On the Road toward 2050:

Potential for Substantial Reductions in Light-Duty Vehicle Energy Use and Greenhouse Gas Emissions

Report

Massachusetts Institute of Technology

Sloan Automotive Laboratory
Engineering Systems Division

November 2015

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Foreword:

This report summarizes the results of an ongoing research program that assesses the extent to which improvements and changes in powertrain and vehicle technologies, and fuels changes, could reduce the fuel consumption and greenhouse gas (GHG) emissions of light-duty road vehicles. This research was done by a team of graduate students from 2009 to 2014, and includes some 20 projects. It continues our group's efforts to provide a more complete summary of the various options available, and an increasingly detailed knowledge base with which to assess these options, as we move forward. It follows on from three earlier reports: *On the Road in 2020* published in 2000 and *On the Road in 2035* published in 2008, and a strategy and policy-based report, *An Action Plan for Cars*, published at the end of 2009.

The report consists of a sequence of chapters, each devoted to an important component in our overall assessment of the options for reducing the energy use and GHG impacts of this major sector in our land-based passenger transportation system. The initial two chapters develop the context within which this sequence of key topic areas is examined. Subsequent chapters focus in turn on: the several propulsion system options in the various types of light-duty vehicles, and their operating characteristics; vehicle weight reduction potential and its impacts; the inherent vehicle performance, fuel consumption, and vehicle size trade-offs; fuel and alternative energy opportunities for this transportation sector and their infrastructure challenges; the process by which improved and new technologies diffuse into the in-use vehicle fleet; driver behavior and vehicle use impacts; extensive scenario analysis of various technology and energy pathways forward that quantifies changes in fuel use and GHG emissions in the United States, Europe, Japan, and China; the policy options available for further reducing these impacts; a summary and set of recommendations.

This final chapter (Chapter 11) provides an overall summary of the key findings in these various areas, and brings these findings together to assess how much the in-use light-duty vehicle fleet fuel consumption and GHG emissions might be reduced in major world regions. The results of plausible yet aggressive scenarios in the United States show the potential for technology improvements to more than offset fleet growth and, by 2050, reduce fuel use and GHG impacts by up to 50 percent. In Europe, the anticipated fleet growth is less, as are the potential reductions from technology improvements, but the overall percentage reduction potential is similar to that in the United States. In Japan, fleet size and use are declining, so the overall reduction in impacts could be larger. In China, though current growth in fleet size is large, reductions in that growth rate and substantial technology improvements over time are expected to level off fleet fuel consumption and GHG emissions by about 2040.

Chapter 11 ends with several recommendations focused on actions that we should consider implementing in the United States and elsewhere. Such actions are likely to be needed to attain close to the factor of two reductions in fleet fuel consumption and GHG emissions by 2050 that our overall assessment indicates are feasible in North America, Europe, and Japan. Larger reductions on this time scale will need additional major efforts, and would likely require significant reduction in travel demand, and more rapid development and substantial distribution and use of low-GHG-emitting alternative sources of transportation energy such as electricity and hydrogen. In China, where vehicle sales and fleet growth rates are expected to be high over the next decade or so, these reductions in fleet impacts will be delayed for two or so decades.

Overall, we believe that this report will help us better identify the more promising options for reducing this light-duty-vehicle component of transportation's energy consumption and GHG emissions. We have developed and characterized what we judge to be realistic, though aggressive, paths forward. Achieving these improvements in mainstream powertrain and vehicle technology and starting to transition to one or more of the greener alternative energy sources in a significant way are very important, but very challenging, tasks. It is clear that coordinated and reinforcing policies are going to be required to achieve the needed changes in vehicle technology, energy sources, and vehicle use.

I want to thank the many graduate students and colleagues who have worked collaboratively with me at MIT over the past 16 years on these multidisciplinary technology-based projects. Together as a team—which individuals join, work on their own research as well as contribute more broadly, then finish and move on—we have stimulated each other in very constructive and creative ways. I have found carrying out such multi-faceted research in this manner extremely rewarding at the professional and personal level. Finally, I would also like to thank Rebecca Marshall-Howarth for her editorial assistance and Karla Stryker-Currier for her administrative assistance. They were both instrumental in producing this book. Thank you all very much.

John Heywood, November 2015

1.0 Introduction

1.1 Personal Transportation and Climate Change

Road vehicles are a key part of the climate change challenge, representing both an important source of petroleum demand and greenhouse gas (GHG) emissions worldwide. In the United States, light-duty vehicles (LDVs, i.e., cars and light trucks) alone account for 43% of petroleum demand and 23% of GHG emissions, when fuel production is considered [MacKenzie, 2013]. The United States, Europe, China, and Japan consume over half of the world's petroleum, making them particularly critical in efforts to reduce petroleum consumption and the associated emissions. The production and use of gasoline and distillate (diesel) fuel in these four regions alone account for 15% of the world's energy-related carbon dioxide (CO_2) emissions [Energy Information Administration (EIA), 2013a]. Changes in our transportation system are necessary to mitigate climate change.

Changes to our transportation system—how much we travel, the vehicles we use, and the fuels that power them—offer the potential for substantial reductions in GHG emissions. This report is a synthesis of research conducted in the Sloan Automotive Laboratory at the Massachusetts Institute of Technology over the past five years, primarily under the direction of Professor John Heywood. It is the third report in a series that records the research findings of this group. The others are *On the Road in 2020* [Weiss et al., 2000] and *On the Road in 2035* [Bandivadeker et al., 2008].

This research addresses topics related to the evolution of vehicle technology and its deployment, the development of alternative fuels and energy sources, the impacts of driver behavior, and the implications of all of these factors on future GHG emissions in the United States, Europe, China, and Japan.

1.2 The Clock Is Ticking

This report is motivated by the simple observation that time is of the essence as we attempt to deal with the threat of climate change. Despite many warnings from the scientific community and the concern from some of our leaders, the levels of GHGs in the atmosphere continue to increase. In 2013, the average daily CO_2 level measured at Mauna Loa, Hawaii, topped 400 parts per million (ppm) for the first time [Scripps, 2013]. The annual average CO_2 concentration at Mauna Loa has increased every single year since record-keeping began (Figure 1.1). Whereas CO_2 concentration increased by less than 1 ppm per year during the 1960s, it has increased by more than 2 ppm annually since 2000. We must make increasingly substantive progress on reducing GHG emissions as we move forward from today if we are to avoid the anticipated damaging effects of climate change.

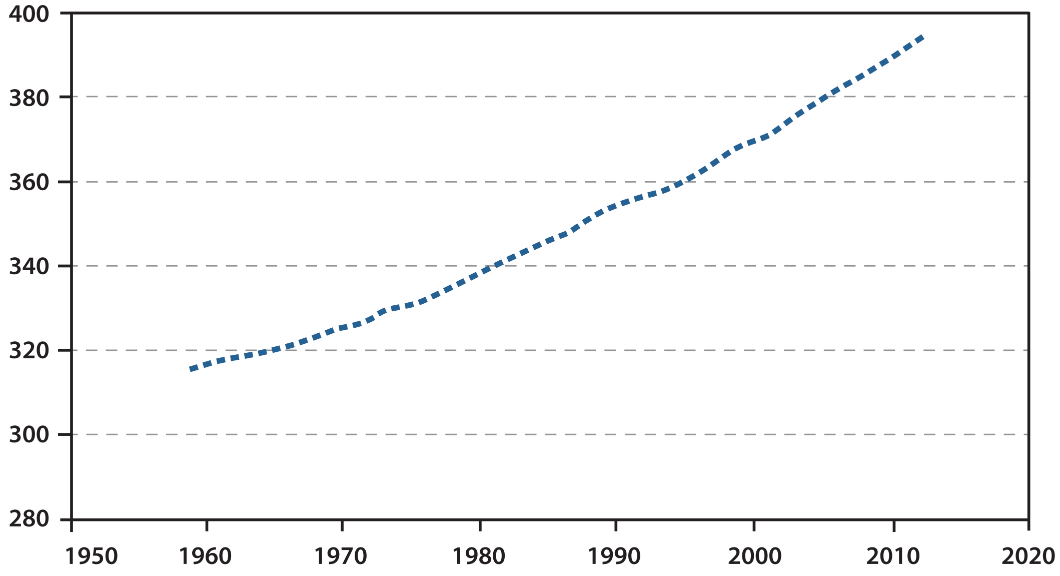

Figure 1.1 Annual average CO_2 concentration (ppm) at Mauna Loa Observatory, Hawaii, 1959–2012 [NOAA, 2013]

Strategies to mitigate climate change must recognize the cumulative nature of the buildup of GHG concentrations in the atmosphere. CO_2 and other GHGs, once released into the atmosphere, accumulate there and are only slowly removed. Moreover, the impacts that they cause are largely dependent upon their concentrations. This has two critical implications for GHG mitigation strategies:

1. To avoid an inexorable increase of GHG concentration levels, GHGs must not be added to the atmosphere any faster than they can be removed. This means that over the long term, emissions from fossil fuel carbon will need to be stabilized at levels substantially lower than today's levels, and possibly close to zero.

2. If GHG concentrations are to be stabilized at tolerable levels, there is an upper limit to the total amount of carbon (and GHGs) that can be dumped into the atmosphere. Thus, we cannot wait indefinitely to make the aforementioned switch to a radically less carbon-intensive energy system.

Transitioning to new energy sources takes decades. As shown in Figure 1.2, coal, oil, and natural gas each took 50–75 years to reach their peak levels of use. An extrapolation of the trend in Figure 1.1 indicates that we are on track to exceed 450 ppm of CO_2—a threshold widely held to be necessary for avoiding the worst effects of climate change—within just 25 years. Even if we begin to transition earnestly to radically lower-carbon energy sources today, we will still continue to rely on fossil fuels for many years to come.

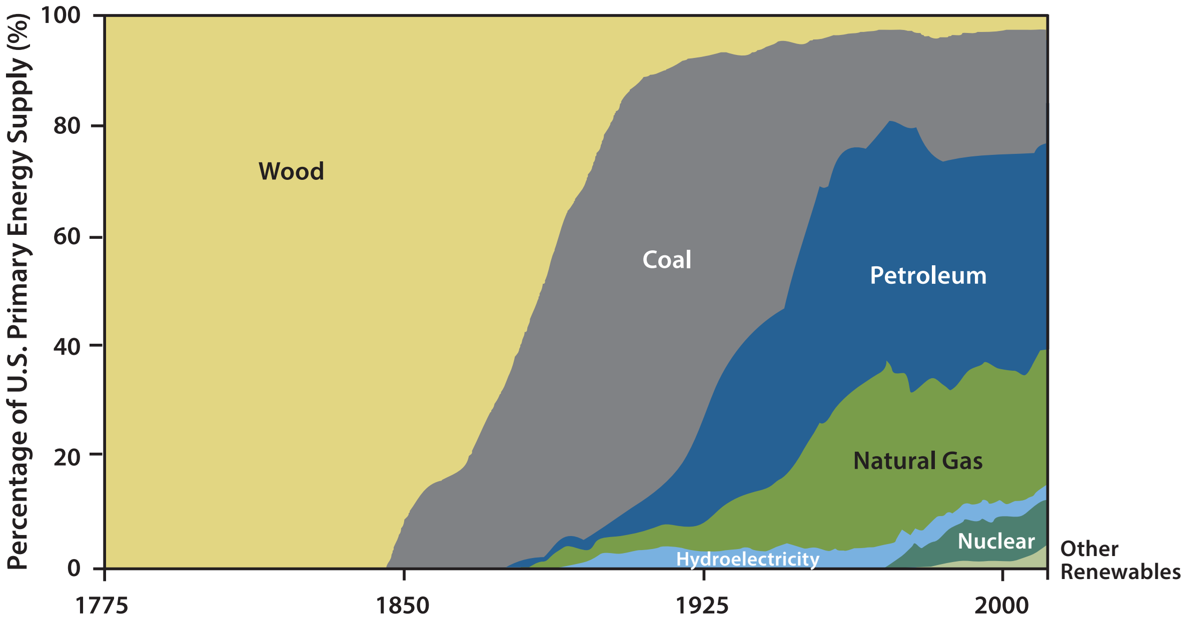

Figure 1.2 Primary energy sources in the United States, 1775–present [Adapted from EIA, 2013b]

An effective strategy for mitigating GHG emissions must, therefore, have both near- and long-term components: a set of long-term solutions to get us to near-zero carbon emissions and near-term actions that can buy us enough time to develop and deploy the long-term solutions. While near-zero carbon energy sources will be needed in the long term, we simply do not have the luxury of waiting to act until these low-emitting alternative energy sources are developed. Reducing demand for energy-using services and increasing the energy efficiency of those services can provide relatively cost-effective reductions in energy demand and emissions, while also buying critical time for alternative energy sources to be developed and deployed. This is illustrated in Figures 1.3 and 1.4.

In Figure 1.3, immediate efforts at improving fuel consumption and conservation lead to reductions in GHG emissions in the near and medium terms. As the potential savings from fuel consumption begin to level out, the transformation toward low-carbon fuels begins to pick up speed and enables continued GHG reductions. Figure 1.4 shows how efforts focused solely on transforming the transportation energy supply lead to continued growth in emissions for several decades, before the alternative fuel technologies begin to grow rapidly. In the meantime, large quantities of GHG will have accumulated in the atmosphere and exceeded the available carbon budget.

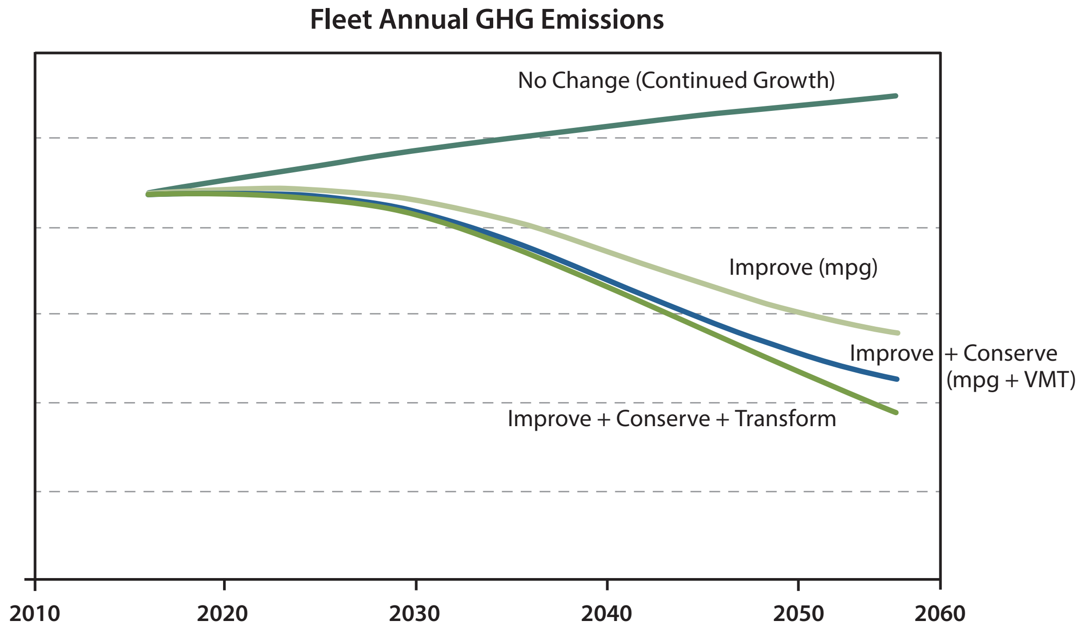

Figure 1.3 GHG emissions pathways under four scenarios: business as usual, improve-only, improve and conserve, and improve-conserve-transform

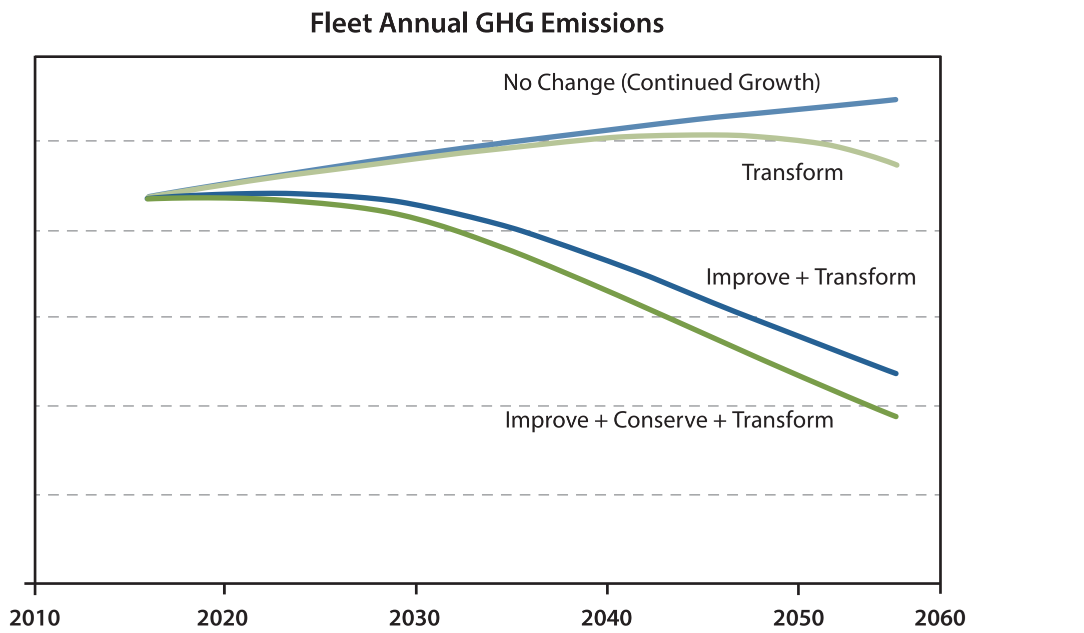

Figure 1.4 GHG emissions pathways under four scenarios: business as usual, transform-only, improve and transform, and improve-conserve-transform

1.3 Improve, Conserve, Transform

The central premise of this report is that a comprehensive strategy for mitigating GHG emissions from our vehicles will include several interrelated sets of actions:

1. **Improving** the fuel economy of conventional, petroleum-powered vehicles through steady gains in powertrain efficiency, reductions in vehicle weight, and assigning a higher priority to lower fuel consumption than to other design goals.

2. **Conserving** energy through changes in individual behavior, such as reducing travel demand, shifting to less energy-intensive travel modes, and operating vehicles more efficiently.

3. **Transforming** the transportation system into one that is radically less carbon intensive, through significant gains in vehicle efficiency and/or a large-scale switch to carbon-neutral energy sources.

These broad strategies are informed by viewing the generation of GHG emissions through a Kaya identity or "ASIF" framework [Schipper, 2002]. This framework notes that the rate of GHG emissions can be calculated from:

$$\text{GHG} = \text{Person Miles}\ \frac{\text{Vehicles Miles}}{\text{Person Miles}}\ \frac{\text{Energy}}{\text{Vehicles Miles}}\ \frac{\text{GHGs}}{\text{Energy}} \qquad \textbf{(1.1)}$$

or

$$GHGs = A \times S \times I \times F \qquad \textbf{(1.2)}$$

In Schipper's ASIF formulation, A refers to activity level (person-miles of travel); S to the mode structure or mix (e.g., $S = 0.65$ vehicle-miles / person-mile for cars in the United States); I to energy intensity or fuel consumption; and F to fuel carbon content. Viewing GHG emissions through this framework emphasizes the fact that improvements in any one of these factors contributes to proportional reductions in GHG emissions. However, it is important to consider that changes in one factor may lead to changes in other factors. For example, changing energy intensity is likely to change person miles of travel and vehicle miles per person-mile through the well-known rebound effect.

Proponents of the familiar "three-legged stool" approach have long asserted that vehicle fuel consumption, travel demand, and alternative fuels should be a part of a comprehensive GHG mitigation strategy. The authors of *Moving Cooler* [Cambridge Systematics, 2009] introduce a fourth category of options that relates to vehicle and system operations. Whereas *Moving Cooler* primarily addresses solutions relating to travel activity and vehicle and system operations, our report focuses primarily on vehicle technology, alternative fuels, and individual driving habits.

Content of this Report

This report addresses the range of propulsion system, vehicle technology, and fuel options available to help mitigate petroleum consumption and GHG emissions from automobiles in the United States and in other major regional markets. It also contains retrospective analyses of efficiency technology improvements in the United States, and examines historic adoption patterns of vehicle technologies. It studies the impacts of individual driving behavior on petroleum consumption. Finally, it presents a range of scenarios characterizing the ways that transportation systems could evolve in major global markets over the coming decades, and evaluates the cost effectiveness of various policy approaches for driving this evolution.

Chapter 1 lays out the basic challenge, which is the urgent need to reduce the GHG emissions from light-duty (predominantly private) vehicles through reductions in petroleum consumption and the substitution of alternative lower-carbon-emitting fuels and other sources of energy. We have also introduced the three broad paths forward that are of comparable importance and urgency: improving the fuel consumption of mainstream-technology vehicles; conserving fuel and energy use through how and how much we drive; and exploring the eventual transformation from our current situation in which internal combustion engine vehicles and petroleum-based fuels dominate our in-use light-duty fleet to alternative travel approaches that use energy sources that have modest impacts on our environment and are ultimately more sustainable. We have outlined here the factors that together provide a structured framework for assessing our options. It is important to keep these broad themes in mind as we progress, topic by topic, through the 11 chapters of the report.

Chapter 2 revisits past work by this research group and highlights some recent major reports from other groups in order to provide context for the present work and the motivation for the Improve-Conserve-Transform framework. The chapter outlines the steps that would be necessary to attain 80% reductions in GHG emissions by 2050. It concludes that aggressive efforts to conserve energy through individual behavior change, the rapid improvement of conventional vehicles, and the transition to radically less carbon-intensive alternatives will need to begin promptly.

Chapter 3 presents an overview of the major propulsion systems options that are available to improve energy intensity and transform the transportation system away from its current reliance on petroleum. It provides an assessment of feasible rates of improvement and examines the ways that the potential improvements vary across different global markets.

Chapter 4 examines the evolutionary changes in weight of U.S. cars over the past 35 years. It addresses the tension between steady improvements in weight-saving technologies and the steady introduction of new features and capabilities that have added weight to cars. It then applies these insights to assess the potential for weight reduction in the future.

Chapter 5 addresses the trade-offs between vehicle fuel consumption, acceleration performance, and weight. It explores the implications of changes in these vehicle attributes for efforts to improve fuel consumption. The chapter provides estimates of the fuel consumption impacts of changes in acceleration and weight, and reviews the Emphasis on Reducing Fuel Consumption (ERFC), a parameter that characterizes the degree to which efficiency improvements have been realized as reductions in fuel consumption. It examines ERFC over the past 35 years and quantifies the roles of other design changes—most notably gains in acceleration performance—that have acted as "sinks" for technology improvements. Given these findings, the chapter closes with an assessment of potential future levels of emphasis on reducing fuel consumption.

Chapter 6 introduces a framework for evaluating the prospective transformation to alternative fuels as the primary sources of energy, highlighting the many challenges to adopting these alternative fuels, including cost, environmental impact, GHG emissions, and compatibility with vehicles and infrastructure.

Chapter 7 presents key results relating to the adoption of new technologies, with implications both for the improvement of conventional technologies and the transformation to alternative powertrain systems. The chapter first discusses the adoption of powertrain, safety, and comfort and convenience features, characterizing their saturation levels and speed of adoption. Next, it presents a model of the adoption of a much more complex technology: hybrid electric drive as represented by the Toyota Prius. Finally, it discusses how the adoption and deployment of new technologies will propagate into and through the on-the-road vehicle fleet through fleet turnover.

Chapter 8 examines several opportunities for conservation. It briefly summarizes research estimating the potential for GHG savings through reductions in travel demand as well as through improvements in transportation system operations. It then presents new work characterizing the aggressiveness of driving, and the implications of aggressiveness for in-use fuel consumption. Finally, it presents the results of a large-scale, plug-in hybrid electric vehicle (PHEV) demonstration, highlighting the significant variability in petroleum savings across different drivers, characterizing factors related to battery charging decisions, and examining the potential petroleum savings from changing charging decisions or from changing battery sizes.

Chapter 9 summarizes several scenarios exploring the potential energy consumption and GHG emissions trajectories from personal transportation in major regions of the world. Each scenario is based on assumptions regarding the evolving context for vehicle deployment and use (e.g., growth in new vehicles sales, mileage driven), the rate of improvement in the various efficiency-improving technologies and their rate of deployment, the development of alternative fuel supplies, and the GHG emissions intensities of these new fuel supplies. These scenarios allow us to assess the uncertainties in the projected impacts, the overall rate of progress in reducing these impacts, and the factors that have the largest effects on outcomes.

Chapter 10 discusses the role of a comprehensive policy approach in driving improvement, conservation, and transformation. It also presents results comparing the cost effectiveness of carbon and fuel taxes to fuel economy standards and renewable fuel standards in achieving emissions reductions.

Chapter 11 pulls together the findings in each of the preceding chapters and concludes with a discussion of where we are, where we are headed, and where we need to go.

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2.0 Overview of Our Options

This report is the third in a series dating back to 2000, which collectively synthesize 15 years of research conducted at the Massachusetts Institute of Technology. The first report in this series, *On the Road in 2020* [Weiss et al., 2000] aimed to develop "optimistic but plausible projections" of the performance of light-duty automotive technologies in 2020. The authors considered characteristics that included cost; full life-cycle performance in environmental, health, and safety terms; and harder-to-measure attributes such as performance and driveability. Finally, they considered the implications of a wide range of emerging automotive technologies from the perspectives of a diverse list of stakeholders, including consumers; fuel producers and distributors; vehicle manufacturers and distributors; and various levels of government. The report also considered a variety of fuels including gasoline and diesel derived from conventional petroleum, synthetic diesel, methanol, hydrogen from natural gas, compressed natural gas, and electricity. The study considered powertrain technologies including spark-ignited internal combustion engines (SI-ICE), compression-ignition (CI-ICE), gasoline–electric and diesel–electric hybrid vehicles (HEV), fuel cell–electric hybrids (FCEV), and battery electric vehicles (BEV). The study acknowledged, but did not explicitly model, the barriers to and dynamics of transitions to new technologies. Key findings from this report are summarized in Table 2.1.

Table 2.1 Key findings from *On the Road in 2020* [Weiss et al., 2000]

Technology	Lifecycle GHG emissions vs. evolved 2020 baseline vehicle	Cost (1997$) vs. evolved 2020 baseline vehicle
1996 Reference	+52%	-$800
2020 Evolved SI-ICE	0	0
2020 Advanced SI-ICE	-11%	+$1,400
2020 Advanced CI-ICE	-22%	+$2,500
2020 Advanced SI-hybrid	-37%	+$3,200
2020 Advanced H_2 FCV	-28%	+$4,100
2020 Advanced BEV	-31%	+$9,000

The second report in this series, *On the Road in 2035* [Bandivadekar et al., 2008], added several important dimensions to the group's work. For example, the report considered additional fuels including ethanol, electricity from a wider variety of sources, and synthetic crude from tar sands. It evaluated additional powertrain technologies, including turbocharged spark-ignition engines and plug-in hybrid electric vehicles (PHEV). The report explored the trade-offs between performance, size, weight, and fuel consumption, and defined a metric called Emphasis on Reducing Fuel Consumption (ERFC) to characterize the degree to which improvements in efficiency technology were realized as reductions in fuel consumption, as opposed to being used to offset the fuel consumption penalties of increased weight and power. *On the Road in 2035* also introduced a model to track the dynamics of vehicle fleet turnover, and expanded the geographical scope to include several major European countries. Recognizing the growing concern over energy security, the report considered changes in petroleum consumption as well as changes in Greenhouse Gas (GHG) emissions, highlighting the fact that, while technologies that cut GHG emissions reduce petroleum demand, the reverse is not necessarily true.

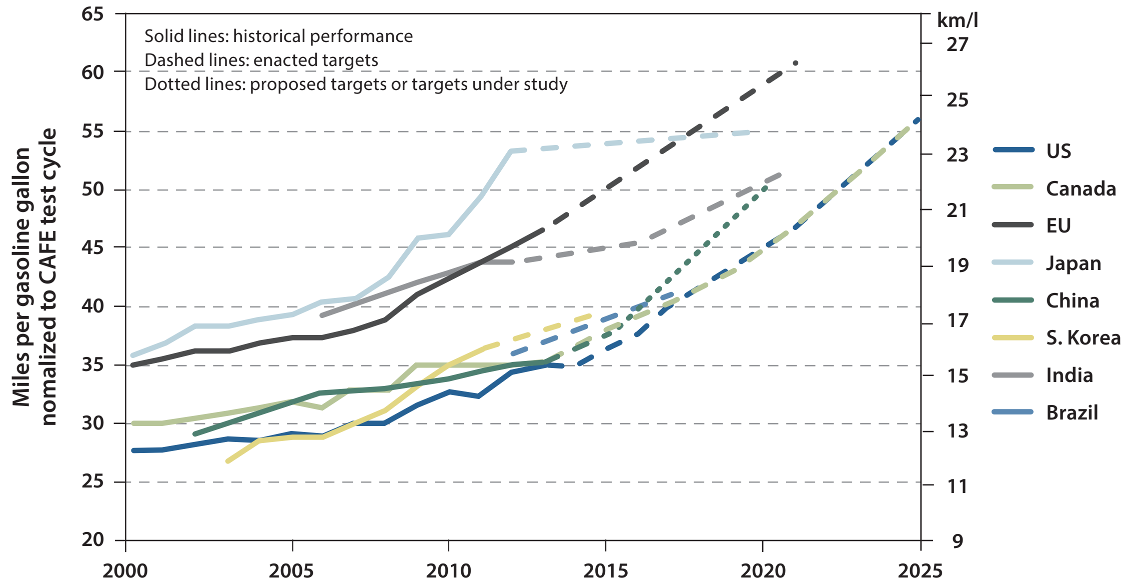
Key findings from *On the Road in 2035* included:

- Evolutionary changes in conventional Internal Combustion Engine (ICE)-powered vehicles offered the greatest potential for cutting fuel demand in the near term
- HEVs offer the possibility of deeper reductions, but major impacts would take 20–30 years to materialize and even longer (~50 years) for full benefits to be realized
- PHEVs combine the advantages of hybrid and electric vehicles, and offer additional GHG reductions beyond those of HEVs, but at a substantial cost
- With the current electricity generation mix, BEVs offer little benefit in lifecycle GHG emissions compared to HEVs
- For the potential benefits of many technologies to be realized, the decades-long trend toward larger, heavier, and higher-performing vehicles must be curtailed
- Weight reductions of 20% appeared likely over 25 years, with reductions of up to 35% being possible
- The contribution of synthetic petroleum from Canadian tar sands to the United States could increase from 3% to 10% by 2030, increasing well-to-tank GHG emissions by 5%. Ethanol could displace 10% of gasoline by 2025, but environmental benefits are expected to be modest, especially in light of the uncertainty over cellulosic ethanol technology. Any GHG reductions from biofuels are likely to be offset by the increased use of fuel derived from tar sands.
- The fuel consumption of new light-duty vehicles (LDV) could be reduced by 30%–50% over 20–30 years, holding vehicle size and performance constant.

Since the publication of our group's last major report in 2008, several major shifts have occurred. First, a deep economic recession led to the bankruptcy of two major U.S. automakers and years of depressed auto sales, from which the industry is only now recovering. Second, automotive fuel economy and GHG emissions standards have been tightened in the United States and worldwide (Figure 2.1, Figure 2.2). In the United States, the Energy Independence and Security Act of 2007 (EISA 2007), passed shortly before publication of the group's last report, mandated an increase in Corporate Average Fuel Economy (CAFE) standards to 35 miles per gallon (mpg) by 2020, as well as a transition to attribute-based standards. Since then, the Obama administration has accelerated the pace so that new cars and trucks are expected to achieve a combined average of 34 mpg by 2016, 38 mpg by 2020, and 49 mpg by 2025.[1] Third, new extraction technologies (horizontal drilling and hydraulic fracturing) have led to a sharp decrease in U.S. natural gas prices, while global oil prices have, until quite recently, remained high. This has rekindled interest in the potential use of natural gas as a transportation fuel. Fourth, cellulosic biofuel production has not

[1]Adjusted U.S. CAFE test cycle value. On-road mpg values about 20% lower.

kept pace with the blending levels mandated by EISA 2007. The country is now running up against the "blend wall"—the maximum amount of ethanol that can be blended with gasoline for use in standard gasoline vehicles. This has led the Environmental Protection Agency (EPA) to reduce mandated blending volumes for 2014. Fifth, U.S. imports of petroleum from Canada rose from 2.5 million barrels per day (mbd) in 2008 to 3.1 mbd in 2013.[2] Over the same period, tar sands accounted for 96% of the growth in Canadian petroleum production, and now account for 58% of total Canadian production. Finally, PHEVs and BEVs have entered volume production, and *Consumer Reports* called the all-electric Tesla Model S the best car that their experts have ever tested. However, production volumes of these vehicles remain low in absolute terms.



[1] China's target reflects gasoline vehicles only. The target may be higher after new energy vehicles are considered.
[2] The U.S. standards are fuel economy standards set by the National Highway Traffic Safety Administration, which are slightly different from the GHG standards due to A/C credits.
[3] While gasoline in Brazil contains 22% of ethanol (E22), all data in the chart have been converted to gasoline (E00) equivalent.
[4] Supporting data can be found at http://www.theicct.org/info-tools/global-passenger-vehicle-standards

Figure 2.1 International fuel economy standards and fuel economy equivalents of GHG standards, normalized to U.S. CAFE test cycle [Adapted from the International Council on Clean Transportation (ICCT), 2014]

[2]http://www.eia.gov/dnav/pet/pet_move_impcus_a2_nus_ep00_im0_mbbl_m.htm

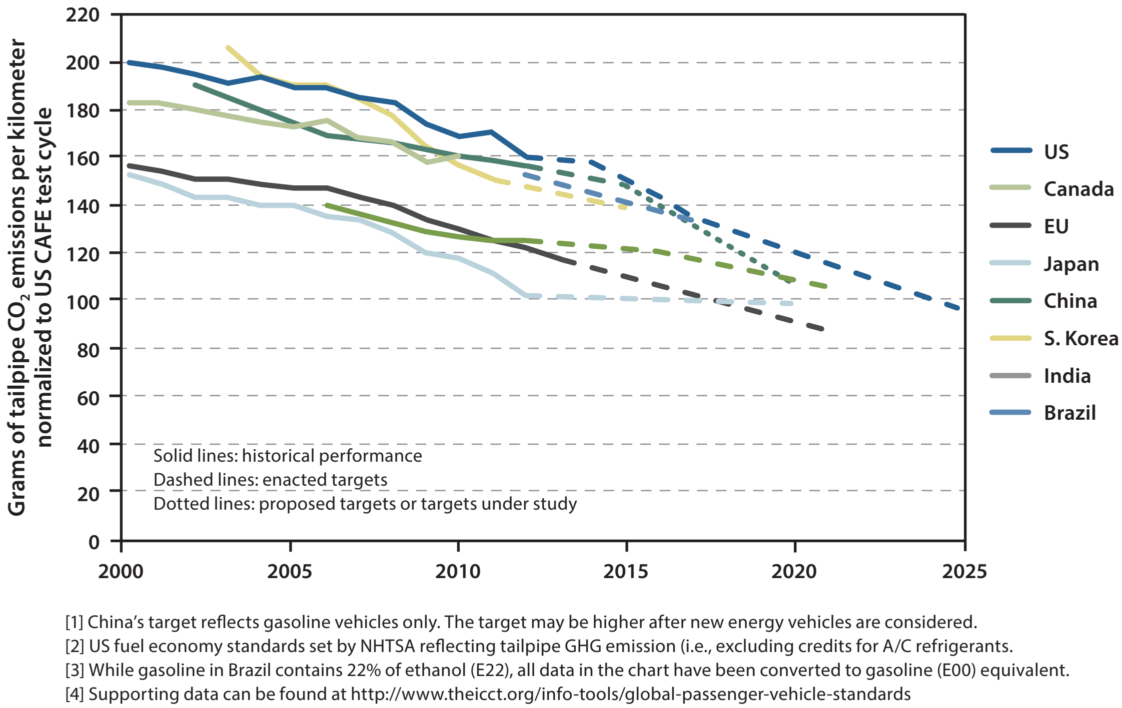


Figure 2.2 International GHG standards and GHG equivalents of fuel economy standards, normalized to U.S. CAFE test cycle [Adapted from the ICCT, 2014]

Aware of this evolving context, this report extends previous work in several important and timely new directions. It presents updated assessments of the potential for improvement in vehicle efficiency through conventional and advanced technologies; presents quantitative analyses of historical rates of improvement in weight-saving technologies and overall vehicle efficiency; examines the speed with which new technologies have propagated across the new vehicle market; and explores quantitatively the role of individual choices—that is, conservation—in reducing transportation energy and petroleum demand.

Several recent major reports complement the work documented here. Here we call attention to two such reports that are distinguished by their particularly deep and broad technical analysis. The first of these reports also contains, as an appendix, a summary of other influential papers and synthesis reports addressing petroleum consumption and GHG emissions in personal transportation, primarily published since 2009.

The U.S. National Research Council's *Transitions to Alternative Vehicles and Fuels* [National Academy of Sciences (NAS), 2013] addressed the goal of reducing the petroleum consumption and GHG emissions from LDVs by 80% (vs. 2005 levels) by 2050. The report's approach started from a premise that there are "four general pathways" that could contribute to deep reductions in both GHG emissions and petroleum consumption: ICE vehicles with very high efficiency, biofuels, hydrogen, and electricity. Additionally, they noted that natural gas can help to reduce petroleum consumption, but cannot provide the required depth of reductions in GHG emissions. Among the key findings of the report were:

- None of the four "general pathways," on its own, is capable of reducing LDV GHG emissions by 80% in 2050.
- There are several combinations of technologies that could reduce LDV petroleum consumption by 80% in 2050. These pathways all depend on fuel economy continuing to improve beyond the current horizon of 2025, as well as a large-scale shift to biofuels, electricity, hydrogen, or natural gas.
- Reducing LDV GHG emissions by 80% by 2050 would be considerably harder, though technically feasible, and would require both significant improvements in efficiency and a shift to (low-carbon) biofuels, hydrogen, or electricity (not natural gas).
- Currently sufficient information is not available to predict which technologies will ultimately prove to be most cost effective in reducing petroleum consumption and GHG emissions.

The National Petroleum Council (NPC) has prepared perhaps the most comprehensive analysis of future vehicle-fuel system options in *Advancing Technology for America's Transportation Future* [NPC, 2012]. The report considers LDVs and heavy-duty vehicles (HDV), as well as the vehicle and fuel supply technologies needed to enable large reductions in GHG emissions through biofuels, electricity, hydrogen, and natural gas. The authors conclude that there is substantial potential for improved fuel economy from existing and emerging technologies, but many technologies face key infrastructure challenges. The authors identify 12 "priority technology hurdles" which, if overcome, would improve the functionality, cost, and scalability of the fuel-vehicle systems. These priority technology hurdles include low-cost light weighting; several improvements in biofuel production processes; energy density and the life of lithium-ion batteries; the durability of fuel cells; compression and storage of hydrogen; and the optimization of combustion in heavy-duty engines.

From the ever-growing body of research by our group and many others, it is becoming increasingly clear that no single technology or approach can deliver the magnitude of emissions reductions required to stabilize atmospheric concentrations of GHGs at acceptable levels. Moreover, the technologies that can deliver the deepest reductions are in the early stages of deployment. Their long-term cost and performance are uncertain and it will take decades for their full benefits to be realized, if they are realized at all. These factors, combined with the urgent need to begin reducing emissions of GHGs, point to the importance of a multi-pronged approach to GHG mitigation. As introduced in the preceding chapter, we have summarized such an approach as "Improve, Conserve, Transform"—recognizing the different types of approaches needed to begin reducing emissions in the near term and achieve deeper reductions in the long term.

Improving mainstream technology includes:

- More efficient engines (e.g., turbocharged downsized gasoline and diesel engines, charge-sustaining hybrids)
- More efficient transmissions
- Vehicle weight, drag, rolling resistance, and performance reduction
- The reduction of emissions from resource extraction and production of liquid fuels from all sources, including biomass, tar sands, shale oil, coal, and natural gas

Conservation refers to changes in individual travel and driving behavior that will reduce vehicle-miles traveled and improve in-use fuel economy. Conservation includes:

- Reducing the distance and/or frequency of trips for commuting and household business
- Developing more alternatives to single-occupancy vehicle travel
- Driving less aggressively (lower speeds on the highway and gentler acceleration and deceleration around town)

Transforming our transportation energy system means transitioning to new energy carriers and new primary sources that have inherently lower GHG emissions (natural gas) or have the potential to be produced from low- or zero-carbon sources in the future (electricity or hydrogen).

It is apparent from prior work by our research group and many others that improving mainstream technologies could reduce U.S. petroleum use and GHG in LDVs by up to 50% from 2010 levels, but larger reductions are unlikely without additional changes. Changes in the sources of liquid fuels, including greater consumption of fuel derived from tar sands and biomass, could contribute to as much as a 25% reduction in petroleum consumption, but will have limited or negative overall GHG benefits. Given these findings, it follows that additional changes will need to occur in order to reach the target of an 80% reduction in GHG emissions by 2050. Specifically, an 80% overall reduction in GHGs represents a 60% reduction in the remaining GHG emissions after the initial 50% reduction.[3] We contend that this goal can only be achieved through aggressively implemented improvements in mainstream technology *and* conservation behaviors, *along with* a successful, aggressive, large-scale deployment of low-GHG fuels and the propulsion systems that can use them. The latter—which may include natural gas, electricity, or hydrogen produced through less GHG-intensive processes than those used today—will be extremely challenging, and is contingent upon technologies that are not presently available.

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[3] Suppose we cut emissions by 50%. This means we have gone from 100 units of emissions to 50. Now, to get to an 80% total reduction, we need to get down to 20. Getting from 50 down to 20 is a reduction of 30 units, and 30 is 60% of 50.

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3.0 Propulsion System and Vehicle Technologies and Their Operating Characteristics

3.1 Context and Scope of Chapter

This chapter reviews our current assessment of the more promising vehicle and fuel options for the future. The impacts that this report discusses—petroleum and energy use along with greenhouse gas (GHG) and air pollutant emissions—start at the vehicle level. Here we review realistic options for improving the relevant operating characteristics of the average new vehicle. These include fuel consumption, acceleration capability, size, and cost; characteristics of greatest importance to vehicle buyers and users; and how these may change over time. These are among the primary performance numbers that determine vehicle sales, use patterns, and thus impacts. There are many options for powertrains (engine plus transmission) or propulsion systems and vehicle types deployed, that are either already in mass production or are showing promising market potential. The current status and potential for improvement in all these will be reviewed and quantified in this chapter.

The technology utilized in light-duty vehicles (LDVs), and especially their powertrains, is always changing and improving. For example, for the last several decades, the average specific power of the engines in new vehicles has increased at about 1.5% per year [Heywood and Welling, 2009], average specific fuel consumption has improved comparably, and air pollutant emissions have been drastically reduced. Anticipated cost and regulatory pressures to reduce petroleum consumption and GHG emissions are expected to intensify the pace as well as the extent of changes in powertrain and vehicle technology. In parallel, there continues to be a compelling need to reduce air pollutant emissions from vehicles by improving the effectiveness and durability of their emissions controls. Reducing the cost of fuel economy improvements and emissions control technology is an important part of this.

LDV fleets in most world regions are dominated by vehicles powered by internal combustion engines (spark-ignition and diesel engines) that drive the vehicle through multi-gear transmissions (automatic or manually shifted). A limited number of hybrid electric vehicles (HEV) with both a battery/electric motor propulsion system and an internal combustion engine (ICE) are now an increasing fraction of this fleet (currently, a few percent). Electric vehicles (EV) and plug-in hybrids (PHEV) (in which the battery can be recharged from the electricity supply system as well as by the engine) have just entered the market. Also, significant changes in the transportation fuels supply are anticipated. Use of ethanol, mostly blended with gasoline as E10, a 10% blend,[4] but with some use as E85 in flexible-fuel vehicles (FFV), has reached about 10% of the gasoline volume consumed in the United States. Fuel options that could be produced from biomass are being explored. If production volumes of EVs grow to become a significant part of total sales, then electricity use in transportation will become important. Natural gas is being discussed as a potential transportation fuel though prospects for this use of natural gas are unclear. The supply of gasoline and diesel from oil sands and heavy oils is already significant (15% or more in the United States),

[4]In Brazil, E20 is used. In much of Europe, E5 is used.

and is steadily increasing, which, due to their higher extraction and production energy demand, increases their GHG emissions above those of petroleum-based fuels. Thus, transportation fuels are under significant pressure to evolve (see Chapter 6).

Table 3.1 Important propulsion system and transportation energy paths forward

1. Improving mainstream technology and fuels
• More efficient engines (e.g., turbocharged downsized gasoline and diesel engines, charge-sustaining hybrids)
• More efficient transmissions
• Vehicle weight, drag, and performance reduction
• Higher-quality gasoline (e.g., octane): diesel
• Liquid fuels from tar sands and biomass (gasoline/diesel)
• Liquid fuels from shale oil, coal, natural gas (future)
2. Transitioning to new energy sources
• Electricity: Plug-in Hybrid Vehicles, Battery Electric Vehicles (PHEV, BEV)
• Natural gas: (spark-ignition engines)
• Hydrogen: fuel cell vehicles (FCV)

The important propulsion system, vehicle, and fuel/energy options are summarized in Table 3.1 under the headings of “improving mainstream technology and fuels” and “transitioning to new transportation energy sources.” As outlined in the table, these distinct categories make sense because mainstream technology (and the fuels that such mainstream technology requires) is deployed and used on a massive scale. Improvements in performance and cost can occur incrementally, and deployment of better or new technology can commence in the nearer term and penetrate the market faster than can the introduction and deployment of alternative propulsion systems and the new forms of energy that they require. This is because both the new propulsion technology and the new fuel must somehow be deployed together in a manner that allows sales and use of these alternative vehicles to grow steadily due to their market appeal. This simultaneous “chicken and egg” problem—introducing the propulsion system and developing its energy supply infrastructure in parallel—has not yet been adequately resolved.

