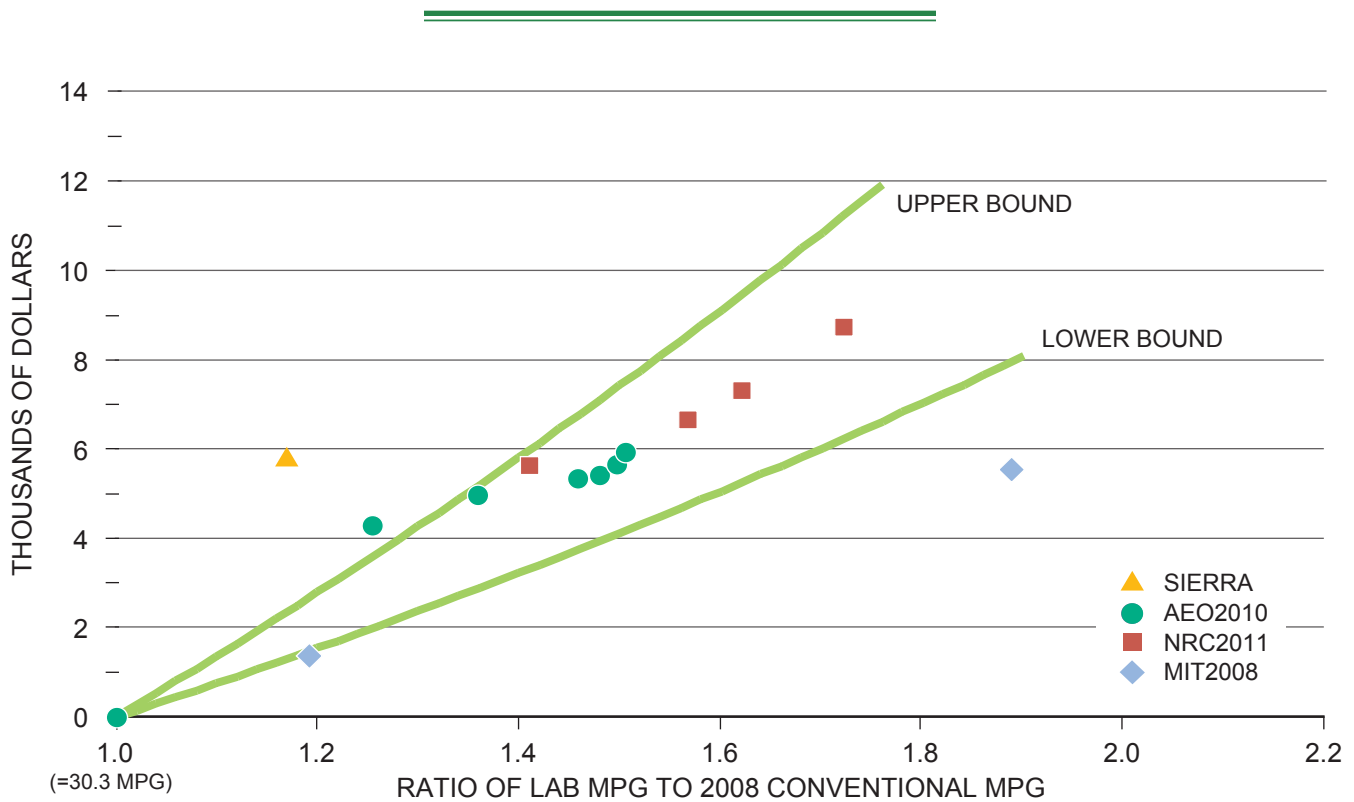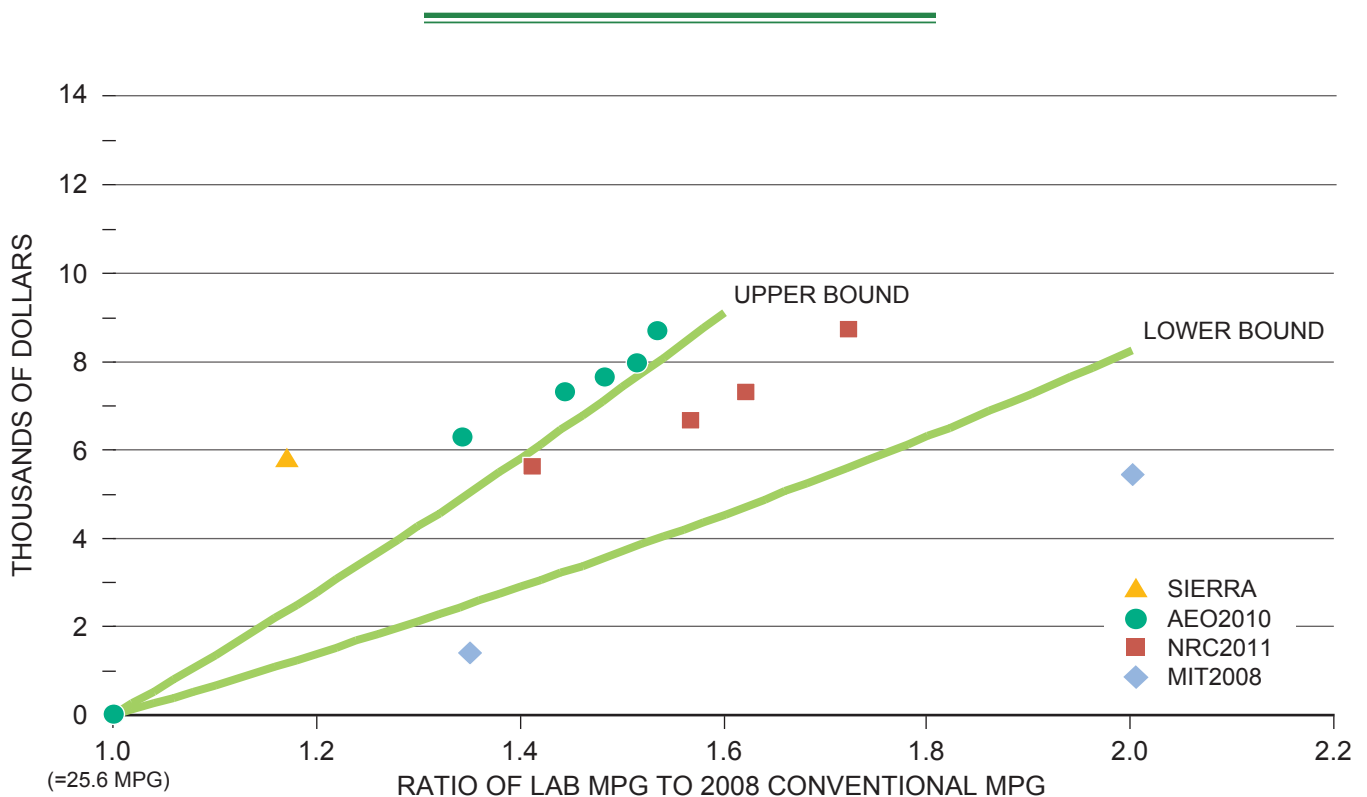

Sources: See Table 9-6 for data sources.