An overview of the ways in which the various vehicles with different propulsion systems use the appropriate fuels to provide both mobility and broader functionality to users is helpful. Figure 3.1 shows the energy flow into and through the vehicle for a typical gasoline-engine passenger car as it is driven through different simulations of on-road driving. (For light trucks, the relative energy flows are similar.) The numbers in the diagram correspond to “units of energy” when 100 units of fuel chemical energy in the vehicle’s fuel tank are utilized in three commonly used US drive cycles: urban, highway, and US06 cycles. The first two cycles (weighted 55% and 45%) are used in the Corporate Average Fuel Economy (CAFE) test and regulation process. The last is a driving cycle that incorporates higher maximum speed and more aggressive driving to reflect current driving behavior. Ranges are given at each point in the energy conversion and use sequence since the “resistances” to vehicle motion (on the right side of Figure 3.1) depend on how the vehicle is being driven (speed and acceleration), and the engine and drivetrain efficiency depend on how the powertrain is therefore loaded: i.e., what the powertrain must provide to achieve these

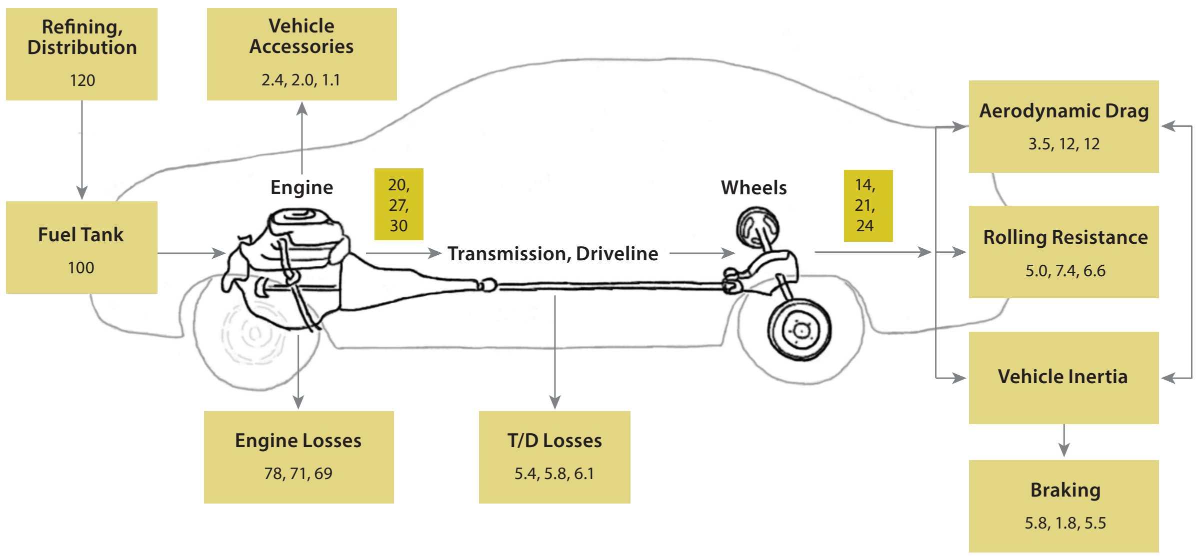

Figure 3.1 Vehicle energy flows in a standard gasoline engine with percentages of fuel energy in the tank: top numbers = urban driving cycle; middle = highway cycle; bottom numbers = US06 cycle [Source: National Petroleum Council, 2012b]

vehicle speeds and accelerations. Note that if the vehicle speed and/or acceleration are low, the engine efficiency is lower but the required fuel flow rate to the engine is also low. If the speed and/or acceleration are high, then the powertrain is more heavily loaded and its efficiency is higher but the fuel flow rate is also higher. The vehicle's fuel use (consumption) per unit distance traveled (km or miles) depends on all these variables—the engine's many different operating conditions as well as the driving pattern's vehicle speed and acceleration versus time; the vehicle's weight (its inertia), size, and aerodynamic drag; and the rolling resistance of the tires on the road. Note that, while the "inertia energy" is largely dissipated in braking, some of it is used to overcome aerodynamic drag and tire rolling resistance as the vehicle slows down or coasts. Note that these numbers are effectively normalized. They represent percentages of the fuel energy drawn from the fuel tank. Since they are relative, they are largely independent of vehicle size and weight. Also, ambient conditions and context (temperature, wind, terrain, and traffic density), and degree to which the engine, transmission, and tires are warmed up, impact real-world driving demands and fuel consumption or energy use.

Figure 3.1 also takes the gasoline back through the fuel distribution system and the refinery to the "well," tracking the amount of petroleum required to supply the fuel (in this case, gasoline) at the refueling station. It requires some 20 units of additional petroleum energy to put 100 units of gasoline into the vehicle's tank. This amount (115–125 units per 100 units of fuel put into the tank) is often called the *primary energy requirement*. The overall well-to-wheels (WTW) vehicle-level energy efficiency is thus about 15%.

For several of the alternative propulsion systems, the energy flow diagram is significantly different.[5] For example, for EVs, the electric motor is highly efficient (up to 90%), but mechanical energy is dissipated in the drivetrain (about 10%). There is electric energy dissipation as the battery is charged and discharged (about 10% each way) and in the power electronics and inverter (about 10% in each). Thus, the propulsion system drives the vehicle at some 50% energy efficiency. But the efficiency of electricity supply, generation, and distribution varies from about 30% with coal-fired power stations, to about 35% in a steam power plant—50% or so with co-generation—with natural gas, and 75% or so for renewables (wind and hydro). The overall source-to-use energy efficiency for an EV, therefore, varies substantially depending on the electrical supply mix used in recharging. With the current generation mix in the United States, the average overall EV energy efficiency is about 18%.

For FCVs, this overall energy picture is again different. While the fuel cell is a significantly more efficient energy converter than an ICE, especially at part-load, the production of hydrogen (e.g., from natural gas through steam reforming, the current industrial hydrogen production approach, or electrolysis of water using electricity) and its distribution and refueling requirements result in a significant loss of the primary energy source. Steam reforming of natural gas to provide hydrogen for refueling FCVs loses about 45% of the original natural gas energy [National Petroleum Council, 2012b]. Thus, when combined with an average in-use fuel-cell system efficiency in the mid-50% range, the overall energy conversion efficiency—natural gas to on-road fuel-cell driving—is less than 30%.

This overall WTW energy assessment indicates the challenge in reducing transportation's energy consumption and especially its GHGs.

3.2 The More Promising Options

In much of the world, gasoline-engine-powered vehicles dominate the LDV parc: the current fleet of cars and light trucks. In the past, the gasoline engines in the majority of these vehicles have been naturally-aspirated: that is, they draw the air into the engine directly from the atmosphere. A fraction, 10%–15%, of these gasoline engines are now turbocharged, and that fraction is steadily increasing.

The situation with respect to gasoline dominance in Europe is substantially different as about half the LDVs are powered by diesel engines, which are more fuel-efficient and are already predominantly turbocharged. In turbocharged engines, a turbocharger (a compressor and a turbine on the same shaft) compresses the air on its way into the cylinder to increase its density, so a cylinder of given size traps more air and can therefore burn more fuel. The turbine, driven by the engine's hot exhaust gases, provides the power to drive the compressor. Thus, turbocharged engines provide more usable power per liter of displaced cylinder volume, and are more efficient than naturally-aspirated engines because the frictional losses are lower and relatively less important. However, turbocharged engines cost approximately $600–$1,000 more. The fraction of gasoline engines that are turbocharged is expected to grow over time, and will become the majority.

[5] Data for this discussion is drawn from the National Petroleum Council, 2012a and 2012b.

The mix of ICEs in LDV sales in Europe, on average about half gasoline and half diesel, is different due to several factors. Primary differences are the higher cost of transportation fuels (approaching $10 per U.S. gallon, €2/liter) and the significantly lower government taxes on diesel fuel due to the heavy dependence of freight transport on diesel. Thus, in Europe, the higher fuel economy of diesel vehicles is especially attractive. In the countries in which the tax difference is highest (e.g., France), the diesel sales fraction is above 70%. In countries in which the taxes are essentially the same (Germany, UK), the diesel sales fraction is about 40%. The diesel share of the in-use vehicle stock in Europe is lower: close to 40%. Thus, the diesel stock share is still rising, steadily increasing the diesel fuel demand [Schipper, et al., 2010]. We do not anticipate significant increases in diesel LDVs in the United States because taxes on fuel are much less than in Europe, and the cost of diesel per gallon is higher than gasoline. Note that, due to its higher density, a liter of diesel fuel contains 10%–12% more chemical energy than gasoline.

HEV sales started in the late 1990s and now represent a small percentage of sales in the United States and other markets. Sales grew faster when gasoline prices were rising, and more slowly when gasoline prices were lower and more stable. Until recently, the Toyota Prius model accounted for the large majority of hybrid sales. Other hybrid model sales have been rising over the past couple of years, but Toyota's share is still well over 50% [Keith, 2012].

Battery electric vehicles (BEV) and PHEVs are now being sold in several parts of the world. The sales volumes to date are very low (and less than anticipated). However, over the next three years, some 30 new BEV and PHEV models are expected to be offered to the public: with both types representing half of the models [*Automotive News*]. FCVs (in a hybrid configuration) have recently been offered to the public, essentially as prototypes, in very limited numbers. Several auto manufacturers (e.g., Hyundai, Daimler, Honda, and Toyota) have announced plans to introduce FCEVs commercially by 2015, in limited numbers, and mainly in European countries, Asia, and in California and Hawaii in the United States, where governments are coordinating efforts to build up hydrogen infrastructures [NRC Alt. Veh. Report, 2013]. Note that development and prototype marketing of these alternative energy source vehicles are being encouraged through various incentives in many countries. Examples are fuel economy and GHG emissions targets and standards, rebates and income tax reductions, and mandates. Important factors in the United States are California's Zero Emissions Vehicle (ZEV) mandate, and the advantageous credits these vehicles receive in the formulas used to calculate the federal government's CAFE numbers.

The use of natural gas as a transportation fuel is now being reassessed in light of substantive new reserves from shale rock becoming available at a significantly lower cost: about two-thirds the cost of petroleum on an energy-equivalent basis. Use in light-duty and heavy-duty vehicles is being considered. The case for natural gas use in heavy-duty vehicles may have promising real-world prospects: in light-duty, privately owned vehicles, the case is less clear and more uncertain. Dedicated natural gas spark-ignition engine vehicles and dual natural gas/gasoline fuel vehicles are available in the United States, but in very limited numbers. Current costs relative to standard gasoline-fueled vehicles are several thousands of dollars higher [National Petroleum Council, 2012b].

3.2.1 Vehicle Improvements

In this section, we provide an overview of the opportunities for reducing vehicle fuel consumption through improvements and changes in the propulsion system and vehicle technologies, and through better matching of the fuel characteristics with the engine's requirements. We will start with the vehicle opportunities, since all of the propulsion system options benefit from reduced vehicle resistances or loads.

When an engine or other propulsion system is driving a vehicle, it must provide enough power to overcome the resistances to vehicle motion and accelerate the vehicle, as well as overcome the losses in the transmission and driveline. The vehicle inertia and resistances are: vehicle acceleration F_a (negative when decelerating), tire rolling resistance F_R, vehicle aerodynamic drag F_D, gravity when climbing a grade F_G (negative when descending a grade), and any braking force F_b. The power required at the wheels to drive the vehicle (P_v) is, therefore,

$$P_v = (F_a+F_R+F_D+F_G+F_b)S_v$$

Where $F_a = m_v a_v$, $F_R = C_R m_v g\cos\alpha$, $F_D = ½ p_a C_D A_v S_v^2$, $F_g = m_v g\sin\alpha$.

S_v is the vehicle speed, a_v is the vehicle acceleration, m_v is the mass of the vehicle (curb mass plus payload), C_R is the coefficient of rolling tire resistance ($0.01 < C_R < 0.2$),[5] and the acceleration due to gravity, α the grade angle, p_a the ambient air density, C_D the drag coefficient, A_v the frontal area of the vehicle (≈ 0.9 × vehicle height × width).

1. Vehicle Weight Reduction

Vehicle inertia or mass is a major factor in the vehicle "loads" that the propulsion system must overcome, as shown in Figure 3.1. Tire rolling resistance and the kinetic energy produced by the vehicle's acceleration together constitute more than two-thirds of the total vehicle driving load, except at really high vehicle speeds. Also, since aerodynamic drag scales with vehicle frontal area (which is dependent on vehicle size), it also depends partly on weight. Thus, weight reduction directly impacts vehicle fuel consumption: a 10% weight reduction yields a 6%–7% reduction in vehicle fuel consumption. Weight reductions can be achieved by the substitution of lightweight materials, redesign of the vehicle structure, and vehicle downsizing. Chapter 4 reviews vehicle weight reduction potential in more detail.

2. Tire Rolling Resistance

The rolling resistance of the vehicle's tires and the energy used up to overcome it are proportional to vehicle mass. This resistance (C_R in the above equation) depends on tire size, shape, tread design, material used, and inflation pressure. Year to year, C_R has been decreasing on average by 1%–2%, and has a current value of about 0.01 [Bandevadekar et al., 2008]. We have assumed a 1.5% per year reduction in C_R, which will yield a 20%–25% reduction in 2030, corresponding to about a 4% reduction in vehicle fuel consumption.

Note that underinflated tires significantly increase rolling resistance. Also, while strict CAFE requirements incentivize vehicle manufacturers to assure that low-rolling resistance tires are fitted on new vehicles, replacement tires offer a major opportunity for useful reductions in the fuel consumption of in-use LDVs. The time scale for the replacement of tires is about three years, so deployment of improved low-friction replacement tires could move us forward much more rapidly than just deployment on new vehicles.

3. Reducing Aerodynamic Drag

In lower-speed urban driving, air resistance to the vehicle's motion is relatively modest (about 20% in the urban driving cycle, Figure 3.1). This resistance is the product of the frontal area of the vehicle A_v and the drag coefficient C_D in the equation on the previous page). This drag force also scales as the square of the vehicle speed (and thus the power used to overcome this resistance scales with the cube of speed). At 80 mph (130 km/hr), where aerodynamic drag is important, this force is two times the drag at 55 mph (88 km/hr) and the power required is three times that at the lower speed.

A 10% reduction in drag results typically in about a 2% reduction in fuel consumption, though obviously this fuel consumption improvement depends strongly on vehicle speed. Current values of C_D for cars are in the 0.25 to 0.29 range, and for SUVs and pickup trucks are in the 0.33 to 0.4 range [Bosch Automation Handbook]. An annual reduction going forward of 1% per year has been assumed [Bandevadekar et al., 2008]. This gives a 15% reduction by 2030, with a corresponding 3%–4% average decrease in fuel consumption.

3.2.2 Propulsion System Options: Engines

1. Naturally-Aspirated Spark-Ignition Engines

The naturally-aspirated spark-ignition engine is the dominant LDV engine currently in use and sold in the United States and other world regions (e.g., Brazil, Korea, Japan, and China). The baseline most commonly used is today's naturally-aspirated port fuel-injected gasoline-fueled engine with a compression ratio of between 10 and 11:1 which draws air directly from the atmosphere past a throttle valve into the cylinder (usually at intake manifold air pressures well below atmospheric pressure). Table 3.2 lists the key areas in which improvement opportunities are being or are likely to be realized in such gasoline engines, with the approximate percentage improvement in vehicle fuel consumption that results. The most important improvement areas are engine friction reduction (through engine design changes and use of improved synthetic lubricants), variable valve control, increasing compression ratio (with management of the ensuing more severe knock constraint, aided by variable valve timing), and direct fuel injection (DI) into the cylinder, with stoichiometric fuel-air ratio engine operation so that the highly effective three-way exhaust catalyst system can be used to obtain very low tailpipe air pollutant emissions.

Table 3.2 Gasoline engines: future improvements

Promising Improvement Areas	Fuel Consumption Reduction
1. Further spread of recent innovations (e.g., VVT, DCT)	3%
2. Improved synthetic lubricants for lower friction	1%
3. Additional friction reduction opportunities	3%
4. Cylinder cut out at lighter loads	4%
5. Variable valve control at full and part load	5%
6. Increased compression ratio	3%
7. Smart cooling systems for managing heat losses better	2%
8. Direct (gasoline injection)	2%
9. Stratified GDI engine operation: Lean NO_x catalyst	6%
10. Turbocharged and downsized GDI engines	8%–12%
11. Engine plus battery system in hybrid (mild/strong)	15%–30%
12. Stop/start (engine off at idle)	4%
13. Higher expansion ratio engines (hybrids)	3%
14. More (7–9) gears; more efficient transmissions	⩽10%

If all of these *engine* improvements are implemented, our estimate for the net reduction in NA-SI-engine average fuel consumption (obtained by compounding these individual improvements) is 25% by about 2030. We are interested in the average *sales-vehicle* NA-SI-engine vehicle improvement. This will be less than the maximum for several reasons. First, not all the various vehicle models in the sales mix will have this "best engine." Some of these technologies will not be deployed because they do not prove to be cost effective, or are only deployed in a fraction of these NA-SI engine models rather than "all" of these engines. Also, not every new vehicle in any model year will have the latest technology. Since each model is redesigned every five or six years, on average the technology will be three years old. Thus, both implementation and deployment will be delayed. For these reasons, we have, in effect, reduced this maximum reduction in vehicle fuel consumption (25% or so) from current vehicle levels and 2030 values, by 0.75 to obtain a 17.5% reduction. We have used this 2030 0.75-scaling-factor to adjust all of the estimated *maximum reductions* in future fuel consumptions for the mainstream technology improvement areas. These final numbers, in our judgment, represent "plausible, real world, yet aggressive" estimates of the average future new vehicle fuel consumptions.

2. Turbocharged Spark-Ignition Engines

An increasing fraction of new gasoline engines are turbocharged. By raising the density of the air entering the engine's cylinders, the amount of fuel burned can be increased generating significantly more torque and power from a given displacement engine. The engine can then be downsized substantially in a given vehicle while providing the same vehicle performance (or can be downsized slightly less for increased performance). The engine's efficiency is increased by 10% or more, primarily because engine friction is reduced (both in magnitude and in relative importance because the engine's torque per unit displaced volume is increased), due to turbocharging and downsizing.

Most of the technologies listed in Table 3.2 can be applied to turbocharged engines as well as naturally-aspirated engines. However, the knock constraint on compression ratio is more severe in turbocharged engines, so the compounding of these improvements is different. We have assessed the average fuel consumption of a typical new turbocharged gasoline engine to be about 11%–14% lower than that of an equivalent performance engine. (Several other assessments agree with this relative difference.) See Heywood (1988) for additional technical discussion.

The fraction of turbocharged gasoline engines that have been sold has been steadily increasing. It is now about 15% in the United States, and is expected to grow over the next 20 or so years to become the majority of gasoline engines sold. Thus, with future gasoline turbocharged engines, vehicle efficiencies (on a gasoline-equivalent energy-content basis) for those vehicles will approach those of diesel vehicles.

3. Diesel Engines

The diesel engine differs from the spark-ignition engine in that it initiates combustion through spontaneous ignition of the diesel fuel, which is directly injected into the cylinder toward the end of the engine's compression stroke. This spontaneous ignition occurs as the fuel jets injected close to the end of compression rapidly vaporize and mix with the in-cylinder air, as a consequence of the high temperature of this air produced by the engine's compression process. This different ignition and combustion process allows several other differences in engine design and operation which result in the diesel engine being more efficient than the gasoline engine. For example, it uses a higher compression ratio and the engine is always turbocharged which increases its output and effectively increases its efficiency by reducing the impact of friction. It operates with the airflow unthrottled, and is always "fuel lean" with excess air. In typical LDV driving, a diesel vehicle is some 20%–25% more efficient on an energy basis (17%–20% less fuel consuming on a gasoline equivalent basis) than a gasoline-fueled NA-SI engine.[6] Note also that, with volumetric measures of fuel used (liters or gallons), diesel fuel contains more energy than gasoline (about 11% [National Petroleum Council Report, 2012b]) because it is a denser liquid. So on a fuel economy basis, with gallons or liters of diesel rather than gallons or liters of gasoline, the diesel vehicle *fuel economy* is 33%–39% higher than that of a gasoline engine vehicle.

Several of the technology changes listed in Table 3.2 for gasoline engines are available to improve diesel and engine powertrain efficiency. Key areas are low-friction lubricants, overall friction reduction, combustion improvements, more efficient engine accessories, and two-stage turbocharging, as well as six to nine gears, and more transmissions. Also, more efficient exhaust air pollutant after treatment devices will reduce their current engine fuel consumption penalties.

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[6]Note the distinction between *fuel economy* and *fuel consumption*. Fuel economy is more commonly used in the United States (as miles per U.S. gallon, or elsewhere as kilometers per liter—to convert from the former to the latter multiply by 0.425). Fuel economy scales with *energy efficiency*. The reciprocal of fuel economy, fuel consumption, is often used elsewhere: e.g., in Europe, as liters per 100 km (or as gallons per 100 miles, multiply *l* /100 km by 2.35). Since the fuel consumed in driving a given trip or distance is the more basic measure of fuel use, fuel consumption is the preferred technical measure. Also, since we are discussing significant fuel use differences (on the order of 20%), the relative changes in fuel consumption and fuel economy are not the same. For example, a 20% reduction in fuel consumption is the same relative change as a 25% increase in fuel economy (1 ÷ 0.8 = 1.25).

We anticipate that the overall vehicle fuel consumption reduction by 2030 (including vehicle weight, drag, and tire resistances) will be about 20%, slightly less in relative terms than gasoline engine vehicle improvements (about 22%).

The diesel engine dominates the heavy-duty vehicle freight market. In Europe light-duty diesel vehicle sales went from about 20% in the early 1980s, to 50% or so by about 2005; elsewhere, the diesel sales LDV fraction has been small. These factors drove the transition in Europe: While European fuel prices are high due to higher taxes, the price of diesel fuel is lower (10%–20%) due to the fact that it has lower taxes than gasoline. Also, high low-speed diesel-engine torque provides attractive driveability. Looking to the future, we anticipate that in Europe average LDV sales will remain about half diesel and half gasoline (turbocharging of gasoline engines narrows the difference between diesel engines compared to gasoline, significantly). In lower diesel-market-share regions, sales of diesel will only rise modestly. The diesel fuel cost is expected to rise due to steadily increasing demand from freight transport while gasoline demand is expected to decline. The availability of hybrids (which will be described in the next section) and their anticipated decreasing price premium relative to standard gasoline vehicles over time will make them a more marketable alternative and, in urban driving, a likely more attractive option.

3.2.3 Propulsion System Options: Electrification

While standard engines are primarily "mechanical and chemical" propulsion systems, they have included significant electrical and electronic components for many years. However, we are in a new and different phase of powertrain evolution in which *electric drive* is now available. The battery-driven electric-motor propulsion system in EVs is also nothing new. But, over the past decade or two, battery technology has developed to the point at which electric drive is now practical. HEVs with two propulsion systems—battery plus an electric motor and an internal combustion engine (usually gasoline fueled)—have been marketed since the late 1990s, and sales have steadily grown. Also, following unsuccessful efforts to produce marketable pure electric vehicles in response to California's ZEV requirements in the mid-1990s [Collantes and Sperling, 2008], LDVs that use electricity as an external vehicle energy source have been developed and produced. They are now being marketed in response to government incentives and requirements, and there is a sense that such electrical propulsion systems are a potential longer-term option that does not consume petroleum. Thus, PHEVs, BEVs, and FCVs with a hybrid propulsion system architecture are now becoming available.

In this section, we review these three electrical propulsion system technologies assessing their relative energy consumption in LDVs and their potential for improvement over time. We also summarize their major performance and market barriers.

1. Hybrid Electric Vehicles

HEVs incorporate electrical energy storage (usually in a battery), an electric motor, a generator, and an internal combustion engine. These hybrids are able to recover much of the vehicle kinetic energy usually dissipated in braking (see Figure 3.1), enable the engine to be switched off at idle, and use the two propulsion systems separately and together in ways that take advantage of their individual strengths (e.g., the high torque of electric motors during vehicle launch from rest, and the higher efficiency of internal combustion engines when used intermittently at higher loads to both recharge the battery with electrical energy, and when the vehicle needs significant power).

There are several different hybrid propulsion system architectures. The “micro” or mild hybrid has limited electrical drive capability: usually engine stop/start and some regenerative braking to recover vehicle kinetic energy and provide electric launch. These features can improve fuel consumption by up to about 20%. Full hybrids (like the Toyota Prius) most commonly use battery-motor and gasoline-engine drive separately and when appropriate, together; also, they recharge the battery while driving with the engine through a generator. The power split architectures so far are the more popular and provide about a one-third fuel consumption reduction in urban driving (but they are the most expensive approach). A somewhat simpler hybrid concept, the parallel two-clutch system or P2 hybrid has independent mechanical and electrical drives that are connected via a clutch. These are less expensive than the power split system, but are also less efficient (providing a one-quarter fuel consumption improvement). These improvement numbers vary with the details and with the vehicle driving patterns, and are thus representative. The reference baseline is the standard naturally-aspirated gasoline engine. We anticipate that the hybrid cost premium relative to standard-engine vehicles (now about $5,000, and depending on the vehicle and thus “engine” size) will decrease over time, maybe by up to about 50% over two decades. We anticipate that the full hybrid’s fuel consumption, relative to the NA-SI gasoline engine, will decrease over time, also.

The technical evaluations that we and others have done offer a comparatively optimistic assessment of the potential for the HEV. Since this is a relatively new technology, there is reason to believe that continued improvement relative to the conventional technologies is likely. These improvements are expected to result largely from improved vehicle integration, which allows for more tightly optimized control of the engine’s operating conditions. In addition, due in part to economies of scale and in part to the anticipated significant reductions in the cost of high-power batteries, the incremental costs of the hybrid are expected to decrease relative to conventional technologies. While questions have been raised about the robustness of the hybrid vehicle’s fuel consumption benefits to both high accessory loads and aggressive drive cycles, these problems are likely to become less important with continued technological development and seem to have been overstated in the first place.

A technology that has already enjoyed market success and is penetrating the market in modest and growing numbers, the hybrid vehicle faces the least technical risk and the greatest leverage for reducing petroleum and GHG emissions in the near term among the newer technologies under evaluation. The hybrid’s primary drawback is that, because it continues to derive all of its power from gasoline, it is inherently constrained in terms of both petroleum and GHG emission reductions by the extent to which low-carbon biofuels are deployed [Kromer and Heywood, 2013].

2. Plug-in Electric Vehicles

The standard HEV has the battery energy storage capacity to drive for a few miles using electricity. The electric drive range can, of course, be extended with a larger capacity battery, which makes direct recharging of the battery from the electric grid feasible. This propulsion system is termed a PHEV, a plug-in hybrid electric vehicle. The major challenges are battery size, weight, and cost. The opportunity is that the cost of electricity (without any road/gasoline tax) is significantly cheaper than gasoline or diesel; however, GHG emissions from the current electricity supply system are only about one-third lower per electric mile than per gasoline mile.

Several PHEV concepts with various “all-electric” range are now being offered. Two broad categories of PHEV architectures are being sold or are in development: the “strong” HEV with a larger capacity battery e.g., the Toyota Prius with a 10-mile electric drive range, though the system is usually used in a blended rather than bi-modal manner, and the *extended range electric vehicle* (EREV), e.g., the Chevrolet Volt model which has about a 40-mile electric range with a fully charged battery pack. The internal combustion engine in these EREV systems, which primarily recharges the battery pack through a generator, either does not drive the vehicle mechanically or does so only occasionally. The most advantageous extent of the electric drive capacity and the optimum overall system architecture are still being explored.

A few PHEV models are now being offered to the public. Overall, sales are modest (a fraction of 1%) since the cost premium is high (some $10,000) and recharging options are limited and slow.

However, by 2016, it is anticipated that some 40 PHEV or full BEV models will be on sale to the public with about half of these utilizing the plug-in hybrid propulsion system [*Automotive News*, 2013].

While the “all-electric range” of these vehicles lists the maximum number of electrically driven miles a PHEV can travel in a single trip, the fraction of total vehicle miles traveled using electricity is more complex. This depends on the distribution of trip lengths that the PHEV drives, the recharging opportunities and how these are used, and the user’s access to another (conventional) vehicle. Studies have estimated the so-called *utility factor*—the percent of vehicle miles traveled using electricity—as a function of a PHEV’s all-electrical range. A set of results is shown in Figure 3.2 [National Petroleum Council, 2012b]. The utility factors for a PHEV-10 (e.g., a parallel/series design with up to 10 miles of driving in all-electric mode) and a PHEV-40 (a PHEV with a series architecture with 40 miles of all-electric drive) are highlighted. Several additional assumptions are needed to accurately read the results. The utility factor for the PHEV-10 varies from 27% to 50% over the spectrum of only home-based charging to recharging everywhere (home, work, and commercial locations). For the PHEV-40, the equivalent spectrum spans 65%–80% [National Petroleum Council, 2012b]. Recent field experience with Toyota’s Prius PHEV-10 with predominantly home charging indicates a utility factor of some 30% (see Chapter 8), consistent with the findings listed here.

The PHEV offers a promising opportunity to reduce petroleum consumption to a level of about half of that offered by the hybrid vehicle. In addition, while the PHEV’s GHG emissions from the current electricity supply system does not project that significant a benefit, they offer a continuous path for incremental improvement through steady decarbonization of the electric power sector—an opportunity that does not exist for the hybrid vehicle. Moreover, because the PHEV can significantly reduce the fleet’s petroleum requirement, it mitigates the scale constraint on biofuel deployment. Whereas biofuels might be able to meet 20% of the transportation energy requirement

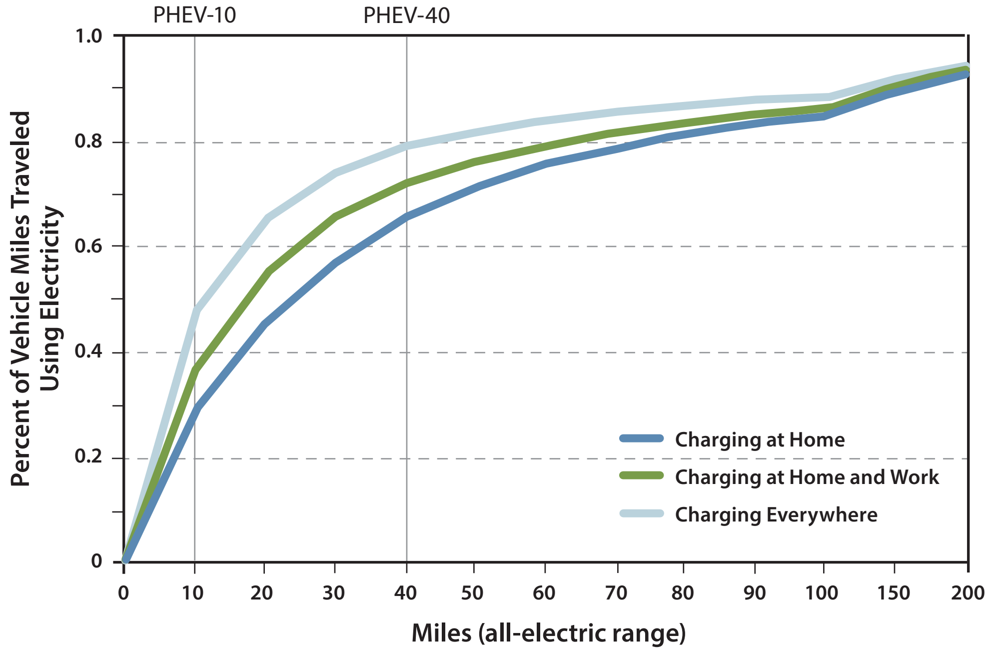

Figure 3.2 Utility factors (percent of vehicle miles travelled using electricity) for various charging scenarios, as a function of the vehicle's all-electric driving range [National Petroleum Council, 2012b]

Source: Electric Power Research Institute analysis, based on data in National Household Travel Survey, 2009

in an NA-SI dominated fleet, they could conceivably meet a larger fraction of the petroleum requirement in hybrid PHEV-dominated LDV fleet.

In essence, successful deployment of the PHEV creates a flexible pathway to GHG reductions. Transportation-sector CO_2 decreases may be pursued by either reducing the emissions rate of the electric grid or by increasing the fraction of low GHG-emitting biofuels. Varying the vehicle's electric range offers an additional element of flexibility for increasing the projected GHG benefit. While the base-case projection for GHG emissions does not change substantially for PHEVs with different ranges, the relative contribution from electricity and petroleum varies a great deal. Should the emissions rate of the electric grid improve significantly, a shift to higher electric range vehicles could be justified.

At the same time, the PHEV is a less cost-effective way to reduce petroleum and GHG emissions than the hybrid (particularly in the near term). Also, due to its higher upfront cost, it will have a harder time penetrating the market. The PHEV faces greater technical and infrastructure risk than the HEV. While the HEV is already enjoying growing market success, the PHEV still requires significant improvements in battery technology to meet the rigors of an automotive duty cycle and market price demands. In addition, while the infrastructure for supporting HEVs is already mature, deploying the PHEV at scale will require electricity production and distribution capacity expansion. While the infrastructure issues represent a relatively low barrier to deployment, the technical challenges for the PHEV will delay its time to market.

3. Battery Electric Vehicles

Pure BEVs do not have an engine on board; only a battery pack, electric motor, power-controlling electronics, and a propulsion system. No engine is a significant technical simplification, an inherent benefit. However, there are many major challenges including battery size, weight, cost, and durability; the range limitations of affordable size battery packs (some 100 miles); and recharging times. Range is extremely sensitive to ambient temperature through the variations in vehicle heating and cooling requirements, which can substantially draw down the battery energy. Also, battery recharging times are long due to practical electrical power distribution constraints, and are essentially independent of the specific battery technology. This last issue is much less discussed than the others.

Note that gasoline-fueled vehicles are refueled for the next 400 miles of driving in 5–10 minutes (20–40 gallons). When refueling, the chemical energy flow rate into the vehicle is about 10 MW! A home-based electricity recharging system at 1.5 kW (Level 1 charger, 120 V) for 8 hours provides the battery energy for some 25 miles in a compact-size electric vehicle. The industry is standardizing on three charging levels (Level 1, low power, 120 V AC, up to about 1.4 kW for homes; Level 2, 240 V AC, from 3 kW up to 19 kW; Level 3, fast charging, 200–450V DC, up to 90 kW). Even with a fast charger, a PHEV-40 would need about one hour for a full battery charge. [National Petroleum Council, 2012b]. Recharging times, which are primarily constrained by the electricity distribution infrastructure, not the technology of the battery, are thus a major issue impacting pure EV use and market appeal.

It is generally agreed that the Lithium-ion (Li-ion) battery will be the battery of choice for EVs for the nearer-term future. Several Li-ion chemistries are being investigated and developed for future EVs. As yet, Li-ion batteries do not offer an attractive enough combination of energy density, power capability, durability, safety, and cost. Note that batteries for PHEVs and BEVs are optimized primarily for high-energy storage and low cost. HEV batteries are optimized for high power delivery and may thus differ (though a shift from nickel-metal-hydride chemistry to Li-ion is occurring) [National Research Council, 2013].

Over much of the time horizon in question, the PHEV appears to be a more viable technology than the BEV for mass-market consumers. It is often assumed that a BEV with a 200-mile electric range is needed to approach the level of utility expected by the consumer and offered by other technologies. Even with this limited driving range, the EV is likely to be priced at an OEM cost increment of over $10,000—far greater than what has been projected for any of the other vehicle technologies. Even with optimistic future battery cost projections, the incremental cost of the BEV sits at the high end of projected future propulsion system technology costs ($7,000 or so), and this optimism regarding cost projections would presumably carry over to the other technologies. In addition, due to the weight of the battery pack, the BEV is projected to offer less GHG and energy reduction than the FCV, HEV, or PHEV.

While the BEV may be recharged from home, this does not address the range limitation on long car trips, and would likely require the installation of dedicated higher-power (220 V, 50 A) charging outlets for residential recharging. As such, a transportation system based around the EV would require the deployment of an electric refueling infrastructure to address the driving range and recharging time limitations—a task that, while less daunting than deploying a hydrogen infrastructure, is still a significant challenge. While there is already an electricity distribution network in place (the electric grid), there are few electric fueling stations.

These barriers are in stark contrast to those posed by PHEVs. The PHEV offers much of the petroleum reduction benefit of the BEV and greater near-term CO_2 and energy benefit at significantly lower cost. It requires less additional infrastructure than the BEV, is not range-limited, and could be driven in the same way as a conventional vehicle whereas, the BEV is expected to be driven less.

This analysis is not meant to infer that the BEV cannot enter and be successful in the light-duty vehicle market as a niche vehicle (for example, as a commuter car or as a “green” sports or luxury car), but rather that the technical and use challenges are too formidable for the BEV to succeed *in the mass market* in the next several decades. Over a longer time horizon, severe GHG emissions and resource constraints may eventually necessitate a transportation system that uses mostly all-electric vehicles.

4. Fuel-Cell Vehicles

The hydrogen fuel-cell vehicle (FCEV) is an all-electric vehicle in which the electric power comes from a fuel-cell system fueled with onboard hydrogen. FCEVs are usually configured as hybrids and use a battery for capturing regenerative braking energy and for supplementing the fuel cell output as needed. Power electronics manage the flow of electrical energy from and to the fuel cell, battery, and electric motor.

The fuel cell system consists of a fuel-cell stack and supporting hardware usually known as the balance of plant (BOP). The fuel cell stack effectively operates like a battery pack with the anodes fueled by hydrogen and the cathodes fueled by air, where the hydrogen is oxidized to water, and the hydrogen’s chemical energy is released as electrical energy. The BOP consists of equipment and electrical controls that manage the supply of hydrogen and air to the fuel-cell stack and support its thermal management. The vehicle is fueled with hydrogen at a fueling station analogous to a gasoline fueling station, and the hydrogen fuel is stored on the vehicle as a compressed gas in a high-pressure storage tank.

The key advantages of FCEVs are: High energy conversion efficiency and the fact there are only water emissions. There are no vehicle GHG or criteria pollutants emissions. Two recent studies provide up-to-date reviews of FCEV systems and hydrogen production options [National Petroleum Council, 2012b and National Research Council, 2013]. Our summary below has drawn extensively on these two sources. Our group’s most recent work on fuel cells was completed by Kromer, 2006–2008 [Kromer and Heywood, 2008].

Hydrogen can be produced from various energy sources. It is currently produced industrially from steam reforming of natural gas. It could be produced from electricity via water electrolysis. Some of the sources could potentially be low carbon-emitting or use renewable energy. Adding hydrogen vehicles into the mix could move our transportation system away from near-total reliance on petroleum with minimally compromised vehicle-on-road functionality: e.g., a 300-mile driving range, and only somewhat more complex refueling. The key challenges facing FCEVs are: adequate fuel cell stack durability; system cost reduction and achieving higher efficiency; the availability of hydrogen fuel while few FCEVs are on the road, and the production and distribution of hydrogen at competitive costs (see Chapter 6). The latter two issues create a formidable “chicken-and-egg” problem for which convincing build-up and transition strategies have yet to be proposed.

Several companies (Hyundai, Daimler, Honda, and Toyota) have announced plans to introduce FCEVs by 2015 in limited numbers, and mainly in Europe, Asia, California, and Hawaii where governments are coordinating efforts to start building up a hydrogen infrastructure.

Fuel-cell stacks used in automotive applications are of the polymer-electrolyte membrane/ proton-exchange membrane (PEM) type. Since PEMs operate at moderate temperatures, they are suitable for the periodic and transient aspects of on-road vehicle use. Precious metal catalysts (primarily platinum) are needed to promote the hydrogen/oxygen reaction that generates electricity in the fuel cell stack. Substantial improvements in stack durability, specific power, and cost have been realized over the past two decades. For example, stack lifetimes of 2,500 operating hours of driving (equivalent to approximately 75,000 miles) have been demonstrated in on-road vehicles, and current developments indicate that this can be more than doubled in the future.

The BOP consists primarily of mature technologies for the management of fluids and thermal energy. Significant improvements in efficiency and cost are anticipated from continuing simplifications in BOP design. Further reductions in the cost of fuel cell systems are expected to result from downsizing associated with improved stack efficiency and faster stack transient response.

Fuel-cell system efficiency measurements for representative FCEVs at several steady-state operating points show high-energy conversion efficiencies. FCEVs incorporating fuel-cell systems with efficiencies, fuel storage capacity, and the vehicle resistances due to weight, aerodynamic drag, and tire rolling resistance are at the lower (better) end of their ranges, are currently capable of 200 to 300 miles of real-world driving before refueling. This would realize an average energy conversion efficiency over twice that of a comparable-performance conventional ICE vehicle with comparable performance. For example, the 2011 Honda Clarity gasoline ICE vehicle fuel economy is 27 mpg, while the FCEV equivalent fuel economy exceeds 60 mpg (both adjusted on-road fuel economy values) [National Research Council, 2013].

Projected costs for high volume production of fuel cells have dropped steeply since 2010 as the technology improved to close to $5/kW for the fuel cell system. The fuel-cell stack generally accounts for 50%–60% of the system costs. Projected (future) cost estimates are very sensitive to anticipated production volumes.

Onboard hydrogen storage costs are a significant element in the overall cost. Compressed gas at 5,000 pound force per square inch (psi) (35 MPa) or 10,000 psi (70 MPa) has emerged as the primary onboard hydrogen storage technology for FCEVs, because it is a well-proven technology. The compressed gas storage capacity and the vehicle driving range are limited by the volume and cost of tanks that can be packaged into light-duty vehicles. Driving range of over 300 miles is expected to be achievable in the future. Carbon-fiber reinforced composite (CFRC) tanks have been employed to achieve sufficient strength at manageable weight. Cost projections for representative usable hydrogen storage systems are $2,900 for 35 MPa maximum hydrogen pressure, and $3,500 for 70 MPa [National Research Council, 2013].

Overall, over the next two decades, the primary focus of fuel-cell system technology development is likely to be on continuing the cost reduction progress of this past decade. Several of the major automobile companies express their judgment that the fuel-cell propulsion system is the most promising option for larger light-duty vehicles in a non-petroleum based, longer-term passenger vehicle transportation system.

In summary, the FCEV has the potential to dramatically decrease the transportation system's GHG emissions and its reliance on petroleum, but these vehicles require the deployment of a new fueling infrastructure and must still overcome a number of daunting technological obstacles. These long-term challenges revolve around developing fuel-cell technology that can withstand the rigors of an automotive duty-cycle, and that allows for a driving range of more than 300 miles. While these challenges are significant, it is important to recognize that the fuel cell is a new technology that has improved markedly in the last decade: a key question is whether this rapid development can continue.

How to develop hydrogen production paths that allow the FCEV to fully realize its potential for near-zero GHG emissions and fossil-fuel consumption is not clear. Natural gas feedstocks are likely to offer the cheapest and least-polluting hydrogen production pathway for decades. However, this begs the question of whether a hydrogen-fueled transportation system will trade reliance on one fossil fuel (petroleum) for a different one (natural gas). The "better" alternatives to steam reformed natural gas as the source of hydrogen are not yet apparent. In addition, while the current fuel-cell propulsion system requires significantly more energy to manufacture than hybrid, plug-in hybrid, or Naturally-Aspired Spark Ignition (NA-SI) and Turbo Charged Spark Ignition (TC-SI) systems, this negative may decrease in the future as the technology matures. This is an important factor in considering how close the well-to-wheel GHG projections are between the different advanced vehicle technologies [National Petroleum Council, 2012a, 2012b].

Even with successful and rapid development of vehicle fuel-cell technology, the scope of the challenge associated with deploying a brand-new technology and fueling infrastructure is such that it will take a long time for the fuel cell to penetrate the market in large numbers.

5. Vehicle Electrification: Summary

Electric powertrains offer important improvements relative to conventional ICE options in terms of both petroleum consumption and GHG emissions. However, these improvements come at significantly increased cost, and with various barriers to entering the market in large numbers. Table 3.3 summarizes the important technological challenges to deploying these different vehicle technologies: HEVs, PHEVs, BEVs, and FCEVs. This table has been developed from an extensive discussion of priorities for technology investment in the National Petroleum Council (2012a) report referenced in the table. It is included here to provide some perspective of the current state of development of the alternative powertrain technologies and their fuel supply requirements.

Table 3.3 Major hurdles to market acceptance of promising propulsion system, vehicle and fuel options[7]

Technology		**Difficulty (Hurdle)**
Light-Duty Vehicle Technology	Mass-market lightweighting (cost, driveability) Low rolling-resistance tires (cost)	High Medium
Internal Combustion Engines	Mass-market acceptance of changes that impact driveability (e.g., turbocharging, stop/start)	Low
Electric Vehicles	Battery energy density and cost Battery degradation and longevity Refuel time (time required to charge battery) Low GHG emitting electricity supply	High High High High
Hydrogen/Fuel Cell EV	Hydrogen compression and storage technology Fuel cell degradation and durability Low GHG emissions hydrogen supply and distribution	High High High
Biofuels	Land use change impacts Biochemical hydrolysis Gasification cleanup and conditioning Upgrading of pyrolysis oil Lignocellulose logistics/densification	High Medium Medium High Medium
Natural Gas	Direct injection for light-duty compressed natural gas (CNG) vehicles Incorporating gasoline powertrain and platform Natural gas refueling system	High Medium Medium

High hurdles range from basic research to technology demonstration. These hurdles require invention or have high uncertainty.

Medium hurdles range from technology development to demonstration. A pathway for success has already been demonstrated and tested, but sustained effort is required to achieve wide-scale material volumes.

Low hurdles range from systems commissioning to operational. These hurdles have minimal or no barrier to wide-scale material volumes.

Our judgment is that the HEV share of new vehicle sales will grow, moderately but steadily, as the cost premium relative to improved gasoline engines (naturally-aspirated as well as turbocharged) is reduced, and improved and more sophisticated system integration occurs. As battery technology improves significantly, a part of this HEV growth will transition to growth in PHEV vehicle sales. First, however, the PHEV vehicle technology will need to successfully emerge from a 5–10-year gestation period in which the current "prototype production PHEVs" steadily become less expensive and more attractive through real-world-use experience, and the further

[7] Developed from Chapter 4, National Petroleum Council Report (2012a) *Advanced Technology for America's Transportation Future: Part One, Integrated Analysis*.

development that engenders. Thus, we anticipate any significant growth in PHEV sales to be at least a decade or so in the future. In our view, these are not pessimistic judgments: rather they are plausible paths to lowering petroleum consumption and GHG emissions over time recognizing the real-world constraints in this largely market-driven, very large-scale vehicle deployment and use arena. While directionally this trend is likely, its rate of progress and ultimate extent are, as yet, uncertain.

Our view of BEVs is that the challenges of significantly higher vehicle costs and real-world driving-range limitations coupled with long recharging times inherently limit the market appeal of this technology. It currently appears to be a niche market for a modest number of specialty vehicles. It is unlikely to be a major "transformation path" for LDVs, because its evolution would need to be accompanied by major GHG emissions reductions from the electricity supply sector to be attractive.

The prospects for fuel-cell (hybrid) vehicles are promising but still uncertain. While the fuel-cell vehicle is some two to three times more energy efficient than the standard gasoline-engine vehicle, on a WTW basis, without practical low GHG-emitting hydrogen supply and distribution, the benefits are significantly reduced. The production and distribution of hydrogen and vehicle refueling entail significant losses of primary energy. Even with natural gas as the feedstock (with its lower carbon to hydrogen ratio), the reduction in WTW GHG emissions, of a fuel-cell hybrid vehicle relative to naturally-aspirated gasoline engine vehicle GHG emissions, is, by our estimates, about 30% by 2030. Initially, FCEVs are expected to cost some 1.4 times more than an equivalent gasoline NA-SI vehicle. FCEV costs are expected to come down and become closer to mainstream technology options. On a fuel cost-per-mile basis, hydrogen could be produced at scale at a comparable price to gasoline. However, a large-scale future for fuel-cell vehicle technology is by no means certain. Significant and sustained investments by industry and government are required for this potentially transforming pathway to achieve commercial success [National Petroleum Council, 2012b, Chapter 15].

3.3 Propulsion-System in Vehicle Operating Characteristics

This report is focused on the options available for reducing future petroleum consumption and GHGs from the in-use LDV fleets in various major world regions. This chapter has focused on the relevant operating characteristics of the propulsion system options at the vehicle level. Obviously, the deployment rates of these various propulsion systems, over time (described in Chapters 7 and 9, are at least as important. Fuel consumption and GHG emissions are the *vehicle* characteristics that are critical as we assess impacts. Several other attributes also need to be defined: e.g., vehicle weight, size, acceleration performance or capability; vehicle type and its specific functions (e.g., passenger car, pickup truck); driving range; refueling/recharging time; and cost. The attributes that significantly affect the vehicle's fuel consumption are summarized here (and are also discussed in subsequent chapters).

Our scenario studies of different world regions require (as inputs) the actual fuel (or energy) consumptions (liters/100km, MJ/km) of the several different technology propulsion system vehicles likely to be sold in each future model year. For example, a full HEV typically has a 30% lower fuel consumption than an equivalent NA-SI engine. The fuel consumption of both of these new HEV and the NA-SI vehicles improves over time at roughly comparable relative rates (note that most of the vehicle-based improvements are common). Figure 3.3 shows our current assumptions as to new-vehicle *relative fuel consumptions* for the different propulsion systems, with current new vehicles (cars) labeled as 2010, and new vehicles in 2030 and 2050. The technology-specific values listed have been normalized by the current NA-SI vehicle which is thus 1.00. These normalized values are obtained from estimated actual fuel consumptions (gasoline equivalent liters/100 km) or energy consumption (electricity kWh/km or hydrogen kg/km) with appropriate unit conversions. For each year, the ratios of the individual technology numbers are comparable but not exactly the same, as a result of modest differences in assumed improvement rates. Note that the differences between vehicles with different propulsion systems are substantial (so the sales mix and its evolution over time are important). As also are the anticipated improvements of each propulsion system over these several decades. Note that these are "vehicle fuel tank to wheels" values (or battery recharging energy to wheels values for BEVs) and do not include the energy supply (well-to-tank) component of energy demand which is needed for broader consumption and emissions evaluations.

The values given in Figure 3.3 assume that the vehicle's size and acceleration performance are held essentially constant. If the average-vehicle size (and thus its weight) changes, so will its fuel consumption. If its performance/acceleration capability increases (as has been the historical trend), so will its fuel consumption increase and worsen. We use a parameter—Emphasis on Reducing Fuel Consumption (ERFC) to quantify this latter trade-off. ERFC is the ratio of the actual reduction in fuel consumption over a given time period to the (potential) reduction over the same time period if other attributes (primarily vehicle size and acceleration capability) remain unchanged.

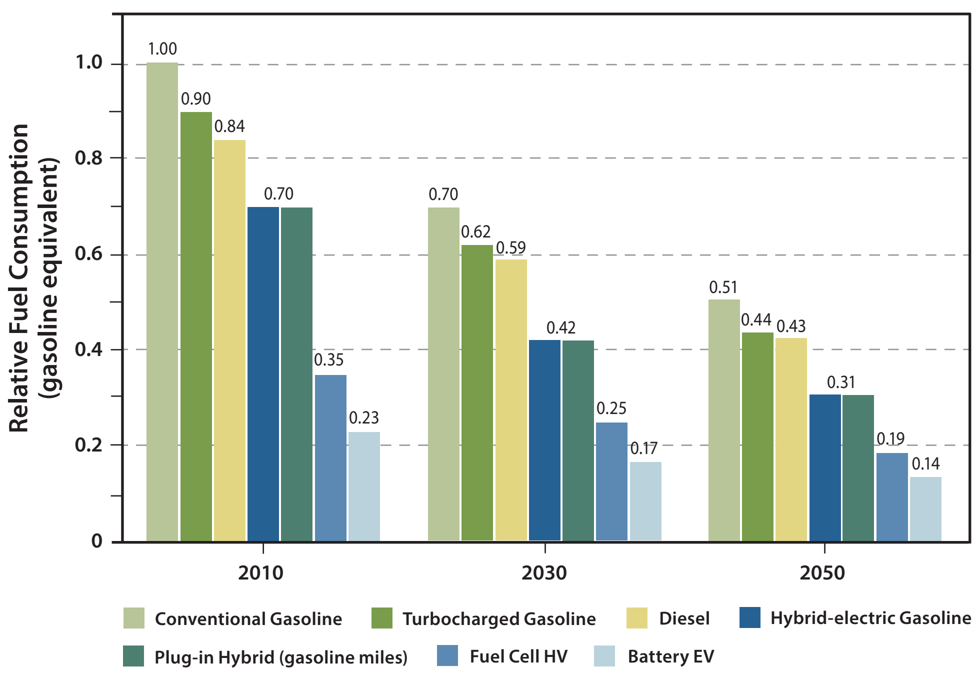

Figure 3.3 On-road fuel consumption of the different propulsion system passenger cars *relative* to a current naturally-aspirated gasoline engine vehicle in 2010, 2030, and 2050. Light trucks have closely comparable relative values when normalized by current average NA-SI gasoline engine value

We have used various methodologies to evaluate and project ERFC based on vehicle weight, size, and acceleration information [see Chapter 5, and Boldek and Heywood, 2008; Cheah et al., 2008; Bastini et al., 2012; and MacKenzie and Heywood, 2012].

While "vehicle size" is held constant across different propulsion technologies and over time, vehicle weight is not. We normally use the Environmental Protection Agency's (EPA) definition of vehicle interior volume for size. The interpretation is not straightforward; therefore, "constant size" can only be implemented approximately. In Figure 3.3, the assumed average weight reduction by 2030 is 15% lower than today's vehicle (reduction is closely comparable for cars and light trucks). From 2030 to 2050, an additional 15% is assumed giving close to a 30% reduction (at the same vehicle size and acceleration capability).

In our assessment and scenario studies, actual fuel consumptions for these different technology average-new-vehicles are required. These are usually obtained by multiplying these relative fuel consumptions by the actual on-road fuel consumption of the current average new standard-NA-SI gasoline-engine vehicle. For the United States, the on-road fuel consumption (FC) for the new car sales mix in 2010 was 26 mpg (FC was 11 liters/100 km) and for light-trucks was 20 mpg (FC was 14.3 liters/100 km). The combined on-road value was therefore 22.8 mpg (FC of 12.6 liters/100 km) [National Petroleum Council, 2012b]. This is close to the sales-weighted combined 2010 fuel economy of 22.1 mpg that is listed in the *EPA Fuel Economy Guide*. This EPA-based sales-weighted new vehicle fuel economy had improved to 24.7 mpg (FC of 11.6 liters/100 km) by the 2013 model year. In Europe, the corresponding current average-sales-vehicle mpg value is 33: The fuel consumption is 8.7 liters/100 km (gasoline equivalent liters).

We use our recent scenario studies in the U.S. context to illustrate the impact of increasing vehicle performance. It has become especially important as a consequence of the ongoing transition from naturally-aspirated to turbocharged gasoline engines which is anticipated (over time) to be extensive. If an NA-SI engine is replaced by a (downsized) TC engine in a given model, the extent of downsizing can be determined by the manufacturer to provide both increases in vehicle performance and fuel economy. In the competitive light-duty vehicle market, this is an attractive option. Also, since there is a distribution among the many vehicle models available in their acceleration capability (a spread from about 7 to 11 seconds in 0–60 mph, [0–97 km/h], times: see Chapter 5), there will always be market pull to increase the acceleration capability of the slower portion of this distribution. Figure 3.4 shows average 0–60 mph (0–97 km/h) acceleration time data (from 1990 through 2010) extrapolated to 2030, suggesting that close to a 10% reduction (average time of 8.1 seconds in 2013, to 7.4 seconds in 2030) could be anticipated before average vehicle performance increases essentially taper off. Our scenario studies [Cheah et al., 2008 and Bastani et al., 2012b] indicate that such a 10% decrease in acceleration time corresponds to an ERFC value in 2030 of about 80%. Figure 3.5 [Cheah et al., 2008] shows that this corresponds to an increase in relative fuel consumption of close to 10% (from 0.7 to 0.77 in 2030). We also assume that by 2050, ERFC has asymptoted to essentially 100%.

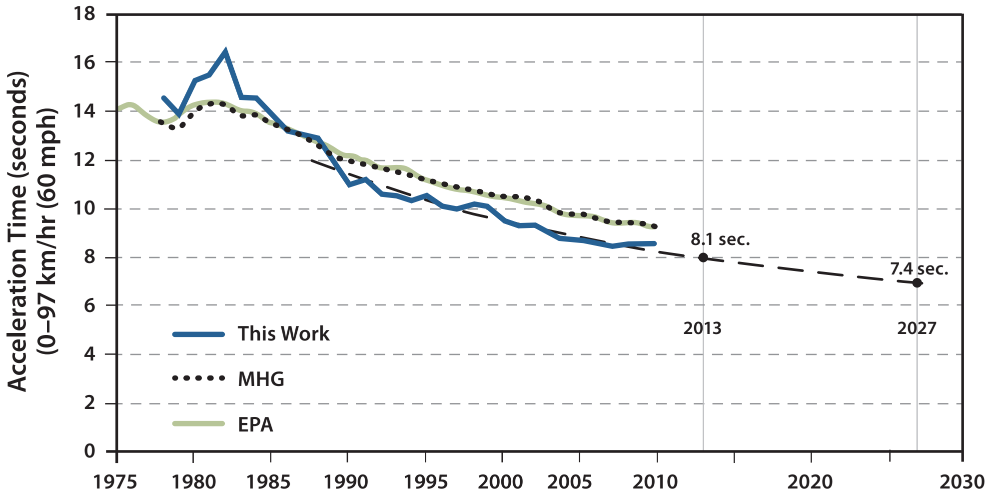

Figure 3.4 Sales-weighted average 0–97 km/h (0–60 mph) acceleration times calculated using our model, method of Maliaris et al. (1976), and averages reported by EPA (2010)

The impact of these appropriate adjustments is summarized in Figure 3.6 which shows relative and absolute fuel consumptions for the average car and average light truck for the different propulsion system vehicles out to 2050. (We have assumed that the relative fuel consumption values for cars and light trucks are closely comparable.) Annual fuel consumption improvements (reductions) of between 1.5% and 2% per year for each of the different propulsion technologies are projected over this 40-year period. The fuel consumption of light trucks is about 20%–30% worse than cars (which currently are about 500 kg (1,100 lb) lighter).[8] Our judgment is that newer technologies (hybrids, fuel cells, batteries) will progress at a more rapid relative pace over the earlier portion of this period. However, our assessments indicate that these differences, while not insignificant, are modest. Note that all of the numbers in Figure 3.6 incorporate an increase in ERFC from some 50%–60% currently, to 80% in 2030, to 100% in 2050. This reflects a modest increase in average acceleration capability (about 20% over the next 20 years or so). Note that the energy consumption rates of FCEVs and BEVs have not been discounted by the roughly 10% degradation of the IC engine (and HEV) powertrain vehicles.

These fuel consumption numbers are the (relative or absolute) average fuel consumptions of the new cars or light trucks sold in a given year, with different technology propulsion systems. They are tank-to-wheels (TTW) values and not WTW values. These numbers are based on engineering analysis as well as judgments, as summarized below. They are generated expecting that policies and regulations will push the development of fuel economy/GHG reducing technology, but not including demand-specific policies. We assume that petroleum prices will rise over time, but not become really high, for the next few decades.

[8]Average curb weight for cars is currently just over 1,625 kg (3,600 lb) and for light trucks is 2,150 kf (4,700 lb). Weight reductions are estimated to be up to about 20% from 2010 to 2030.

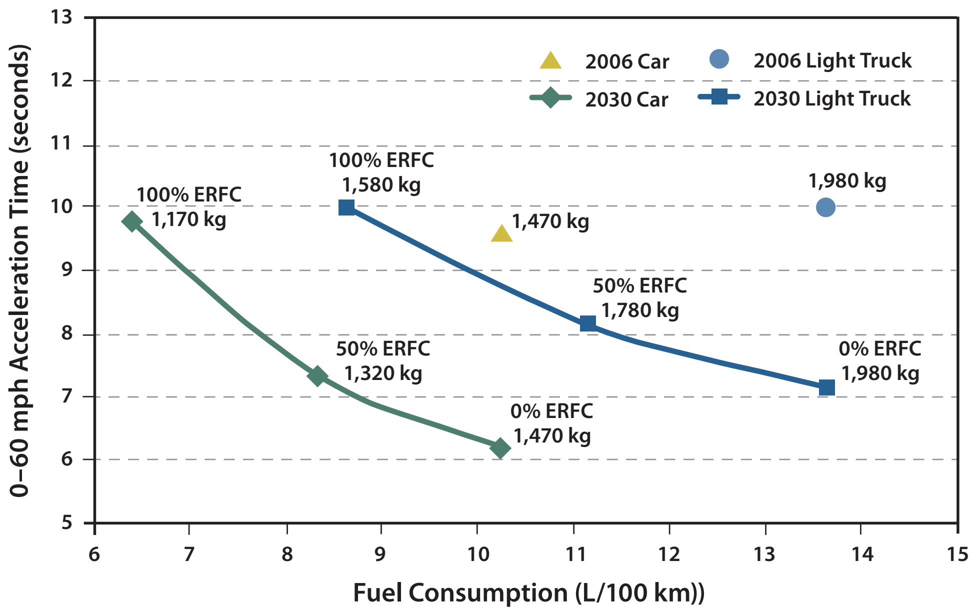

Figure 3.5 Trade-off between acceleration performance (0–60 mph acceleration time), vehicle weight, and fuel consumption for the average passenger car and light truck [Cheah et al., 2008 and Bandivadeker et al., 2008]

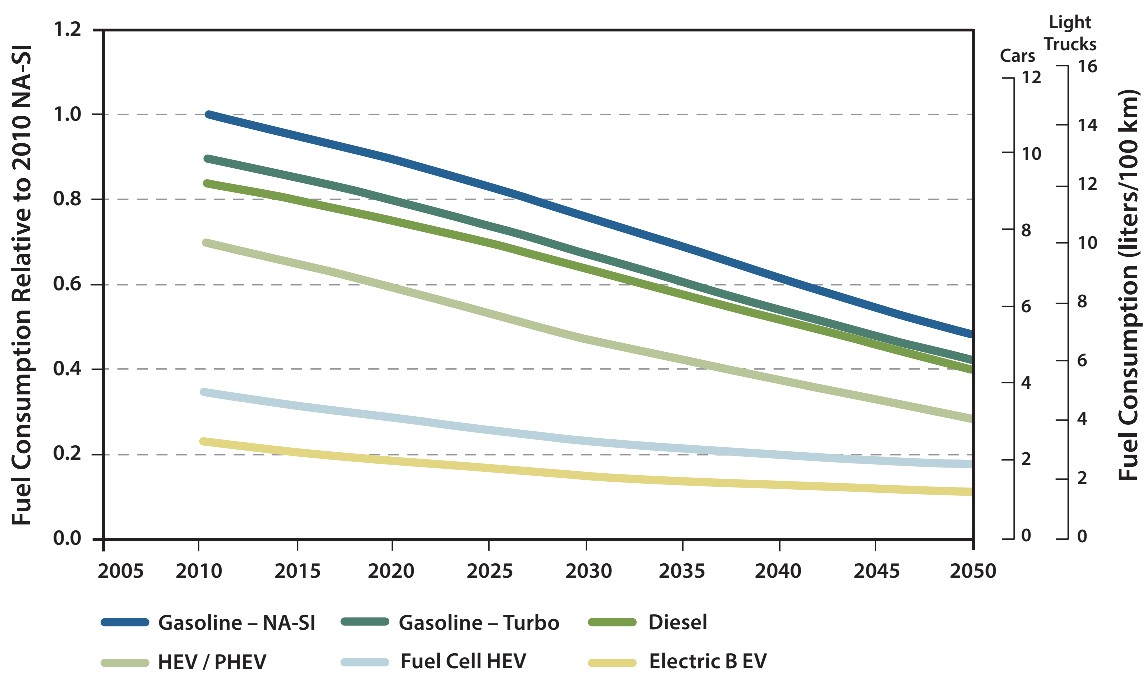

Figure 3.6 Average on-road vehicle fuel consumption relative to current NA-SI engine vehicles: improvements out to 2050 (tank-to-wheels, based on common fuel or energy units); cars and light trucks average value scales on right

We characterize these as "realistic, yet aggressive" on-road average fuel consumption values that are neither overly optimistic nor pessimistic. They incorporate degrading factors for the near- to mid-term due to modest increases in vehicle performance. For our assessment, the average new vehicle technology lags the "best feasible technology vehicle," as has been explained above. Other recent studies [National Research Council, 2013 and National Petroleum Council, 2012a, b] have carried out similar assessments of future vehicle characteristics. It is difficult to make detailed comparisons to check consistency because methodologies and assumptions differ and are not always defined. Our anticipated future fuel consumption improvements are close to those of the National Petroleum Council study. Our findings are not as optimistic as the National Research Council *Transitions to Alternative Vehicle and Fuels*, but the differences with their mid-range projections are not that large (the NRC study assumed vehicle performance remained constant, and stated that a strong regulatory environment would be needed to achieve their values).

3.3 Improvement Potential at the Vehicle Level

3.3.1 Overview

In the previous section, we developed the basic fuel consumption values for several different propulsion system in-vehicle options. These are particularly useful as *relative fuel consumption* values for new vehicles as a function of propulsion technology and time. These relative values and how they change, are closely comparable for different sizes and types of vehicles in the various major world regions, with similar assumptions about the technologies involved and how they combine and progress. This "self-similar" characteristic is not exact, but, given the uncertainties involved, it is usually an appropriate assumption. In this section, we broaden our characterization of the attributes of the average vehicle for both cars and light-trucks (the U.S. definition is SUVs, crossover vehicles, vans, and pickup trucks), and provide a more complete vehicle and fuel life-cycle assessment. We will quantify petroleum-based fuel consumption, ethanol biofuel use, overall energy consumption, and GHG emissions, all at the average new-vehicle level. We incorporate reductions in the vehicle resistances (weight, drag, rolling resistance); improvements in engine-plus-transmission in-vehicle efficiencies; fuel supply and distribution impacts; and the vehicle production cycle, from manufacture to assembly and sales.

These vehicle fuel consumption, energy use, and GHG emissions values are taken from our own work, and were augmented by values for key parameters taken from two recent U.S. reports: the National Petroleum Council's report (2012a, b) *Advancing Technology for America's Transportation Future: Part One, Integrated Analysis, and Part Two, Fuel and Vehicle System Analysis* and the National Research Council's Report (2013) *Transitions to Alternative Vehicles and Fuels*.

As we add fuel supply alternatives (WTT) to our vehicle use analysis (TTW), the derivation of impact parameter values such as fuel consumption (liters/100 km, the inverse of fuel economy, mpg) and GHG emissions grams of carbon dioxide (gCO_2) (equivalent)/km, become more complex. While gasoline and diesel fuel supply from petroleum extraction, refining, and distribution are relatively well defined, they are not well defined for the alternative fuel/energy sources. For these alternatives, while there are several energy source and fuel-producing supply and distribution options, the most promising approaches have yet to be defined and configured. The "greenness," the level of GHG emissions of the WTT component, is a key issue in assessing the overall potential benefits and impacts for an alternative fuel/energy source and its associated propulsion system technology.

3.3.2 Average Fuel Consumption and GHG Emission Levels

The numbers in Tables 3.4, 3.5, and 3.6 that follow need to be characterized by an explanation of "what these fuel and energy consumption and GHG emissions numbers for the average new vehicle (which embody specific propulsion system vehicle technologies, and for WTW assessments, the fuel or energy source), are intended to represent." These values are, of course, assumption dependent. As explained earlier, we characterize our vehicle performance numbers as "realistic, yet aggressive" average on-road numbers. We judge that these numbers are optimistic, but not overly so. We inherently assume that the policy environment (fuel economy/GHG emissions requirements, fuel/carbon tax increases, etc.) continues to prompt continuing change as we move into the future. These numbers incorporate improvements in engine and transmission (propulsion system) drive efficiency, reductions in aero drag, tire rolling resistance, vehicle weight (and size) reductions, and some (10%) increase in acceleration performance over time. They represent the *average new vehicle* sold in a given year and not the *best new vehicle* sold. Real-world degrading factors are included: e.g., not all feasible technologies will be deployed in all vehicles and vehicle content (features) and auxiliary loads will increase over time following recent history. For a given propulsion system technology, the improvements (in TTW fuel consumption and WTW GHG emissions) over the period 2013 to 2050 correspond to between 1.5% and 2% per year, compounded. This is roughly 30%–50% faster than the historical record, which is 1%–1.5% per year.

Table 3.4 lists the projected new car and light truck on-road fuel consumptions in liters of gasoline equivalent per km (to obtain equivalent miles per gallon, divide 237 by the fuel consumption in liters/100 km). The actual numbers are on-the-road values for cars and light trucks in the United States, with a "current combined" value of 10.7 (2010) to 9.6 (2013) liters/100 km, 22.1 to 24.7 mpg.[9] [Schoettle and Sivak, 2013]. The corresponding CAFE test numbers are 8.65 (2010) and 7.95 (2013) liters/100 km, 27.4 (2010) and 29.8 (2013) mpg. These test fuel-consumption numbers are about 18% lower and the test mpg numbers are 22% higher than on-the-road adjusted values. Note that sales-weighted U.S. fuel consumption (on-road and test values) has been improving steadily over the past six or so years due to technology improvements, some weight reduction, and shifts in size distribution to "less big" vehicles.

[9]The higher fuel consumption number is the 2010 value, the lower fuel consumption number is 2013.

Table 3.4 Projected on-road current and 2030 average new vehicle fuel consumption

Propulsion System	Cars			Light Trucks		
	Fuel Consumption (1/100 km)*	Relative to Current NA-SI Gasoline ICE	Relative to 2030 NA-SI Gasoline ICE	Fuel Consumption (1/100 km)	Relative to Current NA-SI Gasoline ICE	Relative to 2030 NA-SI Gasoline ICE
Current NA-SI Gasoline	9.20	1.00	—	11.80	1.00	—
Current Turbo SI Gasoline	8.30	0.90	—	9.80	0.83	—
Current Diesel	7.70	0.84	—	8.70	0.74	—
Current Hybrid	6.40	0.70	—	8.30	0.70	—
2030 NA-SI Gasoline	7.10	0.77	1.00	9.20	0.78	1.00
2030 Turbo SI Gasoline	6.30	0.69	0.90	7.90	0.67	0.86
2030 Diesel	6.10	0.66	0.84	7.30	0.62	0.79
2030 Hybrid	4.40	0.48	0.62	5.80	0.49	0.63
2030 PHEV	1.60[#]	0.17	0.22	2.00[##]	0.22	0.29
2030 FCHV	2.30**	0.25	0.32	3.00**	0.25	0.32

*Gasoline equivalent

**Hydrogen in liters of gasoline equivalent/100 km

[#] Plus 1.0*l* gasoline equivalent/100 km electricity (65% km electric)

[##] Plus 1.3*l* gasoline equivalent/100 km electricity (65% km, electricity)

Note: A modest (10%) increase in acceleration performance by 2030 is assumed, as is a weight reduction of 20%. (Beyond 2030, essentially constant performance is assumed.)

The *relative* fuel consumption columns are most instructive and can be converted to actual fuel consumptions in various world regions by multiplying by the current average new gasoline-engine vehicle on-road fuel consumption in that region: e.g., in Europe, about 7 liters gasoline/100 km for the average gasoline-fueled car, which is about three-quarters of the average current new car value, and two-thirds of the combined car and light truck value in the United States. Note that these TTW fuel consumptions indicate significant improvements over time: 20%–25% reduction in fuel consumption by 2030 and almost 50% by 2050. They also offer the potential of major TTW reductions through switching from ICE vehicles to the alternative propulsion-system vehicle options.

Table 3.5 Vehicle tank-to-wheels on-road energy use, 2010 and 2030: with modest (10%) increase in acceleration performance by 2030; essentially constant performance, 2030–2050

Propulsion System	Cars			Light Trucks		
	MJ/km	Relative to Current NA-SI Gasoline ICE	Relative to 2030 NA-SI Gasoline ICE	MJ/km	Relative to Current NA-SI Gasoline ICE	Relative to 2030 NA-SI Gasoline ICE
Current NA-SI Gasoline	2.97	1.00	—	3.81	1.00	—
Current Turbo SI Gasoline	2.67	0.90	—	3.16	0.83	—
Current Diesel	2.49	0.84	—	2.82	0.74	—
Current Hybrid	2.08	0.70	—	2.67	0.70	—
2030 NA-SI Gasoline	2.29	0.77	1.00	2.97	0.78	1.00
2035 Turbo SI Gasoline	2.05	0.69	0.89	2.55	0.67	0.86
2030 Diesel	1.96	0.66	0.85	2.36	0.62	0.80
2030 Hybrid	1.43	0.48	0.62	1.87	0.49	0.63
2030 PHEV*	0.83	0.28	0.37	1.07	0.28	0.37
2030 BEV	0.53	0.18	0.23	0.69	0.18	0.22
2030 FCHV	0.74	0.25	0.33	0.95	0.25	0.32

1 MJ/km = 3.2 L/100 km, gasoline equivalent

*Includes gasoline (35% km) and electricity (65% km)

Table 3.5 presents essentially the same information as in Table 3.4 but in units of energy (MJ/km). The values for PHEVs now include both the fuel energy and the electrical battery charging energy used to drive the vehicle. The BEV is also included. Since these are TTW values, fuel or energy supply system energy is not included. Note that the high in-vehicle efficiencies of the battery/electric motor and fuel cell/battery/electric motor system give the PHEV, BEV, and FCEV a significant vehicle energy consumption benefit.

Table 3.6 Basic vehicle and energy source GHG emissions data: Average new U.S. vehicle in 2030

Vehicle Propulsion System/Fuel	Cars and Light Trucks			Cars	Light Trucks	Ratio[f]
	gCO_2e/MJ[a]			gCO_2e/km		
	WTT	TTW	WTW	WTW	WTW	WTW
Gasoline NA-SI	22	71	93	213	276	1.00
Turbo SI Gasoline	22	71	93	191	237	0.90
Diesel			99	194	233	0.91
HEV	22	71	93	133	174	0.62
PHEV (10)–(30)[b]				103–77	135–100	0.48–0.36
FCEV[c]	200–100	0	200–100	150–74	190–95	0.7–0.35
BEV[d]	164–88	0	164–88	87–47	113–61	0.41–0.22
Natural Gas NA-SI[e]			74	169	220	0.79
Corn Ethanol NA-SI			73	167	217	0.78
Sugar Cane/Forest Waste Ethanol			34–39	78–89	101–116	0.37–0.42
Tar Sands Gasoline	34	71	105	240	312	1.13

[a] CO_2 per unit of "fuel energy"

[b] Strongly dependent on the percentage of miles electrical and electrical supply system

[c] FCEV – Higher number with standard (improved) hydrogen production: lower number with clean H_2 (with carbon capture and sequestration)

[d] Strongly dependent on the CO_2 intensity of electricity

[e] Assumed same vehicle efficiency as gasoline NA-SI vehicle

[f] Ratio: cars, gCO_2e/km divided by gasoline NA-SI value

Note: Well-to-tank (WTT), tank to wheels (TTW), well-to-wheels (WTW). Vehicle production cycle emissions are additional: 25 gCO2e/km (10%) for ICE vehicles; 43 gCO2e/km (25%) for FCEV.

Table 3.6 summarizes the full GHG emissions situation, currently and projected out to 2030. It includes the WTT and TTW components of the appropriate life-cycle analysis by breaking out GHG emissions intensities of the various fuels or energy sources as well as the vehicle values (in gCO_2 equivalent per MJ of fuel energy). These numbers, with the MJ/km numbers from Table 3.5, then capture all of the WTW GHG emissions per unit of travel (gCO_2e/km). Note that the vehicle production and scrappage cycle emissions (not included in the table) are not insignificant. They are about 25 gCO_2e/km for mainstream ICE technologies (some 10% of the WTW values) and 40–45 gCO_2e/km for FCEVs (some 25% of the WTW value). Note also that ranges in GHG emission for the alternative vehicles and their different fuels/energy sources are shown. These correspond to the different potential energy supply system characteristics (WTT) which could vary from modestly better in terms of GHG emissions than today's levels, to substantially "greener" (lower GHG emissions) in this 2030 time frame. The electricity and hydrogen paths are especially sensitive to this energy supply question (by about a factor of two).

The GHG emissions ratio column is especially useful. While the numbers project 15–20 years into the future (and thus many subjective judgments are embedded), they indicate important aspects of these many options. All of the options become more attractive over time from 2013 to 2030, but the relative differences between the different ICE options in 2030 is only some 10%. Vehicle electrification with the several hybrid options (HEV, PHEV, and FCEV) offer 40%–50% reductions if electricity and hydrogen production still involve significant (though lower than today) GHG emissions. Only the much greener electricity, hydrogen, and biofuels pathway options offer more significant reductions that are some two-thirds below the GHG emissions of the mainstream technology improvement path. Note that standard hydrocarbon fuels from tar sands sources have slightly higher GHG emissions when compared to petroleum sources (by 13%).

3.3.3 Vehicle Cost Estimates

Estimating vehicle costs several decades ahead is a formidable challenge! The costs of new technologies in the prototype production stage are significantly higher than they could be 10 or 20 years into the future, if those technologies are successful in the marketplace and production volumes grow to a significant scale. There are two primary reasons for this: designs improve and costs are reduced in large part from feedback from real-world use of the technology and competition among producers; and as production volumes steadily rise, economies of scale decrease unit production costs. While there are economic models for these processes, they are generalized and speculative, and their validity over decades is unclear. Also, estimating costs is a business for "experts." Such expertise largely resides in the automotive industry, and that expertise is primarily in the nearer-term 5–10-year range.

We have reviewed the cost estimates in two recent studies: The National Research Council's Report *Transitions to Alternative Vehicles and Fuels* (2013); and the National Petroleum Council's Report *Advancing Technology for America's Transportation Future Part One–Integrated Analyses* (2012). We have compared the cost estimates in these studies with the cost estimates developed by our group at MIT [in *On the Road in 2035*, Bandivadekar et al., 2008]. The MIT cost estimates are now some six or so years old. Our cost estimates for improvements in mainstream technologies are still expected to be valid: however, battery and fuel-cell system costs have been decreasing over the past 5–10 years, so we would expect that more recent cost estimates for these alternative technologies will be lower.

We have compared cost estimates from the three sources as follows. We have used the 2030–2035 time frame as the future vehicle target date. Our MIT study estimated incremental price increases (in 2007 $) for future vehicles using the various propulsion system technologies. (These were drawn from technology costs multiplied by a factor of 1.4 to obtain representative *retail price* levels.) The base was 2007 and target date 2035. The National Research Council study plots high-volume retail price equivalents (2009 $) for the different technology vehicles, (their Figure 5.8) versus year from a base of 2010 to 2050 (their Figure 5.8). We have used their 2030 vehicle retail price values. Note that their "ICE vehicle" transitions from a naturally-aspirated gasoline engine vehicle in 2010 to a turbocharged gasoline engine vehicle in 2030. We have subtracted $700 from their turbocharged vehicle price to obtain the naturally-aspirated vehicle price in 2030 to provide a consistent 2030 baseline. The NPC study gives the retail price equivalent for small cars (the MIT study values are for the average car; the NRC study values are for a mid-size car), for 2015 and 2050. We have averaged these two values to obtain an approximation for their 2030 values. The NPC study values are presumed to be in constant current dollars.

Note that an additional cost per vehicle over this time frame of some $2,000 is anticipated due to the development and deployment of substantive active safety systems (sensors, controls, etc.) and stricter air pollutant emissions controls [*Automotive News*]. This anticipated additional cost is not included in these estimates.

Table 3.7 compares the incremental price increases above a baseline of a 2030–2035 naturally-aspirated gasoline engine vehicle (car) for the various mainstream technology and alternative propulsion system vehicles. It also includes the incremental price difference between the current and 2030 NA-SI gasoline vehicle. A negative number means the price went up, when comparing a current vehicle to a 2030 vehicle.

Table 3.7 Incremental price increase estimates, $ per vehicle for various mainstream and alternative propulsion system vehicles relative to 2030 or 2035 future mainstream naturally-aspirated gasoline engine vehicle

	MIT Average Car Base Year: 2035	NRC Mid-size Car Base Year: 2030	NPC Small Car Base Year: Avg. 2015 and 2050
Current NA-SI gasoline	-$2,000	-$1,200	$2,500
Future NA-SI gasoline	$0	$0	$0
Future TC SI gasoline	$700	$700	—
Future Diesel	$1,700	—	$2,800
Future Hybrid	$2,500	$2,600	$2,100
Future PHEV (10)	—	—	$4,400
Future PHEV (30)	$5,900	$5,250	—
Future PHEV (40)	—	—	$9,700
Future BEV	$14,400	$5,150	$13,900
Future FCEV	$5,300	$3,150	$10,800
Compressed Natural Gas Vehicle	—	$2,675	$3,900

While the MIT and NRC numbers show that the standard technology vehicle's price will increase comparably from its current value to the 2030–2035 value,[10] the NPC study argues that improved design and reductions in production costs will actually decrease the base vehicle cost by some 10%. The mainstream vehicle price increments (gasoline engine vehicles and HEV) are about the same in the three studies.[11] However, the BEV, and the FCEV show significant disparities due to differing estimates of future battery costs and fuel-cell system costs. PHEV costs (allowing for the different electric drive capabilities, and thus battery pack size) are not that different nor are the compressed natural gas vehicle price increments.

Overall, we conclude that the cost and price increases for improved future (2030) mainstream technology vehicles are relatively well established and are significant. Whether progress in propulsion system and vehicle design and manufacture will reduce these costs, in parallel, is unclear. BEVs and FCEVs are projected to have more significant cost increases than HEVs, but estimates vary significantly. A key issue in this alternative vehicle cost uncertainty is the extent to which the cost of these new technologies will come down sufficiently over time so they become marketable—then, the extent to which economies of scale continue to reduce their cost as sales volumes increase, so the deployment of these technologies can grow to ever-larger scale.

3.3.4 Summary

Overall, this extensive assessment and comparison of the several potentially promising paths forward indicates that the improvement of mainstream technologies over time is expected to be especially important in reducing petroleum consumption and GHG emissions, Also, the hybrid option (already in production) is an inherently more efficient, though more costly, option. As HEV sales grow and their cost premium comes down, this option provides a base for developing PHEVs that would bring electricity gradually into the transportation energy supply system in a way that does not impose driving range and recharging time constraints. Yet with PHEVs, electrical driving could be two-thirds of the total driving, about the same ratio as BEV miles driven per year to standard vehicle miles per year. The alternative propulsion systems and their corresponding fuel/energy sources could be attractive, but only if their propulsion system technologies continue to improve, their cost continues to decrease substantially, and major reductions in the GHG emissions from the electricity or hydrogen supply system are achieved in parallel. The reductions in impacts between these alternative technology and energy-source approaches and the mainstream technology vehicles that they replace are not as great as many people are hoping.

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[10] Scaling the MIT number (over 28 years) to the same period for the NRC number (20 years) brings these numbers closer.

[11] The National Petroleum Council diesel price is higher than the MIT diesel price due to the fact that the study includes more (and more effective) exhaust emissions reduction components.

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4.0 Vehicle Weight and Size Reduction

Vehicle weight, size, and fuel consumption are all intimately connected. Assessing the prospects for fuel consumption reductions requires an understanding of the ways in which vehicle sizes and weights may evolve in the future. All else equal, a vehicle with a significantly lower weight will consume significantly less energy per kilometer traveled. As discussed in more detail in Chapter 5, a 1% reduction in vehicle weight reduces per-kilometer fuel consumption by approximately 0.6%–0.7%, holding size and acceleration performance constant.

Changes in vehicle weight emerge from two fundamentally opposing forces; it is helpful to think about the weight effects from these two forces separately. On the one hand, improvements in vehicle capabilities, such as higher performance, larger size or carrying capacity, and greater levels of equipment, add weight to a vehicle. Features and functionality that add weight are most appropriately viewed as design attributes to be traded off against size, fuel consumption, and acceleration performance. On the other hand, advances in materials, design, and manufacturing technologies tend to reduce the weight of vehicles. These are more appropriately considered to be sources of technology improvement that expand the feasible set of vehicle designs. Manufacturers must carefully balance content added to vehicles against investments in weight-saving technology during the course of product development. Similarly, analysts attempting to understand future fuel consumption trends should separately consider trends in both weight-increasing capabilities and weight-decreasing technology improvements.

4.1 Vehicle Weight in an International Context

By international standards, vehicles in the United States are relatively heavy. In the United States, average passenger vehicle weight increased dramatically between 1987 and 2004, before leveling off in recent years. As shown in Figure 4.1, this trend has been driven both by the increasing average weights of cars and trucks and by a shift in sales volume from cars to trucks, and lately back to cars.

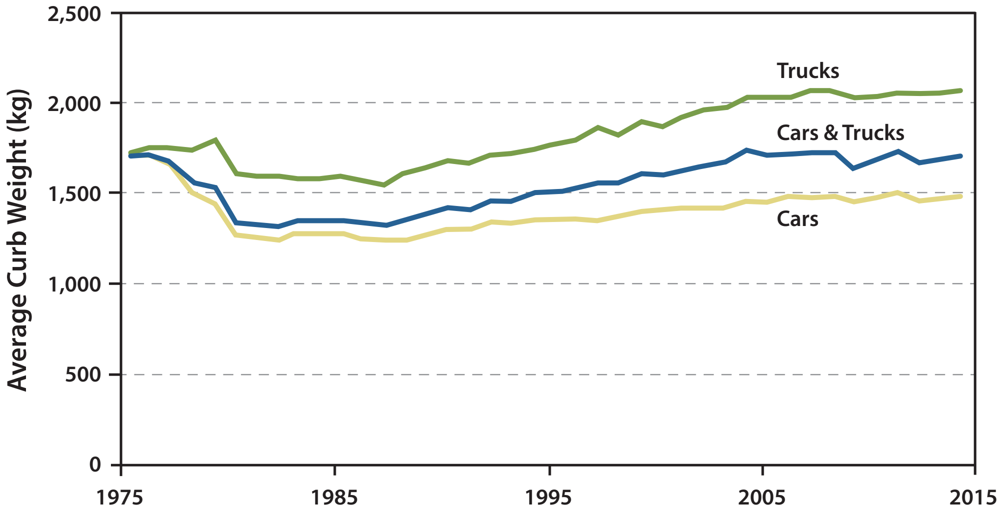

Figure 4.1 Average weight of new cars, new trucks, and cars and trucks combined in the United States from 1975–2010 [EPA, 2014]

In Europe between 2001 and 2008, passenger vehicles averaged 1,380 kg, and no time trend in weight was evident. However, in the United States, the average car weight increased from 1,400 kg (3,080 lbs) to 1,470 kg (3,240 lbs) over this same period, and the average new light-duty vehicle (LDV) (including light-duty trucks as well as cars) increased from 1,620 kg (3,570 lbs) to 1,720 kg (3,790 lbs). It is interesting to note that passenger cars in the United States are only slightly (~5%) heavier than European passenger vehicles. But when light trucks are included, the average U.S. LDV is about 20% heavier than the average LDV in Europe.

In Asia, the contrast with the United States is more pronounced. In China, various estimates have placed the average curb weight of new passenger cars to be between 1,200 kg (2,640 lbs) and 1,300 kg (2,860 lbs) in recent years, which is approximately 10%–20% less than the average new car in the United States (and 20%–30% less than the average new LDV in the United States). In Japan, the average weight of an LDV is approximately 1,200 kg, with cars and light trucks (compact trucks and very small "K-trucks") weighing approximately the same.

4.2 Weights and Sales by Vehicle Class

Increases in average vehicle weight since the mid-1980s have been driven by both shifts from lighter to heavier classes of vehicles, and by weight increases within classes. In 1980, just 16% of the LDVs sold in the United States were trucks, and the overwhelming majority of these were pickup trucks (Figure 4.2). By 2004, trucks comprised over half of all LDVs sold in the United States, with virtually all of the growth coming from (mini-) vans and Sport Utility Vehicles (SUVs). At the same time, small cars represented an ever-shrinking share of the market, while the shares of midsize and large car shares were largely preserved. Coincident with fuel prices beginning to rise in 2004, these trends were reversed in subsequent years. Light trucks fell to below 40% of new LDVs in 2009, with small and midsize cars picking up the slack.

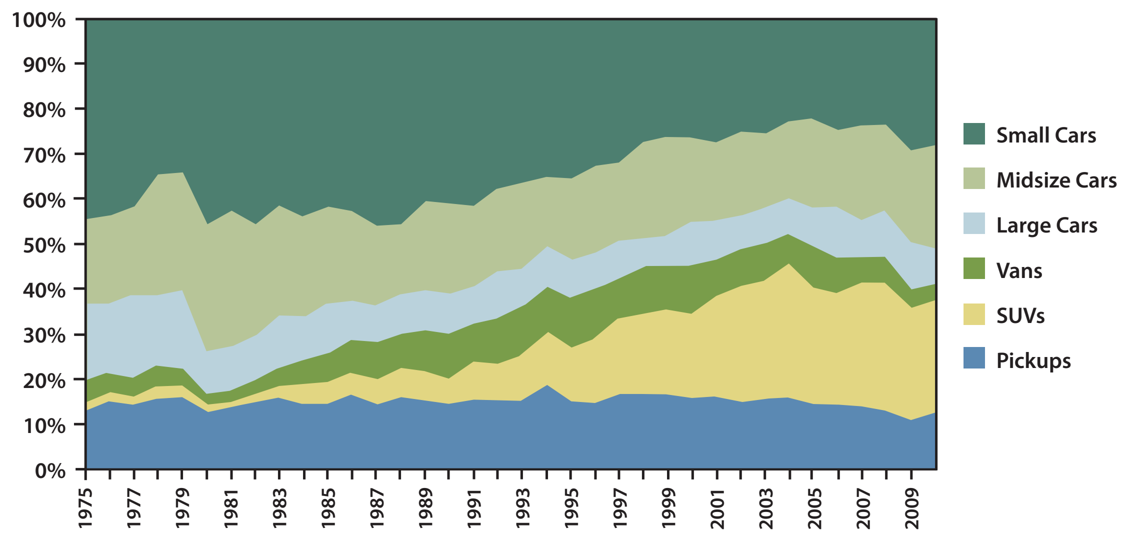

Figure 4.2 Shifting market shares of vehicle types in the United States [EPA, 2014]

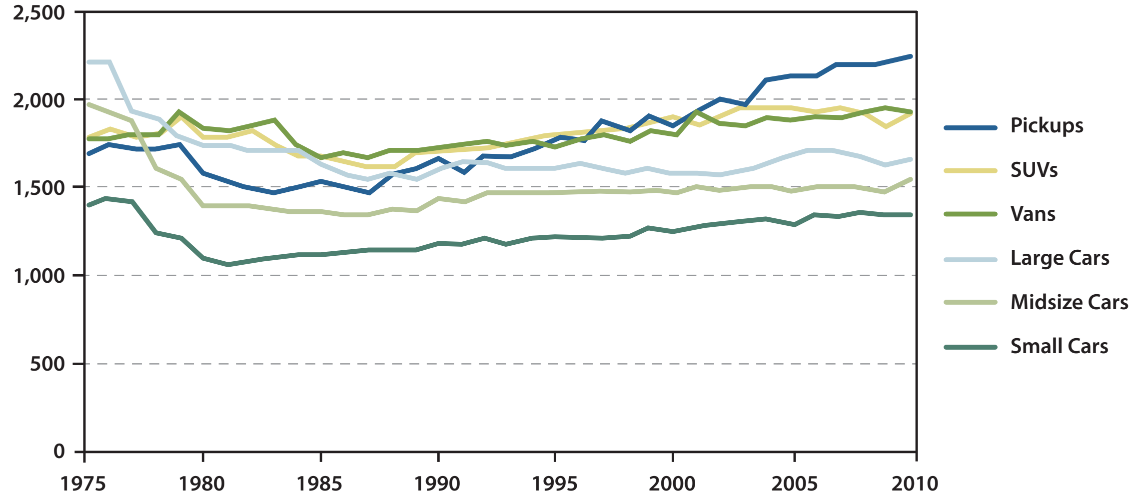

Figure 4.3 Weight differences between different car classes have decreased over time

The weight differences between various vehicle classes (Figure 4.3) are important, but have changed significantly over time. Unsurprisingly, large cars weigh more than midsize cars, which weigh more than small cars. However, these differences have been declining over time. Whereas the average large car outweighed the average small car by more than 800 kg (1,760 lbs) in 1975, this gap had shrunk to a little over 300 kg (660 lbs) by 2010. The weights of vans and SUVs have tracked together since 1975, while the weight of pickup trucks has changed more dramatically. Between 1986 and 2010, the average new van gained 250 kg (550 lbs) and the average new SUV gained 270 kg (590 lbs). Over the same period, the average weight of new pickup trucks increased by 750 kg (1,650 lbs).

4.3 Technologies for Reducing Vehicle Weight

Weight-reducing technologies include a broad range of design and manufacturing techniques, as well as the replacement of traditional materials with lighter and stronger alternatives. Particularly important are major architectural choices in vehicle design including the selection of front-wheel drive versus real-wheel drive, as well as the selection of unitized body (unibody), space frame, or body-on-frame construction. These major architectural changes, and the replacement of conventional steel and iron with lighter materials, are examined here. A broader definition of weight-reducing technologies would also include myriad other advances in engineering, design, and manufacturing practices that permit materials to be used more effectively in building vehicles.

4.3.1 Major Architectural Changes

New cars in the United States underwent significant architectural shifts between 1975 and 1990 that contributed substantially to reductions in weight. In 1975, about half the cars on the market in the United States used unibody construction, and fewer than one in 10 were front-wheel drive. By 1990, 95% used unibody construction and 85% were front-wheel drive [Environmental Protection Agency (EPA), 2012].

4.3.2 Unibody Construction

Unibody construction reduces weight by eliminating the traditional frame and integrating its structural functions into the vehicle's body shell. Data compiled by Audatex North America indicate that the overwhelming majority of cars offered in the United States since 1975 have used either unibody or body-on-frame construction. In addition, a small fraction of cars have used space frame construction, which employs a three-dimensional structure of welded tubes to which non-structural body panels are attached, primarily in low-production, high-performance cars. A few others have used unibody-on-frame construction, incorporating elements of both the unibody and body-on-frame architectures.

Estimates of the weight savings from unibody construction vary widely. Dupnick (1996) suggested a weight difference of more than 450 kg (1,000 lbs) between unibody and body-on-frame cars, whereas a 1970s case study from Ford attributed only 87 kg (192 lbs) of weight reduction to the switch from body-on-frame to unibody [Gutherie, 1978].

The weight savings from replacing body-on-frame with unibody construction can be estimated by creating matched sets of unibody cars and comparable body-on-frame cars, using a Mahalanobis matching algorithm. Size, transmission, drive, and model year data were obtained from a database maintained by the U.S. EPA. Data on construction type by model and year were provided by Audatex North America, and were merged with the EPA database. Matched sets of vehicles were created by matching unibody cars with body-on-frame cars that had the same transmission type and drive type, similar interior volume (within 5 cubic feet or 0.14m^3), and were of similar vintage (within two model years). The difference between these groups indicated that, on average, a unibody car weighs 280 kg (616 lbs) less than a body-on-frame car with the same drive type, transmission type, and size (from the same model year). A similar analysis indicates that the average space frame car weighs 156 kg (344 lbs) less than a comparable unibody car, and that cars using unibody-on-frame construction do not differ significantly in weight from comparable unibody cars. These results are summarized in Table 4.1.

Table 4.1 Estimated weight changes from switching vehicle architectures in cars

Comparison	Applies to	Estimated Difference (kg)	Standard Error (kg)
Construction Type			
Unibody vs. Body-on-Frame	Unibody Cars	-280	5
Space Frame vs. Unibody	Space Frame Cars	-156	19
Unibody-on-Frame vs. Unibody	Unibody-on-Frame Cars	-39	35
Drive Type			
Front-wheel Drive vs. Rear-wheel Drive	Front-wheel Drive Cars	-296	6

4.3.3 Front-wheel Drive

A second major architectural change in cars in the United States is the transition from rear-wheel drive to front-wheel drive. When compared with rear-wheel drive, front-wheel drive yields both a direct weight reduction in the drivetrain, and an indirect weight reduction due to improved packaging of the drivetrain. Eliminating the need for a tunnel running the length of the vehicle increases interior space and permits exterior dimensions and weight to be reduced while maintaining interior volume.

The weight effect of front-wheel drive relative to rear-wheel drive was estimated by matching front-wheel drive vehicles with rear-wheel drive vehicles that had the same transmission type and construction type, similar interior volume (within 5 cubic feet or $0.14m^3$), and were of similar vintage (within two model years). Based on the difference between these groups, a front-wheel drive car weighs an estimated 296 kg (653 lbs) less than a rear-drive vehicle with the same transmission type, construction type, interior volume, and model year.

4.3.4 Engine Size

Engine technology has matured in numerous ways since the 1970s, allowing manufacturers to extract more performance from a given engine mass. Aluminum blocks and cylinder heads have gradually replaced cast iron, and ancillary equipment (such as intake manifolds and accessories) is increasingly made of composite materials. Apart from this shift to lighter materials, however, engines have also just become smaller over time, as significant improvements in power density have enabled the replacement of 6- and 8-cylinder engines with 4- and 6-cylinder engines.

To estimate the weight savings resulting from substituting a smaller engine, vehicle weights were compared between different engine sizes, holding vehicle model, model year, body style, and transmission type constant. There was an average decrease in weight of 64 kg (142 lbs) when decreasing from 8 to 6 cylinders, and an average decrease of 67 kg (147 lbs) when decreasing from 6 to 4 cylinders.

4.3.5 Alternative Materials

Traditional low-carbon steel and iron now make up less than half the weight of a new vehicle in the United States, as they are increasingly displaced by alternatives such as high-strength steel, aluminum, plastics, composites, and magnesium. Since the substitution of alternative materials into a vehicle's design is strongly dependent on the demands of the specific application in question, estimating the amount of weight saved by these materials is difficult. Nevertheless, it is helpful to generate some rough approximations based on the properties of different materials and reports in the literature. Cheah (2010) and Wohlecker et al. (2006) provide relationships for estimating the weight ratios of parts made with alternative materials to those made with conventional materials, in a variety of generic load cases. These provide a useful starting point for estimating the weight-reduction potential of various alternative materials. In addition, a variety of authors have reported rules of thumb and case studies of vehicle designs using alternative materials. Midpoint estimates for the weight-saving potential of key materials are summarized in Table 4.2.