Figure 9-15. Incremental Retail Price Equivalent as a Function
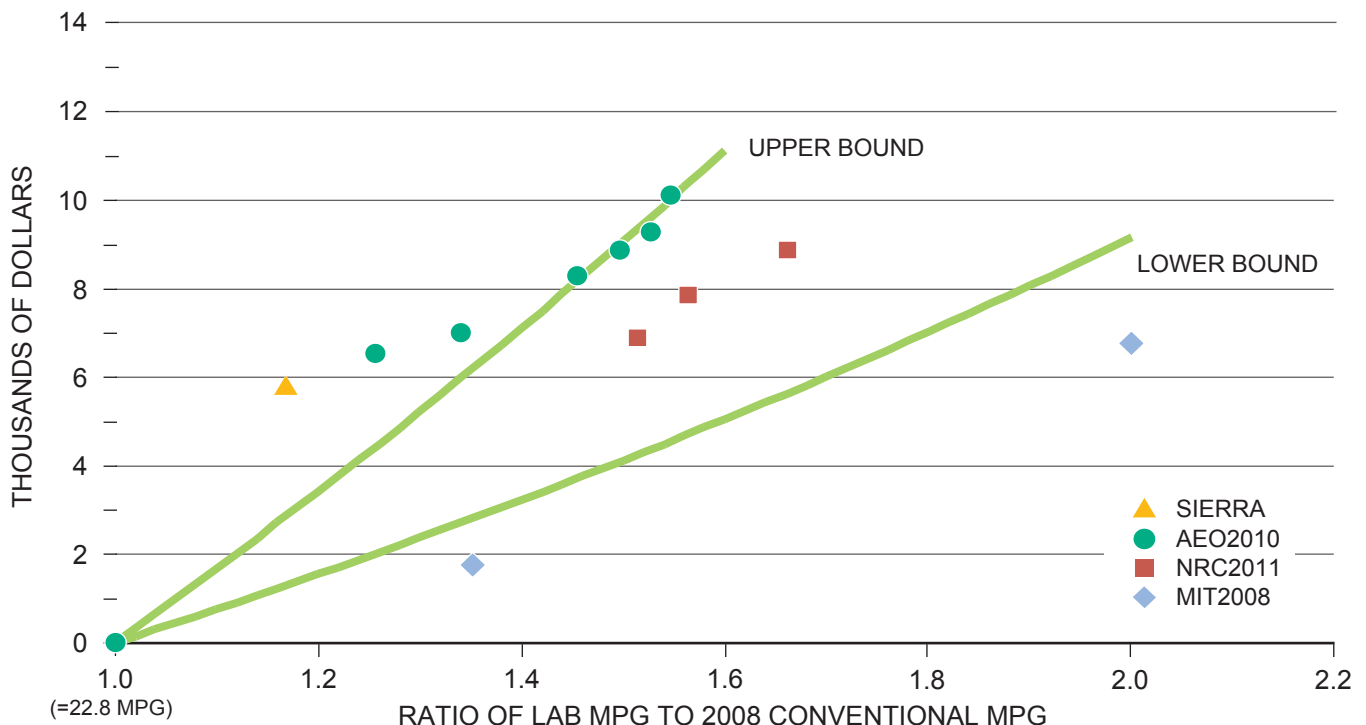of Gasoline-Equivalent Fuel Economy Increase – Diesel Engines in Large Cars in 2015
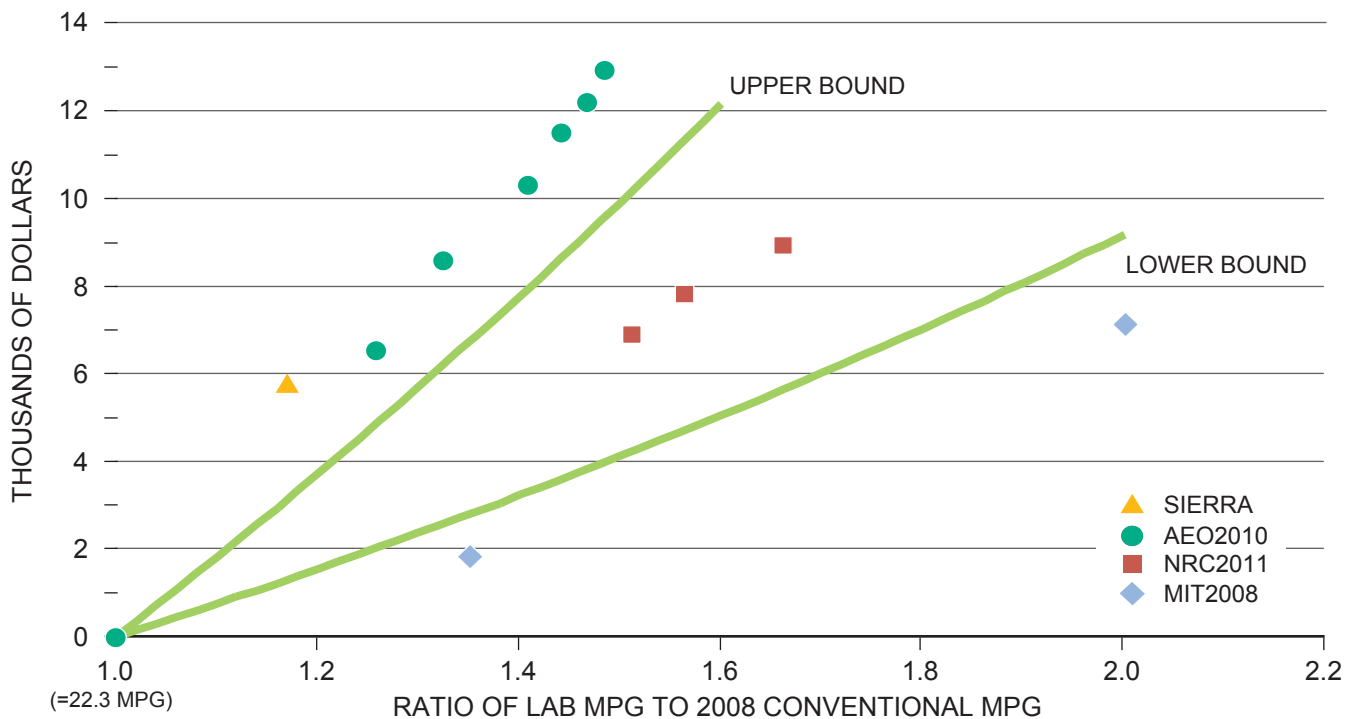
Figure 9-16. *Incremental Retail Price Equivalent as a Function of Gasoline-Equivalent Fuel Economy Increase – Diesel Engines in Pickups in 2015*

Figure 9-17. *Incremental Retail Price Equivalent as a Function of Gasoline-Equivalent Fuel Economy Increase – Diesel Engines in Small SUVs in 2015*

Figure 9-18. *Incremental Retail Price Equivalent as a Function
of Gasoline-Equivalent Fuel Economy Increase – Diesel Engines in Large SUVs in 2015*

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isolate the RPE and benefits of glider technologies alone. Since NRC and EPA/NHTSA included glider technology assumptions and findings roughly aligned with the upper and lower bound curves, respectively, shown previously, glider technology impacts were analyzed using only NRC[60] for the upper bound and EPA/NHTSA[61] for the lower bound. Results for all vehicle classes are shown in Figure 9-19.

The NRC (red square) points will be discussed first. The NRC points were derived from the glider portion of the technology benefits and price tables of NRC, using the NRC methodology for combining multiple technologies. The NRC tables have technology benefits and prices for three vehicle sizes. For this study, the smallest NRC category was associated with small cars, the middle NRC category with large cars and small utilities, and the NRC large category with pickups and large utilities. Starting from the lower left of Figure 9-19, the first point off the baseline is for improved tires, the next is improved

tires and aerodynamics. Each of the remaining sets of points represent improved tires and aerodynamics plus vehicle mass reductions of 5%, 10%, 15%, and 20%, respectively.

The EPA (green square) points are based on EPA/NHTSA assumptions on the costs (adjusted to 2015) of improved tires, improved aerodynamics and mass reduction (3%, 5%, 10%, 15%, 20%, 25%, and 30%). Figure B4.3-2 of EPA/NHTSA[62] shows "marked-up cost" of mass reduction in $/pound for model year 2020. These $/pound values were multiplied by the mass of each vehicle segment and the % mass reduction, then corrected from 2020 to 2015 model year, to compute incremental RPE $ for mass reduction by segment. Fuel consumption reduction for improved tires and improved aerodynamics (Aero1 and Aero2) were given in EPA/NHTSA. Fuel consumption reduction from vehicle mass reduction was not explicit in EPA/NHTSA, so an estimate of the impact of mass on fuel consumption was required.

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60 NRC 2011 (see footnote 6).

61 EPA/NHTSA 2010b (see footnote 13).

62 Ibid.

There are a number of variables that influence the mass effect on fuel consumption. One important variable is the use of regenerative braking. Vehicles with regenerative braking are able to recover a portion of vehicle inertial energy, which is proportional to mass. An assessment of the literature led to the rules of thumb used in this study for a 10% mass reduction: 6% fuel consumption reduction for vehicles without regenerative braking and 4% fuel consumption reduction for vehicles with regenerative braking. Since the glider RPE vs. fuel economy ratio values were for use with plug-in and fuel cell electric vehicles, all with regenerative braking, Figure 9-19 was constructed with the assumption that 10% reduction in vehicle mass provides a 4%

reduction in fuel consumption. The 10 tire, aerodynamics, and mass reduction cases were sorted in the order of increasing $/RPE.

Adjusting RPE Equation Coefficients for Future Years

As discussed earlier, it is anticipated that the RPE of fuel economy technology will decrease in the future due to improvements in technology. To make future incremental RPE follow the trend of Figure 9-6 (page 9-22) for the lower bound curve, the *b* coefficient of Equation 9-3 for 2015 was multiplied by the relative price in the year of interest (2020-2050) then divided by the

Figure 9-19. *Incremental Retail Price Equivalent for Glider Technologies in 2015*
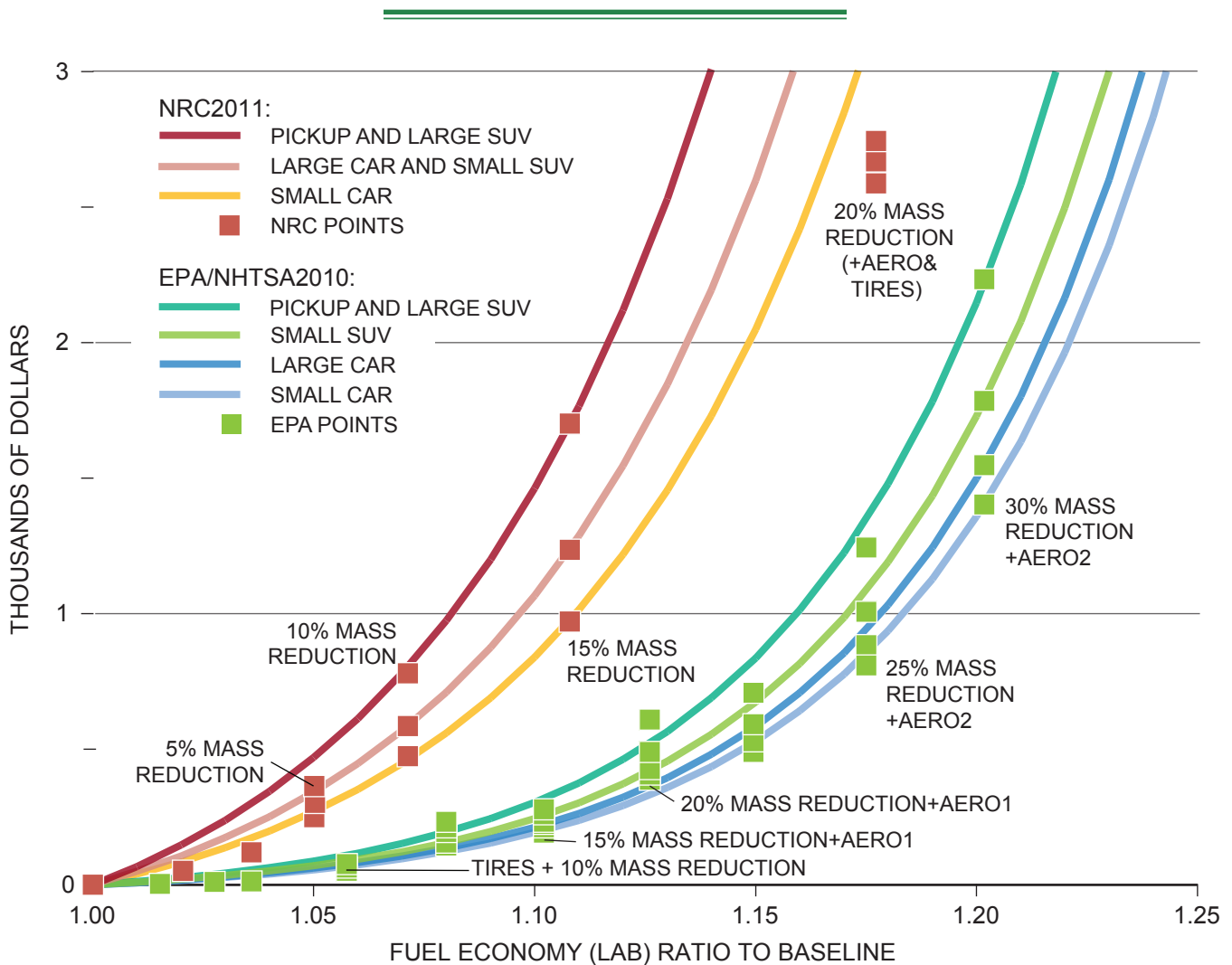
Sources: The National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles,* June 2011 (NRC2011); and U.S. Environmental Protection Agency, National Highway Traffic Safety Administration, and California Air Resources Board, *Interim Joint Technical Assessment Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025,* September 2010 (EPA/NHTSA2010).