Table 4.2 Approximate weight-saving potentials of key materials

Material	Weight Savings[12]	Weight Reduction Potential[13]
Conventional steel & iron	0%	1.0
High-strength steel	23%	1.3
Aluminum	45%	1.8
Magnesium	60%	2.5
Plastics & composites	50%	2.0

High-strength Steel

Based on rule-of-thumb relationships like those mentioned above and typical values for materials properties, parts made from high-strength steel (HSS) are expected to weigh between 0% and 25% less than a conventional steel part, depending on the application. Salonitis et al. (2009) estimated a 10%–30% weight reduction from using advanced high-strength steels, and Roth et al. (1998) reported an advanced steel unibody weighing 25% less than conventional unibodies. Das, Curlee, and Schexnayder (1997) assumed that high-strength steels could reduce weight by 50% relative to conventional steels, but the rationale for this high value was unclear. A particular challenge in estimating the weight-reduction potential is that there is such a broad range of available grades of HSS, with widely varying properties. When focusing on materials substitutions to date, it can be assumed that each kg of HSS replaced 1.3 kg of conventional steel (a 23% weight reduction).

[12]Fraction of weight saved by replacing conventional steel or iron with alternative material.

[13]Mass of conventional material displaced per unit mass of alternative material used.

Aluminum

Rules of thumb based on generic load cases suggest that substituting aluminum for conventional steel can reduce weight by up to 70%, with a 50% reduction predicted in many applications. The trade press has noted that the greatest concentration of automotive aluminum use is in engines, and that aluminum engine blocks weigh half as much as iron blocks [Murphy, 2006]. Stodolsky et al. (1995) estimated that in engine applications, aluminum reduced cylinder head weight by 50% and block weight by 40%. They also reviewed a number of studies and concluded that substituting aluminum for steel in the body reduces weight by about 40%–47%, even when "the design of the vehicle is not completely optimized for aluminum manufacture." Mayer and Seeds (1994) concluded that a 45% reduction in weight for the body-in-white was possible by substituting aluminum for steel in a BMW 3-series. Das, Curlee, and Schexnayder (1997) assumed that substituting aluminum for steel and cast iron delivers a 45% weight reduction, while Carle and Blount (1999) estimated a 40% reduction in weight relative to steel in automotive body applications. Although generic load cases suggest that replacing steel with aluminum can reduce weight by as much as 70%, most of the (considerable) literature on the topic suggests that a value of around 45% is more reasonable in practical applications.

Magnesium

Magnesium still represents a very small fraction (0.3% in 2009) of automotive materials usage, and fewer estimates of its weight reduction potential have been reported. Based on generic load cases, it is estimated that magnesium can reduce weight by up to 70% compared with conventional steel or iron. Luo (2002) calculated savings as high as 80% for some wrought magnesium alloys. Das, Curlee, and Schexnayder (1997) assumed that substituting magnesium for steel and cast iron would deliver a 67% weight reduction. As a general rule, it is reasonable to assume that each kilogram of magnesium replaced 2.5 kg of conventional steel or iron—which represents a 60% weight reduction.

Plastics and Composites

Estimating the weight-reduction potential of plastics and composites is particularly difficult because of the wide range of materials included in this category. However, some rough calculations with typical ranges of values for materials properties indicate that weight reductions in excess of 80% could be possible, relative to conventional steel or iron. For example, Luo (2002) estimated a weight-reduction potential of 35%–70% for polycarbonate/Acrylonitrile butadiene styrene (ABS) based on generic load cases. Das, Curlee, and Schexnayder (1997) assume a 30%–60% weight reduction from substituting composites for steel. The American Chemistry Council (ACC), 2011 has estimated that each kg of plastics and composites replaces 2–3 kg of other materials (a 50%–67% reduction). A report commissioned by Plastics Europe [Pilz, Schweighofer, and Kletzer, 2005] concluded that each kg of plastic replaces an average of 1.5 kg of heavier material (a 33% reduction in weight), but found reductions of up to 75% in some components. As a general rule of thumb, it is reasonable to assume that each kg of plastic or composite material has displaced 2 kg of traditional steel or iron (a 50% weight reduction).

Carbon fiber composites are a promising technology deserving particular attention. Among the many materials included under the "plastics and composites" umbrella, carbon fiber composites offer some of the greatest potential for weight reduction, and have seen significant progress in recent years. In generic load cases, carbon fiber composites offer weight reductions of up to 80% relative to conventional steel and iron. In practical applications, weight reductions of 60% have been reported by a number of investigators [Das, Curlee, and Schexnayder, 1997; Lovins and Cramer, 2004; Prado, 2007]. For many years, carbon fiber composites were found only in a handful of ultra-premium vehicles, most famously the McLaren F1. More recently, the Corvette Z06 employed carbon fiber components, and now BMW is taking carbon fiber mass-market in its i3 city car. Currently, the picture is changing quickly for carbon fiber but it remains to be seen whether longstanding challenges in manufacturing and cost have finally been overcome.

4.4 Weight Added by New Features

While the use of weight-saving technologies has steadily grown, it has been offset (and at times, more than offset) by increases in the deployment of weight-increasing features and a shift toward heavier (larger) car classes. The widespread addition of new features—including safety, emissions control, and comfort and convenience features—has been one of the most obvious changes to vehicles during the past four decades.

Zoepf (2011) multiplied the weights of various features with their take rates in order to estimate their contributions to the weight of the average new car in the United States. In total, he estimated 109 kg (240 lbs) of feature weight in the average 1975 passenger car. In 2010, this number had grown to 223 kg (62 kg safety, 25 kg emissions, 136 kg comfort/convenience—a total of 491 lbs). These estimates include only the weight of the relevant subsystems, and exclude the contributions of secondary weight, discussed in the following section.

Zoepf's analysis is unable to capture all improvements in vehicle quality. Noise, vibration, and harshness (NVH), for example, have dramatically improved in new vehicles as a result of balance shafts, sound-insulating materials, and active noise cancellation. Other metrics, such as reliability and body rigidity, have also improved. Zoepf only reported on the weight effects of discrete features associated with specific identifiable components.

4.4.1 Secondary Weight Effects

For every unit of weight added to (or removed from) a vehicle, the supporting systems and structures must also grow (or shrink) so that structural integrity, braking, acceleration, and handling performance can be maintained. These indirect weight effects are referred to as secondary weight. The addition or removal of secondary weight may be discontinuous, as in the case of a discrete number of existing engines or transmissions being available for inclusion in a particular vehicle model. Moreover, secondary weight effects may vary depending on the subsystem in which the primary weight reduction occurs. Nevertheless, it is common to estimate secondary weight effects by multiplying a single secondary weight factor by a primary weight change occurring at the component level.

Cheah (2010) reviewed more than 20 published studies of secondary weight and identified estimates ranging from 23%–129%, with a mean value of 79.6%. In this report, secondary weight is assumed to be 80% of the primary weight added or removed. This secondary weight coefficient was applied only to the bottom-up analyses of features and materials, in which the initial estimates of weight change were generated from component-level data. However, the secondary weight multiplier was not applied for mix shifting or architectural changes, since the weight effects of these changes had already been assessed at the whole-vehicle level.

4.4.2 Aggregate Effects

The aggregate weight-reduction effects of more weight-efficient architectures and materials can be estimated from growth in the adoption of those technologies, and the weight-savings effects reported above. Figure 4.4 summarizes the estimated contributions of front-wheel drive, unibody construction, alternative materials, and small engines to weight reductions in the average new car in the United States since 1975. Details of this analysis, including the analytical methodology and data on the growth in various technologies, have been reported elsewhere [MacKenzie, Zoepf, and Heywood, 2014].

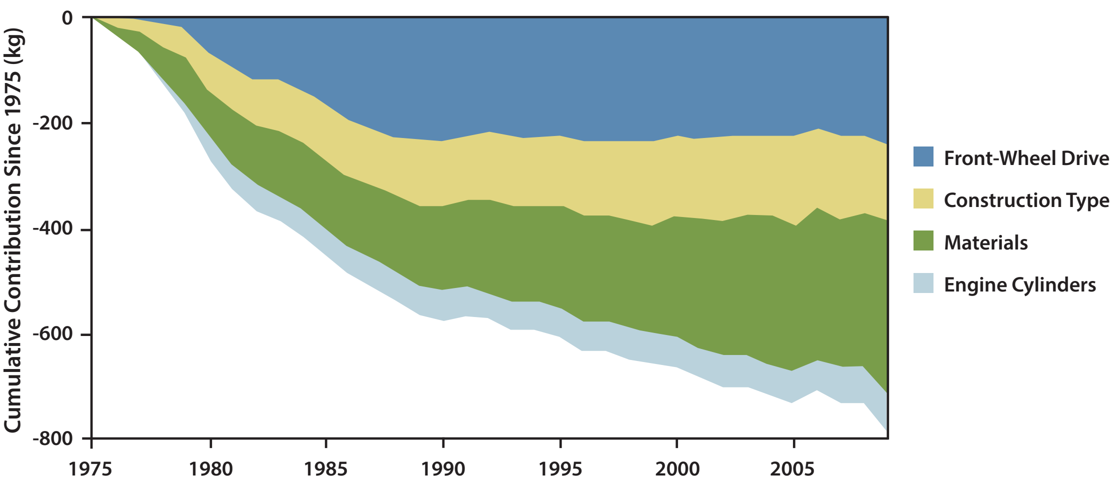

Figure 4.4 Cumulative contributions of major weight-savings technologies since 1975 [MacKenzie, Zoepf, and Heywood, 2014]

Collectively, the growth in the use of unibody construction, front-wheel drive, alternative materials (primarily aluminum and high-strength steel), and smaller engines, has eliminated approximately 750 kg from the average new car since 1975. The overall rate of change has varied over time. Between 1975 and 1982, a sufficient number of new technologies were added to reduce weight by approximately 52 kg per year (115 lbs/year), or about 3% of the average car weight in 1975. Between 1982 and 1990, this figure was about 26 kg per year (57 lbs/year), or about 2% of the average car weight in 1990. From 1990 to 2009, new weight-saving technologies only eliminated about 11 kg per year (24 lbs/year) from the average new car, or roughly 1% of the average car weight in 1990.

Over the same period, sales have shifted from smaller car classes to larger car classes, and more features have been added. Figure 4.5 summarizes the estimated weight increases due to these changes since 1975. The weight increase due to mix shifting was estimated by calculating the average of the 1975 weight in each class, weighted by each year's sales mix. The weight increase due to new features was calculated as in Zoepf (2011), and includes secondary weight effects. Since 1980, new features have added steadily to the weight of the new cars, at an average rate of about 7 kg per year (15 lbs/year).

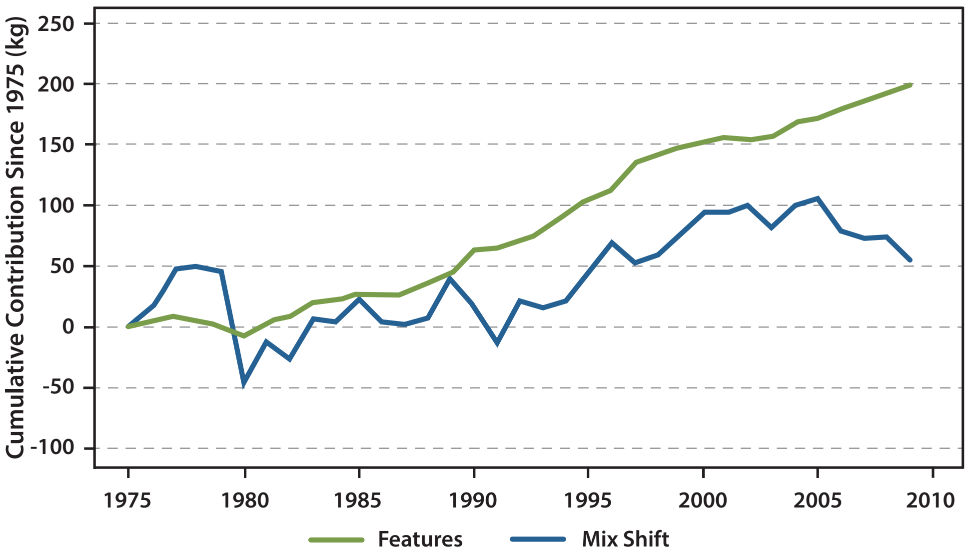

Figure 4.5 Estimated cumulative change in weight of average new LDVs due to the addition of new features and shifts in market shares of size classes. Featured weight estimates include secondary weight effects

4.5 Prospects for Future Vehicle Weight

Automakers in the United States and globally have recently announced plans to reduce vehicle weight by roughly 30–40 kg per year (6–88 lbs/year), or 2%–3% of initial vehicle weight annually in the coming years. For example, Ford has a goal to cut 340 kg (750 lbs) from its vehicles by 2020, and reduced the weight of the F-150 pickup by 320 kg (700 lbs) in its 2014 redesign. Renault and PSA Peugeot Citroen established a goal of cutting 200 kg (440 lbs) by 2018, while Hyundai planned in 2010 to cut its average vehicle weight by 10% [150 kg (330 lbs)] over five years. A recurring source of ambiguity is that it is seldom clear whether numbers like these refer to gross weight reduction (i.e., the weight removed through more advanced technologies) or net weight reduction (i.e., the actual change in the weight of a vehicle, after accounting for the addition of new features and capabilities).

Previous assessments from this group have suggested that plausible targets for weight reduction through materials substitution are on the order of 20% over 25 years, or 30% after accounting for secondary weight savings [Bandivadekar et al., 2008; Cheah, 2010]. This amounts to about 1.2% of base vehicle weight reduced each year, or about 15–25 kg per year (33–55 lbs/year) (depending on the initial weight of the vehicle). Thus, the targets announced by automobile manufacturers appear to be more aggressive than our previous analyses had anticipated. However, the announced goals are within the range of historic rates of weight reduction observed in the 1970s and 1980s.

While historical performance suggests that weight can be reduced quite rapidly through the introduction of new technologies, it is less clear what the ultimate potential is for weight reduction. Some of the technologies available in the 1970s and 1980s—most notably unibody construction and front-wheel drive—are now found on almost all new cars, limiting their potential to deliver further weight reductions. About one-third of new light truck models in the United States still use body-on-frame construction and one-quarter employ rear-wheel drive, so the potential for weight reduction among light trucks may be somewhat greater than among cars (though front-wheel drive and unibody may never be appropriate for heavy-duty towing applications). Additional weight reductions might still be found through greater use of alternative materials and space frame construction, though this is not without challenges. As of 2006, more than half of new engines in North America used aluminum blocks, including 85% of those in cars [Murphy, 2006]. Only 25% of trucks had aluminum blocks, but this share has been growing rapidly. As the market for aluminum engine blocks becomes saturated (as has already happened with aluminum cylinder heads), further materials substitution will shift toward body structures. Conventional steel and iron still comprise about 40% of the weight of new vehicles. If all of this material could be replaced with alternatives that cut component weight by an average of 40%, then weight reductions on the order of 30% might be possible through materials substitutions (accounting for secondary weight effects). If processes can be developed that make space frame construction practical for high-volume models, its universal adoption might reduce average car weight by a further 11%.

Greater replacement of conventional steel and iron with well-developed alternatives, along with a switch to space frame construction, could cut vehicle weight by a maximum of about 35%–40% from current levels. Absent a switch to more radical alternative materials such as carbon fiber composites, or downsizing or de-featuring the vehicle mix, this seems like a plausible upper bound for weight reductions in the United States. If new technologies were added to reduce vehicle weight by 2% annually, this potential would be fully realized in 23 years. Though it is hard to foresee such a path right now, if new technologies could continue to cut weight by 2% annually through 2050, vehicle weight would be reduced by a little more than half relative to today.

In the United States, new features have added about 7 kg per year to new cars since 1980 (including secondary weight effects). To accommodate continued improvements in emissions, safety, and comfort and convenience of vehicles, it is reasonable to assume continued weight increases of up to 7 kg per year. However, it is also possible that the auto industry may shift to a greater emphasis on "virtual performance," a term that refers to a philosophy of shifting design efforts to characteristics that do not add weight or otherwise increase fuel consumption [DeCicco, 2010]. This includes, for example, richer connectivity and media capabilities. If such features—which rely heavily on software—become the main profit center for new automobiles, then the functionality of vehicles could continue to be improved without necessarily increasing weight.

Downsizing the vehicle mix is another way to cut weight. Starting with the mix of new vehicles in 2010 in the United States, consider what would happen if every vehicle could be replaced with one from the next class size down. Suppose that large cars were replaced with midsize cars, midsize cars with small cars, and existing small cars remained the same. Suppose also that this scenario were repeated for SUVs, vans, pickups, and wagons. Based on the average weights of these segments, such a shift in volume would reduce average vehicle weight by approximately 9%. On the contrary, if the opposite shift occurred (small cars were replaced with midsize cars, midsize cars with large cars, etc.), the average weight would increase by about 9%.

Synthesizing the results noted here, it appears to be likely that by 2050, enough new technology will have been adopted to cut vehicle weight by 30%–50% (an average of 1%–2% per year). Assuming that the shares of various car and truck classes remain constant and new features add 4–7 kg per year (9–15 lbs/year) to new vehicles, the average new vehicle in the United States would weigh between 1,000 kg (2,200 lbs) and 1,460 kg (3,220 lbs) in 2050. This would represent a net reduction of somewhere between 13% and 40% from the 2010 average of 1,680 kg (3,700 lbs).

5.0 Fuel Consumption, Performance, and Weight Trade-Offs

Attempts to assess potential improvements in fuel consumption are confounded by simultaneous changes in vehicle acceleration performance, feature content, size, and weight. The prospects for fuel consumption reduction depend not only on what might happen to efficiency technology in the future, but also on assumptions about these other attributes. Further complicating the picture, these other attributes interact with not only fuel consumption, but also with one another. Thus, one key to understanding the prospects for fuel consumption reduction is to understand the trade-offs between various vehicle attributes.

Faster acceleration performance requires more powerful engines, which (*ceteris paribus*) end up being heavier and spending more time operating at inefficient, part-load conditions. These effects mean that all else being equal, vehicles with faster acceleration capabilities tend to consume more fuel per mile than those with slower acceleration capabilities.

Increasing vehicle size increases fuel consumption in several ways. First, greater size increases weight, which increases the amount of energy needed to accelerate the vehicle. Absent any regenerative braking capabilities, this energy is all lost when the brakes are engaged. Second, greater weight means increased rolling friction. Finally, larger vehicles may have a greater frontal area, which increases aerodynamic resistance.

Adding more features to a vehicle can increase fuel consumption in at least two ways as well. First, any feature that includes additional hardware will increase vehicle weight, increasing the energy needed to accelerate the vehicle and to overcome rolling resistance. Second, features that require power to operate will place parasitic loads on the engine, increasing average fuel consumption. In most cases, the former effect is thought to be dominant.

In order to assess the prospects for future fuel consumption, and to better understand historic improvements in efficiency technology, it is useful to quantify the relationships showing the ways that fuel consumption, acceleration performance, size, features, and weight relate to each other. As suggested by the discussion above, however, the variables' interactions are somewhat complicated and nonlinear, making the exact nature of the trade-offs somewhat ambiguous. Estimates of these trade-offs can nevertheless be developed using one of two main approaches.

One approach to characterizing attribute trade-offs is to use vehicle simulation software to model fuel consumption while varying vehicle weight, power, and acceleration performance capabilities, but holding vehicle technology constant. This is the approach employed by Cheah et al. (2009), Shiau et al. (2009), and Whitefoot et al. (2011).

A simplified econometric model based on observed vehicle characteristics offers a tractable alternative approach to estimating attribute trade-offs and technological improvements based on the characteristics of vehicles that have actually been offered in the market. This is the approach taken by Knittel (2011) to characterize the trade-offs between power, weight, and fuel economy. A slightly different approach is to estimate the trade-offs between fuel consumption and weight and acceleration performance (rather than power), controlling for several covariates including engine and transmission type, engine specific power, body style, and all-wheel drive. Doing so yields the trade-off estimates reported in Table 5.1. More complete details of this work can be found in MacKenzie & Heywood (2015).

Table 5.1 Fuel consumption trade-offs associated with changing key attributes of cars, holding efficiency technology and other attributes constant.

Design Change	Fuel Consumption Response
1% increase in inertia weight	+0.69%
1% increase in 0-97 km/h time	- 0.44%
Manual transmission*	-5%
All-wheel drive*	+3%

*Manual transmission and all-wheel drive effects are estimates for 2012, and represent the additional fuel consumption changes beyond those expected from the weight change from a manual transmission or all-wheel drive system. The magnitude of these effects has been declining over time, by about 0.3% per year for manual transmissions and 0.2% per year for all-wheel drive.

The estimates reported in Table 5.1 are broadly consistent with results previously reported in the literature. They indicate that holding acceleration and vehicle technology constant, increasing vehicle weight by 1% will increase fuel consumption by about 0.7%. Cheah (2010) previously reviewed several studies on this topic and found estimates ranging from a 2%–8% increase in fuel consumption for a 10% increase in weight. Her empirical analysis found that for a weight increase of 10%, fuel consumption of cars increases by about 5.6%, though she did not simultaneously control for other vehicle attributes. Finally, Cheah reported a set of vehicle simulation exercises, which yielded a 6.9% increase in fuel consumption for a 10% increase in weight, holding acceleration performance constant.

Several investigations in the early 1990s addressed the trade-offs between weight and acceleration performance and fuel consumption. Among these, typical effects of a 10% reduction in weight were a 3% increase in fuel economy at constant power, or a 6.6% increase in fuel economy at constant acceleration performance. Similarly, they used a value of a 0.44% increase in fuel consumption for a 1% decrease in the 0–97 km/h acceleration time, identical to the results obtained here [OTA, 1991; DeCicco and Ross, 1993; Greene and Fan, 1994].

More recently, a number of authors have used vehicle simulations to explore the trade-offs between fuel consumption and power or acceleration performance. Figure 5.1 illustrates the results of several such exercises for midsize U.S. cars, along with the trade-off reported in this work. The trade-off identified in this chapter is very similar to that reported by Whitefoot et al. (2011). Compared with the results of Cheah et al. (2009), the present work and the findings of Whitefoot et al. imply a smaller fuel consumption penalty for decreasing acceleration time. The substantial variability in the estimated trade-offs between acceleration and fuel consumption point to the importance of vehicle-to-vehicle variation, and the need for caution when generalizing from trade-offs for a single vehicle model to the entire fleet.

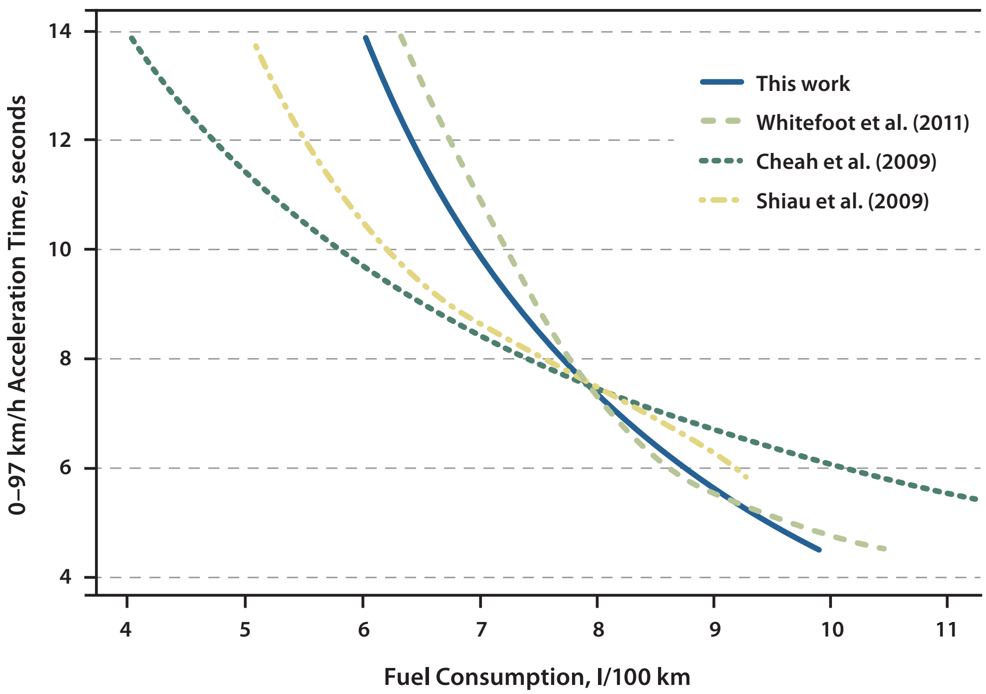

Figure 5.1 Recent results from our group characterizing the trade-off between acceleration performance and fuel consumption, compared with results from other recent investigations.

5.1 Fuel Consumption Potential

As shown in the preceding section, changing the acceleration performance, size, or feature content of a vehicle changes its fuel consumption significantly, even if the efficiency technology used in the vehicle is unchanged. An important corollary of this is that improvements in vehicle technology will not necessarily lead to lower fuel consumption. Instead, technology improvements may be dedicated to offsetting the fuel consumption penalties that would otherwise have resulted from changes in feature content, size, and acceleration capabilities. To get an accurate picture of how much vehicle technology has improved over time, it is necessary to consider not only reductions in fuel consumption, but also any changes in related vehicle attributes over the same period. We use *fuel consumption potential* as such a measure of technology improvement.

Fuel consumption potential is used to characterize how much vehicle efficiency technologies have improved over time. It is simply the change in average fuel consumption that could have been achieved over some period of time, given actual improvements in technology but holding other vehicle attributes (acceleration performance, size, and feature content) at their initial levels. Fuel consumption potential is estimated by adjusting improvements in average fuel consumption to account for changes in acceleration performance, size, and feature content, based on the trade-off coefficients discussed previously.

Figure 5.2 shows the estimated progress in technology for cars manufactured in the United States between 1975 and 2009, expressed as fuel consumption potential. This highlights the vast improvements in fuel consumption potential that have been made since 1975. If acceleration, size, features, and functionality had remained constant, per-mile fuel consumption could have been reduced by approximately 70% between 1975 and 2009. Over the same period, the actual fuel consumption of the average new car was reduced by 50%. More details on this analysis can be found in MacKenzie & Heywood (2015).

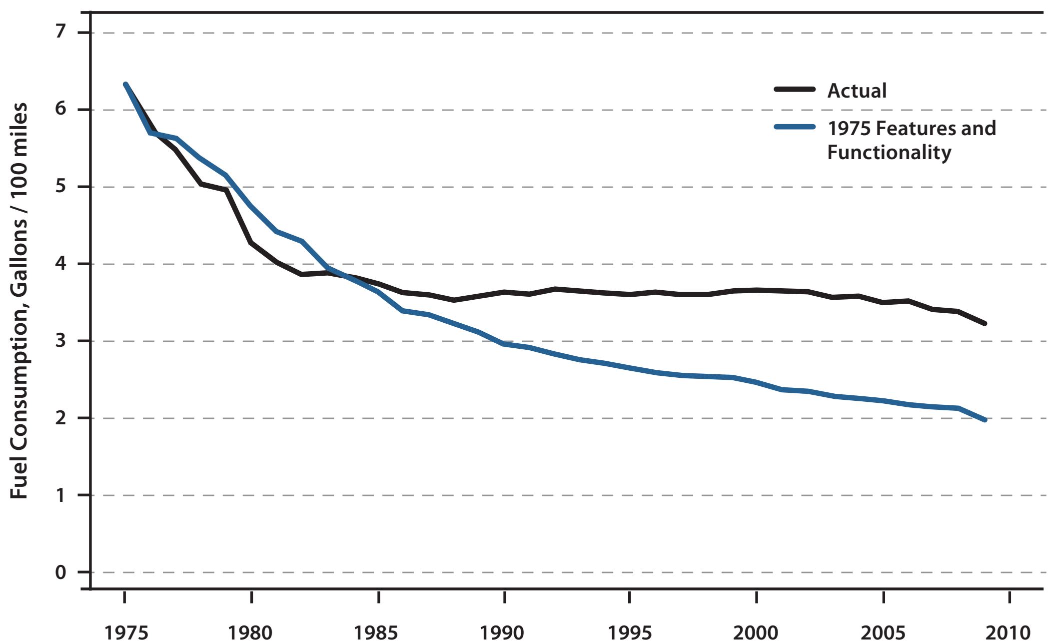

Figure 5.2 Potential reductions in fuel consumption for new U.S. cars since 1975, if acceleration, size, features, and functionality had remained unchanged (blue). Also shown is the actual average fuel consumption of new U.S. cars (black).

While the improvements in technology since 1975, measured by fuel consumption potential, have been impressive, they have not occurred consistently over time. Between 1975 and 1990, the potential reduction in fuel consumption averaged 5% per year. That is to say, per-mile fuel consumption could have been reduced by 5% annually over this period if not for changes in acceleration, features, and functionality of new cars. Between 1990 and 2009, however, the average rate of change was just 2% per year.

5.2 Emphasis on Reducing Fuel Consumption

To enable a more quantitative analysis of the relationship between actual fuel consumption reductions and the technical potential, our research group has developed and previously reported on the concept of Emphasis on Reducing Fuel Consumption (ERFC) [Bandivadekar et al., 2008]. Intuitively, ERFC is simply the ratio of the actual reduction in fuel consumption over some interval to the potential reduction over the same period, if other attributes had remained unchanged. It is calculated as follows:

$$ERFC = \frac{FC_t - FC_0}{FC_t^{potential} - FC_0}$$

In the equation above, FC_0 is the average fuel consumption in the base year, FC_t is the actual average fuel consumption in year t, and $FC_t^{potential}$ is the potential fuel consumption in year t if other vehicle attributes had remained at their base-year levels.[14]

5.2.1 Emphasis on Reducing Fuel Consumption for U.S. Cars

Figure 5.3 summarizes the emphasis on reducing fuel consumption calculated for new cars in the United States between 1975 and 2009. Each bar represents the ERFC over a five-year interval.[15] Also shown are the annual average gasoline prices over the same period. Between 1975 and 1980, ERFC exceeded 100%, indicating that per-mile fuel consumption decreased by more than would have been expected at constant acceleration, features, and functionality. This suggests that there was some pull-back in the levels of other attributes that enabled the larger decrease in fuel consumption. Between 1980 and 1985, ERFC fell to approximately 50%, and fell further in subsequent years, as gasoline prices remained low. Between 1995 and 2000, ERFC was negative, reflecting the fact that the average fuel consumption of new cars actually increased over this period. The emphasis on reducing fuel consumption became positive again between 2000 and 2005, and increased further between 2005 and 2009 when fuel prices were increasing.

[14]In past work [Bandivadekar et al., 2008], our group has defined ERFC as the ratio of the realized fuel consumption reduction to the reduction possible with constant performance and size. In the work reported here, the denominator is instead the potential reduction with constant performance, size, features, and functionality. As a result, ERFC values calculated here will be different (generally lower) and not directly comparable with those we have reported in the past. Although we have refined the details of our methodology over time, the results of all methods have yielded qualitatively similar trends. Moreover, the central point remains that technological improvements can be dedicated to reducing fuel consumption or to offsetting the fuel consumption effects of changes in other vehicle attributes, and ERFC enables quantification of the relative focus on each of these goals.

[15]The last interval is four years, between 2005 and 2009.

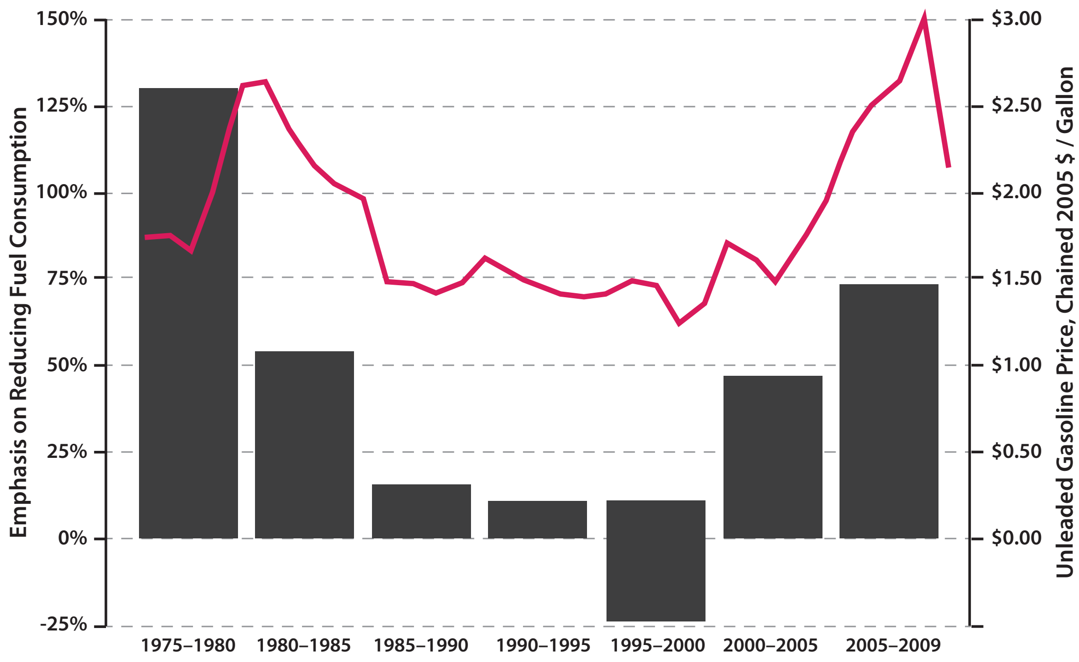

Figure 5.3 Emphasis on reducing fuel consumption over five-year intervals for cars manufactured in the United States, 1975–2009 (black columns). Also shown (red line) are annual-average real gasoline prices.

5.3 Technology Sinks

While the ERFC tells us how much of the technically feasible reductions in fuel consumption were actually realized, it does not tell anything about the other ends to which the technology improvements were applied. However, by applying trade-off coefficients like those reported above to the changes in acceleration and to changes in weight due to size and feature content, it is possible to estimate how much fuel consumption might have been reduced if the changes in the other attributes had not occurred. This can provide an estimate of how much new technology was "consumed" by the need to offset the fuel consumption penalties of these other design changes.

Figure 5.4 summarizes the technology improvements that were needed to offset changes in acceleration, feature content, and size changes in the average new car sold in the United States since 1975. These figures are expressed as the equivalent fuel consumption reductions that could have been achieved if not for the changes in size, feature weight, and acceleration performance. The lower edge of the stacked areas represents the potential fuel consumption reduction that could have been achieved if size, acceleration performance, and feature content had remained unchanged at their 1975 levels. Above this, each wedge represents the potential fuel consumption reduction that could have been achieved if a certain attribute had remained at its 1975 level. (The light green wedge represents the technology that went into actual fuel consumption reductions.)

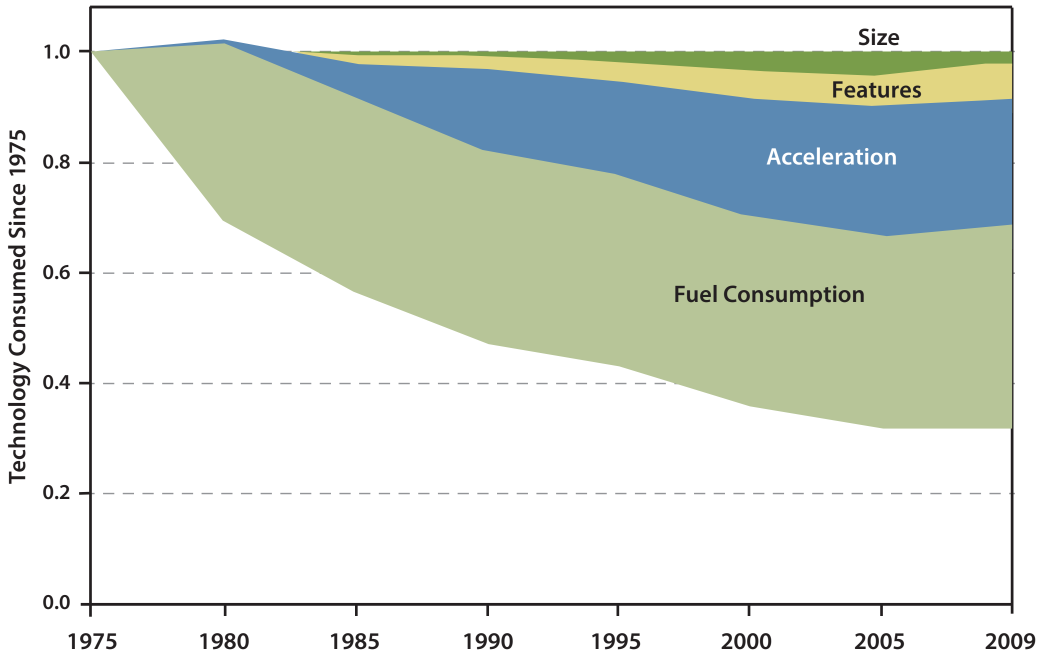

Figure 5.4 "Sinks" for technology improvements in new U.S. cars. Each of the top three bands represents the equivalent improvement in fuel consumption that could have been achieved if not for changes in another vehicle attribute. The light green, lowermost band represents the actual improvement in fuel consumption since 1975. The lower edge of the lower band represents the overall fuel consumption potential since 1975, i.e., the relative fuel consumption if size, feature content, and acceleration performance of the average new car had remained unchanged.

Apart from reductions in fuel consumption, the largest "sink" for efficiency technologies in new U.S. cars has been in offsetting the fuel consumption penalties of faster acceleration. Offsetting faster acceleration has consumed a large and continually growing amount of new efficiency technologies since the 1970s, as shown by the blue wedge in Figure 5.4. Between 1975 and 1990, the average acceleration time decreased by 30%, which "consumed" enough technology to have reduced fuel consumption by 15%. In contrast, shifts in car size and feature content have had little effect on fuel consumption. The dark green wedge shows that at its peak, offsetting the fuel consumption effects of greater size (among cars, but excluding the shift from cars to light trucks) consumed enough technology to have reduced fuel consumption by about 5% or less. Similarly, the ultimate effect of more feature content in new cars has been a single-digit percentage effect on fuel consumption.

Fuel consumption improvements have been the largest sink for new efficiency technologies since 1975. While foregoing acceleration improvements could have reduced fuel consumption by an additional 15% from 1975–1990, fuel consumption actually decreased by 43% over this period. Average fuel consumption changed much less after 1990, but nevertheless still accounted for the largest "sink" for technology changes from 1990–2009.

5.3.1 U.S. Vehicle Acceleration Trends

Recent reappraisals of the relationship among power, weight, and acceleration performance [MacKenzie & Heywood, 2012] indicate that acceleration performance has been improving even more rapidly than is indicated by commonly cited sources such as U.S. EPA's Fuel Economy Trends Report [U.S. EPA, 2012]. The EPA relies on a simple correlation between power/weight ratio and acceleration performance. MacKenzie & Heywood showed that this relationship no longer holds, because of improvements in both vehicle attributes that are widely reported (e.g., transmission type and number of speeds) and in technologies that are not as commonly tracked and reported (such as aerodynamic improvements and driveline efficiency). Between 2006 and 2009, the average acceleration calculated using the EPA's methods was approximately 1 second, or 11%, greater than the average of 8.8 seconds calculated using MacKenzie & Heywood's model. Between 1982 and 2009, the estimated average 0–97 km/h acceleration time of new U.S. vehicles decreased from 16.6 seconds to 8.8 seconds. Over the same period, the average 0–48 km/h acceleration time decreased from 5.5 seconds to 3.2 seconds, and the average 72–105 km/h passing acceleration time fell from 10.9 seconds to 5.6 seconds.

Reductions in 0–97 km/h acceleration times occurred within both high- and low-performance vehicles. Figure 5.5 shows how 0–97 km/h acceleration times have changed since 1978 for the median vehicle as well as for vehicles at the fastest (5th percentile) and slowest (95th percentile) ends of the market.

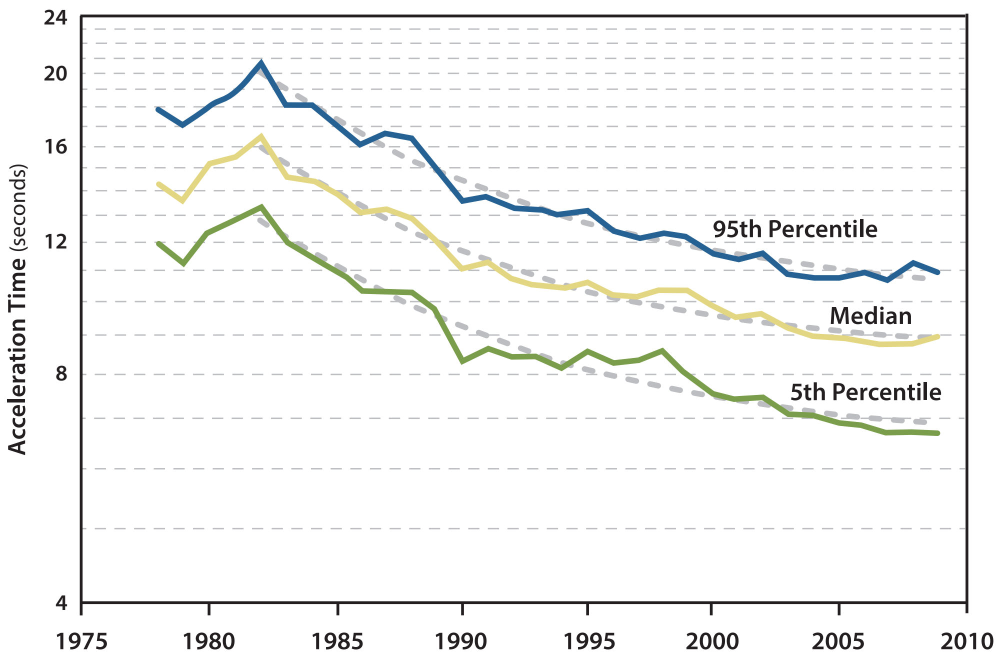

Figure 5.5 Distribution and trends in acceleration performance among new U.S. vehicles.

Two features of Figure 5.5 are especially striking. First, 95% of vehicles sold today achieve a level of acceleration performance that beats the average from 1992, and would have put them in the top 5% in 1985. As an example, consider three venerable sports cars from the mid-1980s: the 1985 Mazda RX-7, Nissan 300ZX, and Toyota Supra. They all had 0–97 km/h times of 11.0 seconds. Three recent "econo-boxes": the 2009 Honda Fit and Toyota Yaris, and the 2008 Nissan Versa, all had 0–97 km/h times between 10.9 and 11.1 seconds. This is virtually identical to the level of acceleration performance seen in sports cars of a generation ago.

Second, the chart shows that although acceleration times have been getting faster, the rate of change has been declining. In fact, the chart appears to suggest that acceleration performance may be asymptoting. A model of exponential decay toward an asymptote captures both the asymptotic acceleration level and the rate of approach toward that level:

$$Z97_t = a \cdot e^{b(t-1980)} + c$$

Parameter c in the equation above represents the estimated asymptotic performance level, while parameter *b* captures the average rate at which acceleration performance has been approaching this level, and parameter *a* is a constant. These parameters were estimated using least-squares estimation for the years 1982–2009, and the curves fitted in this manner for the median, 5th percentile, and 95th percentile performance levels have been added to Figure 5.5. The fitted parameters suggested, firstly, that the rate of decay, *b*, is fairly stable regardless of whether vehicles are high-performance, low-performance, or in the middle of the pack. In addition, the estimated asymptotic performance levels ranged from 6.1 seconds for vehicles in the 5th percentile to 10.1 seconds for vehicles in the 95th percentile. It is interesting to note that even high-performance vehicles are today within 1 second of their estimated asymptotic values. This is, of course, far from proof that reductions in acceleration times are going to stop anytime soon, but it at least suggests that Americans' thirst for power in their cars may in fact be quenchable, and offers guidance for making future projections of acceleration performance levels.

5.4 Prospects for Future Vehicle Characteristics in the United States

5.4.1 Fuel Consumption Potential

Assessments of future potential reductions in fuel consumption benefit from both historical perspectives on what has been achieved, and forward-looking assessments of available technologies.

As discussed in Chapter 4, automakers are currently talking about reducing vehicle weight at a rate of 2%–3% per year in the near term. These sorts of rates were observed in the late 1970s and early 1980s, but were only sustained for a few years. Over the longer term, sustained reductions of 1%–1.5% per year, totaling some 30%–45% weight reduction by 2050, appear more plausible. This weight reduction would lead to fuel consumption reductions of 0.6%–1% per year.

As discussed in Chapter 3, future improvements in aerodynamics and rolling resistance should each be able to deliver a potential fuel consumption reduction of close to 0.2% per year. Incremental powertrain improvements in naturally-aspirated, spark-ignition engines could contribute about 1% per year in potential fuel consumption reductions, while growth in more advanced powertrains, including turbocharged gasoline and hybrid electrics, might contribute an additional one-third to this.

Considering all of the above sources of improvement, our forward-looking assessment suggests that an overall rate of technology improvement of about 2%–2.5% per year is feasible. Comparing this projection with the historic rates of improvement documented in this chapter, we note that it is somewhat higher than the 2% per year measured between 1990 and 2009, but considerably less than the 5% per year observed between 1975 and 1990.

Note that our analysis in Chapter 3 incorporates two key assumptions. First, our estimates of the benefits of technology improvements are based on the average vehicle: i.e., *all vehicles* benefit (on average) from these improvements. Second, not all of the potential opportunities for improving the technology are implemented in practice. We assume that only some 75%–80% of the fuel consumption gains (again, on average) are realized.

5.4.2 Emphasis on Reducing Fuel Consumption

To assess the prospects for future emphasis on reducing fuel consumption in the United States, we can begin by estimating the amount of technology that will be needed just to offset future acceleration performance gains and new feature weight.

If historic trends hold, future increases in performance will be relatively modest compared with what we have seen over the last 30 years. Extrapolating the trends reported in the preceding section suggests that, relative to 2009 levels, 0–97 km/h acceleration times could decline about 5% by 2025, and 6% by 2050. Offsetting this reduction in acceleration time would require technology improvements equivalent to about a 2%–3% reduction in fuel consumption. In other words, technology (expressed as fuel consumption potential) would have to improve by about 0.1% per year to offset future acceleration gains. If we suppose that future acceleration gains were larger, reaching 10% through 2025 and 15% through 2050, offsetting the fuel consumption penalties of these changes would require improvements in technology of about 0.2%–0.3% per year.

As shown in Chapter 4, the average weight of feature content in new cars has increased steadily at about 7 kg/year since the early 1980s. If we assume that this rate continues, then features would add an additional 105 kg to the average car by 2025, and 280 kg by 2050, relative to 2009 levels. This would constitute an increase in inertia weight of 7% by 2025 and 18% by 2050. As reported above, each 1% increase in inertia weight is estimated to increase fuel consumption by 0.7%. This implies that improvements in fuel consumption potential of about 0.3% per year—totalling 5% by 2025 and 12% by 2050—would be required to offset the effects of increased feature content.

It appears that improvements in fuel consumption potential of approximately 0.5% per year would be needed to offset the effects of greater feature weight and faster acceleration, if feature content and acceleration performance continued to follow trends observed over the past 30 years. If overall fuel consumption potential continues to improve at about 2% per year, as it has since 1990, then ERFC values of 75% may result, and fuel consumption would fall by about 1.5% per year. Naturally, if acceleration performance or feature weight changes more slowly, ERFC will be higher, and if they change more quickly, ERFC will be lower. Similarly, if technology improves more quickly than the 2% per year assumed here, and the additional improvements are directed toward fuel consumption reduction, then ERFC would be higher.