	b 2015	b 2020	b 2025	b 2030	b 2035	b 2040	b 2045	b 2050	k all years
Conventional and Hybrid Spark Ignition									
Lower Bound									
Small Cars	1,180	1,016	919	874	832	791	752	716	0.9
Large Cars	1,290	1,110	1,005	956	909	865	823	782	0.9
Pickups	1,570	1,351	1,223	1,163	1,106	1,052	1,001	952	0.9
Small SUVs	1,220	1,050	950	904	860	818	778	740	0.9
Large SUVs	1,500	1,291	1,168	1,111	1,057	1,005	956	910	0.9
Upper Bound									
Small Cars	2,800	2,410	2,181	2,074	1,973	1,877	1,785	1,698	0.7
Large Cars	3,080	2,651	2,399	2,282	2,170	2,065	1,964	1,868	0.7
Pickups	4,010	3,451	3,123	2,971	2,826	2,688	2,557	2,432	0.7
Small SUVs	2,970	2,556	2,313	2,200	2,093	1,991	1,894	1,801	0.7
Large SUVs	3,950	3,400	3,076	2,926	2,784	2,648	2,519	2,396	0.7
Diesel									
Lower Bound									
Small Cars	4,430	3,813	3,450	3,282	3,122	2,970	2,825	2,687	0.9
Large Cars	4,430	3,813	3,450	3,282	3,122	2,970	2,825	2,687	0.9
Pickups	6,790	5,844	5,288	5,030	4,785	4,551	4,329	4,118	0.9
Small SUVs	4,430	3,813	3,450	3,282	3,122	2,970	2,825	2,687	0.9
Large SUVs	5,060	4,355	3,941	3,749	3,566	3,392	3,226	3,069	0.9
Upper Bound									
Small Cars	10,500	9,037	8,177	7,779	7,399	7,038	6,695	6,369	0.7
Large Cars	10,500	9,037	8,177	7,779	7,399	7,038	6,695	6,369	0.7
Pickups	16,100	13,857	12,539	11,927	11,345	10,792	10,266	9,765	0.7
Small SUVs	10,500	9,037	8,177	7,779	7,399	7,038	6,695	6,369	0.7
Large SUVs	12,000	10,328	9,346	8,890	8,456	8,044	7,652	7,278	0.7
Vehicle Technologies Only									
Lower Bound									
Small Cars	0.077690	0.066868	0.060505	0.057554	0.054747	0.052077	0.049537	0.047121	9
Large Cars	0.085654	0.073723	0.066707	0.063454	0.060359	0.057416	0.054615	0.051952	9
Pickups	0.122751	0.105653	0.095599	0.090936	0.086501	0.082282	0.078269	0.074452	9
Small SUVs	1.098794	0.085033	0.076941	0.073189	0.069619	0.066224	0.062994	0.059922	9
Large SUVs	0.123660	0.106436	0.096307	0.091610	0.087142	0.082892	0.078849	0.075004	9
Upper Bound									
Small Cars	0.001108	0.000954	0.000863	0.000821	0.000781	0.000743	0.000706	0.000672	15
Large Cars	0.001405	0.001210	0.001094	0.001041	0.000990	0.000942	0.000896	0.000852	15
Pickups	0.001927	0.001659	0.001501	0.001428	0.001358	0.001292	0.001229	0.001169	15
Small SUVs	0.001405	0.001210	0.001094	0.001041	0.000990	0.000942	0.000896	0.000852	15
Large SUVs	0.001927	0.001659	0.001501	0.001428	0.001358	0.001292	0.001229	0.001169	15

Table 9-9. *Coefficients for Equation 9-3 –
Describing Incremental Retail Price Equivalent by Vehicle Size and Vehicle Type*

relative price in 2015 (0.78). The *b* coefficient for the upper bound curve was assumed to decrease 1%/year, the rule of thumb for mature technologies. Results for conventional and hybrid spark ignition, diesel, and vehicle technologies only are given in Table 9-9 and were used as inputs to the integrated analysis.

Consumer Cost-Benefit Analysis

In the absence of constraints or incentives, the fuel economy of the LD vehicle fleet depends on the desirability of fuel economy as a vehicle attribute. Changes in the vehicle mix can impact fleet fuel economy, but for this analysis we assume the vehicle mix is that projected in the AEO2010. The target year used for the cost-benefit analysis is 2025. In 2025, the sales mix derived from AEO2010 for the five segments, small cars, large cars, pickups, small SUVs, and large SUVs, is 27.7%, 33.6%, 10.3%, 14.4%, and 14.0%, respectively. If this had been the fleet mix in 2008, the LD new vehicle average laboratory fuel economy would have been 28.1 mpg (not too different from the actual 2008 average of 27.6 mpg).

The willingness of consumers to buy improved fuel economy technology is a topic of much debate. The Manufacturer's Technology Choice Model of AEO2010 evaluates the economics of fuel technologies on the basis of a 3-year payback period and a real discount rate of 15%. Assuming monthly payments at 3 years/15% discount, customers want to save $42/year in fuel for every $100 of increased vehicle price. Assuming 13,000 miles/vehicle/year and 21.9 mpg, the breakeven RPE of future fuel economy can be calculated using Equation 9-4.

Equation 9-4:

$$\text{Breakeven } \$RPE = \frac{\$}{\text{gallon}} * \frac{\dfrac{13{,}000\ \text{miles/yr}}{0.42}}{} * \left(\frac{1}{\dfrac{\text{future}}{\text{mpg}}} - \frac{1}{\dfrac{21.9}{\text{mpg}}} \right)$$

Results of calculations using Equation 9-4 are shown by the blue lines in Figure 9-20 at gasoline prices of $2.16, $3.61, and $5.51/gallon, 2025 AEO2010 gasoline prices for low oil price, reference, and high oil price scenarios, respectively. Results show that customers would be willing to
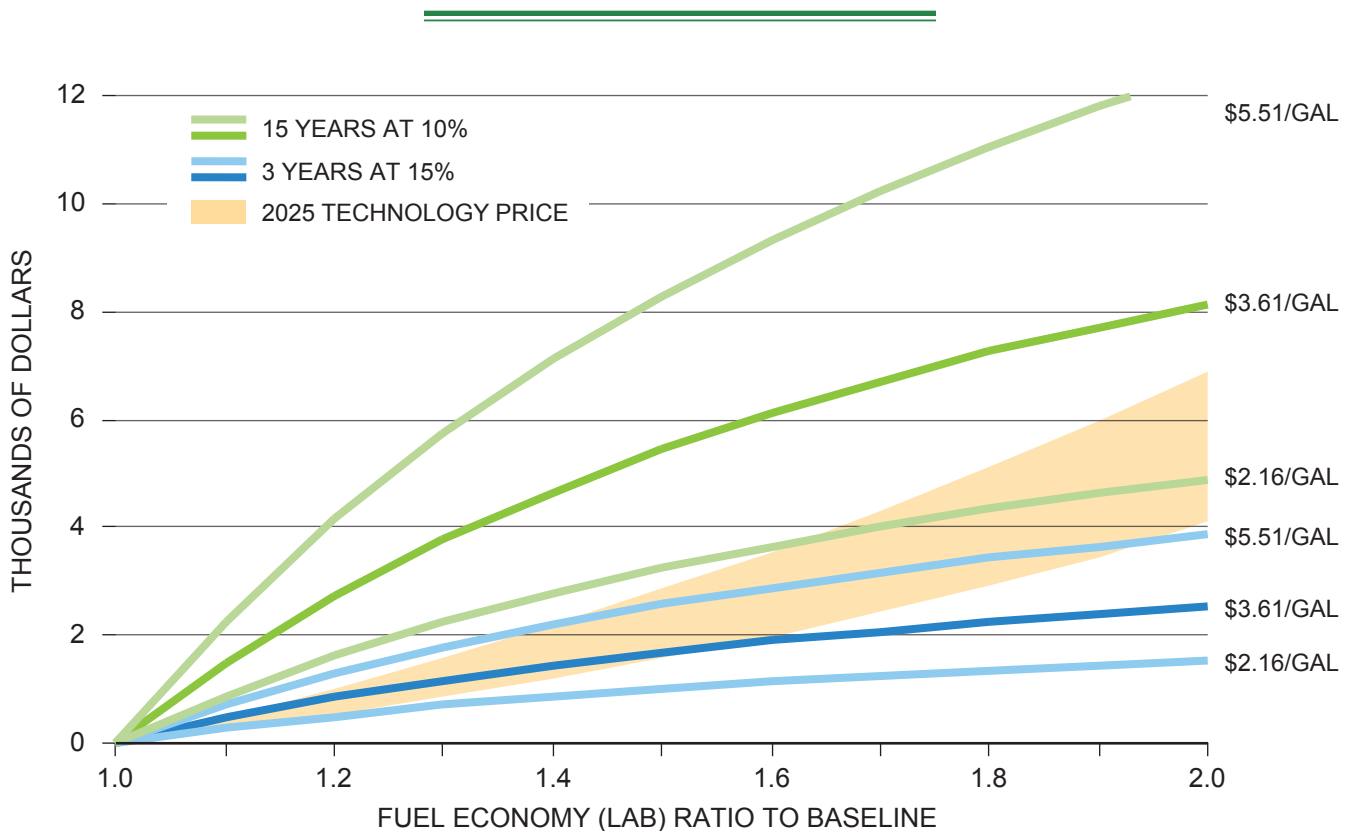
Figure 9-20. Breakeven Fuel Economy Technology Price as a Function of Fuel Economy, Gasoline Price, and Payback Criteria (Years/Discount Rate) – Fleet Average for 2025