5.5 Conclusions

Looking ahead toward 2050, overall rates of technology improvement sufficient to reduce fuel consumption by between 2% and 4% per year (holding size, feature content, and acceleration performance constant) appear to be feasible. The lower end of this range is consistent with the pace of improvements since 1990, and could be realized primarily through continued weight reduction at about 1% per year and incremental improvements in aerodynamics, rolling friction reduction, and conventional gasoline powertrains. The upper end of this range is closer to the rates of improvement that were observed between 1975 and 1990, and improvements at this rate will be required if 2025 Corporate Annual Fuel Economy (CAFE) standards are to be met without sacrificing other vehicle attributes. This rate of improvement could be realized through weight reduction targets announced by various automobile manufacturers, combined with incremental improvements in conventional gasoline engine technology and steady but manageable shifts toward higher-efficiency alternative powertrains.

Reductions in acceleration times have "consumed" more technology improvements than any other vehicle attribute since 1975, except for fuel consumption reduction. Technology needed to offset the fuel consumption penalties of continued reductions in acceleration times will likely amount to 0.1%–0.3% per year, while offsetting the weight of new features may require a further 0.3% per year. Thus, it appears likely that at least 70% of new technology improvements going forward will be dedicated to reducing fuel consumption.

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6.0 Fuels and Energy Pathways Forward

6.1 Scope of Chapter

For over a century, the U.S. transportation sector and petroleum industry have benefited and matured from a mutual dependency. Currently, 71% of the U.S. petroleum consumed each year fuels 94% of the country's transportation sector as jet fuel, diesel, gasoline, and other fuel products. However, growing concerns over geopolitical uncertainties and climate change with continued petroleum use, as well as rapid increases in oil and gasoline prices, have presented new challenges for policy makers, industry stakeholders, and consumers. Questions regarding the sustained use of petroleum have reignited interest in alternative fuels and explorations into non-conventional fuel sources.

This chapter reviews the fuel pathways that have been widely discussed for near-term light-duty vehicle (LDV) applications, including non-conventional fossil fuel sources and alternative fuels such as ethanol, compressed natural gas, and electricity. Specifically, it helps to provide conceptual frameworks for these fuel options, with particular emphasis on the tensions between commercial viability and reducing petroleum consumption and greenhouse gas emissions (GHG). Much of this chapter draws from published reports, including the National Petroleum Council's 2012 Transportation Study [NPC, 2012], National Research Council's 2013 Alternative Vehicles and Fuels Study [NRC, 2013], as well as data from the Energy Information Administration (EIA), Environmental Protection Agency (EPA), Department of Transportation (DOT), and the Office of Energy Efficiency and Renewable Energy (EERE). Section 6.2 describes policy motivations and challenges with alternative fuel development. Sections 6.3 and 6.4 discuss possible directions for fuel development and their implications on fuel compatibility and scalability and stakeholders. Section 6.5 discusses how the various degrees of consumer involvement can align with or complicate policy goals, and Section 6.6 concludes with a summary.

It is important to note that this chapter makes no pretense of completeness on the issues, but attempts to instead present conceptual ways for understanding why there has been a proliferation of options but little consensus on a path moving forward. Shifting to alternative fuels can address energy security and climate change issues, but depends on how they are produced, distributed, and used. All have a range of low-carbon and high-carbon producing pathways, and in some situations, they can increase the separation between national security and supply security dimensions of energy security, making their precise impacts on broader policy issues difficult to assess. Though both energy security and climate change issues share some common ground in potential mitigation strategies, the proposed options often invite challenging trade-offs, raising more fundamental questions to better define and prioritize the objectives and problems.

For purposes of clarity, the fuels and fuel sources are described and differentiated in Table 6.1. The vehicle options described in Chapter 3 are used.

Table 6.1 Fuel Definitions by Chemical Composition and Source

	Chemical Composition	**Fuel Source** (Average Feedstocks 2011)
Gasoline	Liquid hydrocarbon mix C_4 to C_{12}	(estimates in Wang et al., 2012 reference case) 82% Conventional crude oil 13% Canadian tar sands 5% Venezuelan heavy and sour crude
XTLs (hydrocarbon liquids)	Liquid hydrocarbon mix C_4 to C_{12}	Coal (CTL) Natural gas (GTL)
Ethanol	Liquid alcohol CH_3CH_2OH	99.53% Corn 0.47% Other cellulosic biomass
E10/E15/E85	Blends of ethanol and gasoline: E10 = 10% ethanol 90% gasoline E15 = 15% ethanol 85% gasoline E85 = 85% ethanol 15% gasoline	
CNG	Nearly all methane (CH_4)	(estimates are aggregated supply reserves) 57% Conventional and tight natural gas 38% Shale gas 4% Coalbed methane 1% Renewable natural gas (RNG)
Electricity	Elementary charged particles generated by friction, induction, or chemical change	(national average, varies by state) 37% Coal 30% Natural gas 19% Nuclear 12% Renewables 1% Oil and other liquids
Hydrogen Fuel Cell		50% Natural gas 30% Liquid hydrocarbons 18% Coal

6.2 Policy Motivations and Context for Alternative Fuels

While U.S. energy policies have predominantly been implemented in response to supply shocks and have focused on mitigating them, the associated challenges have evolved and grown more complex. Geopolitical uncertainties and petroleum's persistent role as a strategic commodity continue to create political and economic tensions that conflate issues of national security and foreign policy with supply security. Climate change due to GHGs has widespread additional social, political, and economic consequences, which are often measured by its impacts on various indicators such as health, population displacement, resource vulnerability, Gross Domestic Product (GDP) loss, or price volatility with certain products, for example [Foti et al., 2012]. Though some of the uncertainties associated with climate change are aleatoric, many are epistemic, due to a lack of reliable historical data, indeterminacy, or ignorance, which amplifies climate change's costs and makes planning difficult.

Land-based transportation, specifically LDVs, remains the largest user of petroleum and the highest GHG emitters, and has been an appealing area for transformation. In the United States, passenger cars and light-duty trucks represent 76% of the vehicles on the road and consume over half of the petroleum utilized each year as gasoline—in 2011, roughly 370 million gallons of gasoline were consumed in 254 million registered passenger vehicles [FHWA, 2013]. That same year, the United States contributed 19% of global CO_2 emissions, or 6.7 $GtCO_2$, making it the second highest CO_2 emitting country after China. Of these emissions, 33% or 2.2 $GtCO_2$ were related to the transportation sector. Over half came from passenger cars and light-duty trucks, while the remainder was from other modes of transportation, including freight trucks, busses, commercial aircrafts, ships, boats, and trains as well as pipelines and lubricants (Figures 6.1 and 6.2) [EPA, 2013]. When well-to-wheels (WTW) CO_2 emissions are included, which take into account upstream emissions associated with fuel production and distribution, the scope for impact is even greater.

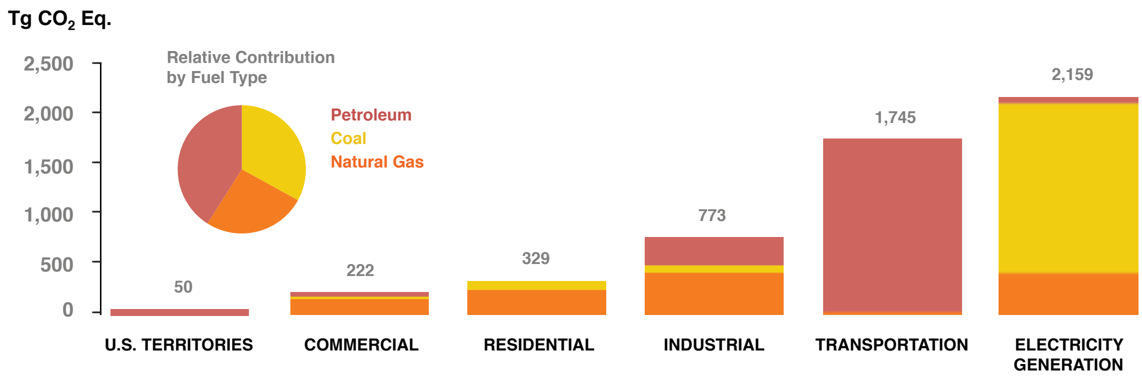

Figure 6.1 EERE (2014) CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

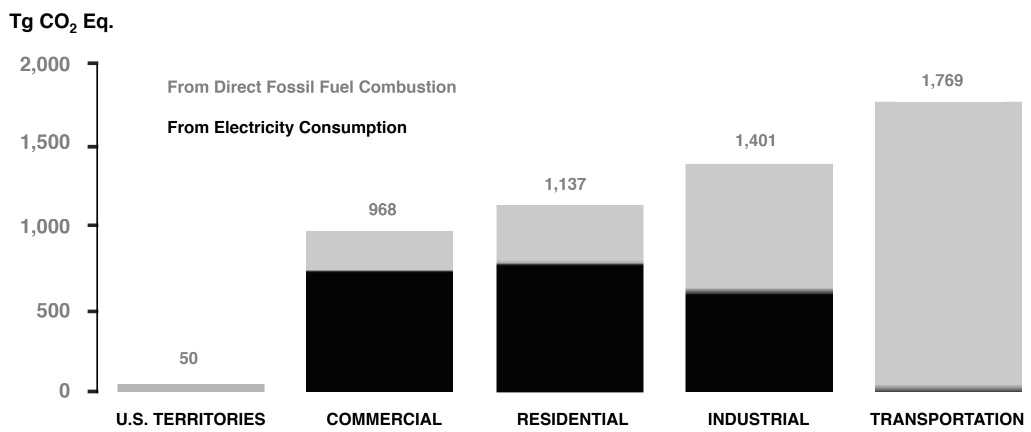

Figure 6.2 2011 End-Use Sector Emissions of CO_2, CH_4, and N_2O from Fossil Fuel Combustion

Source: Inventory of U.S. GHG Emissions and Sinks: 1990–2011 [EPA, 2013].

While altering the LDV and fuel mix may be seen as an appealing opportunity for bringing about these policy goals, the realities of fuel switching or mixing make it a complicated and massive undertaking and a coordination challenge. First, alternative fuels and vehicles would have to demonstrate the ability or potential to produce fewer lifecycle emissions than mainstream options, to be widely available as supply grows, and to mitigate the security dimensions of energy use. Second, they would have to compete with mainstream options and be directly integrated into the transportation system. Either situation would require coordinating new and incumbent stakeholders—fuel supply chain companies, fuel retailers, auto manufacturers, car retailers, and consumers. Introducing new fuels and/or vehicles and making them competitive with incumbent technology on prices and traditional metrics is not only a significant challenge, but also one that grows in difficulty as low demand generates negative reinforcement within the existing system.

Policy approaches to aid in the transition are often broadly thought of either as centralized planning or market-based, both of which have faced criticism as “picking winners” and/or “low-hanging fruit” strategies. Approaches abroad, particularly ethanol in Brazil and compressed natural gas (CNG) in India, have mostly resembled the former, in which both governments aggressively pursued alternative fuel programs to reduce oil dependence and air pollution, respectively, and were able to rapidly integrate alternative fuels into their transportation mix. Many studies are in general agreement that, during their initial periods, these programs were successful in achieving their goals. Since flex fuel cars were introduced in 2003 in Brazil, now virtually all cars sold in that country are flex fuel and comprise over 55% of vehicles on the road, or over 16.5 million vehicles in 2012. Additionally, their sugarcane-ethanol industry has had beneficial spillovers in reducing transportation and some electricity-related emissions by 600 million tons since 1975 and 25.8 million tCO_2eq/year through cogeneration plants [Brazilian Sugarcane Industry Association (UNICA), 2012; EIA, 2012; FAS, 2013; Carvalho, Macedo et al., 2004]. India’s program, which was notably brought about by a different branch of government, namely, through a Supreme Court decision enforcing the government’s constitutional authority to manage environmental pollution, was able to successfully phase out older busses in favor of CNG, which for a time, improved air quality. Both alternative fuel programs have recently run into new complications. As Brazil’s ethanol industry begins its deregulation process, it faces greater demand volatility and more direct competition with gasoline, partly enabled by the flex-fuel vehicle design and tensions with trade agreements. For India, while air particulates are less a concern, new pollutants such as NO_x have returned air quality to its prior state.

While these cases make it easy to dismiss centralized policies as short-term gains and long-term losses, they provide valuable insights into the relationships needed to have the right political structures, policy instruments, and enforcing mechanisms in place. In both of the case studies discussed above, part of their initial success emerged from having an established legal framework that gave certain institutions the authority to manage these issues, as well as avenues through which they could be checked, challenged, and enforced. However, they both struggled in being able to adapt policy standards to new and evolving situations. In the United States, policy can take place or be contested in a number of ways—through legislative, administrative, executive, and judicial avenues, as well as on federal, state, and municipal levels—and often by setting legal precedence. Understanding how these institutional authorities can affect change helps frame the ways in which these sometimes problematic transitional periods might evolve.

Generally, the United States has adopted a mixed strategy toward alternative fuel development, with a preference for economic or financial instruments but also a technology-centric approach. Several key federal legislations have set the tone for their development:

- **to reduce mobile sources of pollutants**

  Clean Air Act of 1970

- **to establish fuel economy standards and incentivize alternative vehicle manufacturing through Corporate Average Fuel Economy (CAFE) credits**

  Energy Policy and Conservation Act in 1975
  Alternative Motor Fuels Act of 1988

- **to directly fund AFV infrastructure**

  Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA)
  Energy Policy Acts of 1992 and 2005

- **to grant tax credits and exemptions for AFV technologies and Renewable Fuel Standards (RFS1 and 2)**

  Energy Independence and Security Act of 2007
  Energy Improvement and Extension Act of 2008
  American Recovery and Reinvestment Act of 2009
  Tax Relief, Unemployment Insurance Reauthorization, and Job Creation Act of 2010
  American Taxpayer Relief Act of 2012

Financial incentives can aid in solving the low demand problem by artificially lowering prices to make the alternative options more economically attractive, but this does not necessarily bring policy demand and transportation demand into alignment. While the general consensus is that raising gasoline taxes—which would actively curb demand-side petroleum consumption and emissions by extension—currently seems politically infeasible in the United States, federal policies like the Renewable Fuel Standards (RFSs) and potential Open Fuel Standard have instead focused on enabling the supply of alternative fuels and vehicles that would reduce petroleum consumption and GHG emissions and help make them more competitive before “letting the market decide.” However, only enabling supply can leave AFVs vulnerable to low and unstable demand, where they are often regarded as voluntary or moral choices, and still subject to traditional price metrics and brand heuristics. Education and marketing can help change public attitudes to internalize these policy motivations, but can be slow-moving strategies.

Understandably, there is no silver bullet approach and policies often have unintended consequences—centralized planning has been criticized for discouraging innovation, governments have an inconsistent record for picking “winners,” and global markets can undermine deregulated domestic programs. However, encouraging alternatives to compete with incumbent technology can mean increasing requests for funding or tax exemptions, as well as the need to develop standardizing metrics to compare all of the options, which can be time consuming. Further, policy incoherence can also be costly and slow down development. For instance, separately, California's zero emissions (ZEV) standard and the federal CAFE standard both incentivize technologies with zero tailpipe emissions, but together they create an accounting loophole that enables the production of less-efficient vehicles through credit trading; double counting provides electric vehicle manufacturers with a surplus of credits that other auto manufacturers can purchase to continue manufacturing vehicles with lower miles per gallon (MPG) while appearing to improve fuel economy on an aggregate level [Knittel, 2014]. Though well intentioned, these policy strategies can be disjointed and sometimes conflicting.

While the effectiveness and economic impacts of these policy instruments have been extensively debated, there still remains the fundamental question of how urgently climate change issues should be addressed. Notably, even though climate change has been receiving more attention recently, the only piece of legislation through which these issues and GHG emissions could be addressed is the Clean Air Act of 1970. Nonetheless, alternative fuels and vehicles have been developed domestically in this political context that focuses on achieving policy goals through cost competitiveness and technological feasibility. The effects of this political context will be discussed in subsequent sections.

6.3 Directions for Fuel Development

As mentioned earlier, alternative fuels and vehicles have to satisfy two broad criteria: to demonstrate an ability or potential to improve energy security or GHGs and to be commercially viable. Given that explorations into alternative fuels have been policy-motivated, possible directions for their development are the following:

1) Improve fuel economy but continue with mainstream options using hydrocarbon fuels and modest fuel blending with ethanol to satisfy oxygenate requirements;

2) Incorporate higher alternative liquid fuel blends to displace and reduce gasoline use;

3) Switch to new fuels and dedicated fuel systems; or

4) Allow for a degree of flexibility in the selection of fuel options.

These directions for fuel development reflect different opinions about technology and infrastructure timing, investment requirements, consumer involvement, and the urgency in addressing energy security and climate change issues. Depending on the ways that policy conditions and markets evolve, they can reflect increasing changes to the system and to the stakeholders. Based on these different directions, Table 6.2 summarizes the currently available fuels, fuel sources, and vehicle options that are competing. (See also Table 6.1.)

Table 6.2 Fuel Directions and Competing Options

	"Status Quo"	Fuel Blending	Fuel Switching	Fuel Flexibility
Competing Fuel Options	Gasoline XTLs E10/E15	Gasoline XTLs E10/E15 E85	Gasoline XTLs E10/E15 E85 CNG Electricity Hydrogen	Gasoline XTLs E10/E15 E85 CNG Electricity Hydrogen
Competing Fuel Source Options	Crude Oil Unconventional oil Natural gas Coal Corn/Biomass	Crude Oil Unconventional oil Natural gas Coal Corn/Biomass	Crude Oil Unconventional oil Natural gas Coal Corn/Biomass Nuclear Other renewables	Crude Oil Unconventional oil Natural gas Coal Corn/Biomass Nuclear Other renewables
Competing Vehicle Options	Conventional Hybrids	Conventional Hybrids Flex-fuel	Conventional Hybrids Flex-fuel NGV BEV Hydrogen Fuel Cell	Conventional Hybrids Flex-fuel NGV BEV Hydrogen Fuel Cell Bi-fuel PHEV

A cursory glance suggests that allowing for fuel switching or flexibility fosters greater competition, and/or diversification, but the implications are not so obvious. Fuel and fuel source variability disproportionately affect different aspects of the transportation system, expanding certain functions while reducing others and shifting the stakeholders involved. Global and regional markets can also be impacted if and where these fuels and vehicles are produced, distributed, or used. Without clearly defined directions or targets for alternative fuel developments, all of these fuel options will have to compete for market share based on their commercial viability. Thus, without having discrete pathways that can be readily compared and evaluated, having this many options creates a confusing redundancy.

In the following two sections, the impact this redundancy can have on fuel compatibility and scalability, stakeholders, and consumers will be discussed.

6.4 Fuel Compatibility and Scalability

Fuel compatibility is often desirable from an economic feasibility standpoint, in that it may minimize requirements for infrastructure and vehicle modification and also have potential financial or political benefits. However, the feasibility argument can be difficult to deconstruct and assess as it involves a set of technical and economic interactions and feedback. In the case of these alternative fuels, ethanol and methane, among others, are common byproducts of several existing processes where the technical ability exists, but the economics strongly influence the upstream decision of which pathway to pursue as well as the scalability of the production of these alternative fuels. Since current vehicle designs have little margin for fuel variability, these proposed alternatives lack downstream compatibility with this LDV end use, whereas other alternatives, like hydrocarbon fuels produced from various feedstocks (synthetic liquid transportation fuels or XTLs), have that compatibility. Scaling up fuel production without also significantly changing vehicle fleets would have inherent advantages over those requiring new vehicle fleets; however, their successful deployment and adoption ultimately depend on their demand.

6.4.1 Current Transportation Fuel Mix and Supporting Infrastructure

Hydrocarbon fuels, mostly derived from petroleum, still hold the largest market share in terms of fuel consumption, and much of the supporting transportation infrastructure facilitates their movement (Figures 6.3 and 6.4). 76% of fuels consumed in 2011 was gasoline, while 5% was ethanol and 0.4% was other alternative fuels. The supporting infrastructure for each of these fuels will be discussed in greater detail below, and for purposes of clarity, gasoline, E10, and XTL hydrocarbon fuels, though they typically support each other as mainstream fuels, will be discussed separately.

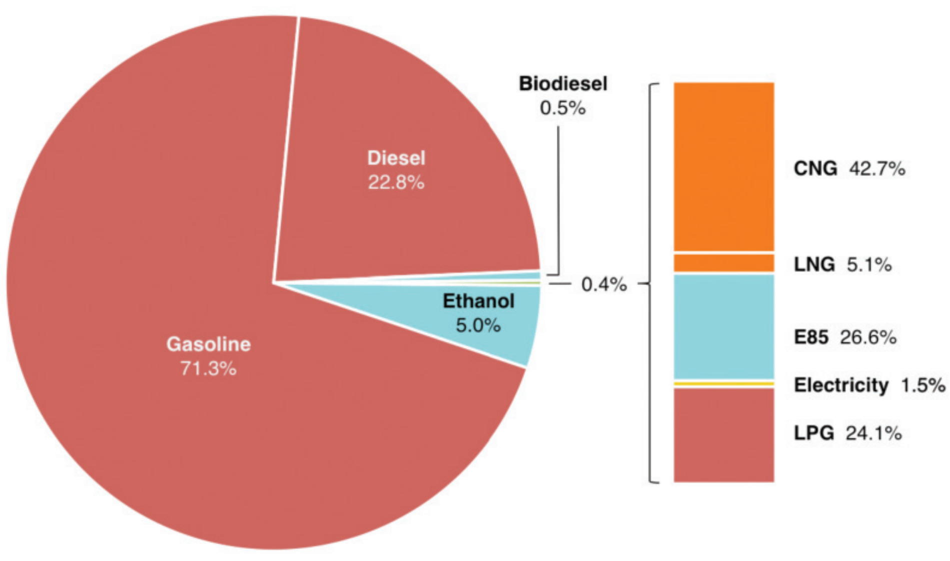

Figure 6.3 2011 Composition of Consumed U.S. Transportation Fuels (gge)

Source: EIA (2014).

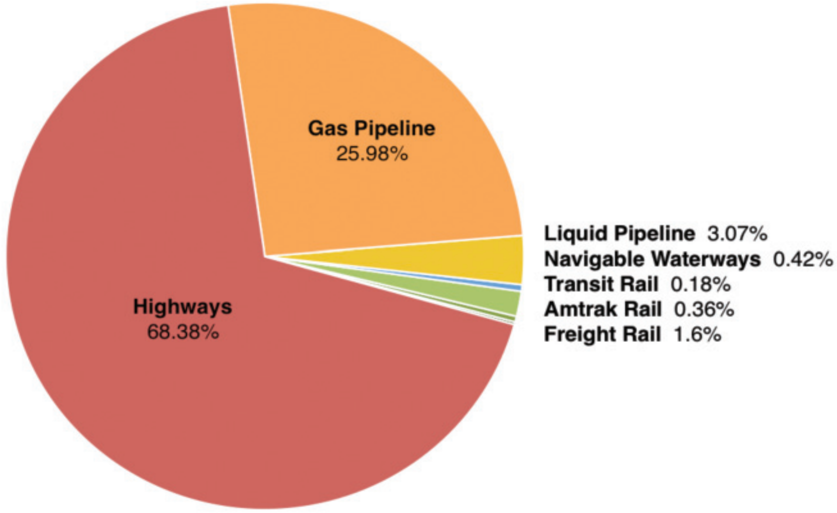

Figure 6.4 Miles of U.S. Transportation Infrastructure

Source: AFDC (2013). Available at http://www.afdc.energy.gov/data/tab/all/data_set/10335

Gasoline

Gasoline production and distribution infrastructure is supported by a complex and coordinated network of oil and gas producers, refineries, pipeline, and railway companies. 97% of gasoline consumed in the United States is domestically refined and distributed by 143 petroleum refineries operating around 90% annual capacity, which produce 134 billion gallons annually or approximately 370 million gallons of gasoline per day. From these refineries, gasoline product is transported through 95,000 miles of refined product pipelines, along 140,000 miles of freight railroad, and/or by local delivery trucks to approximately 160,000 gasoline retail stations concentrated in population dense coastal areas [EIA, 2013]. This infrastructure is often used as a baseline for comparison to large-scale deployment of alternative fuels; though it is not necessarily a requirement, as some of the proposed alternative fuels can utilize other distributed networks for their delivery.

Hydrocarbon Fuels

Apart from their production challenges, liquid hydrocarbon fuels from natural gas, coal, biomass, and potentially other sources, could be considered a perfect fuel substitute for gasoline, as they are chemically indistinguishable and differentiated only by their fuel source. As such, they could integrate seamlessly into existing distribution and storage infrastructure as well as be compatible with conventional vehicles. However, natural gas-to-liquids (GTL), coal-to-liquids (CTL), and biomass-to-liquids (BTL) fuels are complicated to produce and have only been commercially demonstrated outside the United States. Currently, there are five GTL plants operating globally. Shell operates two facilities in Malaysia and one in Qatar, Sasol has one in South Africa as well as a joint-venture with Chevron also in Qatar: one plant is currently under construction in Nigeria, as are two proposed plants in Pennsylvania and Ohio. The large-scale Shell facility in Louisiana was cancelled in December of 2013. Sasol also owns and operates the only CTL plant in the world. Due to market conditions, XTLs are often considered a backstop to supplement petroleum, and waxes and lubricants are typically more profitable manufacturing products for the chemical industry [EIA, 2014]. The five GTL plants have capacities ranging from 2,700 barrels per day (bbl/d) to 140,000 bbl/d, while Sasol has considered expanding its CTL plant's capacity from 160,000 bbl/d to 275,000 bbl/d by 2040 [EIA, 2014].

E10/15

To satisfy an oxygenate requirement to aid in cleaner fuel combustion, gasolines sold in the United States are typically blends with up to 10% ethanol. Prior to ethanol, methyl tertiary butyl ether (MTBE) was the preferred oxygenate until leakages from gas station tanks and groundwater contamination were reported. Ethanol is not only biodegradable and considered less detrimental to groundwater, but also its oxidative properties help improve combustion efficiency, although only to a limit before its corrosive attributes and lower relative energy content create complications for vehicle durability and performance. According to some studies [Greenwire report], even 10% ethanol damages older vehicles, and ethanol's hydrophilic nature can create fuel separation during storage and use, particularly at colder temperatures. However, the EPA still permits E15 use in cars built after 2001, although many auto manufacturers note that their warranties will not cover any damage caused by fueling with E15.

To support 10% ethanol blending—as well as modest amounts of higher ethanol blends—193 biorefineries operating on average at 92% capacity produced 14 billion gallons of ethanol in 2011, mostly from corn, and 67.4 million gallons, or 0.47%, were from other feedstock materials, including brewery/beverage waste, milo/wheat starch, waste sugars, wood waste, cheese whey, potato waste, and sugarcane gallons [EIA, Annual Energy Review, 2011]. Once blended, E10 can be distributed and stored with other gasoline product lines and requires little additional infrastructure. From these refineries, ethanol is delivered to gasoline blending facilities primarily by truck, though in 2008 Kinder Morgan became the first company to transport ethanol through their Central Florida Pipeline from Tampa to Orlando. In 2010, POET and Magellan Midstream Partners proposed the construction of a dedicated ethanol pipeline connecting the Midwest and Northeastern states, but abandoned the project in 2012 due to lack of government financing.

E85

While conventional and modified vehicles are both capable of operating on pure ethanol, its corrosive attributes and lower relative energy content can diminish the vehicles' durability and operation. It is thus restricted to a blending limit of 85% ethanol and 15% gasoline by the EPA. Modifying vehicles to run on higher ethanol blends is estimated to cost an auto manufacturer approximately $100 per vehicle. As many as 10.6 million vehicles on the road are considered flex-fuel vehicles that can operate on blends up to E85. E10 and E85 differ in infrastructure requirements after they are blended, since E85 requires reinforced storage tanks during transport and at retail stations. As U.S. gasoline stations generally have an average of 3.3 tanks, providing

E85 would require an additional tank or converting an existing tank, which can cost on average $71,735 (median $59,153) and $21,031 (median $11,237), respectively [Alternate Fuels Data Center (AFDC) and National Renewable Energy Lab (NREL), 2008]. Currently there are about 2,500 E85 refueling stations in the United States.

CNG

Composed mostly of methane compressed from a pressure of 400 psi to 3,600 psi, CNG can be produced or co-produced from a variety of sources, including shale natural gas, oil, conventional gas, coal (coalbed methane), and renewables (renewable natural gas or RNG), that are typically considered part of the aggregate natural gas supply though they differ in recovery and processing methods. As such, CNG competes with a number of other uses for the natural gas supply, a third of which currently goes to electricity production, another third for industrial purposes, and the remaining for residential heating. Only 3% of natural gas is currently used for transportation-related activities. Nonetheless, due to recent expansions in domestic supplies that have enabled relatively cheap natural gas, as well as its cleaner combustion compared to gasoline, natural gas applications in transportation have experienced modest success in heavy- to medium-duty vehicle applications. As noted in Chapter 3, CNG requires a modified vehicle. It can be used alone, though some vehicles are designed to carry a backup gasoline fueling system and tank. Dual fuel operation, while possible, is still undergoing R&D and has not been commercially demonstrated. The size limitations for these tanks impact vehicle design as well as create trade-offs in performance and fuel economy. CNG may be better suited for larger vehicles with high annual mileage, such as in fleets. With few LDVs available on the market, CNG distribution infrastructure is fairly limited—of the available 1,358 retail stations, 687 are public and 671 are private, though more than half are quick-fill (475 stations, 4–6 min refill) and 125 are time-fill stations (4–6 hours to refill). These stations vary from $400,000 to $1.7 million, for capacities less than 500 standard cubic feet per minute (scfm) to greater than 2,000 scfm, respectively. Home CNG compressing units, which can leverage natural gas's distribution network of 300,000 transmission lines and 2.1 million miles of local utility distribution pipes, are also available for $4,500, although approximately eight hours is required to fill a tank.

Electricity

Electricity production, transmission, and distribution are well established, with 19,023 individual generators and 6,997 operational power plants supplying approximately 4,106 billion kilowatt hours (kWh) of electricity annually. There are approximately 6,719 public vehicle recharging stations, as well as home chargers available, though there are currently fewer than 100,000 plug-in hybrid vehicles (PHEV) and battery electric vehicles (BEV) on the road. While the press has occasionally compared power draw from electric vehicles to be equivalent to a small house, according to the AFDC, the annual energy use of the Chevy Volt would be 2,520 kWh, which is less than that required for a typical water heater or central air-conditioning system. In addition, it could be programmed to draw power only at certain times, thereby shifting the load to off-peak hours. From an emissions standpoint, electric vehicles generally have zero tailpipe emissions, but WTW emissions depend strongly on the local electrical energy supply mix.

6.4.2 Pathways for Expanding Fuel Supply

Based on assumptions regarding current technological timescales and the state of the industry, the NPC and NRC studies estimate that for E85 to supply 10% LDV fuel demand, approximately $40–$56 billion would be needed to build biorefineries. For CNG to displace 30% LDV, $100–$200 billion would be needed for retail infrastructure. For electricity to displace 10% LDV, $16–$42 billion would be needed for recharging stations [NPC, 2012 and NRC, 2013]. This section provides a context for examining the ways in which fuel production and distribution could expand. It is important to keep in mind that building up the alternative fuel supply to help it achieve economies of scale could reduce costs and increase competitiveness, but market forces still determine fuel prices and demand. Market dynamics and its structuring will not be discussed in this report directly.

Gasoline and Hydrocarbon Fuels

Each year, approximately 11.6 million new vehicles are added to the U.S. auto market, of which 99% still operate on hydrocarbon fuels. Satisfying this fuel demand has given rise to increased exploration of "unconventional" crude oil sources as well as aforementioned XTLs, both of which have been environmentally and financially controversial and invited debate over various technical intricacies and sources of uncertainty. Unconventional plays in the United States expand into conventional Texas and Gulf Coast plays (Permian Basin and Eagle Ford), as well as extend into North Dakota (Bakken Formation), Oklahoma (Granite Walsh), Wyoming, and Colorado (Niobrara Formation). As crude oil is easy to transport over long distances, nearby expansions, as with the tar sands from Canada, have also helped to rapidly increase supply. Unconventional crudes have become more of the norm and not the exception, in part because the technical and geological distinctions between conventional and unconventional crudes have somewhat blurred. In some cases, "unconventional" has been used as a catchall term for resources that have poor permeability or characteristics that differ from sandstone and carbonate reservoirs; in others it has referred to where techniques, such as horizontal or vertical fracturing can be implemented. Both conventional and unconventional crude oil sources can require similar drilling and fracturing techniques to extract the crude, but the latter have more variability in site locations, difficulty in extracting the material, and assuring material quality, as well as land and water use. These variations not only present new technological challenges but also can result in higher investment costs, as well as environmental and legal challenges regarding land and water use. Some emissions from explorations into unconventional plays fall within normal ranges, but others expand them.

Unconventional oil plays impact both midstream and downstream operations. Refineries in the United States, which are designed and optimized to run on nearby or readily available crudes, are impacted by changes to crude oil feedstock, both in terms of supply and crude quality, as well as costs for transporting materials [NPC, 2012]. In the past, the highest-capacity petroleum refinery plants, which are located primarily in the Gulf Coast region, had a tendency to process heavier crudes, but now have seen a recent influx of lighter crudes from the Eagle Ford play. Major refiners such as Tesoro, Valero, HollyFrontier, and Marathon Petroleum are now expanding existing refineries in Utah, Texas, and Kansas to process these oil shales. In contrast, other refineries, particularly in Michigan and Illinois, have had to undergo multi-billion-dollar upgrades to process heavier crudes from Canada, where oil-refining capacity has declined and shifted to the United States [EIA, 2013 and CBC, 2011]. In the United States, at least $20 billion has already been invested in similar projects.

Product mix and energy use for these refineries are also impacted by unconventional oil. With conventional crudes, distillation methods typically convert about half the output of a barrel of crude oil into fuel products, while chemical refining via cracking and unification produce the rest, typically dependent on demand. In 2011, nearly half of the crude oil was refined into gasoline, and a little less than half was refined into diesel oil [EIA, 2013]. Figure 6.5 is a simplified schematic of typical crude oil refinery processes, which better shows the relationship between refining methods and preferred products. Heavier crudes generally take more energy to process, have more polluting byproducts, and are more valuable as diesel or other less-refined byproducts, thereby increasing upstream environmental impacts associated with crude oil use.

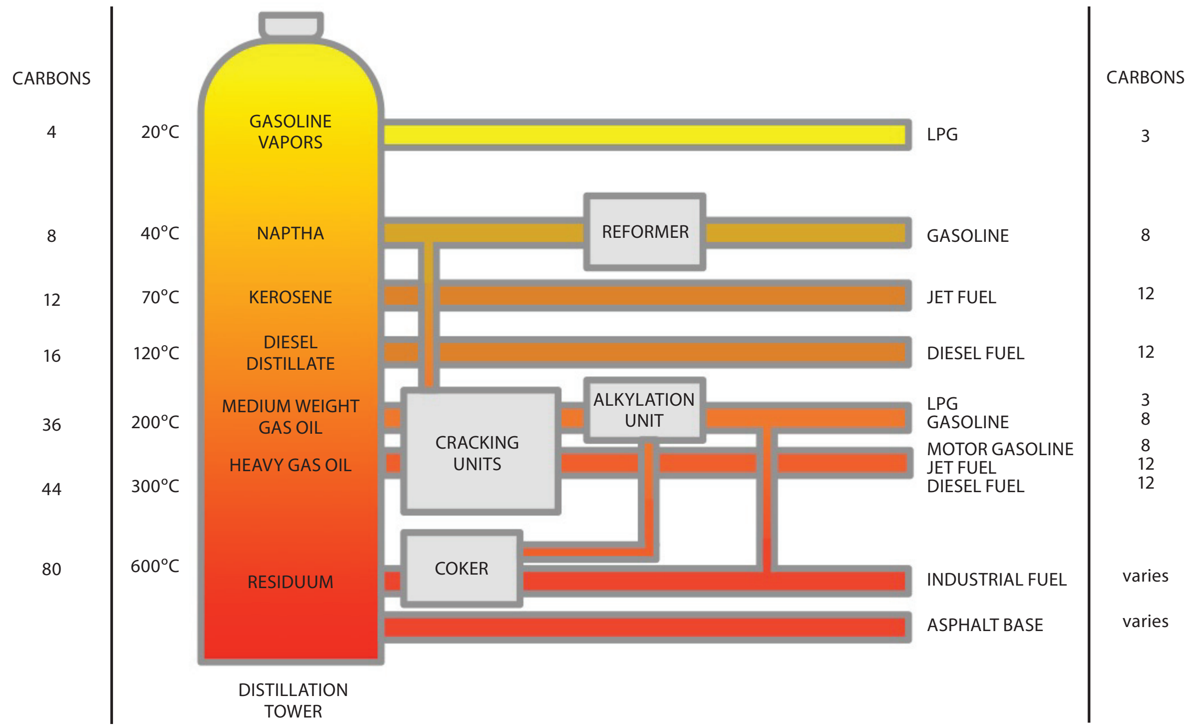

Figure 6.5 Simplified Schematic of Crude Oil Refinery Processes

As mentioned earlier, XTLs typically supplement the petroleum supply by producing similar fuel products from other feedstocks. The two dominant feedstock sources for hydrocarbon fuels are fossil fuels, namely, coal and natural gas, though biomass has been increasingly used. While the refining process itself can be applied to a relatively more heterogeneous feedstock, refineries often specialize in one particular type of feedstock and prefer materials that require fewer purification or treatment steps. This is because the desired intermediate products, hydrogen gas and carbon monoxide gas, or syngas, can be produced from all of the feedstocks through thermochemical conversion, but have different processing requirements, which creates cost trade-offs in energy consumption and material processing. For instance, natural gas and coal typically undergo pyrolysis, while gasification is preferred for biomass. After conversion to syngas, however, all undergo a Fischer-Tropsch (FT) process to be catalytically converted into a broad range of paraffinic hydrocarbons, which can then be converted directly to gasoline or other products. Figure 6.6 illustrates the wide range of products that can be created from syngas.

Product purification and waste disposal can create additional financial and environmental reasons for selecting one conversion method over another. For instance, coal generally requires extra processing to remove sulfur compounds, and likely carbon capture and sequestration (CCS) as it produces more CO_2 emissions than natural gas.

Although XTLs have been produced commercially as early as the 1930s from coal and the 1980s from natural gas, these plants are still considered high-risk investments as they face high capital costs and are very sensitive to changes in coal and natural gas prices [National Academy of Sciences (NAS) and National Renewable Energy Lab (NREL), 2008]. For instance, the

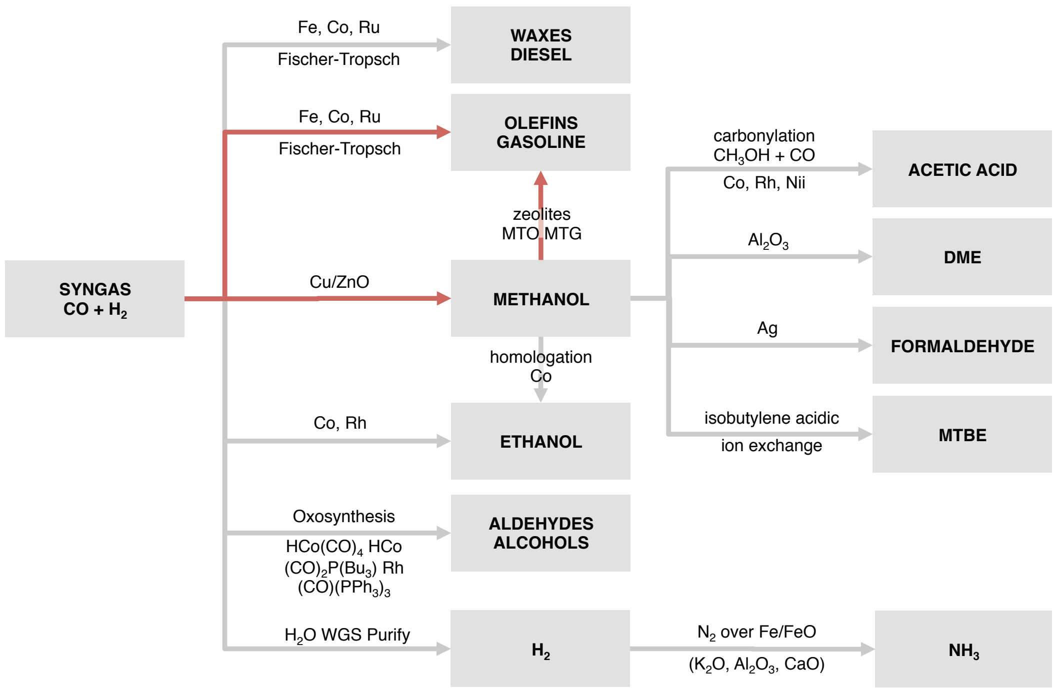

Figure 6.6 Syngas products and pathways

Sasol Oryx plant that was constructed over five years ago at a cost of about $35,000/daily barrel, while the Escravos plant in Nigeria costs $200,000/daily barrel or $8.4 billion for 33,000 barrels per day of GTL product. Shell's Pearl GTL plant in Qatar is expected to cost $18 billion for a production capacity of 140,000 daily barrels of FT fuels and 120,000 daily barrels of natural gas liquids [NPC, 2012, Part II]. Based on NAS and National Energy Technology Laboratory studies, GTL are relatively more economical than CTL or coal-biomass to liquids (CBTL) plants [NPC, 2012, Part II]. The EIA's Annual Energy Outlook [EIA, 2014] notes that producing waxes and lubricating products could help improve the long-term profitability of GTL plants, as they have experienced a steady increase in demand in the chemicals market.

E85

While ethanol production in the United States has been spurred by RFS2 mandates and continues to receive political support, it still faces some supply challenges and E85 blending is partly conditional on aspects of its demand as well as for ethanol. The questions are whether new vehicles will be required to be flex fuel and whether conventional blends will be E10 or E15. Also in question is whether trade barriers with Brazil, which has plans to expand its ethanol industry, will be reduced. Distributing E85 would also require expansion—to support 20 million vehicles, approximately 7,000 more rail tank cars and 20,000 E85 stations would be needed [NRC, 2012]. The total estimated cost for these additions would be \$50–\$70 billion, with 80% of that for biorefinery construction (150 corn ethanol plants, 76 cellulosic biorefineries, and/or 16 biodiesel plants) and the remaining 20% to support the biofuel delivery system. In the United States, corn is likely to remain a dominant feedstock for ethanol production, though RFS2 caps it to 14 billion gallons, and the amounts above that cap can be from cellulosic ethanol—which includes energy crops, as well as forest, agricultural, and municipal wastes (Figure 6.7).

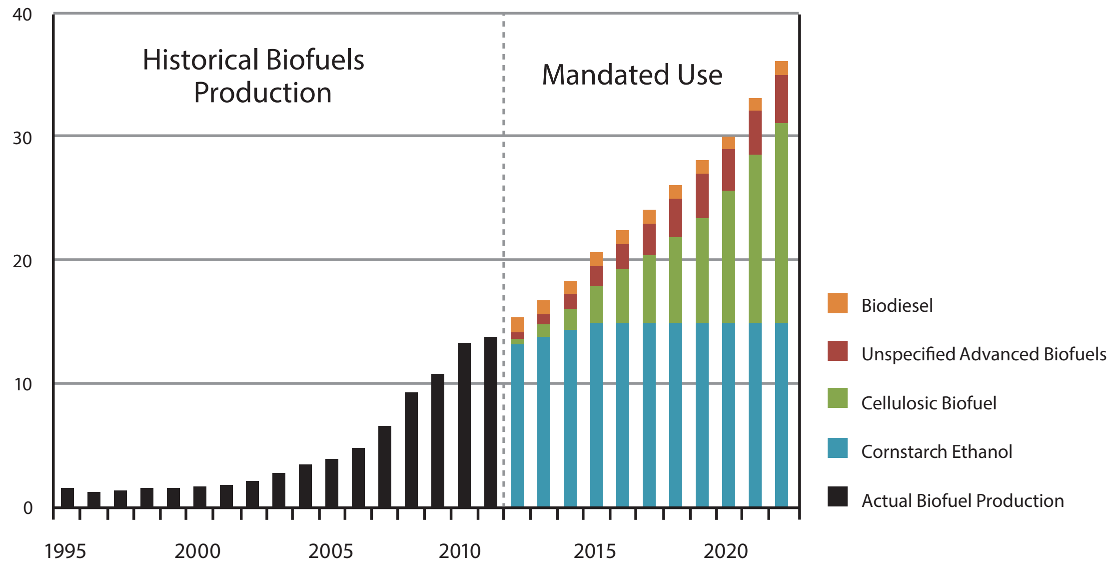

Figure 6.7 RFS2 Mandate and Composition

Source: Congressional Research Service, January 2012. Available at http://nationalaglawcenter.org/wp-content/uploads/assets/crs/R40155.pdf

In terms of expanding ethanol supply, corn and cellulosic biomass feedstocks have different technology requirements and challenges, which can affect how the industry is organized. Despite the initial controversy over energy, water, and land use changes, corn has two distinct technical advantages as a feedstock: 1) it is a reliable, fast-growing, low-cost, and high-yield crop, and 2) its predictable chemical composition and high starch content are ideal for enzymatic or chemical hydrolysis to break it down into sugars, which microorganisms can then ferment into ethanol. These advantages enabled rapid industry growth and concentration in the Midwest. In contrast, the difficulty with using cellulosic materials is in part due to their unpredictable and/or small crop yields, as well as their heterogeneity, which still require more R&D to identify the biological pathways suitable for breaking down specific feedstocks. From an industry standpoint, cellulosic refining expands the geographical area for ethanol production, but its development may be slower. According to the NPC study, there is still considerable room for refining capabilities to improve, though their low density and geographic variability make it uneconomical to transport biomass feedstocks over long distances to centralized production facilities and instead favors feedstock specialization and smaller local economic densification technologies. Explorations into high-yield, perennial energy crops, including miscanthus, as well as forest and agricultural residue recovery, can help reduce some of these challenges with cellulosic materials as well as those associated with corn. It is expected that these explorations will continue while still in the research and development (R&D) phase [U.S. Department of Energy (DOE) Billion-Ton Update, 2011]. Expansion of photo-synthetic cultivation of microalgae, which has been practiced commercially for nutritional products, into fuel applications has also been proposed, though it would require offshore cultivation and different technologies.

Whether from corn or cellulosic, ethanol typically is produced from either a biological pathway involving enzymatic processes, acid hydrolysis, and fermentation or from a thermo-chemical pathway similar to XTLs involving a combination of chemical reactions to create a biocrude that can be gasified and restructured into ethanol. Hybrid approaches have also been used to further speed up the ethanol conversion process. There are advantages and drawbacks to each of these pathways in terms of speed, material efficiency, and energy and water use which are still continuously improving. With the high variability in feedstock materials, and by extension fairly specialized refining requirements, there is still considerable potential for future ethanol development, though its fuel applications depend on a number of other factors.

The net GHG emissions from ethanol production (from these several biomass sources) remain an, as yet, unresolved issue. More recent assessments are indicating that CO_2 emissions for the extensive land use required for planting and growing biomass for fuel production are significant and detract from this alternative fuel option.

CNG

As mentioned earlier, scaling up CNG is more dependent on market conditions, as there are many competing uses for natural gas. While recent developments in expanding domestic natural gas supply have been controversial, the technical barriers with CNG are those generally associated with transporting gases over long distances. Requiring either pressurized tanks for transport as a gas or cryogenic tanks for liquid transport, natural gas's properties affect distribution and vehicle design, as well as impact its market structure which is primarily regional markets that are sensitive to changes in the domestic resource base.

Developments in the natural gas supply base, particularly shale gas, has been the primary motivation for considering expanding natural gas use in the transportation sector, though the most environmentally contested. Renewable natural gas (RNG) has been discussed as an area for growth and development for improving natural gas production's environmental footprint, though its resource base, which can be from biogas sources (landfill gas, agricultural manure) in addition to cellulosic biomass and waste, is estimated to be 4.8 tcf, or 1% U.S. natural gas supplies, and also has competing uses, like ethanol and electricity production. Shale plays, in contrast, are expected to account for nearly two-thirds of gas production growth and will expand total natural gas supply to approximately 2.5 trillion cubic feet (tcf) [AEO, 2011 and IEA, 2013]. U.S. estimates of technically recoverable shale gas are 860 tcf [EIA, 2011—based on 2009 data]. Proven reserves, which are currently 317 tcf shale gas, comprise about a third (132 tcf). However, the cost for drilling wells in the seven major shale plays, located mostly in the Texas-Oklahoma region, the Rockies, and in Pennsylvania, can range from \$4.5 million to \$8.5 million each, where deeper wells are typically more expensive to drill. For example, Marcellus wells are 6,000–6,500 feet deep. Others like Granite Wash in Texas-Oklahoma Panhandle are 11,000–15,000 feet deep and cost \$7.5–\$8 million each. The total expenditure for drilling in 2012 was \$54 billion.