pay an incremental $1,500, $2,500, or $3,800 for new LD vehicle average of 56 mpg laboratory (double the 2008 average laboratory fuel economy) at gasoline prices of $2.16, $3.61, and $5.51/gallon, respectively.

It is also possible to look at breakeven from more of a societal perspective rather than a customer purchase perspective. From a societal perspective, the payback time could be closer to the vehicle lifetime. There are no clear guidelines on the appropriate payback years and discount rate for a societal perspective. This analysis selected a 15 year payback and 10% discount rate. These parameters require $13/year in fuel savings per $100 increase in vehicle price. For this analysis, Equation 9-4 was used, but the constant in the denominator was changed from 0.42 to 0.13. Results are shown in the green lines of Figure 9-20. The green lines indicate breakeven prices, at 15 years payback and 10% discount, for doubling laboratory fuel economy to 56 miles/gallon of $4,900, $8,200, and $12,400 for $2.16, $3.61, and $5.51/gallon, respectively.

Figure 9-20 shows that both fuel price and payback parameters have a large impact on the breakeven price. Also shown in Figure 9-20 are the upper and lower bound technology prices using Figure 9-13 adjusted to 2025. Technologies are cost effective whenever the 2025 technology price boundaries fall below the blue or green lines. For example, if lower bound technology RPE is achieved and the societal criterion of 15 years/10% is used, technologies are clearly cost effective over the range of gasoline prices. On the other hand, if technology RPE is at the upper bound and 3 years/15% is the payback criterion, technology is marginally cost effective at fuel economy ratios of about 1.4 and lower if gasoline price is $5.51/gallon. At lower bound technology price and 3 years/15% payback criterion, technology is marginally cost effective up to a fuel economy ratio of about 1.5. at $3.61/gallon, and cost effective up to about 2.0 at $5.51/gallon. At upper bound technology price and a 15 years/10% payback criterion, technology is cost effective if gasoline price is $3.61 or $5.51/gallon, or up to a fuel economy ratio of 1.6 at $2.16/gallon. Clearly, assumptions about technology price, payback criteria, and gasoline price all have a large impact on cost effectiveness.

Technology Accelerators and Breakthroughs

There are several areas of advanced technology that could have a significant impact on personal mobility, vehicle design, engineering, and manufacturing that in turn could have an effect on transportation GHG emissions. Most major auto manufacturers are, to varying degrees, researching and experimenting with these technologies.

Smart, connected, and possibly "autonomously" driven vehicles are increasingly regarded as a real possibly, largely due to the advent of advanced sensors, electronics, and high-bandwidth wireless communications technologies. The ability to have vehicles electronically "connected" and communicating positional and other data to other vehicles, infrastructure, pedestrians, etc., suggests the potential for a much more efficient mobility network in which routing can be optimized to avoid hazards, congestion, and weather impacts, and parking location and availability information is readily accessible. The close coupling or "platooning" of vehicles going in the same direction has also been suggested as a way to improve throughput efficiency (capacity) of roadways. In its fullest application, truly autonomous vehicles—vehicles that control themselves—would effectively mean vehicles that do not crash. If so, many of the passive and active safety systems now required on manually operated vehicles to avoid or mitigate harm in a crash would no longer be needed. This could remove significant mass and design constraints from current vehicle design, thus enabling more energy efficient vehicles. Implementing such technology will require significant development, testing and validation, and revisions to safety regulations.

The possibility for ultra-lightweight mass-market vehicles has been researched and experimented with for decades. Most of this work has focused on high-strength steel, aluminum, magnesium, and carbon fiber reinforced plastics. While most of the applications to date have been in high-strength steel and aluminum (mostly premium vehicles), there is increasing interest and potential for broader use of carbon fiber in non-structural, structural, and possibly "class-A" surface panels. Historically, these materials have been hampered by significantly high cost and slow manufacturing cycle time relative to

mainstream materials. If breakthroughs could be achieved, the benefits of "de-compounding" in which aggressive use of ultra-light chassis and body materials enable significant downsizing and mass reduction of other vehicle systems (such as powertrains, brakes, and suspension systems), a cross-over point might be reached in which the higher material cost of carbon fiber could be offset by the lower costs of major systems, and operating savings realized from an overall lighter and more efficient vehicle.

A third category of advanced technology that could impact transportation GHG emissions is products tailored to provide personal mobility in dense urban areas. The desire for personal mobility could clearly come into direct conflict with the needs and realities of dense mega-cities, in which the ownership and operation of conventional vehicles could become physically and economically impractical. Recent concept vehicles from several manufacturers suggest the possibility of very small footprint one- or two-person devices that could be used on dedicated lanes, or if operating in a highly connected smart-vehicle/smart-infrastructure environment could be semi or fully autonomous. Combining these designs and technologies with experimental business models in vehicle sharing could lead to more efficient use of space, infrastructure and time, while retaining options for personal mobility besides mass transit systems.

Technology Barriers, Opportunities, and Challenges

The principal technology and other barriers for achieving significant reductions in petroleum-based fuel consumption are shown in Figure 9-21 and summarized below:

- High material and manufacturing costs for application of advanced lightweight materials to mass-market vehicles

- Cost competitiveness of incremental ICE improvements such as stratified charge/lean burn, HCCI, clean diesel, exhaust heat recovery, and fuel flexibility

- Cost of components required for hybridization, including batteries, motors, and controllers, regenerative braking

- Widespread availability of cost competitive low-carbon fuels

- Lengthy design and manufacturing lead times for implementing new technologies

- Slow turnover of the vehicle fleet hampers rapid penetration of new technologies in the vehicle fleet.

- Development, testing, and deployment of connected smart vehicles with smart infrastructure to improve traffic throughput

The major barrier to high-volume deployment of advanced vehicle and engine technologies for improved fuel economy is that many available and forthcoming technologies are not cost effective for the mass-market consumer at current petroleum based fuel prices in the United States. Several ICE technologies under development could provide incremental improvements when cost-competitive. Hybrid electric vehicles provide more significant improvement, but need lower cost batteries, motors, power electronics, and regenerative braking systems to reach high volumes in more segments of the market. Technologies to reduce vehicle mass also require cost reduction and improved technology for high volume manufacturing. In addition to improved vehicle related technologies, significant carbon reduction goals for LD vehicles will also require high volume, low cost, low carbon fuels such as advanced biofuels.

There is also a significant market and business model barrier in that high volume saturation of the U.S. vehicle fleet with advanced technology vehicles that consume significantly less fuel can take many decades, driven mainly by the compounding effects of lengthy vehicle and technology development lead times, the time to cascade technology through any given manufacturer's product portfolio, and the increased longevity of vehicles which leads to the gradual replacement of old vehicles with new ones. Process technologies enabling significant reductions in design, development, testing, and validation time and cost could have a material impact on the ability of industry to bring new technologies to market.

The previous section of this chapter briefly described the potential impact that advanced vehicle-to-vehicle and vehicle-to-infrastructure communications (sometimes referred to as V2X) technologies might have on vehicle design, engineering, and content. In addition to the technology

HURDLE		REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
VEHICLE:				
MASS	LIGHT-WEIGHTING	Low cost structural applications of aluminum, carbon fiber or other advanced materials for mass market vehicles	🔴	New materials involve new supply chains, manufacturing processes and service processes
ACTIVE SAFETY	CONNECTIVITY	Ubiquitous "smart" vehicles and "smart" infrastructure	🔴	"Crashless" vehicles enable significant light-weighting (e.g., removal of structure, airbags)
AERODYNAMICS	DESIGN	Low drag designs compliant with other design criteria	🟡	Matters more at high speeds; can be at odds with other design and regulatory criteria (pedestrian protection)
ROLLING RESISTANCE	TIRES	Low cost application of low rolling resistance tires	🔵	Rolling resistance / traction trade-offs are being overcome
POWERTRAIN:				
INTERNAL COMBUSTION ENGINE	STRATIFIED CHARGE/ LEAN BURN	Cost competitive, robust lean aftertreatment	🟡	Incremental benefit relative to existing technology
	HOMOGENEOUS COMPRESSED CHARGE IGNITION	Cost competitive robust control system	🟡	Incremental benefit relative to existing technology
	CLEAN DIESEL	Cost competitive robust aftertreatment	🟡	Fuel + Vehicle must cost less than gasoline hybrid to be competitive
	EXHAUST HEAT RECOVERY	Cost competitive fuel economy improvement	🔴	Thermoelectric and rankine cycle approaches being developed
	FUEL FLEXIBILITY	Cost competitive ultra-low emissions	🟡	High cost exhaust and evaporative emissions control with LEVIII standards
HYBRID POWER BATTERIES	COST	HEV fuel savings offset incremental vehicle price	🟡	Hybrid system cost is primary barrier
	RECYCLING	Zero or positive value at vehicle disposal	🟡	Significant disposal cost with today's technology; second use applications under study
	MATERIALS	Multiple geographic sources for key raw materials	🟡	Some materials used in batteries and motors are sourced primarily in one country and have dramatically risen in price
HYBRID SYSTEMS	MOTORS	Lower cost, mass and alternative (non-rare earth) materials	🔵	Hybrid system cost is primary barrier
	CONTROLLERS / POWER ELECTRONICS	Lower cost, simpler systems with better thermal management characteristics	🟡	Hybrid system cost is primary barrier
	REGENERATIVE BRAKING	HEV fuel savings offset incremental vehicle price	🟡	Hybrid system cost is primary barrier
FUEL:				
CARBON FOOTPRINT	AVAILABLE VOLUMES	Widespread, cost competitive low carbon fuels (cellulosic ethanol)	🟡	Scaling to high volume has been slower than anticipated
OCTANE	ENGINE EFFICIENCY	Minimum U.S. RON increases from 90 to 95 (Europe minimum)	🟡	Alcohols more effective than hydrocarbons at same RON
INDUSTRY MODEL:				
TECHNOLOGY & VEHICLE DEVELOPMENT	LONG LEAD-TIMES	Economically viable faster development and deployment	🔴	Need advanced math-based design, development, testing, and validation tools
VEHICLE LONGEVITY	SLOW STOCK TURN-OVER	Economically viable faster turnover of vehicle stock	🔴	Requires massive reduction in vehicle cost
MOBILITY MODEL:				
VEHICLE UTILIZATION	VEHICLE OWNERSHIP	Improved utilization of vehicle stock for personal mobility	🔴	Car-sharing programs emerging
TRAFFIC MANAGEMENT	CONGESTION/ POOR THROUGHPUT	Integration of "smart" vehicles and roads	🔴	Improve traffic throughput efficiency to reduce wasted time and energy

🟩 PRIORITY FOCUS AREA TO ENABLE WIDE-SCALE COMMERCIALIZATION

🔵 MINIMAL/NO BARRIERS

🟡 WILL TAKE INVESTMENT AND TIME, BUT PATHWAY FOR SUCCESS HAS BEEN IDENTIFIED

🔴 SIGNIFICANT BARRIER OR HIGH RISK OR HIGH UNCERTAINTY OR REQUIRES "BREAKTHROUGH OR INVENTION"

***Figure 9-21.** Hurdles for Light-Duty Engine and Vehicle Technologies*

related barriers in this area, there is also a basic deployment obstacle. The ultimate value in what the technology might lead to—crashless vehicles—requires near ubiquity in a market area, and significant changes to existing concepts and regulations about safety.

There could be a compounding synergy amongst several of these key technology barriers areas if breakthroughs are realized. The combination of ubiquitous V2X connectivity and autonomous vehicles leading to crashless vehicles, advanced vehicle electrification technology, and advanced lightweight materials and manufacturing processes could enable dramatic and completely new clean-sheet approaches to vehicle design, engineering and assembly. Speculation on what these vehicles might look like or how they might perform in terms of fuel economy or carbon emissions is beyond the core quantitative study literature cited for this report. However, there has been some recent work and emerging thinking that suggests that this technology synthesis could lead to vehicles or other personal mobility devices that are by design significantly simpler, cheaper, lighter, safer, smaller, and more efficient. The integration of these could be considered a tipping point for personal mobility.[63,64]

POTENTIAL IMPACT ON 2050 LIGHT-DUTY FLEET GHG AND PETROLEUM USE

Two of the key metrics for this study are examined through economics: GHG reductions for 2050 compared to 2005, and petroleum usage reductions for 2050 compared to 2005. A simplified analysis was used in this chapter to examine how application of technology to increase the fuel economy of the vehicle fleet impacts GHG emissions and petroleum usage.