Environmentally, shale gas has additional land-use and water impacts, as hydraulic fracturing techniques involve moving large quantities of highly pressurized water and chemicals that can disrupt nearby infrastructure. It is also difficult to dispose of them safely. These techniques, which are also used for oil plays, are most effective with certain types of formations, particularly those with lower clay content and high in brittle materials such as quartz, feldspar, and carbonates, and tend to be from marine-deposited shales. Non-marine deposited shales, which are higher in clay and more ductile, tend to absorb energy and produce smaller fractures, making extraction techniques like hydraulic fracturing less effective.

Shale gas is similar to other fossil-natural gas and does not require significantly different processing and refining requirements, unlike RNG which in some ways parallels cellulosic ethanol and XTL production, in that it can be produced via purpose-built anaerobic digesters or thermochemical gasification. However, the anaerobic process for methane is entirely different and requires a biological system composed of two basic types of bacteria, one that solubilizes organic solids and ferments them into acids and alcohols, while the other converts the acids and alcohols into methane. It is difficult to keep these processes stable because they require temperature and pH balances favorable to several microbial populations; methane producers are sensitive to changes in their environment whereas acid formers are fairly robust and will continue to thrive in a broad environmental pH and temperature, which can easily unbalance the system. Further, heavy metals, chlorinated compounds, and detergents are highly toxic to both of these organisms, which often means pretreatment is necessary. By comparison, thermochemical conversion can be simpler, but it is often used to treat waste products and fired in cogeneration plants to produce electricity. According to the Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, results show that, despite increased total energy use, both fossil fuel use and GHG emissions decline for most RNG pathways as compared with fossil natural gas and petroleum [Han et al., 2011]. However, GHG emissions for RNG pathways are highly dependent on the specifics of the reference case, as well as on the process energy emissions and methane conversion factors assumed for the RNG pathways. The most critical factors are the share of flared controllable methane and the quantity of methane lost during natural gas extraction, the magnitude of the nitrous oxide lost in the anaerobic digestion process and residue, and the amount of carbon sequestered in anaerobic digestion residue. Though promising, RNG developments are slow and compete with other current processes.

Distributing CNG is one of the major hurdles for direct use of natural gas in transportation, but depends on its high-volume end users. Though roughly 92% of natural gas distribution lines serve residential units, 7% commercial business, and 1% electric power generation customers, in terms of volume, a small number of large-volume users consume more than 60% of the natural gas. As such, the bulk of the $100–$200 billion investment costs associated with CNG would be for retail distribution. Home installation units, while possible, add an additional $4,500 [Pacific Northwest National Laboratory study for DOE, 2010].

Electricity

While electricity has many benefits in terms of its supply security, domestic production and markets, and zero tailpipe emissions that would address many of the issues with petroleum, it still faces a number of legal and regulatory challenges as a transportation fuel in addition to its vehicle technology limitations. Unlike other proposed alternative fuels, these regulatory challenges are more fundamental. For instance, questions include who—the public, utilities, or EV users—builds and pays for charging infrastructure and how should prices for residences and central stations be regulated and who regulates them. Further, if electric vehicles are allowed to be used as distributed electricity storage devices that can be charged or discharged back into the grid, vehicle owner compensation and vehicle maintenance could become areas in need of policy and regulation. Though these challenges are not insurmountable, they will likely involve municipalities, state public utility commissions, and the federal government, which could lengthen the process of integrating them into the transportation system.

From an environmental standpoint, electric vehicles improve emissions, but as a sector, electricity production contributes 33% of GHG emissions, a large fraction of which are produced by coal-fired power plants. While this may improve as natural gas plants displace coal-fired plants, this would be an important area for reform. Currently 90% of U.S. coal consumption is used for electricity production, which translates to 20.8 quadrillion British Thermal Units (Btu) of coal. [EIA, 2014]. The EIA forecasts that the U.S. coal-fired generating fleet will likely decline from 317 gigawatts in 2010 to 278 gigawatts in 2040, with overall improving utilization rates. Figures 6.8 and 6.9 show the current electricity generation mix by state as well as by plant.

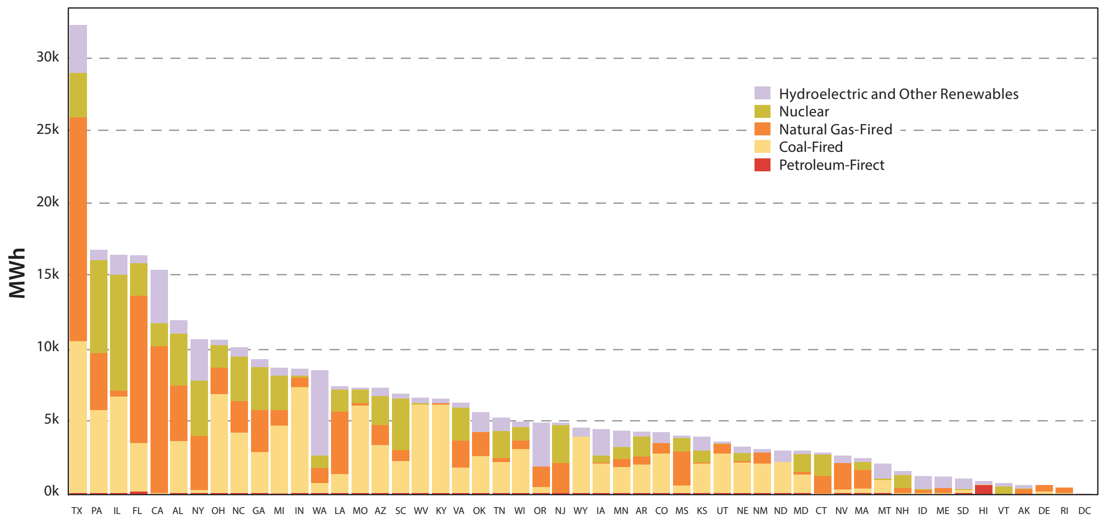

Figure 6.8 Electricity Production and Mix by State

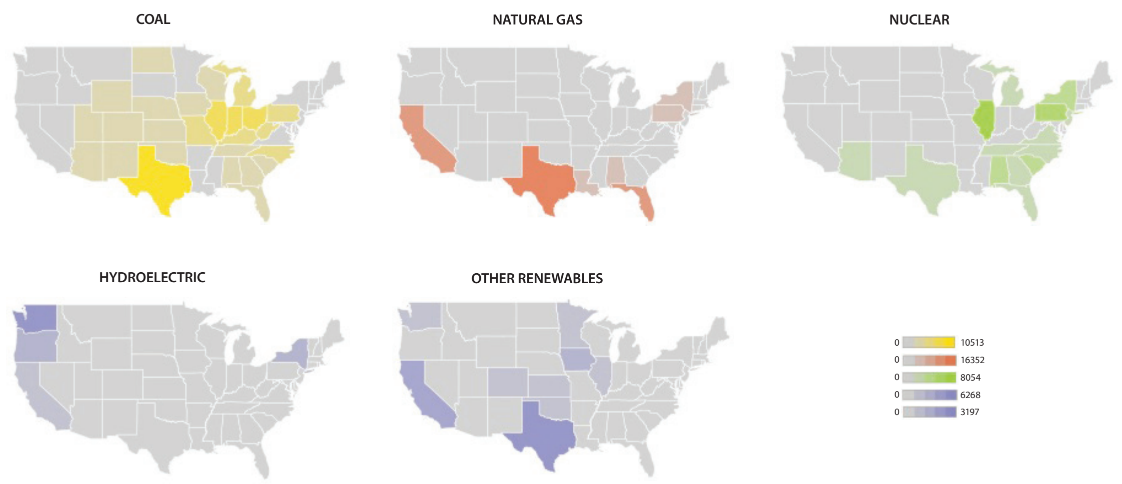

Figure 6.9 Electricity Production by Plant

6.4.3 Impacts of Alternative Fuel Development on Industry Stakeholders and Organization

As noted earlier, the transportation sector is a complex and highly interconnected system involving many stakeholders. Alternative fuel developments, through complementarities with other related energy systems and demands on shared feedstocks, can be disruptive. Collectively, their growth could help expand their respective industries, introducing new technologies and products, but the pressure they place on resources could also tighten them, causing fluctuations in the interim that increase overall market uncertainty and affect parts of the fuel supply chain differently.

The process and prospect for scaling up alternative fuels, as discussed in the earlier sections, have enabled a number of potential new technologies, some biological approaches and others thermochemical, some of which rely on favorable market conditions to succeed. While there are some basic similarities between them, such as the gasification-based system, when applied to producing XTLs, ethanol, methane, or electricity, the fuel pathways individually often become highly specialized and can be difficult to compare or standardize. Interestingly, fuels produced from cellulosic and waste materials, in particular, seemed on a broad level to consistently improve GHG emissions, but also had the most variable specialized pathways due to the nature of these materials. The effects of which, on an industry level, have created surprising shifts in ownership (particularly true for ethanol).

Facing more competition from other industries and increasing market uncertainty, the ethanol industry experienced more industry integration and shifts in ownership. A 2010 report produced by Cardno Entrix for DOE [Urbanchuk, 2010] describes the ethanol industry as still relatively un-concentrated, but notes that the third-largest ethanol producer is a gasoline refiner and marketer—Valero, while Flint Hills Resources, the tenth largest producer, is a subsidiary of Koch Industries, Inc., one of the largest private companies in the world. While local farmer ownership has been a hallmark of the U.S. ethanol industry, ownership of ethanol production has changed. By 1991, the majority of ethanol plants and production were corporate owned and operated, and farmer-owned cooperatives accounted for only a small share of ownership and production. In 2005, with the Energy Policy Act, there was a return to farmer ownership, in which nearly half of all ethanol plants were owned and operated by farmer cooperatives or limited liability companies (LLC), which accounted for 38% of total ethanol production. In recent years, this share of ownership has declined again, due to a substantial influx of non-farmer venture capital into the ethanol market, as well as by the outright acquisition or majority ownership stake of farmer-owned cooperative ethanol plants by POET. While ethanol became more integrated, other fuel exploration and production companies became more diversified. As more large oil and gas companies have invested in various biofuel technologies as well as wind and solar projects, the fuel and energy industries have become more tightly connected.

While the direct consequences of these industries becoming more tightly connected as more of their products begin to overlap are unclear, they could be used as insightful case studies on industrial organization and stakeholder development to better understand the potentially political aspects of policy making. At a state level, for instance, where the primary feedstocks for these fuels are produced, a compelling case for aid in growing that particular industry could be made, regardless of whether its eventual application is for domestic or exported transportation fuels or as an input in the industrial sector (Figure 6.10).

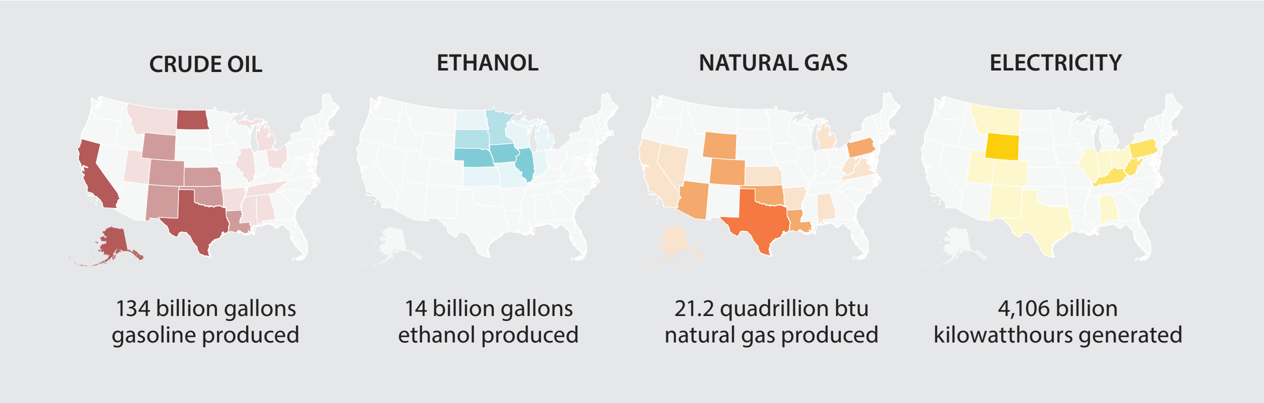

Figure 6.10 Geographical Regions for Fuel Feedstock Production

In terms of integrating alternative fuels into the transportation mix, bottlenecks resulting from fluctuations in the production volume of these fuels have occurred in some midstream activities, but mostly by downstream activities. For midstream activities, pipelines—which are still one of the more efficient ways of delivering liquid products—can be highly contentious as shown by the Keystone Pipeline, or particularly vulnerable as indicated by cancelled ethanol pipeline projects. For downstream activities, fuel retailers are often reluctant to invest in alternative fuel tanks as they are expensive and they face unstable demand. With CNG and electricity, they would also have to compete with companies that provide home refueling or other localized options. This combination leads to insufficient demand from end users and can create negative reinforcement within the system. This will not necessarily halt fuel production, but possibly will slow down the necessary distributional infrastructure for fuel use.

6.5 Consumer Involvement and Policy Impacts on Alternative Fuel Demand

In situations in which financial policy instruments are used without coherent policy directions, consumers and policy makers can be two competing sources of demand. The degree to which consumers are involved in selecting from a variety of fuel and vehicle options, if at all, impacts not only their market potential but also their potential to address policy goals or targets. Some of the fuel options do not necessarily require consumer choice, namely, hydrocarbon fuels and E10/15, while others, namely, E85, CNG, and electricity, require varying levels of commitment to change. Depending on whether these fuels are intended for commercial or personal vehicles can also alter their infrastructure and vehicle manufacturing requirements as well as the timescales at which they are deployed. With low adoption rates, many are considered high-risk investments, which could be temporarily assuaged with financial incentives, but does not necessarily address the underlying issue that, without meaningful choices, consumers are left with a proliferation of options. This section conceptually explores the possibility where consumers are left to decide.

6.5.1 Consumer Alternative Fuel Demand within Traditional Market Segmentation

A number of case studies and consumer choice models that have attempted to characterize demand identify average payback and fuel savings as some of the key drivers for new vehicle purchasing decisions. However, as many of the alternative fuels and vehicles have not yet reached economies of scale in their production, they are not yet price-competitive with mainstream options, which creates greater price variation within some of the traditional ways vehicle markets can be segmented. Table 6.3 summarizes the cost premiums by vehicle model and fuel prices. Figure 6.11 shows how they relate and compare to mainstream vehicles. While cost premiums for each fuel are similar across model types, alternative fuels add more variation in the prices for each vehicle size.

Table 6.3 Summary of Alternative Vehicles by Cost Premiums ($)

Vehicle	Cost Premium	Models	Fuel Price (2014)
Ethanol Flex	+0.1k	all models	E85 $3.04/gal
Hybrid	+3.3–4.2k	all models except small pickup, large van	Gasoline $3.34/gal
CNG/LNG Bi-fuel	+6.1–7.5k	compact car, large cars; large pickup, large van	CNG $2.09/gge
CNG/LNG	+7.5–8.3k	compact car, large cars; large pickup, large van	
PHEV 40	+17k	compact car	Electricity $0.12/kWh
100 mile BEV	+15k, +21k	compact car, small utility	
200 mile BEV	+67.6k	2 seater car	

Source: Data from EIA (2014), available at http://www.eia.gov/oiaf/aeo/tablebrowser/#release=AEO2013&subject=0-AEO2013&table=48-AEO2013&region=1-0&cases=ref2013-d102312a. AFDC 2014, available at http://www.afdc.energy.gov/fuels/prices.html

Incorporating fuel prices, driving patterns, and vehicle fuel economy to determine payback periods, intuitively it becomes clear that to compete, alternative fuels and vehicles may have to cast traditional metrics in a different way, for instance, redefining fuel reliability and accessibility as well as vehicle functions. Depending on the fuel, this could also lessen the pressure on distribution infrastructure. The next section describes some ways this could occur.

6.5.2 Opportunities for Market Differentiation

When strictly comparing conventional vehicles to alternative vehicles, it is not a surprise that conventional vehicles have a clear price advantage over alternatives and that certain alternative vehicle designs gravitate toward certain sizes—for instance CNG vehicles are typically larger cars, in which the compromises with storage space become less problematic, and PHEVs and BEVs are smaller vehicles due to battery limitations. While this makes practical sense, it could also be leveraged in terms of vehicle function. Based on typical vehicle sales, which are summarized in Table 6.4, midsize cars and utilities represent the highest percentage of vehicles sold, followed by compact cars, which could be complementary for CNG and electric vehicles, respectively.

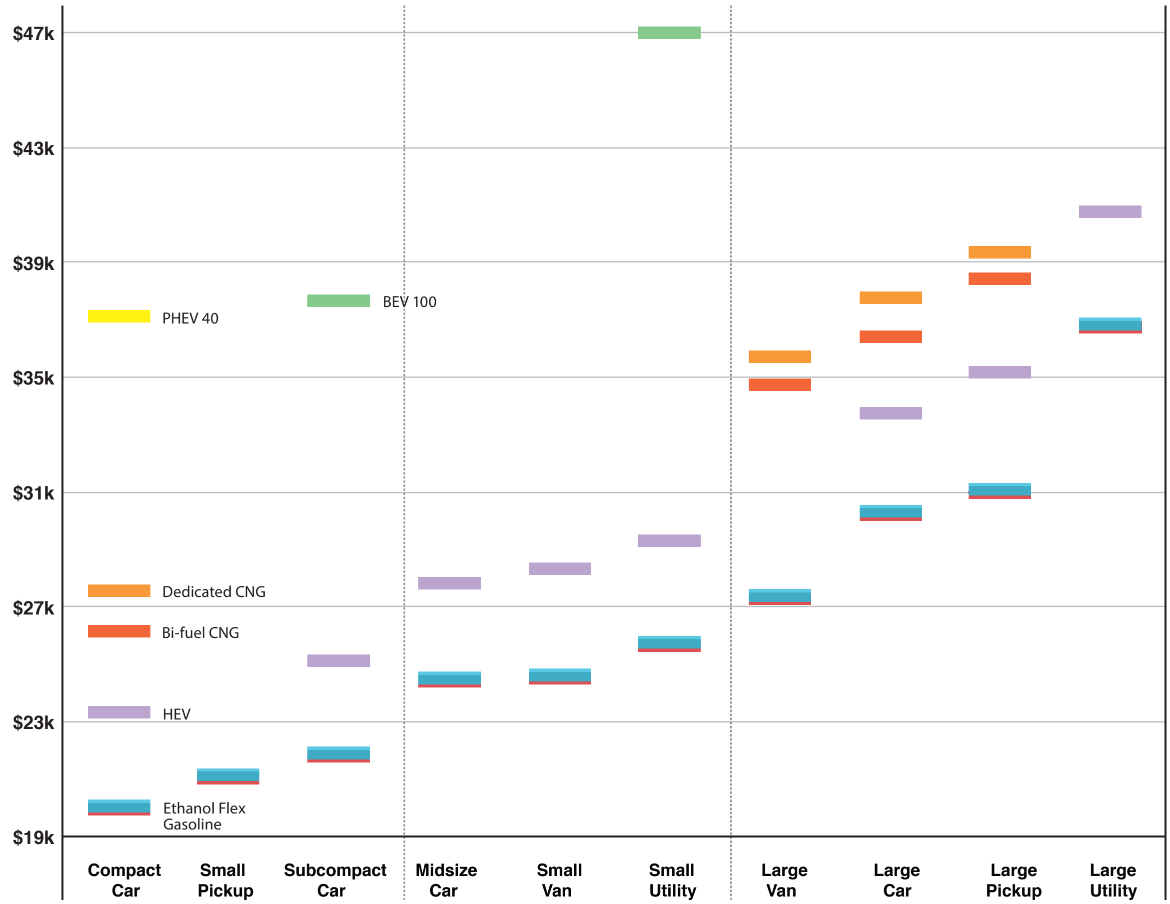

Figure 6.11 EIA Baseline Reference Case of New Light-Duty Vehicle Prices in Thousand 2011 Dollars (2013)

Source: Data from EIA (2014), available at http://www.eia.gov/oiaf/aeo/tablebrowser/#release=AEO2013&subject=0-AEO2013&table=48-AEO2013&region=1-0&cases=ref2013-d102312a

Notably, some of the vehicle models do not follow this trend, which could be explained by the effects of alternative fuel vehicle credits in CAFE standards, in which provisions for electric vehicles for model years 2012 and beyond have been more favorable. When flex fuel vehicles had experienced a similar situation, they were built to strategically improve overall fuel economy, while enabling continued production of vehicles with lower MPG.

Table 6.4 New Vehicle Models Sold by Type

Conventional Cars	
Midsize	41.50%
Compact	35.39%
Subcompact	11.06%
Large	10.63%
Minicompact	0.83%
Two Seater	0.58%

Trucks	
Small Utility	39.75%
Large Utility	23.17%
Large Pickup	22.96%
Large Van	8.68%
Small Pickup	4.52%
Small Van	0.92%

If vehicle type and new vehicle shares are used to rearrange the earlier figure, Figure 6.12 emerges.

While Figure 6.12 makes these vehicle options seem more confusing, redefining ways vehicles are used could potentially reduce the impact of cost premiums on new vehicle purchasing decisions. Notably, consumers who are highly sensitive to price may continue to purchase the lowest-cost vehicle or a used vehicle, which is not reflected in this figure. Other consumers, who are less concerned with prices, may instead regard the cost premium as a convenience premium or lifestyle choice consistent with brand heuristics. In this regard, electric vehicles with home refueling options and large cargo space could be convenient for urban settings and sold as luxury vehicles. SUVs and pickup trucks, which are typically more rugged vehicles and may have higher mileage, could leverage fuel savings from CNG.

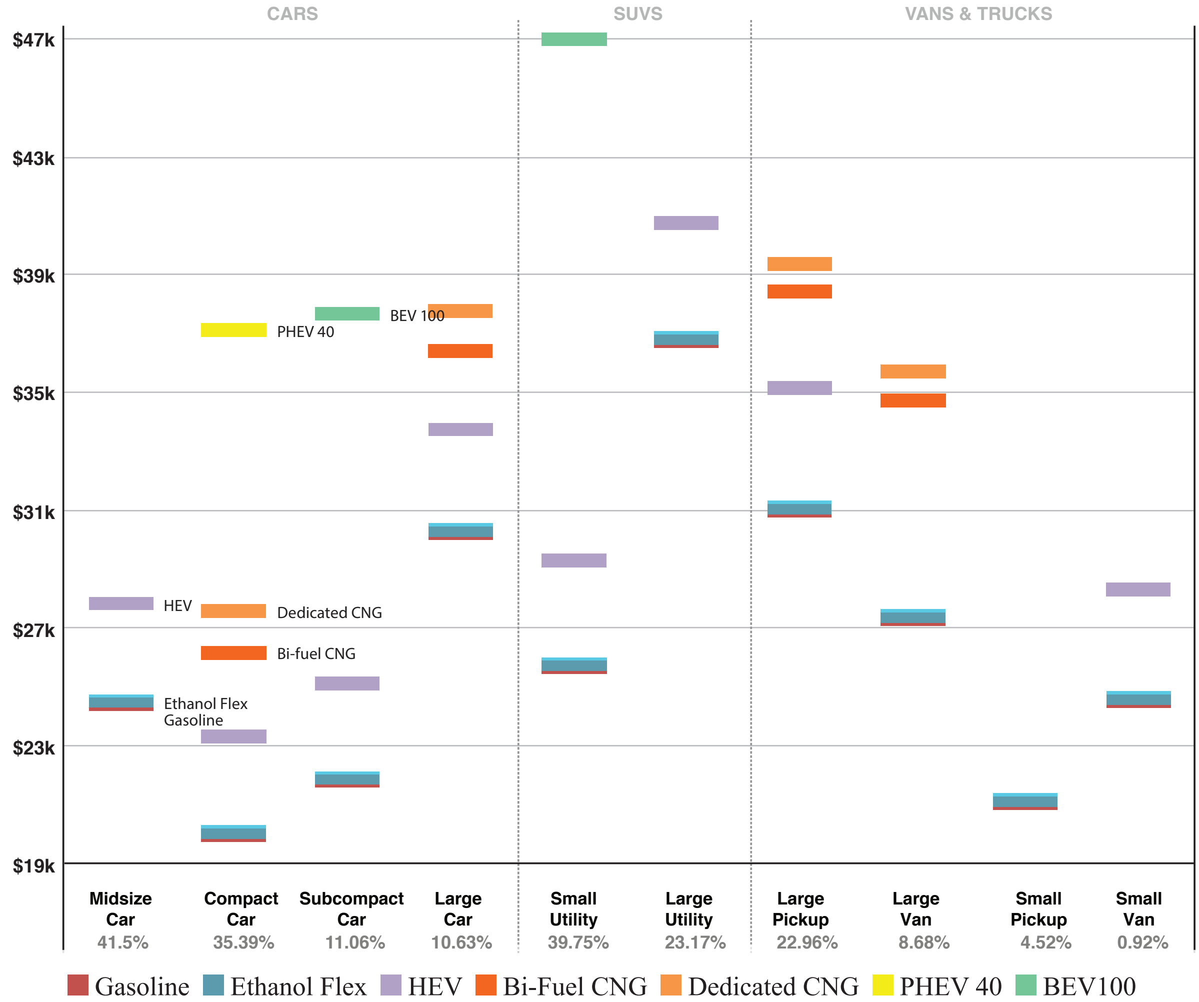

Figure 6.12 New Light-Duty Vehicle Prices in Thousand 2011 Dollars, Ordered by New Vehicle Model Sales (2013)

Notably, in segmenting markets this way, alternative fuel options compete but are more meaningfully differentiated. For instance, with midsize and compact cars, hybrid electric vehicles and CNG vehicles have similar costs (about $30k on average) but can reflect different lifestyle choices, driving habits, and vehicle requirements. This differentiation can also apply to the grouping with large cars, SUVs, and pickup trucks, for consumers with families or who expect to share the vehicle. As such, while fuel savings and vehicle payback periods can be useful metrics, recasting them in terms of behavioral or lifestyle needs can be more useful for differentiating among alternative vehicle choices.

6.5.3 Implications of Market Differentiation on Policy and Policy Demand

While market segmentation could allow multiple alternative options to coexist, slow adoption rates may reduce the potential policy benefits from using these alternative fuels, which raises the question of whether or not consumers should be involved in fuel choice, or whether these fuels should be used in more clearly defined markets, namely, centralized fleet operations. Figure 6.13 shows the low, medium, and high WTW GHGs/mile estimated for a 2035 mid-sized car based on the GREET model. Our group's equivalent assessment of the GHG emissions intensities and WTT and WTW $C0_2$-equivalent vehicle emission rates is summarized in Table 3.6, in Chapter 3. The two assessments are comparable in their findings.

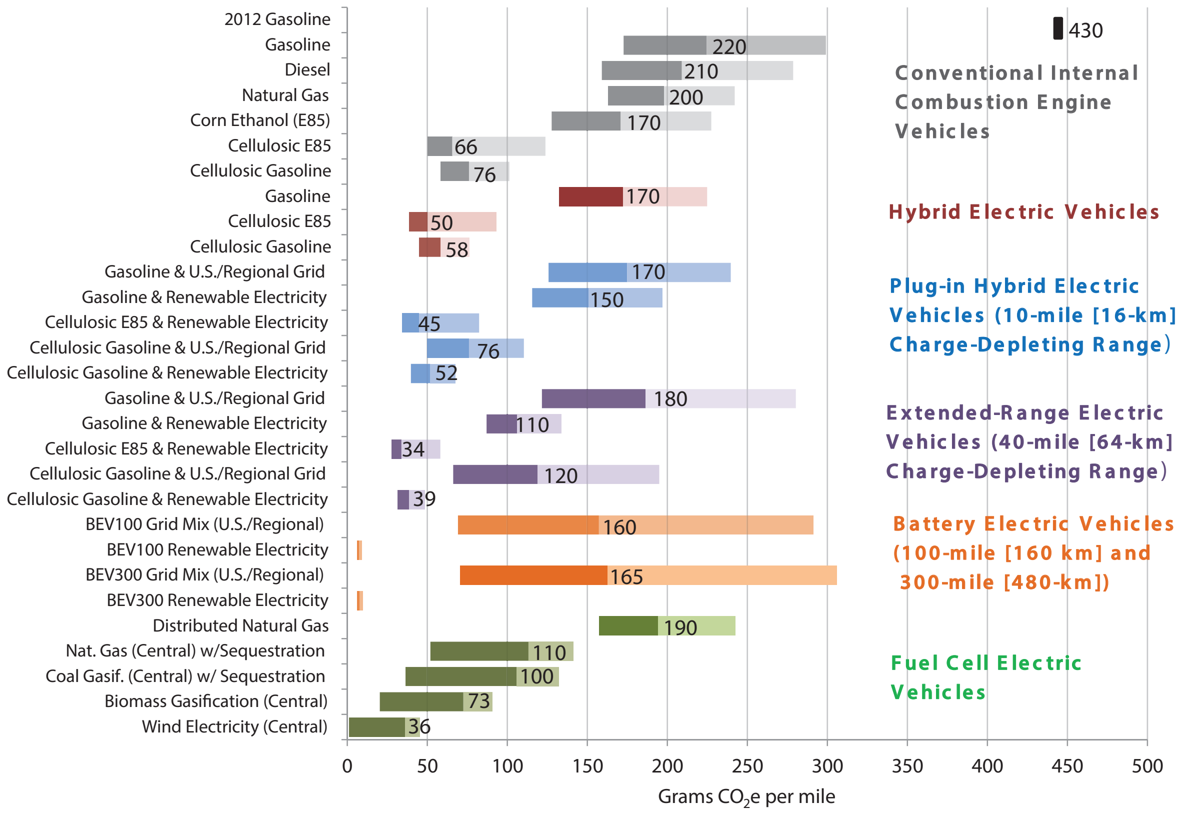

Figure 6.13 Well-to-Wheel Greenhouse Gas Emissions for a 2035 Mid-Sized Car

Source: EERE (2013), available at https://www1.eere.energy.gov/vehiclesandfuels/facts/2013_fotw783.html

It is clear that if reducing GHG emissions is a political priority, there are a number of alternative energy source options and strategies, namely from cellulosic materials, that can improve emissions. BEVs, due to the impact of the electricity mix (Figure 6.14), noticeably do not seem an especially attractive option unless the electricity supplied is largely from renewable sources. However, given that BEVs also have range and recharging rate limitations and seasonal heating/cooling constraints, introducing them in states that use a higher percentage of renewables could be beneficial. Based on state electricity generation mix shown earlier (Figure 6.8), PHEVs and BEVs could have a higher impact in Washington, California, Texas, and Oregon.

6.6 Summary

Bringing all of the various issues concerning alternative fuel development together, from fuel scalability and compatibility requirements to making them attractive to consumers, while also attempting to address policy issues, can be an overwhelming task. In a simplified way, Figure 6.14 illustrates the primary relationships between fuels, fuel sources, and vehicles. While this may seem to support mainstream ideas regarding how certain industries may have or be perceived to have vested interests in several fuel-vehicle options, in reality, these connections are even more interlinked if one considers the full lifecycle for a single fuel or vehicle. As noted in earlier sections, ethanol, for instance, has often been considered a primarily agrarian fuel, but shifting ownerships and technology complementarities bring it more closely in line with the chemical industry as well as oil and gas. RNG, which is considered to be part of the natural gas supply, can also be produced from agricultural energy crops or waste products, which further blurs some of the technical distinctions between these industries.

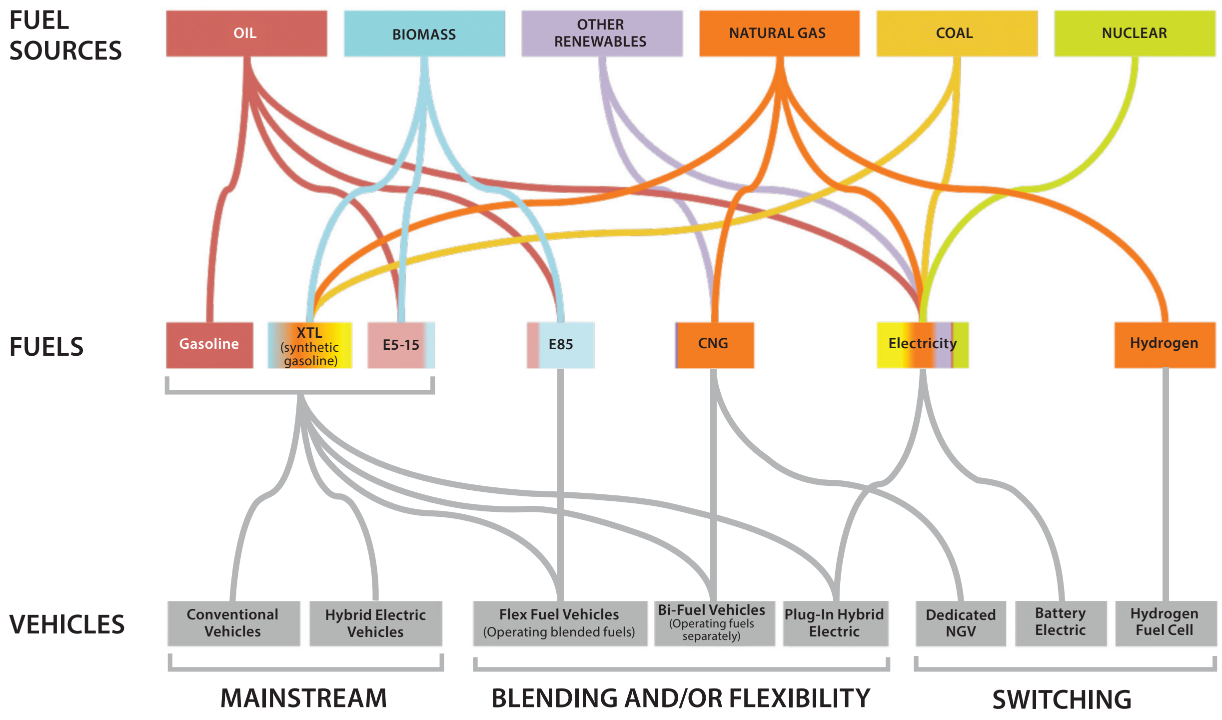

Figure 6.14 Simplified Relationships between Fuel Sources, Fuels, and Vehicles

As technologies that improve the efficiency of the use of conventional fuels continue to develop through the CAFE Standard schedule, alternative fuels and related technologies face greater technical and economic hurdles. From the perspective of maintaining the status quo and minimizing investment costs, the extent to which alternative fuel development can attain the necessary infrastructure compatibility, consumer acceptance, and parity to mainstream fuels and vehicles is unclear. It continues to be a source of debate. While these are often the most highly discussed aspects of alternative fuel and vehicle development, it is important to keep in mind that the pressure for alternative fuels to achieve infrastructure and vehicle parity as well as market competitiveness represents only one dimension of our broader energy use and GHG emissions issues; market organization, and the policies that govern or shape their direction are two critical factors that influence not only how economically viable or feasible the alternative fuels and vehicles are or can become, but also on helping to achieve energy security and climate change mitigation goals. Emphasis on “low-hanging fruit” or cost-conscious indicators can sometimes conflict with or distract from commitments toward these goals. It is also worth noting that even with petroleum-based fuels, there is no longer-term assurance of supply security.

As the demand for petroleum and other fossil fuels has led to more advanced resource-extractive practices and increasingly more environmentally controversial expansion and development activities, climate change has become the platform and reducing GHG emissions the opportunity for alternative fuels and vehicles to compete. However, their ability to have positive environmental impacts depends very much on the process by which these alternative fuels are produced, distributed, and used in vehicles. We have yet to determine the most effective option.

Although the layers of complexity can be parsed into discrete categories of desired fuel characteristics (Table 6.5), it becomes clear that no single fuel or vehicle can address all of the important issues.

More likely, it seems, an integrated approach involving several alternative fuel and vehicle options will have to be used to meet potential energy security and climate goals. Though attempts to address energy security and climate change have created new complications for policy makers and immediate stakeholders—fuel supply chain companies, fuel and car retailers, automakers, and consumers—alike, it is worth noting that the climate systems and anthropogenic impacts are inseparable and not bounded by political boundaries. Whether fuel switching or mixing becomes a reality or remains an elusive but appealing option in the United States, domestic decisions can have global spillovers. Without an international effort toward agreeing on mitigating global climate change, exportable fuels that are valued abroad will still be produced and sold to those markets.

Table 6.5 Considerations for Assessing and Comparing Alternative Fuels

Desired Fuel Characteristics	Considerations for Assessing and Comparing Alternative Fuels
Compatible with existing infrastructure or simplifies and streamlines supply chain	**Production/exploration:** scaling up raw material extraction or harvesting and related technology development, new site discovery and turnover. **Processing/development and refining:** scaling up capacity, retrofitting existing plants, building new plants, or outsourcing operations. **Transport:** building new or using existing highways, pipelines, waterways, or rail. **Distribution:** expanding existing service stations, retrofitting existing service stations, or building new stations.
Compatible with vehicles or improves function	**Performance metrics:** drivability, power, torque, etc. **Vehicle design:** retrofitting existing cars, adding fuel capacity, or building new cars (with either single or multiple fuel systems). **Regulatory standards:** safety, fuel economy, emissions, etc.
Environmental benefits	**Emissions:** lifecycle greenhouse gases, evaporative emissions, tailpipe emissions. **Land and water use:** efficient, non-destructive, sustainable. **Waste management:** byproducts, non-contaminating.
Safe during handling, operation, and disposal	**Health risks:** toxicity, inhalation, ingestion. **Safety metrics:** hazardous material, flammability.
Secure supply	**Diversified risk:** seasonality, geography constraints, geopolitics (domestic vs. imported), prediction and forecasting capabilities. **Diversified fuel sources:** exhaustible or renewable raw materials, frequency, magnitude and duration of extreme weather events and/or geopolitical conflicts, etc.
Competitive with mainstream options	**Factors that affect demand:** fuel prices, fuel quality and differentiation, vehicle cost and performance impacts, safety, fuel supply reliability, number of substitutes, etc. **Factors that affect supply:** cost changes to supply chain, raw materials, risks and uncertainties, substitutes, competing uses for inputs and products, etc. **Factors that affect both:** policy changes, R&D, accuracy and precision of forecasting models.

Better understanding the various parts of the fuels and vehicles system will not only help to find ways to bring policy objectives and transportation demand into better alignment, but also bring policy makers and stakeholders together in developing strategies with greater coherence and potential for impact.

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7.0 The Diffusion of Advanced Vehicle Technologies

7.1 Introduction

Since automobiles were introduced over a century ago, thousands of innovations have been introduced to their powertrains, structures, and other vehicle systems. New technologies allow manufacturers to provide vehicles of increasing levels of utility to consumers—better performance, greater efficiency, more features, and greater carrying capacity. Some innovations, such as new structural materials, deliver improved quality or performance, but are otherwise transparent to customers. Others, such as automatic transmissions, require a consumer to become familiar with the new technology and choose to purchase a new vehicle that incorporates it over an existing vehicle that does not.

The potential benefits of advanced technologies are only realized when those technologies are introduced into vehicles available in showrooms, and consumers purchase those advanced technology vehicles, replacing older vehicles in the vehicle fleet. The spread of new technologies depends upon millions of individuals *adopting* those technologies; the aggregation of these actions leads to the *diffusion* of these technologies across the market. To assess the benefits of advanced technologies, it is therefore critical to understand how long this diffusion process will take. The purpose of this chapter is to demonstrate empirical evidence on the diffusion of automotive technologies to help calibrate our predictions about future technology adoption, energy consumption, and emissions, and inform the development of effective strategy and policy decisions.

This chapter is divided into four sections, each addressing a theme related to the diffusion of innovations (technologies) in the automotive sector. First, a review of the innovation diffusion literature is provided, focusing on automotive applications. Second, the diffusion of vehicle features is analyzed using evidence from the United States over the past 40 years. Third, the diffusion of entire alternative fuel powertrains is considered, focusing on the case of the iconic Toyota Prius hybrid-electric vehicle (HEV) in the United States. Finally, the projection of future technology adoption to estimate future energy use and emissions impacts is discussed.

7.2 Literature Review

Extensive literature examines the diffusion of innovations: the process by which new ideas, practices, and technologies spread through a population. The following section summarizes the theoretical foundations of the innovation diffusion literature, the modeling approaches used to quantify the diffusion of innovations, and the application of these tools in the automotive context.

7.2.1 The Diffusion of Innovations

The diffusion of innovations commonly follows an S-shaped or logistic pattern over time, giving rise to Rogers' adopter classifications such as "innovators" and "early adopters." More specifically, the diffusion of *successful* innovations follows an S-shaped pattern toward 100% market share; however, most innovations fail. Less successful innovations may stagnate at some lower market share between 0% and 100%, or may experience "boom and bust," in which the innovation enjoys some initial success before being rejected by adopters.

Rogers (2003) proposes that the rate of adoption of innovations is governed by the following factors:

1. The *relative advantage* of the innovation;
2. The innovation's *compatibility* with existing systems, values, and behaviors;
3. The *complexity* of adoption and use of the innovation;
4. The *trialability* of the innovation, enabling experimentation prior to adoption; and
5. The extent to which the benefits of the innovation are *observable* to others.

7.2.2 Modeling the Diffusion of Innovations

The Bass diffusion model [Bass, 1969] is the foundation for a family of models commonly applied to the diffusion of innovations, generating the commonly observed logistic or S-shaped form. The Bass model distinguishes roles for innovators, commonly interpreted as those who adopt through exposure to advertising, and imitators, usually interpreted as those who adopt as a result of word-of-mouth communication [Sterman, 2000]. Numerous extensions have since been made to the Bass model, including the addition of prices [Robinson and Lakhani 1975], multiple product generations [Norton and Bass, 1987] and dynamic adopter populations [Mahajan and Peterson, 1978].

7.2.3 Technology Diffusion in the Automotive Industry

Nakicenovic (1986) discusses the logistic form of the diffusion of technology in a variety of fields and identifies several examples of the diffusion of automotive features. Nakicenovic also discusses differences among varying types of vehicle features, a concept continued here with the differentiation among safety, powertrain, and comfort/convenience features. Nakicenovic cites examples of the time to reach 50% penetration of a new technology, a parameter referred to later in this chapter as "developmental lag time."

DeCicco (2010) applies regression with a logistic form to feature data available from EPA for front-wheel drive, fuel injection, multivalve engines, and variable valve timing (VVT). The analysis proposes a logistic function and discusses both the steepness parameter of the adoption curve and also the number of years since the "first significant use," although it is difficult to discern the criteria being used to establish this date. DeCicco also proposes a logistic function within the range of other powertrain technologies as a plausible deployment scenario for HEVs, although the author notes that HEVs will compete with other technologies for incorporation into future vehicle fleets.

Applying generalized diffusion models such as Bass and Gompertz to estimate the future success of advanced powertrains (such as Lamberson (2009) and Cao (2004)) generates widely varying predictions, due to both the inherent difficulty in predicting future technology diffusion and the lack of decision variables in these models. Struben and Sterman (2008) reconcile the process of innovation diffusion with the discrete choice literature, distinguishing between the social exposure through which consumers develop familiarity with new technologies, and the attributes of the technologies that influence consumer choice. This approach has since been applied in a range of contexts, including the diffusion of diesel vehicles in Europe [Zhang, 2008] and the diffusion of HEVs in the United States [Keith, 2012]. For a detailed review of HEV and electric vehicle (EV) diffusion and consumer choice studies, see Al-Alawi and Bradley (2013).

Consumer behavior is not the only factor to consider. The supply side of the automotive product development cycle also places limitations on the speed at which innovations can be introduced into new vehicles. First, the complexity of modern automobiles means that the design and engineering process for a single product takes years. According to Clark and Fujimoto (1991) and Ellison et al. (1995), U.S. and European automakers reduced overall product lead-time by nearly a year between the 1970s and 1990s, but still stood between four and five years as of publication. While this has been further reduced, the National Highway Transportation Safety Administration (NHTSA) continues to note lead time as an issue of concern with regard to fuel economy standards [NHTSA, 2012].

Additionally, most automotive manufacturers design and produce large portfolios of products, not just a single vehicle. In order to maximize the efficiency of its engineering staff, manufacturers will typically stagger major vehicle redesigns over approximately five years. Plotkin et al. (2013) suggest that this phasing means that an automotive manufacturer needs 8–10 years to introduce an innovation over its entire product line. Such phasing presents a "floor" in the ability to bring new innovations to market, regardless of their appeal to consumers or other potential constraints such as intellectual property restrictions or material shortages. All of these factors tend to place dampers on the adoption process, contributing to the characteristic S-shaped curve.

7.3 Adoption of Features

The technological changes to vehicles over the past 100 years vary widely in magnitude. Many new design tools, fabrication techniques, and materials are transparent to purchasers, delivering incremental improvements in weight, strength, or cost but otherwise remaining undetected by typical consumers. Other changes, such as switching from gasoline to electric power, are so complex that purchasers may consider them a different class of vehicle.

This section examines a specific set of technologies: "features" that manufacturers market to consumers as options on new vehicles or advertise as offering improved functionality. A complete discussion of these results is available in Zoepf (2012).

7.3.1 Regression Analysis of Feature Adoption Rates

The fraction of consumers adopting a feature (known as the take rate of a feature) in year *t* was modeled by using least-squares regression to fit market share data to a logistic curve of the following form:

$$Take\ Rate(t) = \frac{Limit}{1 + \alpha e^{-\beta t}}$$

Regressions were performed on 35 individual features of passenger cars in the United States, and then secondary regression is performed on two parameters identified from the primary regressions: Maximum Growth Rate and Developmental Lag Time, as shown in Figure 7.1 below.

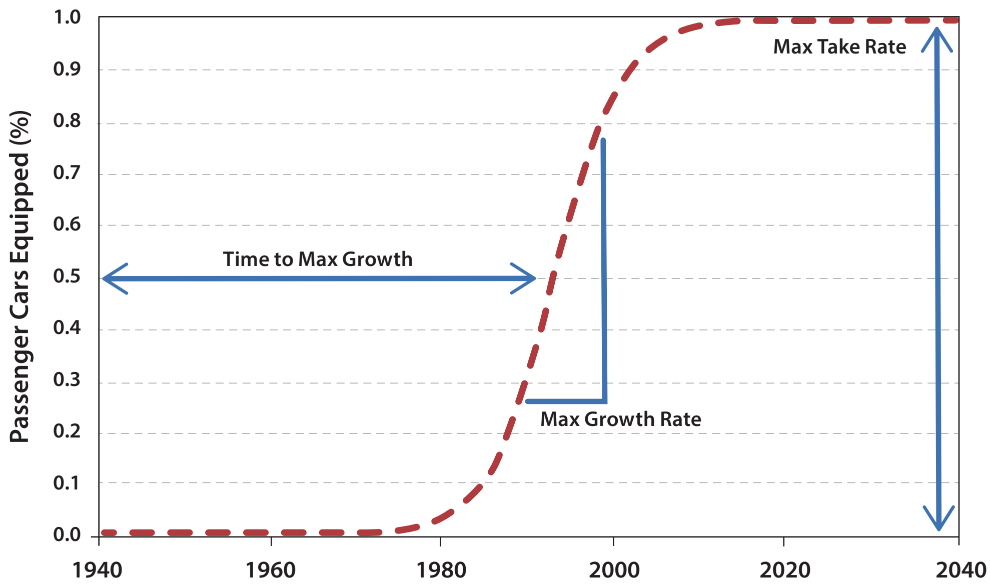

Figure 7.1 Key parameters of feature adoption

7.3.2 Maximum Growth Rate

The maximum rate at which the take rate of a technology grows is dependent on a variety of factors: consumer demand, producers' ability to bring the technology to market on its fleet and, in some cases, the influence of regulation. Figure 7.2 examines a histogram of the maximum growth rate of all features divided into the functional categories of safety, powertrain, and comfort/ convenience.

Annual growth rates for comfort and convenience features ranged from 0.8% to 11.6% (Mean 3.6%). Powertrain features were generally adopted faster, with maximum growth rates from 2.4%–13.4% (Mean 7.1%). Safety features saw maximum growth rates from 4.0%–23.9% (Mean 13.6%). Thus, on average, safety feature growth rates are approximately double those of powertrain features, which are in turn approximately double those of comfort and convenience features.

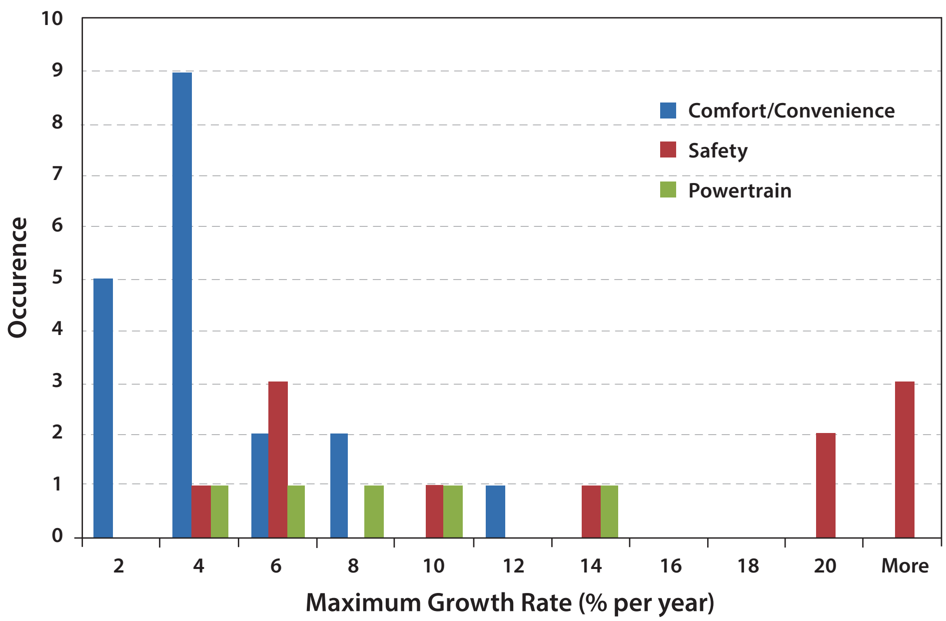

Figure 7.2 Histogram of maximum feature growth rate by category

These maximum growth rates seems to support the view, espoused by NHTSA (2011) and others, that an average five-year product development cycle is appropriate for modeling the automotive industry. Even technologies with a clear life-saving benefit cannot be deployed much faster than 20% of the new vehicle fleet per year.

7.3.3 Developmental Lag Time

The developmental lag time is defined here as the number of years between the appearance of the first production, street-going vehicle to use a technology and the year of inflection point in that technology's S-curve, as estimated in the primary regression. Figure 7.3 shows an exponential decline in the developmental lag time of features deployed over the past century.

There are a variety of explanations for such a change in the automotive industry. It is theoretically possible that the marked decrease in developmental lag time of features is the result of more stringent consumer expectations resulting from more exposure to new products and features through new media, and a higher level of communication between consumers leading to greater "word-of-mouth" interaction between adopters and potential adopters.

However, improvements in supply side capabilities have likely played a strong role as well. Clark and Fujimoto (1991) and Ellison et al. (1995) highlight that U.S. and European automakers reduced overall product lead-time by nearly a year between the 1970s and 1990s. The resultant increase in product changes allows a manufacturer to incorporate new features into the product mix more quickly. The structure of the automotive industry itself has also changed significantly over this same time period. Ellison et al. (1995) highlight the increased role that suppliers play in the product development process. Increasing reliance on suppliers suggests that intellectual property is distributed more quickly as suppliers are free to market a new technology to multiple manufacturers.

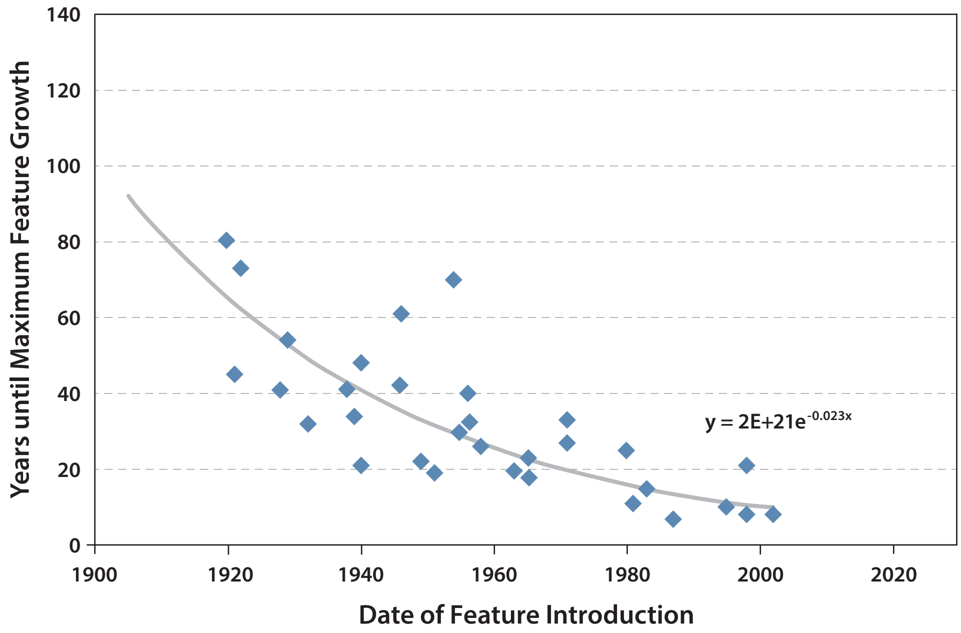

Figure 7.3 Historical phase-in time of all features

These factors have dramatically changed the competitive landscape. Developmental lag times have been significantly reduced, but remain just under a decade for new vehicles. The regression equations suggest that developmental lag time is halved in approximately every 30 years. This trend suggests that lag time could be five years in 2030. Plotkin et al. (2013) similarly note the possibility that the current eight to ten years of lead time may need to be re-examined.

7.4 Adoption of Alternative Fuel Powertrains

In contrast with the diffusion of individual vehicle features, the diffusion of entire alternative fuel vehicle (AFV) powertrains represents an even more complex challenge. While AFV technologies, such as HEVs and EVs, have substantial future potential for sustainable mobility, no AFV technology is clearly superior to the dominant gasoline internal combustion engine (ICE) regime, when cost and performance are taken into account. The diffusion of AFVs is both enabled and impeded by several strongly positive feedbacks, including the accumulation of consumer familiarity from word-of-mouth communication, technological improvements resulting from R&D and learning by doing, economies and scale and scope, the coevolution of complementary assets including refueling infrastructure, and the turnover of the vehicle fleet as seen in Figure 7.4 [Struben and Sterman 2008].

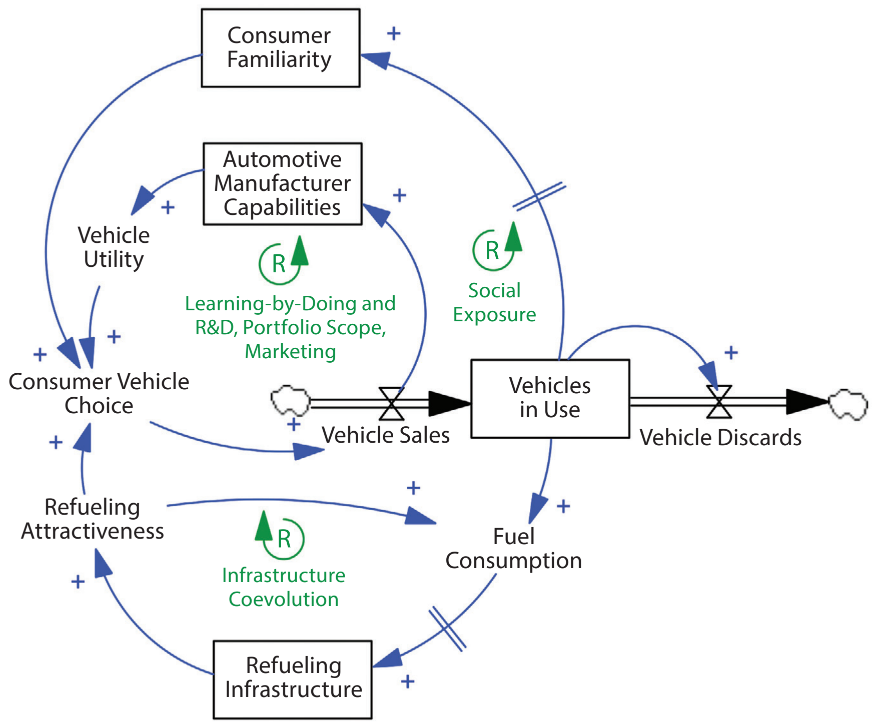

Figure 7.4 Feedback dynamics governing the diffusion of alternative fuel vehicles [Keith, 2012]

Numerous previous attempts to introduce AFVs into the U.S. automotive fleet have failed, despite optimistic assessments by political leaders, researchers, and technology advocates. The notable exception since 2000 has been the relative success of gasoline hybrid-electric vehicles (HEVs), with more than 2.5 million HEVs sold in the United States to date. Given this experience, the diffusion of HEVs, and the iconic Toyota Prius HEV in particular, is an instructive case study to inform the future potential for AFVs to permeate through the U.S. automotive fleet.

HEVs combine a conventional ICE engine with an electric powertrain to achieve improved fuel economy and reduced greenhouse gas (GHG) emissions, which result from the capture of kinetic energy through regenerative braking, automatic engine stop/start whenever the vehicle is stationary, and the complementary performance attributes of the gasoline engine (long range) and electric motor (low-end torque and energy efficiency). HEVs are not strictly "alternative fueled," as they refuel from the existing ubiquitous gasoline station infrastructure and generate electricity for the electric motor on-board the vehicle. However, HEVs cost up to $5,000 more than comparable gasoline vehicles [Bandivadekar et al. 2008], and substantially change the driving experience with the introduction of electric drive, making the purchase of an HEV a complex decision for consumers.

The first HEV in the United States was the two-seat Honda Insight introduced in late 1999. The Toyota Prius, introduced in July 2000, with sales growing rapidly after the second-generation Prius was introduced in October 2003, has become the dominant HEV model sold in the United States. By the end of 2012, the Prius family has accounted for more than 50% of the more than 2.5 million HEVs sold in the United States, including recent Prius 'c' and 'v' variants (Figure 7.5). Further discussion of the diffusion of the Toyota Prius is available in Keith (2012). Today, more than 45 HEVs are available in the United States (not including plug-in hybrid-electric vehicles (PHEVs)) across most market segments.

A range of incentives has been offered by federal, state, and local governments to encourage consumer adoption of HEVs, including income tax credits, sales tax exemptions and priority access to High Occupancy Vehicle (HOV) lanes. For example, the Federal Government's "New Energy Tax Credits for Hybrids" program provided tax credits of up to $3,150 between 2006 and 2010. The actual credit varied, based on the relative fuel economy of the HEV and the number of HEVs sold by each manufacturer. California's law that allowed single-occupant hybrid vehicles access to HOV lanes was subsequently valued at approximately $4,000 based on the price of used hybrid vehicles with and without qualifying vehicle stickers [*USA Today,* 2007]. Retrospective analysis suggests these incentives have been effective at accelerating HEV sales, particularly when the benefit of the incentive is seen up front [Diamond, 2009; Gallagher and Muehlegger, 2011], although evidence of significant incentive for free riding also exists [Gillingham and Kamala, 2012]. High gasoline prices have also been an important incentive for consumers to adopt HEVs, increasing vehicle operating costs and improving the payback on investments in improved fuel economy. The U.S. average price of gasoline rose from $1.33/gallon in January 2000 to $4.11/gallon in July 2008, before settling to $3.38/gallon in December 2012 [EIA, 2012]. It remains to be seen if more recent declines in gasoline prices will continue, and how large an impact they will have on sales of HEVs.

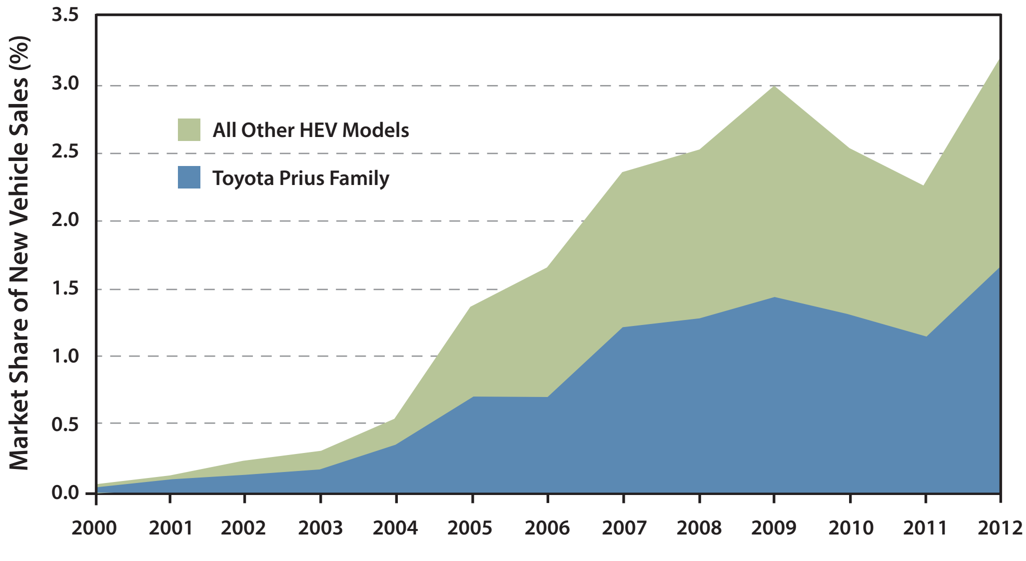

Figure 7.5 Historic sales of HEVs in the United States

Even considering these market forces, growing consumer familiarity with HEVs is critical in explaining the observed diffusion of HEVs in the United States [Keith, 2012]. Consumers will only purchase a new and complex technology such as an HEV once they have gained "…enough information about, understanding of, and emotional attachment to a platform (technology) for it to enter their consideration set" [Struben, 2006]. This familiarity accumulates through social exposure to marketing and "word of mouth," such as conversations with friends, observing the technology in use, and "trialing" the technology, such as taking a ride in a Prius taxi or getting an HEV as a rental car. Marketing is particularly important early in the process of new product launch, providing the external information needed to educate early adopters who then generate word-of-mouth communications. Toyota invested an estimated $300 million marketing the Toyota Prius in the United States between 2000 and 2010 [Kantar Media, 2010], educating consumers about the unique aspects of the Prius' hybrid-electric powertrain.

The relative success of HEVs in the United States over more than a decade, compared to previous short-lived attempts to introduce AFVs, represents an important reference case to understand the future potential of alternative fuels and vehicle technologies. Even with favorable market conditions, such as high gasoline prices, the availability of government purchase incentives and compatibility with the existing ubiquitous gasoline station infrastructure, the diffusion of HEVs into the U.S. light-duty vehicle fleet has played out over many years, governed by the slow rate of vehicle fleet turnover and the gradual accumulation of consumer familiarity with this new, complex, and expensive technology. Looking forward, the success of HEVs depends not only on consumer acceptance of the HEV platform, but also on competitive pressures from increasingly efficient gasoline vehicles and emerging plug-in electric vehicles (PHEVs).

7.4.1 Evidence from the Early Market for Electric Vehicles

The introduction of the Chevrolet Volt PHEV and the Nissan Leaf battery–electric vehicle (BEV) in December 2010 represents the latest attempt to introduce AFVs into the U.S. automotive fleet. As of June 2013, more than 112,000 plug-in electric vehicles (PHEVs and BEVs) had been sold in the United States supported by policies including an income tax credit of up to $7,500 from the federal government and California's Zero Emissions Vehicle (ZEV) mandate, which compels automakers to sell a prescribed minimum number of EVs.

Opinions are mixed on whether the launch of PHEVs and BEVs into the U.S. market has been successful. Early statements such as Carlos Ghosn's prediction in 2010 of 500,000 EV sales annual by the Renault-Nissan alliance by the end of 2013, and President Obama's goal of putting one million EVs on U.S. roads by 2015, only served to raise the bar against which the diffusion of EVs has been judged, leading to unfavorable comparisons. Others, such as MIT's *Technology Review* (2013), have suggested that the launch of EVs has succeeded because sales of EVs in the first three years (PHEVs and BEVs) has exceeded the rate at which HEVs were sold during their first three years in the U.S. market in the early 2000s (Figure 7.6).

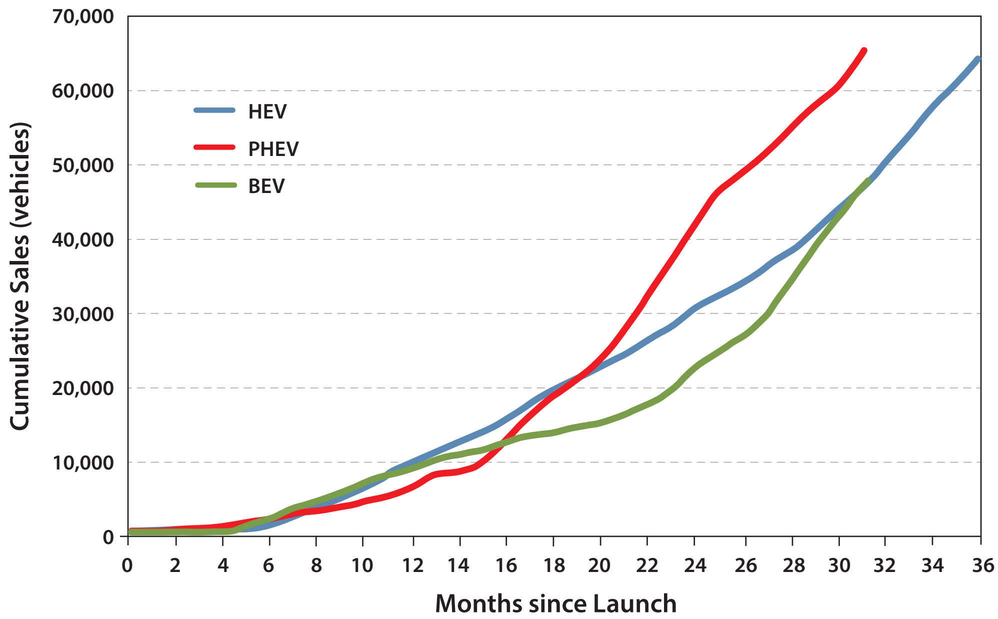

Figure 7.6 Cumulative U.S. sales of EV platforms immediately post-launch

It is too early to predict whether the early success of EVs in the U.S. market will lead to their sustained diffusion of EVs through the U.S. light-duty fleet in future years. Growing sales of early EV models, and the expanding range of EV models available to consumers (Figure 7.7), are causes for optimism. However, any comparison with the diffusion of HEVs must take into account the market advantages EVs have enjoyed, including: substantial government incentives, high gasoline prices in the early years after their introduction, and consumer familiarity with electric drive resulting from the relative success of HEVs over the past decade. Automakers have been forced to internally subsidize the development and sale of EVs to meet mandated sales targets in California, and some EV models have been acerbically dubbed "compliance cars," because manufacturers including Chrysler have signaled their intention to only sell the minimum number of vehicles necessary to satisfy their regulatory obligations [Green Car Reports, 2013]. Previous efforts to introduce AFVs, including Compressed Natural Gas (CNG) vehicles in New Zealand and an earlier attempt to introduce EVs in California in the early 2000s, collapsed when government support was removed. The continued success of EVs depends on finding economically and ecologically sustainable markets as well as overcoming perceived barriers to mainstream adoption, including high battery costs and long recharging times.

7.5 Projection of Future Technology Adoption: Fleet Modeling

While it is important to understand the dynamics of technology adoption, it alone does not capture the impact of technology on future fuel consumption. Each year, 10–15 million new vehicles are sold in the United States, but they represent fewer than 10% of the approximately 240 million vehicles on the road. These 240 million vehicles are generally called the "car parc" or "in-use fleet." The large number of vehicles in use dampens the impact of new technology as new vehicles slowly replace old vehicles that are scrapped.

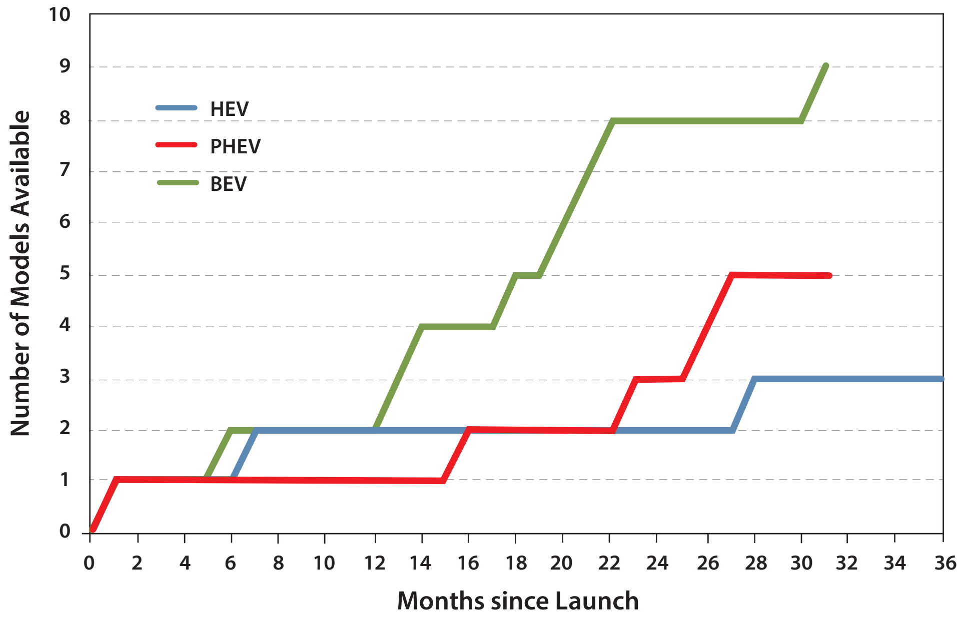

Figure 7.7 Adoption of early HEV, PHEV, and BEV products

To understand the dynamics of in-use vehicle turnover and the broader impact of technology adoption, we use a fleet model, which is a generic term for a numeric representation of vehicles on the road, along with the associated age, distance traveled, and other attributes of each vehicle.

The fleet model establishes a baseline by estimating current vehicle stock based on known average fuel economy of the car and light truck fleets, reported annual sales, detailed estimates of Vehicle Kilometers Traveled (VKT), and scrappage rates. Typically a "Business as Usual" or "No Change" scenario will assume that current vehicle attributes do not change in the future, or will continue to change in accordance with recent trends. To estimate future fuel consumption and emissions, the fleet model incorporates estimates of future fuel consumption, which are derived from predicted penetration rates of advanced vehicle technologies such as hybrids and AFVs.

Various research groups have developed fleet models that perform fundamentally similar calculations. Such models include VISION from Argonne National Laboratories or LEAP from the Stockholm Environment Institute. These models are similar in function and structure; the most significant differences that arise from the use of fleet models are in the input assumptions.

Figure 7.8 shows a block diagram representation of these calculations as used in the Sloan Automotive Lab fleet model, first developed by Bandivadekar (2008). More detailed information on the sources of input estimates can be found in Bandivadekar et al. (2008).

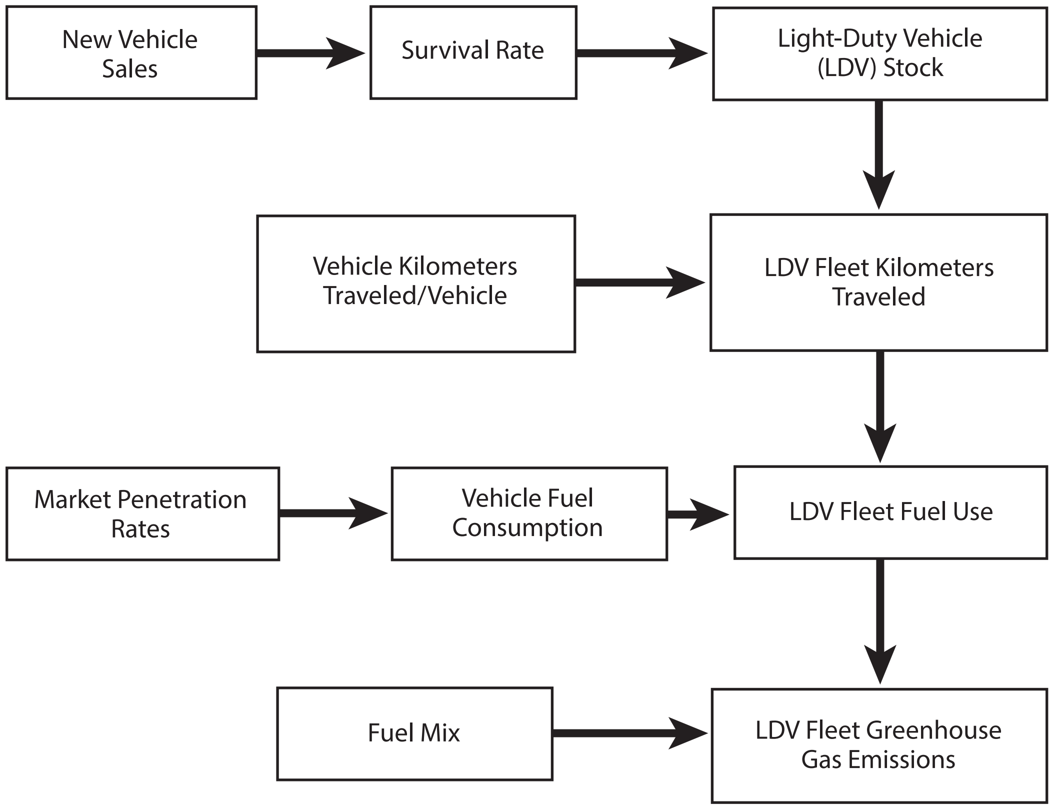

Figure 7.8 Block diagram representation of calculations in the Sloan Automotive Laboratory fleet model

7.5.1 Fleet Modeling Conclusions

The fleet model reveals that new technologies, even those that are adopted and deployed quickly, will take more than a decade to have a significant impact on fuel consumption. R. L. Polk finds that the average age of vehicles in the United States has been climbing consistently, with the average age of a vehicle in the United States now standing at 11.4 years. The increasing durability of vehicles *counteracts* our ability to deploy technology rapidly, as obsolete vehicles remain on the road longer.

Cheah (2010) investigated scenarios incorporating the most aggressive deployments of alternative powertrain vehicles and lightweighting technologies. These aggressive scenarios predict a net savings of fuel of 1,551 billion liters of gasoline by the year 2030, compared to a baseline scenario with unchanging fuel economy. However, even under the aggressive assumptions in this scenario, naturally-aspirated gasoline engines still hold more than a 50% market share more than 16 years into the future as seen in Figure 7.9.

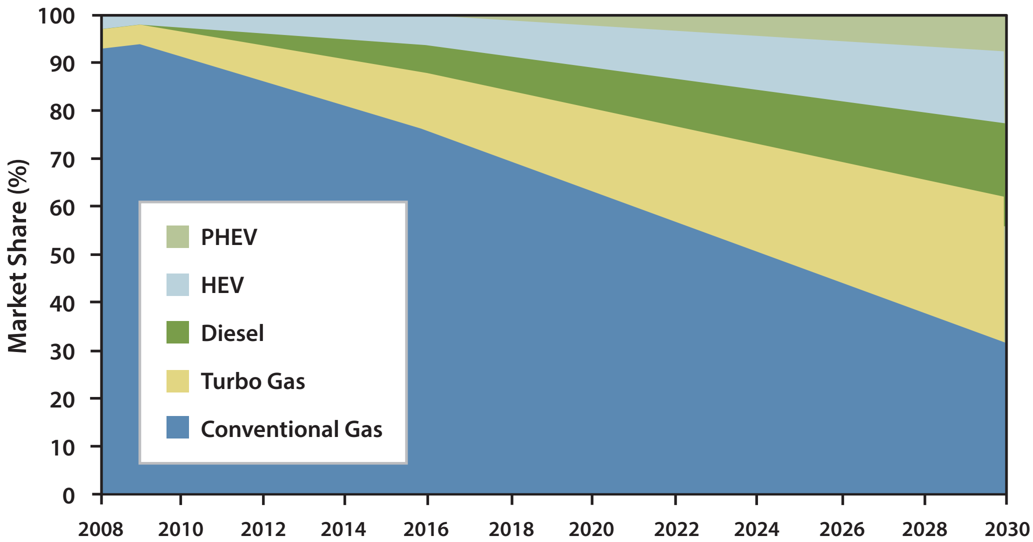

Figure 7.9 Predicted market share of alternative fuel vehicles using a sample fleet model input scenario

The impact of new technologies is dampened significantly by the slow turnover of the fleet and the longer useful lifetime of new vehicles, meaning the impacts of new technologies are significantly delayed. Even those technologies that are ubiquitous in showrooms may be seen in fewer than half of the vehicles on the road. Predictions of future technology impact in the automotive industry must carefully consider the necessity to replace an enormous volume of vehicles on the road before the technology impact is felt at the pump, oil wells, and the electrical grid.

7.6 Conclusions

The introduction of technology into the automotive fleet can be viewed as a three-phase process, which serves to limit the rate at which new technologies can reduce fuel demand or displace petroleum. Technology must first be brought into a few production vehicles, where consumers can experiment with the new technology. Sales are limited both by consumer willingness to try the technology and automaker capability to produce these vehicles in larger volume. Therefore, only a few percent of new vehicles include the technology.

In the second phase, consumer word-of-mouth communication and advertising drive technology beyond early adopters to mainstream consumers. In parallel, automakers bring the technology into a larger fraction of their product portfolio as it is redesigned, meeting the demands of the growing market. In this phase, a technology may be commonplace in new vehicles. However, it still represents a tiny fraction of the on-road vehicle fleet and its environmental impact remains small.

In the last phase of technology introduction, older vehicles that do not include the technology are scrapped and replaced with newer vehicles that do. This phase is largely independent of consumer adoption and supply constraints. The timing of this phase depends on more fundamental issues such as the durability of new cars and macroeconomic factors that may influence the decision to scrap or repair vehicles.

7.6.1 Near-Term Trends in Technology Adoption

These examples of technology adoption in the automotive sector provide a reason for being cautiously optimistic. The time for bringing automotive features to market has been substantially reduced, suggesting that the 8–10 year minimum deployment time may continue to decrease in the future.

Evidence from more expensive, complex technology adoption, such as EVs, suggests that PHEV and BEV sales are growing more quickly than HEV sales despite their greater complexity and price premium. It is too early to tell whether such adoption is the result of latent consumer demand or the presence of substantial federal, state, and manufacturer incentives.

7.6.2 The Influence of Regulation

Fuel economy regulations are often cited as a means of accelerating the deployment of fuel-efficient technology in the marketplace. However, recent work by MacKenzie (2013) failed to identify a significant effect of Corporate Average Fuel Economy (CAFE) regulations in bringing fuel-efficient technology to market faster.

However, MacKenzie also specifically notes that, during a period of increasingly stringent regulation, a technology-forcing effect may well be present. As a result, as newly adopted CAFE standards through 2025 come into effect in the next few years, it may well be possible to observe an uptick in the adoption of technology.

7.6.3 Opportunities to Accelerate Technology Deployment in the Longer Term

The results of this chapter suggest a number of additional mechanisms that may be effective in stimulating technology growth in the automotive sector.

Fuel taxes are a commonly cited way to create an incentive for consumers to purchase fuel-efficient technologies. Fuel taxes, unlike fuel efficiency standards, create an immediate incentive to scrap older vehicles in favor of newer, more efficient models. As a result, fuel taxes act in two ways: first, as an incentive to invest in technology in a new vehicle purchase, and second, to pull forward a decision to scrap an older, less efficient vehicle. One challenge of such regulations is that older vehicles may not actually be scrapped, but rather simply exported to countries with lower fuel costs or laxer regulations. As a result, policy analyses that show increased scrappage should carefully consider whether such vehicles are truly removed from the fleet or simply moved.

While better technologies and more favorable markets are important, so too is the behavioral role of consumer familiarity with emerging AFV technologies in the adoption process. Traditional marketing on television, radio, and in print media is important for introducing new technologies to consumers, but social exposure through word-of-mouth communication is critical subsequently. Interactive opportunities, such as extended test-drives, deployment of vehicles in taxi fleets, and low-cost, flexible leases, provide consumers with the opportunity to experience the novel aspects of AFVs. Understanding the role of consumer familiarity is also important for policy makers. Incentives will be most cost effective in markets in which there is high consumer familiarity with a new technology as a result of prior adoption, and where those consumers have a high willingness to adopt. In markets with low prior adoption of the new technology, efforts to build consumer familiarity, for example, by deploying AFVs in government and taxi fleets, may be more effective initially.

AFVs also face the chicken-and-egg problem of refueling infrastructure coevolution. To overcome this barrier, a common tactic is to incorporate flex-fuel capability. E85 vehicles, for instance, generally can operate on conventional gasoline and PHEVs can be refueled at a gas station when the battery is depleted. While such flexibility offers additional utility to buyers, assessing the actual benefit of such vehicles is complex. How often are they run on each fuel? Early results from a trial of PHEVs by Zoepf et al. (2013) suggest that there can be enormous variation in consumer recharging behavior (see also Chapter 8 of this report). Similarly, it is widely suspected that many E85 flex-fuel vehicles are rarely run on E85. *Such evidence means that it is not only necessary to deploy new technology, but to ensure that it is purchased by those who will actually use it*.

Bringing new technology to market may also depend on changing vehicle ownership models. Vehicle sharing, short-term rentals, and partial ownership offer the opportunity to expose larger numbers of consumers to new technology quickly, increasing the *trialability* of these technologies. Such services also offer the added benefit of accumulating the miles traveled by dozens of users onto a small fleet of vehicles, accelerating their turnover. As a result, such services may accelerate both the communication of new technology in the first and second phases of deployment, and the turnover of the fleet in the final phase of deployment.

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8.0 Opportunities for Changing Traveler and Driver Behavior

There are many opportunities for conserving energy, reducing petroleum consumption, and cutting greenhouse gas (GHG) emissions through changes in individual traveler and driver behavior. These opportunities include changes in when, where, and how we travel. Understanding these factors is the purview of "travel behavior," which addresses decisions that are made on timescales ranging from years to hours. These decisions determine the level of travel activity (i.e., vehicle kilometers traveled). With the introduction of alternative- and flexible-fueled vehicles, refueling or recharging behavior now also has a significant effect on the carbon intensity of the fuel consumed. Other opportunities exist for changing how vehicles are operated. These real-time decisions fall within the realm of "driver behavior," and influence the energy intensity of vehicle travel.

8.1 Travel Behavior: Demand Reduction and Mode Shifting

Transportation energy consumption and GHG emissions can be reduced by decreasing demand for travel or by shifting travel toward less carbon-intensive modes. From a technical standpoint, these strategies are relatively straightforward. The challenge to implementing these solutions lies in creating the necessary incentives to motivate millions of individual travelers to alter their behavior and in mustering the political will to invest public money or adopt potentially unpopular policies.

The range of options for reducing and shifting travel demand is broad. In general, these solutions may act either by increasing the cost or reducing the convenience of more damaging travel modes (such as single-occupancy vehicle travel) or by reducing the cost or increasing the availability and convenience of less-damaging modes (such as carpooling, public transportation, and non-motorized modes). In the former case, the cost of travel may be increased directly through pricing mechanisms such as tolling or fuel taxation. Alternatively, regulations may be imposed in an attempt to indirectly reduce demand for travel. For example, urban growth boundaries may help to stem growth in commute distances. Similarly, tactics for shifting travel to less-damaging modes can include both direct reductions in costs for those modes (e.g., subsidies for transit) and approaches meant to make those alternatives more convenient (e.g., support for public transportation, establishment of bicycle routes and lanes, and promotion of walkable communities).

A comprehensive survey of approaches to reducing and shifting travel demand can be found in *Moving Cooler* [Cambridge Systematics, 2009]. That study also reports estimates of potential GHG reductions achievable through "bundles" of tactics that could be implemented to reduce travel demand and improve system operational efficiency. The authors conclude that by 2050, an aggressive strategy emphasizing land use changes and the promotion of transit and non-motorized transportation modes could cut emissions by about 9%, while an all-out effort to deploy these solutions could deliver a reduction of up to 15%. The authors also present a range of alternative strategies that suggest that transportation emissions could be cut by as much as 24% by 2050 through reductions in travel demand and operational improvements. However, in the latter case, much of the additional reduction comes not from reductions in travel demand, but from improvements in operational efficiency, which is the subject of the next section.

8.2 Fuel Consumption and Vehicle Speed

The effect of vehicle speed on fuel consumption provides a useful context for evaluating driver behavior impacts. The main factors involved in steady speed driving are the vehicle's aerodynamic drag at high speeds, tire rolling resistance, power-to-weight ratio, and the number of gears. In normal non-steady driving, the aggressiveness of vehicle accelerations becomes important.

Figure 8.1 shows the fuel consumption versus speed for four vehicles, operating at constant speed. Vehicle weight differences are a major cause of the separation of the four examples shown. Differences in base engine efficiency also contribute. Note the rising fuel consumption at high speeds. Engine efficiency is increasing, but the vehicle (steady-speed) resistances (tires and aerodynamic drag especially) are increasing/worsening, too. At low speed, as engine load decreases, the engine efficiency is decreasing rapidly because the engine load becomes steadily lower (and this engine friction consumes an increasing fraction of the power the engine generates).

Figure 8.2 plots similar curves for various driving cycles for the Ford Focus vehicle. Three standard drive cycles and four real-world driving patterns were modified by scaling their velocities without altering acceleration rates. The horizontal axis is now *average* vehicle speed over the velocity-scaled driving trace. The inclusion of vehicle accelerations (and decelerations) adds the inertial kinetic energy resistance, and fuel consumption increases relative to Figure 8.1. The shape of these two sets of curves is similar for the same basic reasons. Below 30–40 km/hr (~25 mph), as speed goes down, fuel consumption rises rapidly. At higher speeds (above 60–65 km/hr), fuel consumption steadily increases with rising average speed, with increasing slope due to the dependence of aerodynamic drag on the cube of the vehicle velocity. There is a surprising speed range (of some 30 km/hr or 20 mph) over which the vehicle fuel consumption during normal driving varies little. Additional details can be found in Berry (2010).

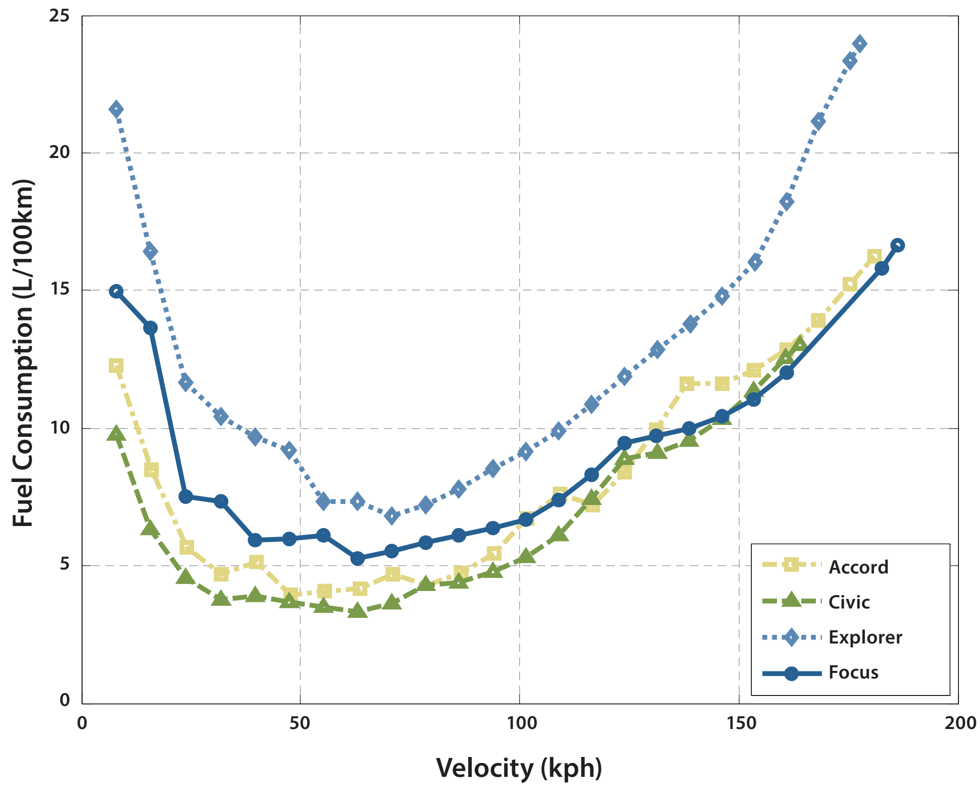

Figure 8.1 Vehicle fuel consumption as a function of vehicle speed, constant speed driving.

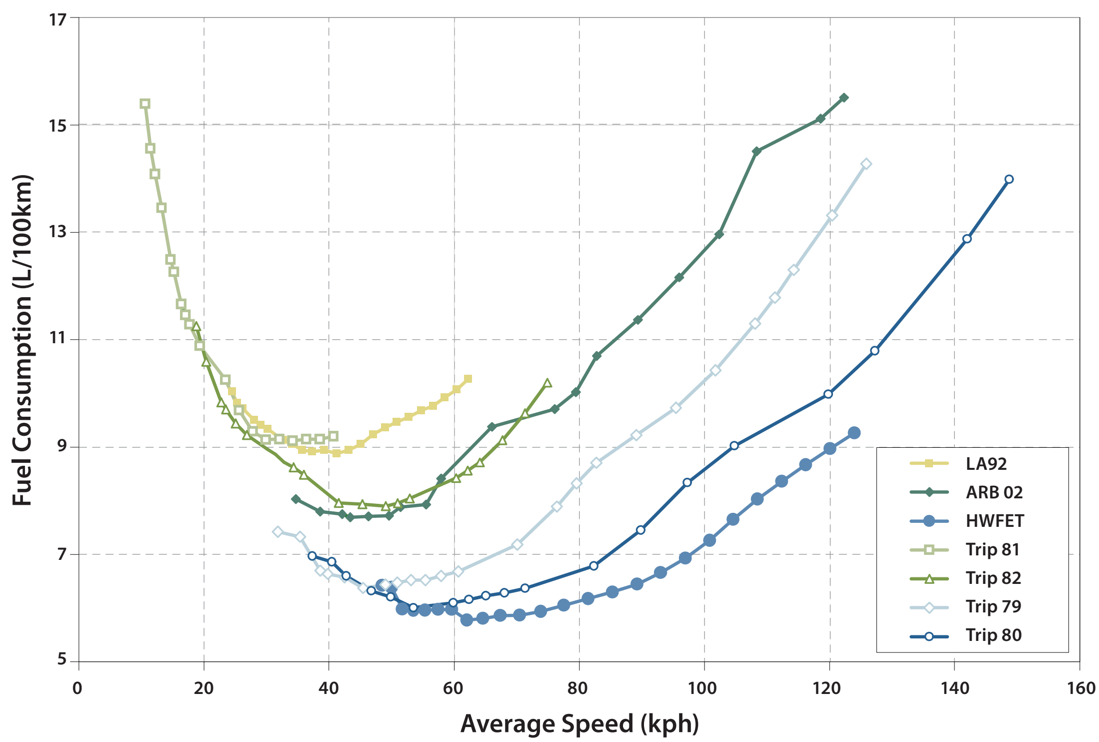

Figure 8.2 Fuel consumption versus average speed for Ford Focus over various real-world and standardized driving traces.

8.3 Driver Behavior: Improving Operational Efficiency

Driver behavior refers to the second-by-second decisions made by drivers when operating their vehicles. Driver behavior with respect to speed and acceleration can significantly influence in-use fuel consumption, even for the same vehicle. Characterizing these aspects of driver behavior, linking them to fuel consumption, and assessing opportunities to change this behavior offer a meaningful opportunity for energy conservation.

In most major automotive markets, vehicles are assigned fuel economy or fuel consumption ratings based on standardized test cycles. In the United States, compliance with federal Corporate Average Fuel Economy (CAFE) standards is based on two test cycles: the Federal Test Procedure (FTP) and the Highway Fuel Economy Test (HWFET), both of which were developed in the 1970s. Initially, consumer fuel economy labels also presented the results of these tests, but by the early 1980s, it had become clear that most consumers were not realizing the tested levels of fuel consumption in real-world driving. The U.S. Environmental Protection Agency (EPA) responded by introducing correction factors that were subsequently applied to the FTP and HWFET results to produce adjusted fuel economy values for consumer labels (though the unadjusted test results remained the basis of CAFE compliance calculations).

In the mid-2000s, EPA once more revisited its procedures for determining the fuel economy estimates presented on consumer information labels. Beginning in 2008, the consumer labels would incorporate results from three more test cycles: the US06 cycle (high-acceleration highway driving), the SC03 cycle (city driving with air-conditioning), and the cold-FTP cycle.

There are many reasons why real-world fuel consumption is higher than the levels published in these standard laboratory tests. These include higher speeds; harder acceleration; the extent to which the engine and drivetrain are warmed up; the use of power-sapping accessories like air-conditioning; the addition of roof racks; maintaining lower-than-recommended tire pressure; and variations in environmental conditions including temperature, humidity, precipitation, wind speed, and direction; and roadway grade. Of these, the effects of speed and acceleration, which together characterize the overall aggressiveness of driving, are especially important, yet they have previously defied simple characterization.

8.3.1 Quantifying Driving Aggressiveness[16]

Since more aggressive driving habits tend to increase fuel consumption per mile, it is desirable to develop an aggressiveness factor or factors that:

1. considers only driving patterns and vehicle characteristics,
2. reflects driving style,
3. correlates with fuel consumption, and
4. is normalized for vehicle mass.

[16]This section summarizes work carried out by Irene Berry, a member of our team from 2007–2010: see Berry (2010).

Meeting these criteria would permit the development of factors that are useful for isolating and quantifying the aggressiveness of driving, without relying on vehicle weight, fuel consumption, or fuel flow data.

However, to be useful for studying impacts on fuel consumption, the aggressiveness factors must correlate directly with fuel consumption. To illuminate which driving behaviors have the greatest impact on fuel consumption, the aggressiveness factors must quantify driving behaviors based on how they impact fuel consumption. Recognizing the significance of vehicle mass in fuel consumption, in order to be more comparable across vehicles, the aggressiveness factors should be normalized according to mass.

This section introduces a method for quantifying and comparing drive cycles, driving patterns, and drivers. In developing these aggressiveness factors, a range of options was considered. However, as shown in Berry (2010), average speed and wheel work,[17] together, can illuminate and predict fuel consumption. The aggressiveness factors rely on these parameters. In addition, because fuel consumption behavior differs in different speed bands, separate aggressiveness factors were defined for each of three separate speed bands: below 20 mph (32 km/h), between 20 and 45 mph (32 and 72 km/h), and above 45 mph (72 km/h). The vehicle's speed versus time traces are sorted into these speed bands based on average speed. For simplicity, they have been given the names of "neighborhood," "city," and "highway" driving. The threshold speeds separating these bands (20 and 45 mph) were selected based on observations that the relationships between speed, acceleration, wheel work, and vehicle efficiency are qualitatively different in these distinct speed bands. Specifically, vehicle simulation studies have shown that:

1. At neighborhood speeds (below 20 mph): with increasing speed, efficiency increases more than wheel work; and with increasing acceleration, wheel work increases more than efficiency.

2. At city speeds (20 to 45 mph): with increasing speed, efficiency and wheel work increase proportionally; and with increasing acceleration, wheel work increases more than efficiency.