GHG emissions in 2050, in million metric tons of CO_2 equivalent (CO_2e), can be represented as the product of vehicle fleet energy consumption, fuel carbon footprint, and vehicle miles traveled, as shown in Equation 9-5.

63 Amory Lovins, E. Kyle Datta, Odd-Even Bustnes, Jonathan Kooney, Nathan Glasgow, *Winning the Oil Endgame,* Rocky Mountain Institute, 2004, www.oilendgame.com.

64 Amory Lovins and the Rocky Mountain Institute, *Reinventing Fire: Bold Business Solutions for the New Energy Era,* 2011.

Equation 9-5:

$$\text{GHG} [10^6 \text{ metric tons } CO_2e] = \text{Fuel Cons}_{\text{fleet}} \left[\frac{\text{mmBTU}_{\text{HHV}}}{\text{mile}} \right]$$

$$* \text{Fuel}_C \left[\frac{\text{kg } CO_2e}{\text{mmBTU}_{\text{HHV}}} \right] * \text{VMT[billions]}$$

For this analysis, only the LD vehicle fleet in the year 2050 is considered. From Equation 9-5, it is clear that vehicle efficiency, fuel carbon footprint, and VMT all impact GHG emissions. However, this section only looks at the impact of changes in efficiency of the vehicle fleet. The fuel carbon footprint is assumed to remain at the 2050 Reference Case value of 84 $kgCO_2$/million BTU (1,652 million tons CO_2e divided by 19.7 quadrillion BTU of energy). Similarly, total LD vehicle VMT is assumed to remain at the Reference Case value of 5,240 billion miles in 2050. It should be noted that these three parameters are often not independent. For example, if biofuel volume remains constant as efficiency of the fleet improves, the fuel carbon footprint can decrease due to an increased proportion of low-carbon biofuel. Also, the reduction in cost of driving caused by an increase in vehicle efficiency can increase VMT.

Total LD vehicle GHG emissions are computed as a function of fuel economy of the 2050 LD vehicle fleet. For consistency, the 2050 fleet fuel economy is shown as a fuel economy ratio to 2008 new vehicle average fuel economy, which was 28 mpg laboratory. The energy-based fuel consumption parameter in Equation 9-5 was calculated by dividing gasoline heating value by on-road fuel economy. Equation 9-6 shows how energy-based fuel consumption of the fleet was calculated as a function of laboratory test fuel economy. In the denominator on the right hand of Equation 9-6, laboratory fuel economy is multiplied by 80%. This discounts laboratory fuel economy to an estimated on-road value. The 80% factor is not precisely consistent with the current EPA 2-cycle derived label, which discounts as much as 30% for hybrids and battery electric vehicles; 80% was used in this study as a simplification. Using the 20% discount, the 27.9 laboratory fuel economy, using 2008 technology, would correspond to an on-road fuel economy of 22.3 mpg.

Equation 9-6:

$$\text{Fuel Cons}_{\text{fleet}} \left[\frac{\text{mmBTU}_{\text{HHV}}}{\text{mile}} \right] = \left[\frac{0.125 \frac{\text{mmBTU}_{\text{HHV}}}{\text{gal}}}{80\% * \frac{\text{miles}}{\text{gal}_{\text{lab}}}} \right]$$

Results of the 2050 LD vehicle fleet GHG emissions calculations are shown in Figure 9-22. The gold line shows change in 2050 total GHG emissions relative to the 2050 Base Case and the red line shows change in 2050 GHG emissions relative to 2005. As expected, the GHGs decrease as fuel economy of the LD vehicle fleet increases. Note that with the fleet fuel economy ratio at 1.4 (40 mpg laboratory), LD vehicle GHG emissions *increase* 20% compared to 2005. This results from the increase in VMT.

If the LD vehicle fleet had a 2.0 fuel economy ratio (56 mpg), LD vehicle GHG emissions would decrease by 16% compared to 2005. Based on the retail price range shown in Figures 9-8 through 9-12, the incremental increase in RPE for a 2.0 fuel economy ratio (56 mpg) would range from about $3,100–$6,200/vehicle.

As indicated by Equation 9-5, there are additional measures that could reduce GHG emission of the vehicle fleet: reduction in VMT and reduction in fuel carbon footprint. VMT is discussed in Chapter One, "Demand," and the fuel carbon footprint of liq-uid fuels is discussed in Chapter Eleven, "Hydrocarbon Liquids," and Chapter Twelve, "Biofuels."

Figure 9-23 shows the corresponding results for petroleum use in 2050 as a function of fleet fuel economy ratio. LD vehicle petroleum use decreases 50% from the Base Case in 2050 as the 2050 LD vehicle fleet fuel economy ratio increases to 2. Relative to 2005, petroleum use decreases 20% as 2050 fleet fuel economy ratio reaches 2.

One unintended consequence of reducing fuel consumption of the vehicle fleet could be an increased in miles traveled. Consumers will see a different value proposition when faced with a high vehicle price (sunk cost once the vehicle is purchased) and a lower operating cost. This will produce some degree of rebound effect that offsets part of the fuel consumption and GHG reduction in the above analysis. A typical assumption for rebound effect is 10%; this means that 10% of the reduction in cost per mile of driving is offset by an increase in VMT.[65]
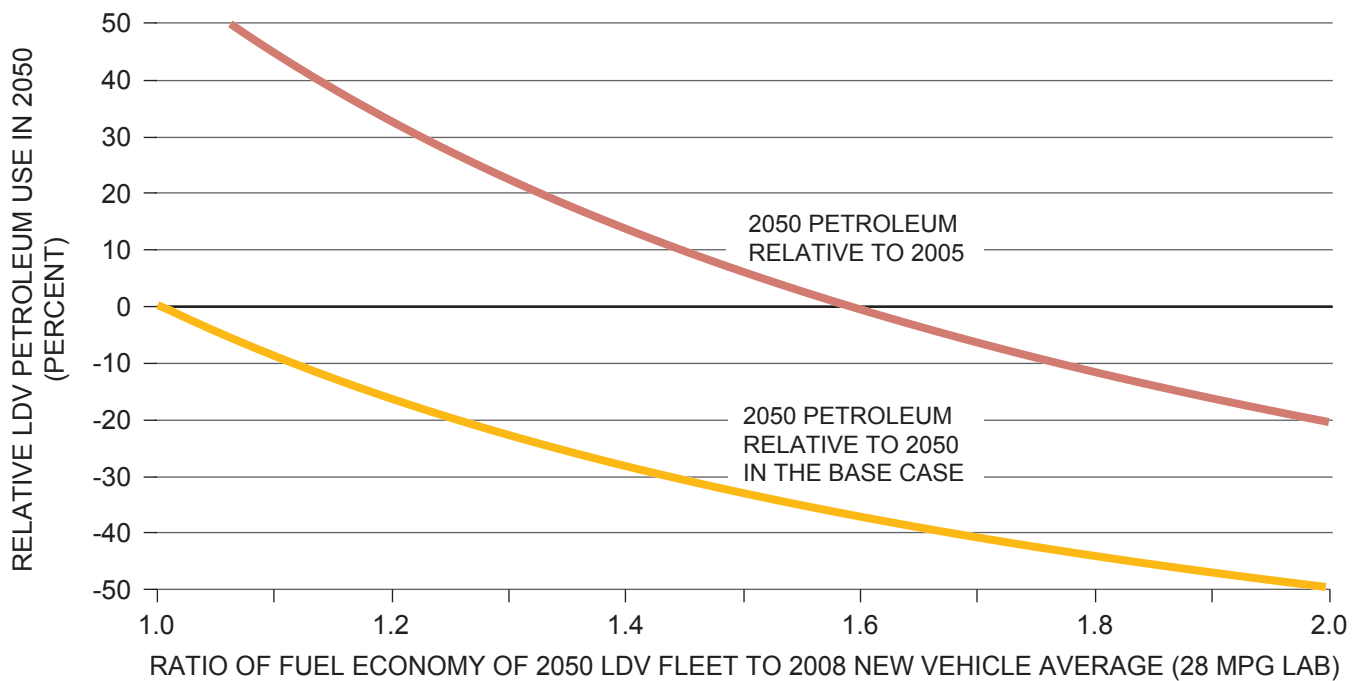
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65 EPA/NHTSA 2010a (see footnote 12).
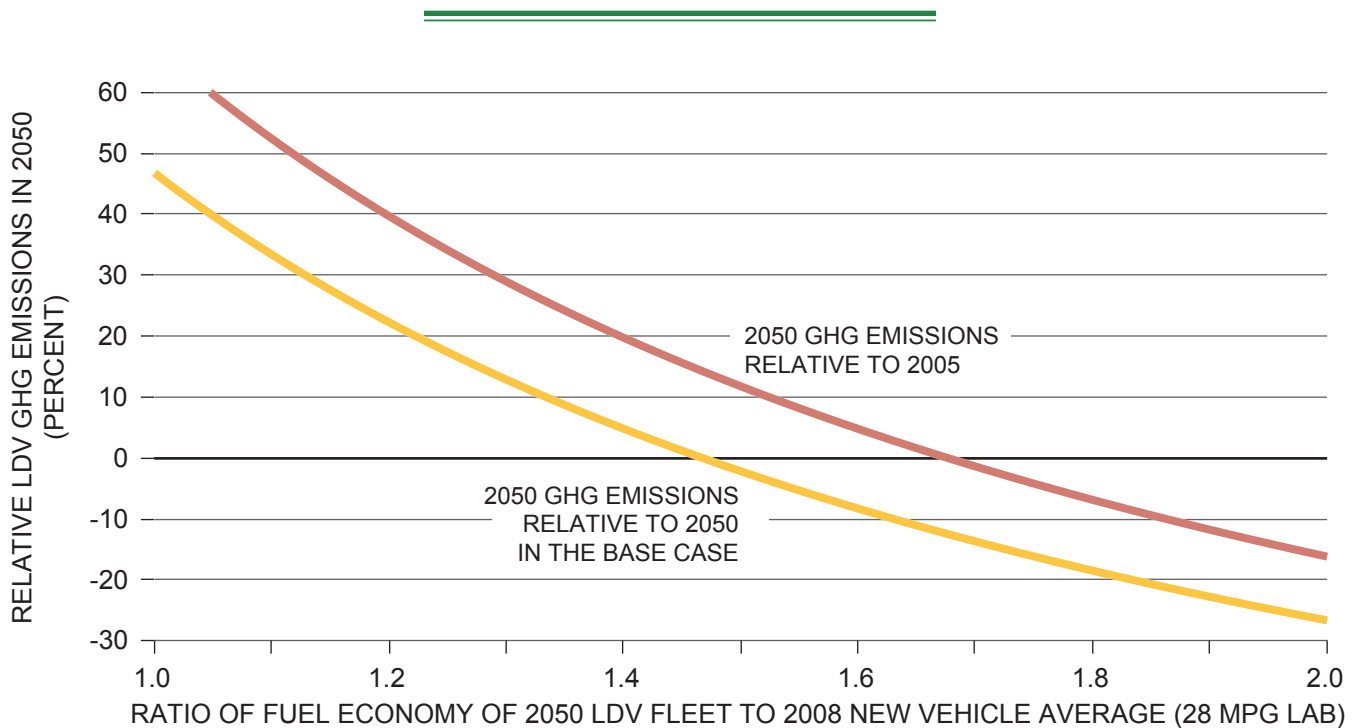
Notes: LDV vehicle miles traveled: 5.2 trillion in 2050, 2.7 trillion in 2005.
Fuel = 84 grams CO_2 per million BTU in 2050 (Reference Case).
On-road mpg = 80% of lab.

Figure 9-22. *Light-Duty Vehicle (LDV) Greenhouse Gas Emissions in 2050 as a Function of 2050 Fleet Fuel Economy Ratio*

Figure 9-23. *Light-Duty Vehicle (LDV) Petroleum Use in 2050 as a Function of 2050 Fleet Fuel Economy Ratio*

FINDINGS

- There are many technologies that have the potential to both incrementally and significantly improve LD vehicle fuel economy. The primary issues are the cost and time to bring them to market.

- There is no single technology that can deliver significant improvements. Multiple technologies will need to be developed and deployed as systems.

- It will take significant time for many advanced engine/vehicle/fuel technologies to materially impact overall U.S. fuel/LD vehicle portfolio and fleet due to the combination of long development times, vehicle lifecycles and vehicle longevity in the market.

- Conventional LD vehicles deliver 1/5 to 1/7 of fuel energy as traction energy to the wheels and this energy is consumed in the tire-road interface, as drag, and in vehicle braking. Technologies exist or are under development to improve

vehicle fuel efficiency but some losses are unavoidable due to thermodynamics.

  - Advances in LD powertrain technologies are applicable to both liquid and gaseous fueled engines. Technologies include: friction reduction, valve management, direct injection, downsized turbocharging, accessories electrification, dual clutch transmissions, and hybridization. Achieving the maximum potential of fuel economy increase from downsizing requires a substantial increase in the minimum octane number of U.S. gasoline or vehicles dedicated to the use of high concentration alcohol-gasoline blends. Improved vehicle technologies, such as improved tires, improved aerodynamics, and reduced mass are applicable to all LD vehicles in this study.

- There are large differences, even among comprehensive, high-quality studies, in estimates of the incremental RPE of technology that achieves major reductions in vehicle fuel consumption. Data from these studies establish upper and lower bound technology price

ranges that can be used to assess various economic scenarios.

- Time and cost barriers to technology development and deployment are significant, as are business and mobility model impediments. Integrating the benefits of intelligent transportation systems, new materials, and electric propulsion could enable new types of vehicles that are inherently simpler, cheaper, lighter, safer, smaller, and more efficient.

- Even with full implementation of vehicle technologies that double the fuel economy of the LD vehicle fleet, GHG emissions in 2050 would only be about 16% lower than those in 2005, due to increased VMT.

  – Reduction in the carbon footprint of liquid transportation fuels, incorporation of alternative vehicle and fuel technologies into the fleet, and/or reduction of VMT will be required to achieve greater reductions.

- The timing and cost for deployment of technology for advanced connected/autonomous vehicles and active safety controls is a big uncertainty.

  – The full value requires technology penetration throughout the vehicle fleet, infrastructure, and other mobility modes (transponders for pedestrians, bicyclists, etc.).