3. At highway speeds (above 45 mph): with both increasing speed and increasing acceleration, wheel work increases dramatically, but efficiency changes little.

The following sections define and discuss each of these three aggressiveness factors, starting with city driving, which is the simplest and most intuitive.

[17]Wheel work is the total positive energy (or work) required at the wheels to move a vehicle over a unit distance in a drive cycle. It is calculated by dividing the time integral of positive tractive power by the distance covered by the drive cycle.

8.3.2 Aggressiveness Factor for City Driving

City driving is taken as any driving with average speed between 20 and 45 mph (32 and 72 km/h). Figure 8.3 shows 590 speed traces[18] that fall within the city speed band (each point representing an entire trace with an average speed between 20 and 45 mph) for the Ford Focus. The chart shows that the acceleration wheel work[19] and fuel consumption are tightly, and approximately linearly, correlated. The aggressiveness factor in this speed band is defined as the acceleration wheel work, normalized for mass as shown in the equation below. Intuitively, this aggressiveness factor for city driving can be understood as capturing the increase in fuel consumption that will be required because of deviations in the speed trace away from the average speed of the trip.

$$\textit{Aggressiveness factors} = \frac{\textit{Wheel Work} - \textit{Steady Speed Wheel Work at Average Speed}}{\textit{Mass}}$$

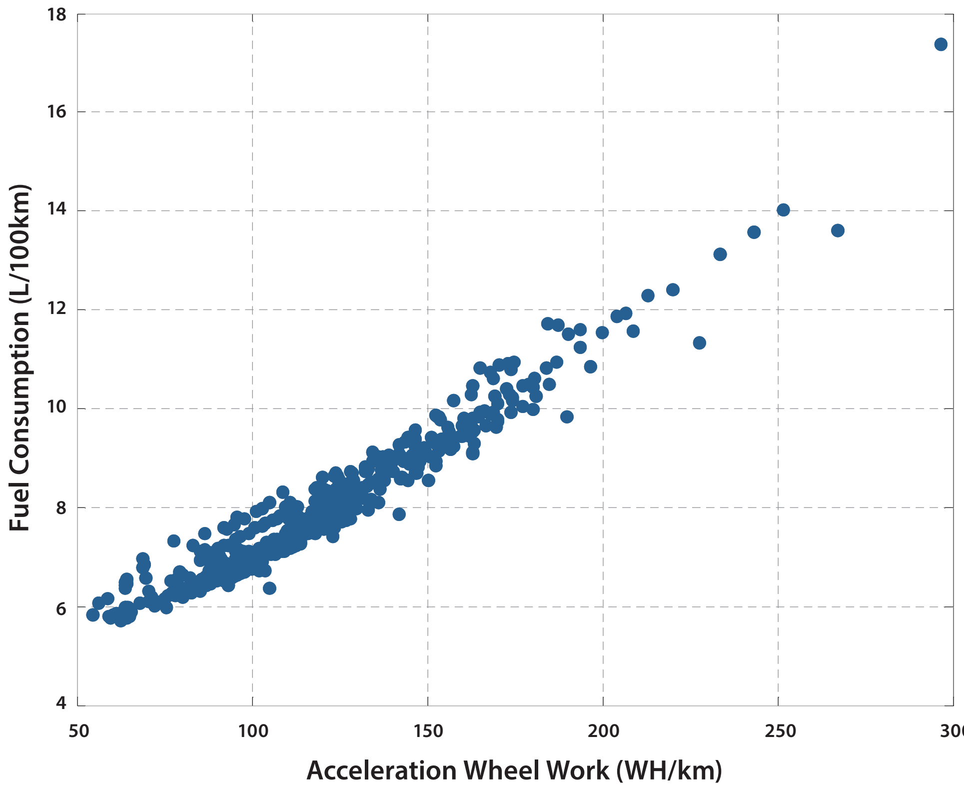

Figure 8.3 Relationship between acceleration wheel work and fuel consumption for Ford Focus vehicle on drive cycles with average speeds between 20 mph and 45 mph.

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[18]Speed traces included regulatory drive cycles from jurisdictions around the world; real-world drive traces logged in Boston, Massachusetts, and Greensboro, North Carolina; and modified drive cycles created by applying speed and/or acceleration scaling to 12 regulatory and real-world drive cycles.

[19]Acceleration wheel work is the total wheel work minus the wheel work needed to propel the vehicle at a steady speed equal to the average speed of the drive cycle.

The resulting aggressiveness factors have units of acceleration. However, they are not actual accelerations and are not proportional to any acceleration values. As shown in Figure 8.4, this factor is linearly related to fuel consumption. For the Ford Focus, every 1 m/s^2 increase in city aggressiveness causes an increase of 4.4 l/100km in fuel consumption.

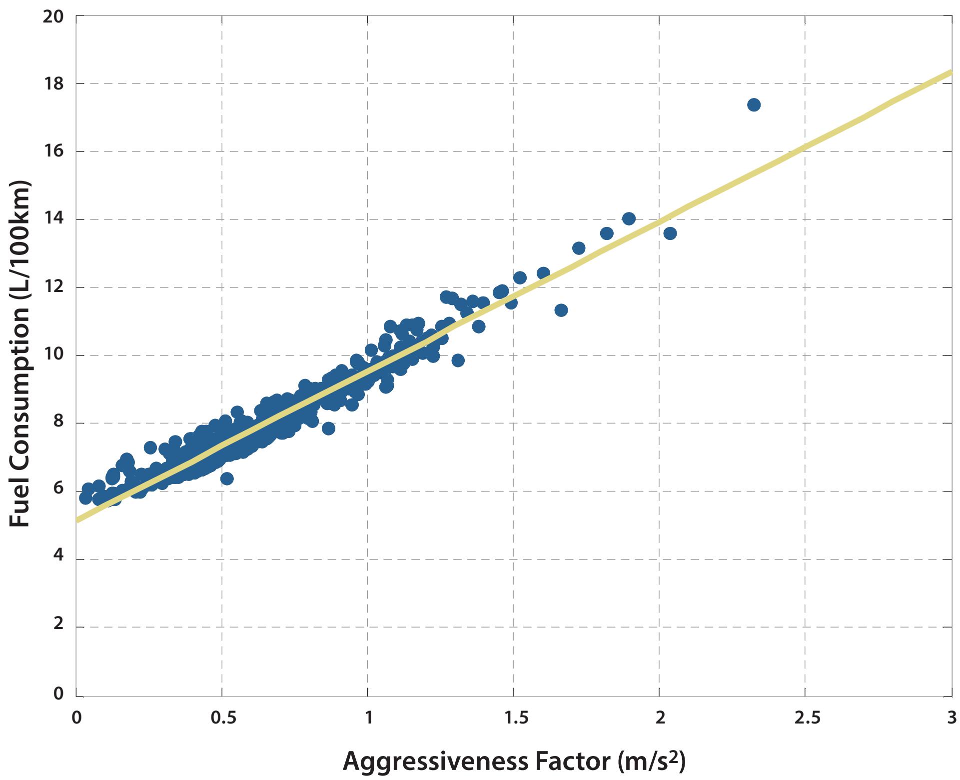

Figure 8.4 Relationship between city aggressiveness factor and fuel consumption for Ford Focus vehicle.

In addition to providing a tool to quantitatively compare driving cycles, each of the three aggressiveness factors provides insight into the driving behaviors that most impact fuel consumption in the associated speed band. For city driving, acceleration and fuel consumption are the key determinants of aggressiveness. Figure 8.5 shows instantaneous aggressiveness factors for the Ford Focus over a range of accelerations and city velocities. This figure is for illustrative purposes only to help interpret city driving. It is not a look-up table of aggressiveness factors, which are based on average driving, not instantaneous driving. Nonetheless, Figure 8.5 shows graphically how the city aggressiveness factor depends on acceleration but not on speed. Thus, driving less aggressively in this speed range is more about accelerating more gently than about adjusting speed.

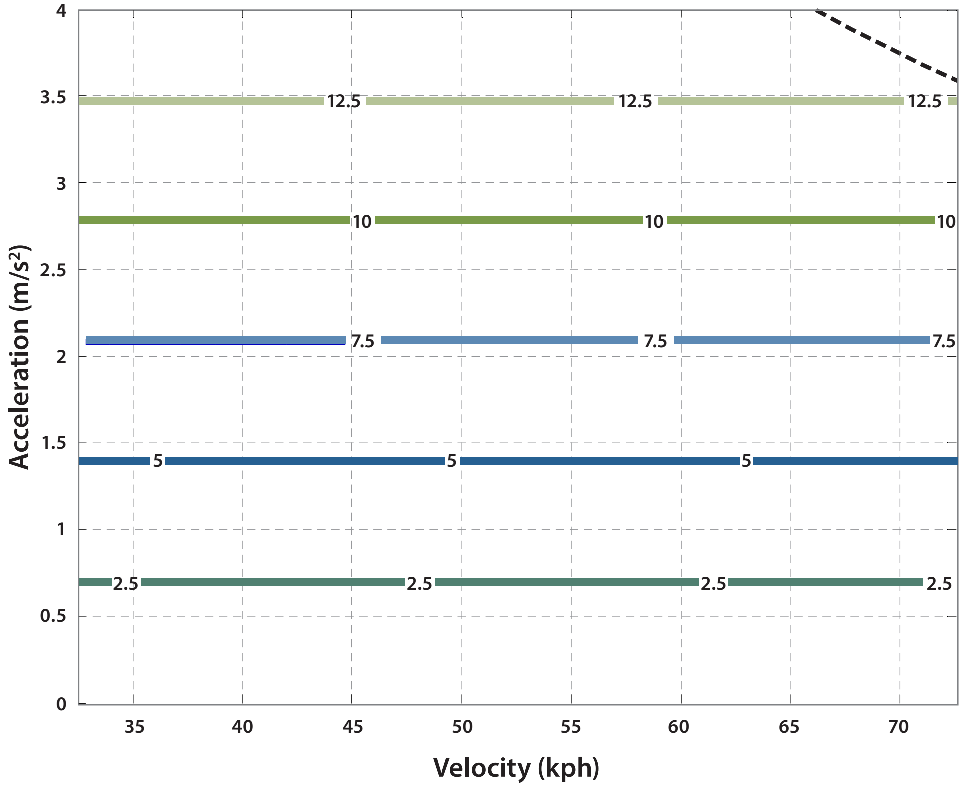

Figure 8.5 Instantaneous city aggressiveness factors for a range of accelerations and velocities.

8.3.3 Aggressiveness Factor for Highway Driving

Highway driving is taken as any driving with average speed greater than 45 mph (72 km/h). Figure 8.6 plots the wheel work and the fuel consumption for 310 drive cycles that fall into the highway driving band. Wheel work alone is closely correlated with fuel consumption. To ensure that the city and highway aggressiveness factors are equal at the threshold speed, wheel work was adjusted by subtracting the constant-speed wheel work at the threshold speed (45 mph).

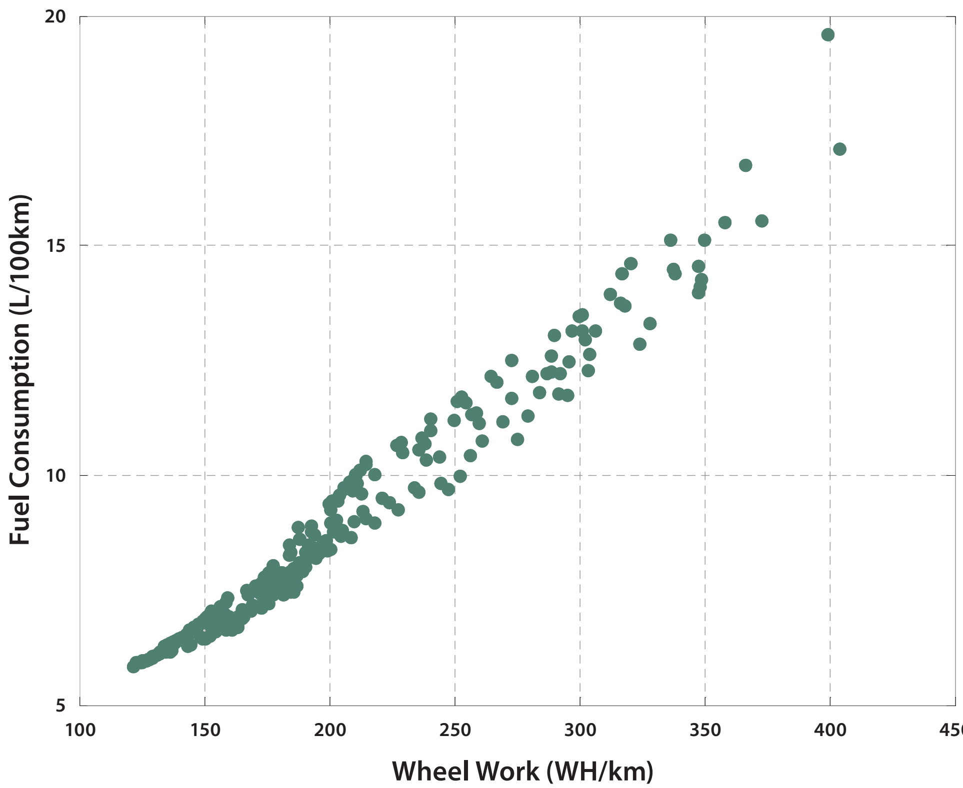

Figure 8.6 Wheel work and fuel consumption for Ford Focus vehicle over 310 speed traces in the highway speed band.

As with city driving, the adjusted wheel work value is then normalized by vehicle mass to give the aggressiveness factor (in units of acceleration). The final aggressiveness factor for highway driving can be expressed in words as:

$$\textit{Aggressiveness factors} = \frac{\textit{Wheel Work} - \textit{Steady Speed Wheel Work at 45 mph}}{\textit{Mass}}$$

Intuitively, this highway aggressiveness factor can be understood as capturing increased fuel consumption due to *both* higher average speeds *and* variation in speed around that average. As shown in Figure 8.7, the highway aggressiveness factor is linearly correlated with fuel consumption at average speeds exceeding 45 mph. For the Ford Focus, every 1 m/s^2 increase in city aggressiveness factor causes an increase of 4.4 l/100km in fuel consumption, approximately the same as for city driving.

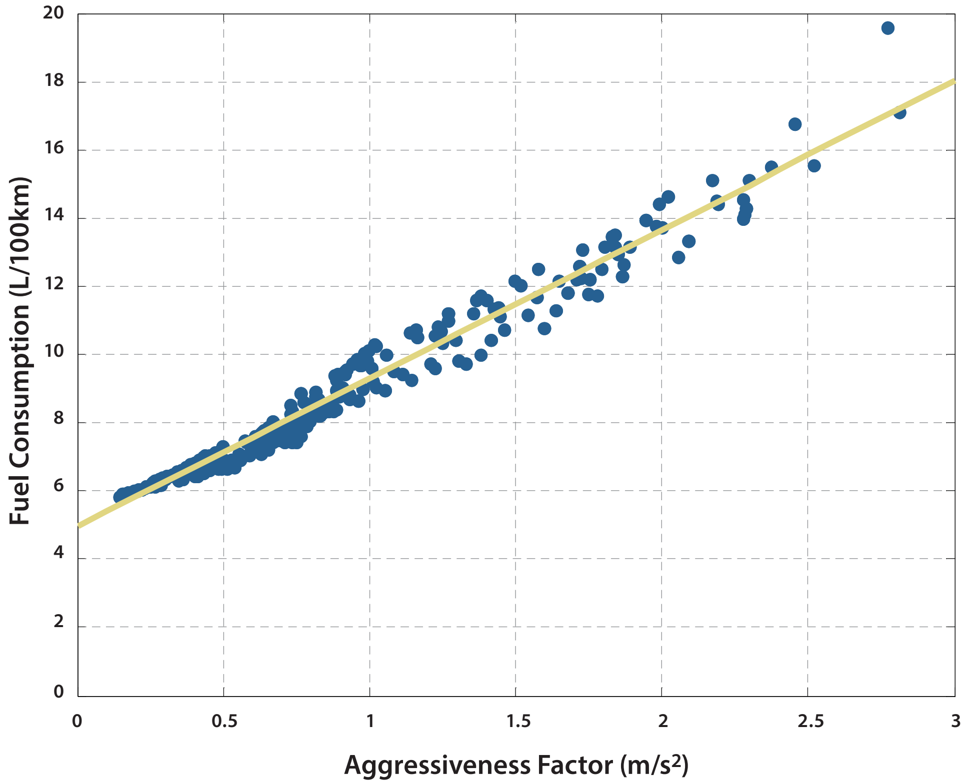

Figure 8.7 Highway aggressiveness factor and fuel consumption for Ford Focus vehicle over 310 highway drive cycles.

As with the city aggressiveness factor, the highway aggressiveness factor equation allows us to identify the key features of highway driving that impact fuel consumption. Here, any increase in wheel work causes a proportional increase in consumption, regardless of whether that increase in wheel work came from either high acceleration or higher average speed. As shown in Figure 8.8, while the aggressiveness factor is heavily dependent on acceleration, it is also dependent on velocity. Not only does the aggressiveness factor increase at higher speeds, but so too does its sensitivity to acceleration. For illustrative purposes only, Figure 8.8 shows the instantaneous aggressiveness factor for the Ford Focus for a range of accelerations and highway velocities. The upper bound represents the maximum acceleration of the vehicle, which decreases as velocity increases. The plot illustrates that, at highway speeds, accelerating more gently is still key to driving less aggressively, but moderating speed helps as well.

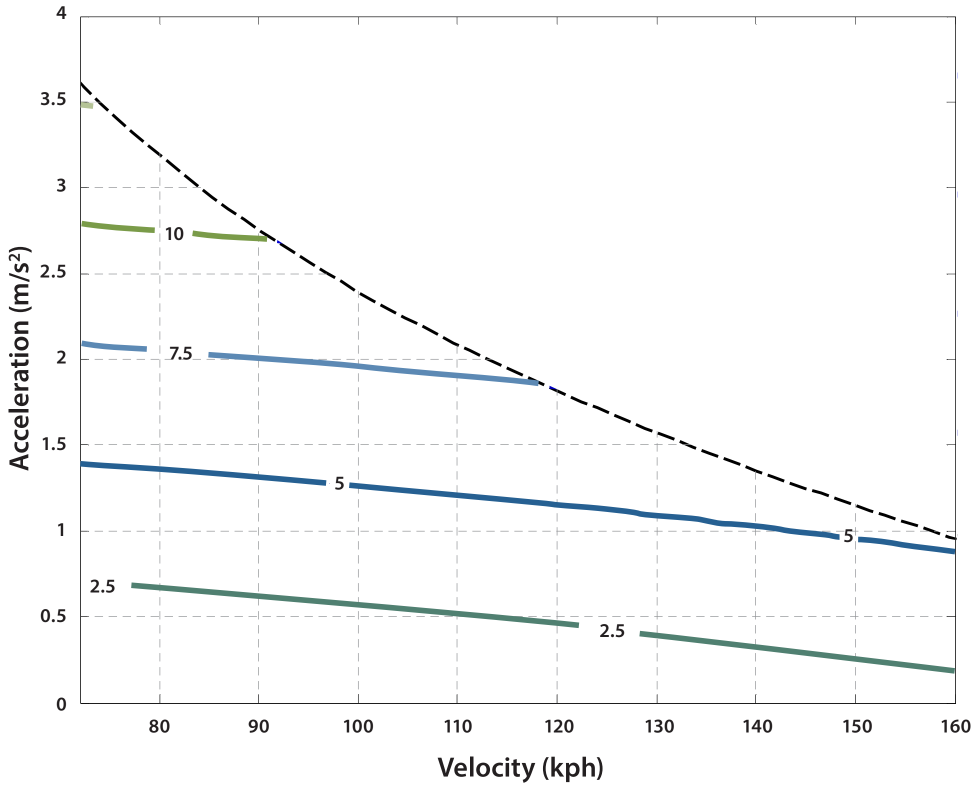

Figure 8.8 Instantaneous highway aggressiveness factors for a range of velocities and accelerations.

8.3.4 Aggressiveness Factor for Neighborhood Driving

Neighborhood driving is taken as any driving with average speed less than 20 mph (32 km/h) and is the most complicated to characterize in terms of aggressiveness. This is due primarily to the large effect of vehicle speed. As shown by Berry (2010), for steady-speed driving at less than 20 mph, vehicle efficiency falls rapidly with decreasing vehicle speed, causing dramatic increases in per-mile fuel consumption. As a result, during neighborhood driving, wheel work has very little correlation with fuel consumption. This is evident in Figure 8.9, which plots wheel work and fuel consumption for 280 speed traces that fall within the neighborhood speed band.

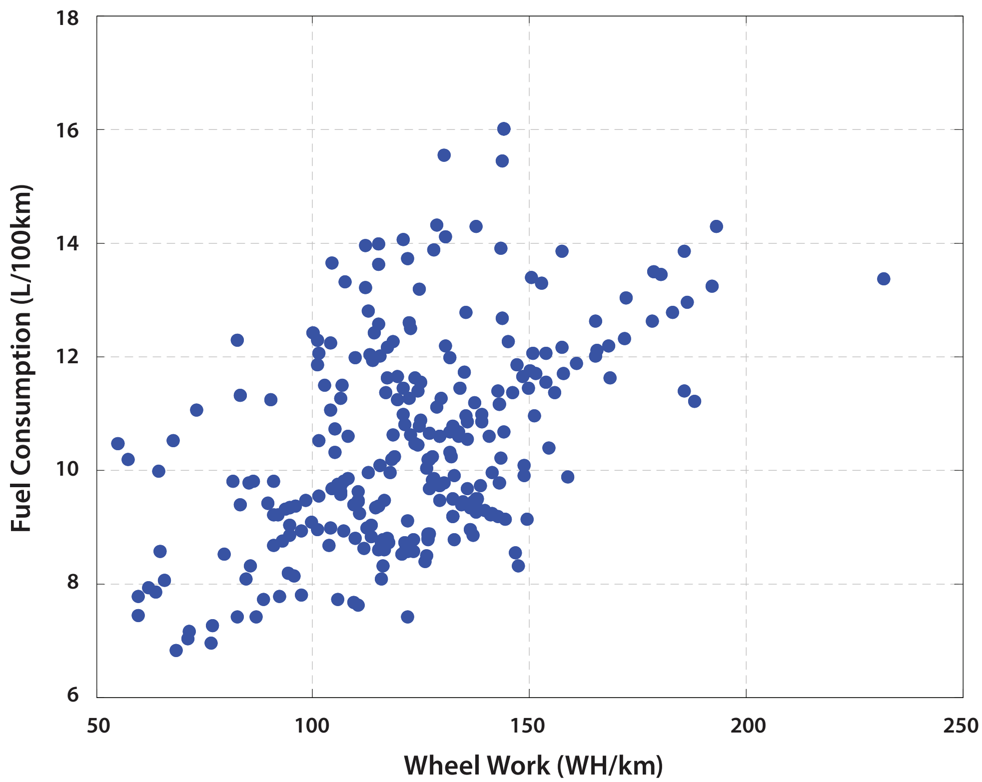

Figure 8.9 Wheel work and fuel consumption for Ford Focus over 280 speed traces with average speeds of less than 20 mph.

In order to capture the role of average speed in fuel consumption during neighborhood driving, extra terms are needed that relate the average speed of the cycle to some reference speed. In this case, the reference speed is taken to be 20 mph (32 kph), the upper bound on neighborhood driving. First, the wheel work term (numerator) is generated by adding the acceleration wheel work of the cycle to steady-speed wheel work at 20 mph. Then, the ratio of the reference to average speed is applied as a multiplier. These terms account for the fact that vehicle efficiency decreases dramatically with decreasing vehicle speed. The reference speed was chosen to be 20 mph, in order to optimize the overall fit while maintaining a consistent trend between aggressiveness factor and fuel consumption for all neighborhood driving. A slightly higher reference speed would improve the overall fit, but selecting a reference speed above the neighborhood/city split (20 mph) distorts the trend.

This value is then normalized by vehicle mass as with city and highway driving. The final aggressiveness factor can be expressed in words as:

$$AF_{\text{Neighborhood}} = \left(\frac{(\text{Acceleration Wheel Work} + \text{Steady-Speed Wheel Work at 20 mph})}{\text{Mass}}\right)\left(\frac{\text{20 mph}}{\text{average speed}}\right)$$

Figure 8.10 shows the relationship between the neighborhood aggressiveness factor and fuel consumption at speeds below 20 mph. For the Ford Focus vehicle, every 1 m/s^2 increase in neighborhood aggressiveness factor causes an increase of 2.6 L/100km in fuel consumption.

For neighborhood driving, speed has the largest overall impact on aggressiveness. As speed decreases, the aggressiveness factor increases, but so does the sensitivity of the aggressiveness factor to acceleration. This is shown clearly in Figure 8.11, which is, again, for illustrative purposes only.

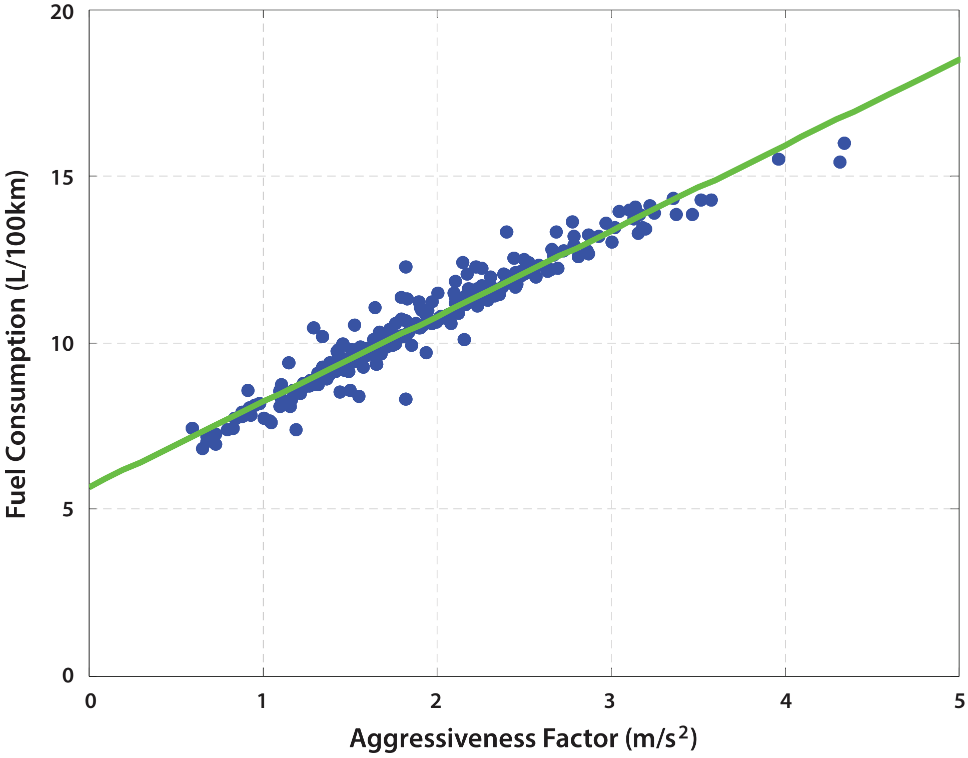

Figure 8.10 Neighborhood aggressiveness factor and fuel consumption for Ford Focus over 280 drive cycles that fall into the neighborhood speed band.

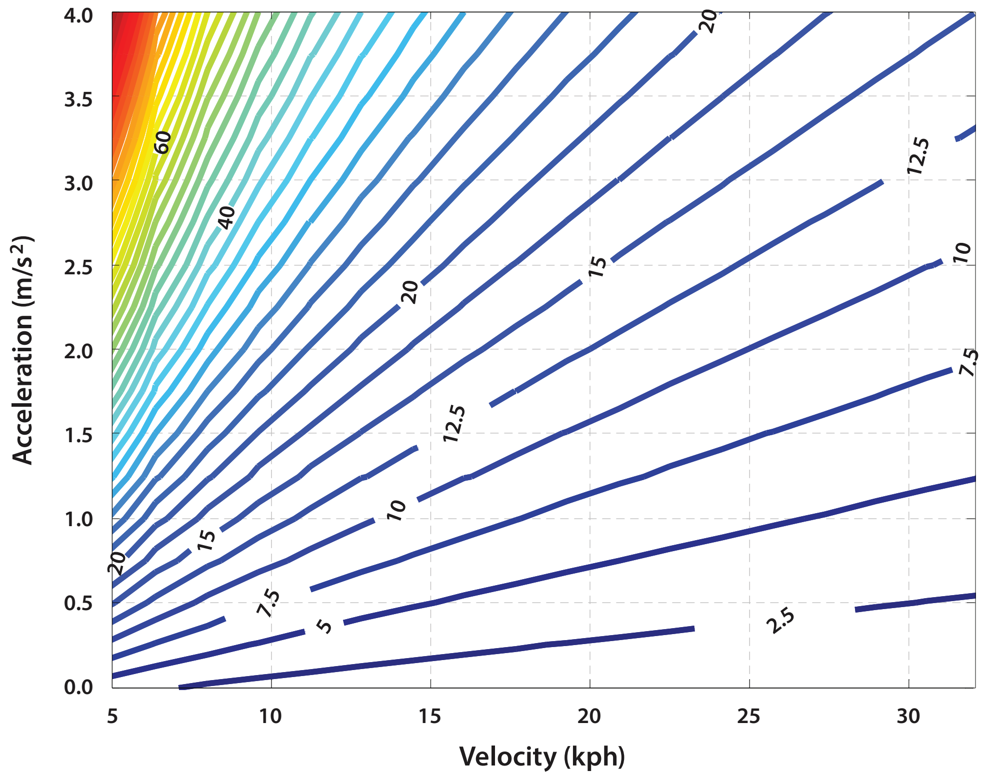

Figure 8.11 Instantaneous neighborhood aggressiveness factors for Ford Focus vehicle over a range of speed and acceleration values in the neighborhood speed band (< 20 mph).

8.3.5 Aggressiveness of Standard Drive Cycles and Real-World Driving

One application of the aggressiveness factors is to compare standard drive cycles to each other and to real-world driving. Table 8.1 lists the fuel consumption and aggressiveness factor for the Ford Focus for a range of drive cycles from the United States, Europe, and Japan. The four cycles used for the post-2008 EPA fuel economy labels are highlighted. Of the neighborhood cycles, the FTP falls between the Economic Commission for Europe (ECE) and Japan 10-mode cycle. Only one of the four U.S. regulatory drive cycles is a city cycle: the SC03. This cycle has similar aggressiveness as the New European Driving Cycle (NEDC) and is much more aggressive than the Extra Urban Drive Cycle (EUDC) and Japan15 cycles. The newer U.S. cycles, the ARB02 and LA92 are the most aggressive city cycles. Of highway drive cycles, the Highway Fuel Economy Test (HWFET) and the US06, both regulatory U.S. cycles are the least and most aggressive, respectively. Neither the E.U. nor Japan has a regulatory drive cycle with average speed greater than 45 mph.

Table 8.1 Fuel consumption and aggressiveness factors for Ford Focus vehicle over selected United States and international standard drive cycles. The four highlighted drive cycles are those used by U.S. EPA for fuel economy labeling purposes.

Drive Cycle	Fuel Consumption (L/100km)	Cycle Description	Aggressiveness Factor (m/s^2)
Neighborhood Cycles			
Japan10/15	9.36	Japanese Reg.	1.53
FTP	8.39	U.S. Reg.	1.54
Japan10	10.67	Japanese Reg.	1.76
ECE	10.52	European Reg.	1.77
INRETS urb	10.67	Other European	1.92
INRETS urb3	11.36	Other European	2.15
INRETS urb1	11.38	Other European	2.17
NY City	16.02	Other U.S.	4.29
City Cycles			
EUDC	6.76	European Reg.	0.41
Japan15	7.74	Japanese Reg.	0.44
INRETS road2	7.21	Other European	0.52
INRETS road1	7.83	Other European	0.56
NEDC	8.14	European Reg.	0.63
SC03	8.64	U.S. Reg.	0.67
INRETS road	7.91	Other European	0.72
ARB02	8.75	Other U.S.	0.77
LA92	8.95	Other U.S.	0.86
Highway Cycles			
HWFET	6.05	U.S. Reg.	0.22
Rep05	7.61	Other U.S.	0.61
INRETS hwy	8.03	Other European	0.76
INRETS hwy1	8.61	Other European	0.77
US06	8.92	U.S. Reg.	0.81

The aggressiveness of the standard drive cycles can be compared with that of real-world driving. Across all driving in a 100-car study conducted in Northern Virginia and metropolitan Washington, D.C., the average (city) aggressiveness factor was 0.80 m/s^2, which is at the higher end of the range of all city cycles reported in Table 8.2.

In a smaller but more granular study of drivers in Boston, MA, and Greensboro, NC, the average (city) aggressiveness over all driving in the study was 0.54 m/s^2, considerably lower than that found in the 100-car study. For the 446 individual trips that had an average speed from 20–45 mph, the average city aggressiveness factor was 0.42 m/s^2, with a standard deviation of 0.10 m/s^2. Among the 38 trips with an average speed above 45 mph, the average highway aggressiveness factor was 0.55 m/s^2, with a standard deviation of 0.13 m/s^2. This is well above the aggressiveness of the HWFET used for determining compliance with fuel economy standards. Among the 313 trips with average speeds below 20 mph, the average aggressiveness factor was 1.35 m/s^2, with a standard deviation of 0.78 m/s^2.

8.3.6 Using and Interpreting the Aggressiveness Factors

The aggressiveness factors described here are metrics that combine and quantify the impacts of driving behaviors on both wheel work and vehicle efficiency. Although aggressiveness factors have the units of acceleration, they are not accelerations and are not proportional to any acceleration values. They are mass-normalized, distance-weighted measurements of the driving behaviors that increase fuel consumption. As a result, the aggressiveness factors illuminate which behaviors have the greatest impact on fuel consumption in each of the three speed bands. They also allow us to quantify driving behaviors in a way that is proportional to fuel consumption. This means that we can compare drive cycles, driving patterns, and drivers using a single metric. However, it is important to understand the key features and limitations of the aggressiveness factors, which are discussed in more detail by Berry (2010) and summarized here.

1. **Neighborhood, city, and highway aggressiveness factors are not interchangeable or directly comparable.** Although they share the same units, the different calculation methods produce different values of aggressiveness factor even for the same vehicle and driving patterns.

2. **The aggressiveness factors are distance-weighted.** As long as they are of the same type (neighborhood, city, or highway), the aggressiveness factors from multiple trips can be combined through distance-weighted averaging to obtain the average aggressiveness of the combined trip.

3. **Aggressiveness factors vary slightly between vehicles.** Aggressiveness factors depend on parameters estimated from a coast-down test, which differ from vehicle to vehicle. Practically speaking, however, the resulting differences in aggressiveness factors are small, and the aggressiveness factors for one vehicle can be usefully projected onto another vehicle.

4. **Sensitivity of fuel consumption to aggressiveness varies by vehicle.** This is due mainly to differences in mass, and engine and transmission characteristics, as well as aerodynamics. In general, vehicles with less powerful engines are more sensitive to aggressiveness than are those with more powerful engines.

Table 8.2 Overview of literature evaluating potential energy savings through eco-driving.

Citation	Study Type and Size	Short-Term	Long-Term
Quality Alliance			11.7%
Eco-Drive (2004)	Driving instructors and experts in Switzerland		12% (8 months) 21% (17 months)
	Eco-Drive course		12%
	simulator course	15%	17%
	simulator driving		25% (max)
	Eco-training as part of the new driver training		0%
Henning (2008) (Ford of Europe)	German-wide (1998–2000); 300 participants	25% (average)	15% (max) 10% (average)
	Leipzig Motor Show; (74 people trained)	26.1%	
	Frankfurt Motor Show; (765 people trained)	20.65%	
Ford Motor Company (2008)	Intense 4-day class	24% (average)	
Onoda (2009)	Summary of Eco-Drive Program in Europe	5% to 15%	5% (no feedback) 10% (w/feedback)
Vermeulen (2006)	Study by TNO: 24 drivers over predefined route		7% (gasoline) 8% to 10% (diesel)
Taniguchi (2007)	Study of eco-driving training	20%	
Beusen and Denys (2008)	VITO study of 8 drivers following training		-1.7% to 7.3%
Beusen et al. (2009)	VITO study of 10 drivers following training	12% to -3% 5.8% (average) (4 months)	
Barth and Boriboonsomsin (2009)	Simulations with limited real-world experiments	10% to 20%	
Bragg (2009) (FuelClinic.com)	620 FuelClinic.com users following driving tips	5.23%	
Saynor (2008) (Ford Motor Company)	Driving trials by Ford Motor Company and Energy Savings Trust: total of 494 drivers	17% to 25%	
Mele (2008)		35% (average)	
WBSD (2008)	Fuel economy training courses offered by Volkswagen and Naturschutzbund Deutschland	13% (average) 25% (max)	

8.3.7 Reducing Aggressiveness: Eco-driving

Eco-driving is a way of driving that uses less fuel. It involves following a set of techniques such as upshifting to avoid engine speeds over 2,500 rpm, maintaining steady vehicle speed, anticipating traffic, accelerating and decelerating smoothly, and avoiding long idles. Although most eco-driving advice includes lower highway speed, eco-driving is most common in city or urban driving, where fuel savings can be achieved without lowering the average speed or planning for longer travel times.

There are wide-ranging estimates of the fuel that drivers can save by employing these and other related techniques for saving fuel. Table 8.2 summarizes the fuel savings projected by some of these studies. Additional estimates are summarized by the International Transport Forum [ITF, 2007]. Of note, the short-run savings seem to be greater than the long-run savings. For example, Degraeuwe and Beusen (2013) found that without continual reminders, drivers who took an eco-driving course reverted to less-efficient habits over time. In general, over the long term, a 5%–15% reduction in fuel consumption seems feasible through eco-driving. However, the overall percentage of fuel that might be saved depends on a combination of an individual's willingness to drive differently and the sensitivity of the specific vehicle to changes in driving aggressiveness. The above discussions are based on "each vehicle." The overall impact depends on the fraction of drivers who make these positive adjustments to their driving behavior.

8.3.8 Charging Behavior: Increasing Petroleum Displacement and Reducing Emissions

Plug-in electric vehicles (PEVs), including both pure battery electrics (BEVs) and plug-in hybrids (PHEVs), are entering the vehicle mix in small but growing numbers. These vehicles present both new opportunities for cutting emissions and saving petroleum, and new challenges in assessing their impacts.

Powering vehicles with electricity introduces new uncertainties into assessments of their environmental impacts. Unlike petroleum-based fuels, which are stored between refining and use, there is virtually no capacity for storing electricity. As a result, the source of the electricity—the location of generation, its fuel source and efficiency, associated emissions, and transmission losses—depends directly on the specific time and location of charging [Peterson, Whitacre, and Apt, 2011]. In the case of PHEVs, there is a further source of variability. The relative mix of gasoline and electricity used by the vehicle depends on the distribution of trip lengths and on charging decisions made by the operator.

Due to limited market penetration, most existing knowledge of PHEV usage and energy consumption, such as the impact of battery size and the grid impact of recharging, is based on analysis of known mobility patterns, surveys, and retrofitted hybrid vehicles [Denholm and Short, 2006; Hadley and Tsvetkova, 2007]. Various efforts have attempted to develop more realistic assessments of how PHEVs will perform in the real world. Vehicle-level simulation has been used to model the effects of design attributes and control strategies [Gonder and Simpson, 2006; Vyas, Santini, and Johnson, 2009], while survey data and, more recently, GPS-based datalogging are used to characterize driving patterns [Vyas, Santini, and Johnson, 2009; Lin and Greene, 2011; Khan and

Kockelman, 2012; Gonder, Markel, and Simpson, 2007]. The validity of these approaches requires an assumption that driving behavior will be the same for PHEVs as for conventional vehicles.

Charging behavior is an area of even greater uncertainty. Due to a lack of real-world data, charging behavior in existing work has been largely assumption driven [Khan and Kockelman, 2012] or based on small samples. Axsen and Kurani (2008) surveyed respondents about possible charging behavior, based on availability and perceived importance. Davies and Kurani (2010) reported results from a study of 40 vehicles for a one-week period during which the authors identified a mean of one daily charge, including two participants who did not recharge at all. Williams et al. (2011) noted the paucity of real-world information on recharging behavior, and presented the results of one prototype PHEV vehicle rotated among 12 households over one year to gather more information on real-world charging behavior. Using small samples to predict fleet-wide impact generates substantial uncertainty [Gonder, Markel, and Simpson, 2007].

This section summarizes key results from a yearlong study of 125 instrumented PHEVs deployed around the United States. The results show that the fraction of miles powered by electricity was highly variable, even for identical vehicles. In addition, they show that charging behavior is heterogeneous, and depends on a large number of variables. The vehicles in this study were based on the 2010 Toyota Prius, equipped with 3 kWh of working battery capacity in charge-depleting mode, and could be recharged from 110 V or 220 V outlets.

Heterogeneity in Petroleum Displacement by PHEVs

The amount of petroleum that is displaced by electricity is an important figure of merit for PHEVs, as it is closely tied to the cost-effectiveness, energy security, and environmental benefits of those vehicles. A petroleum displacement factor (PDF) can be defined as the ratio of distance powered by electricity to total distance traveled:

$$PDF = \frac{Dist_{Electrified}}{Dist_{Total}}$$

The PDF is similar in concept to the utility factor (UF), which is the fraction of miles traveled in charge-depleting mode:

$$UF = \frac{Dist_{CD}}{Dist_{Total}}$$

UF and PDF are, by definition, identical for vehicles that lack a blended operating mode.[20] However, for vehicles that use blended mode, UF will overestimate fuel displacement because a portion of the tractive force during charge-depleting (CD) mode is derived from petroleum.

Figure 8.12 displays the distributions of utility factor and petroleum displacement factor

[20]Blended mode is a PHEV operating mode in which tractive energy is provided by both a liquid fuel and from discharge of the battery, with the battery's state of charge declining over time. It is contrasted with EV-mode, in which energy comes only from the battery, and with charge sustaining mode, in which the battery's state of charge exhibits no longer-run time trend.

values that were calculated over the 125 vehicles in this study. The average PDF over all vehicles in this trial was found to be 13.7%, and the average UF was 28.1%. The average PDFs and UFs observed in this trial are lower than predicted by the methods of SAE standard J2841 standard for UF. This is likely due to differences in the distribution of trip lengths between this trial and the National Household Transportation Survey that underpins J2841, and to charging patterns deviating from the once-a-day assumption used in J2841.

There was a very wide spread in the values of PDF and UF across different vehicles, even though all vehicles were of the same design. The highest PDF was 59%, indicating that with the right combination of driving patterns and charging habits, even a very small battery can displace a large amount of gasoline. On the other hand, five of the 125 vehicles in the study had PDFs of less than 1%, and another 16 had PDFs between 1% and 5%, indicating that they derived almost none of their energy usage from grid electricity.

A Model of Charging Choices in PHEVs

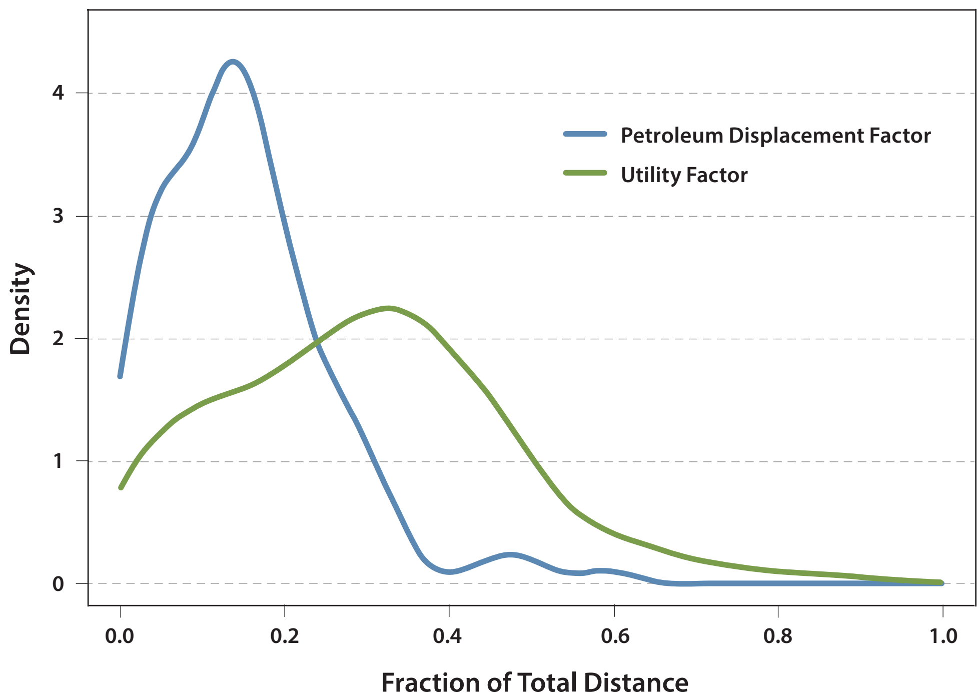

Figure 8.12 Distributions of petroleum displacement factors and utility factors over 125 PHEVs.

Although PHEV analyses are increasingly grounded in real-world driving patterns, there has been very little data collected on charging behavior, because of the dearth of PHEVs and BEVs in real-world service. As a result, assessments of these vehicles to date have relied on assumptions about how people might charge their vehicles. In this section, a mixed effects logistic regression model is presented, with results that tend to validate the belief that overnight charging is the most likely charging behavior. However, the results also show significant heterogeneity in the relationship between various predictors and the probability of charging for different vehicles. The mixed-effects logit specification is shown below:

$$P(Charge_{it}) = \frac{e^{V_{it}}}{1 + e^{V_{it}}}$$

Where $Charge_{it}$ is a binary variable indicating whether vehicle i was charged at the end of trip t, and V_{it} can be interpreted as the observable portion of the utility of charging U_{it}. (Since there is no information on whether a charging point is available at each stop, what is modeled here is the probability of locating and using a charging point.)

$$U_{it} = V_{it} + \varepsilon_{it} = X_{it}\beta + Z_{it}b_i + \varepsilon_{it}$$

In the equation above, X_{it} is a vector of variables characterizing the conditions encountered by vehicle i at the end of trip t, and β is a vector of fixed effects and coefficients capturing the average effect of those variables on the utility of charging. Z_{it}, which may be the same as X_{it}, is a vector of variables with effects that vary over the vehicles in the sample, and b_i is a vector of independent, normally distributed random effects which capture heterogeneity in the effects of the variables in Z. The final term, ε_{it}, represents the unobserved utility and is assumed to be independently, identically distributed (i.i.d.) with extreme value distribution. The utility of choosing not to charge is normalized to zero by assumption.

The model tested the dependence of charging on the battery's state of charge (SOC), expressed as percentage of working battery capacity at the end of the trip, characteristics of the completed trip, the time until the next trip, and the day and time at which the trip was completed. Initially, both fixed and random effects were estimated for all of the independent variables. Random terms relating to the hours before the next trip were dropped from the model after initial analyses indicated that they would have no practical significance. State of charge was included linearly, along with dummy variables indicating that the battery was fully charged or depleted, with the expectation that the probability of charging would increase as the battery is depleted. The length of the completed trip was included, since longer trips might make drivers more aware that the battery is depleted (alternatively, longer trips might leave a driver more fatigued and less likely to plug in). Also included were dummy variables indicating whether the trip was the last trip of the day, or ended at the same place the vehicle started the day, both of which tend to be associated with overnight stops. Finally, dummy variables were defined to identify the approximate time the trip ended, and whether it ended on a weekend or a weekday.

The results of the model estimation, which was done using the *lme4* software package in R, are presented in Table 8.3. The parameter estimates and associated standard errors are presented for the fixed effects/constant coefficients in the first column. The estimated standard deviations of the random parameters are presented in the second column. Because of the asymmetry in the sampling distribution of the random parameters, standard errors are not reported and significance testing was not based on t-tests. Instead, significance of each random parameter was assessed using likelihood ratio tests on restricted versions of the model in which the random parameter in question had been dropped. The test statistic for the likelihood ratio test is provided in parentheses for each random parameter; under the null hypothesis these will be χ^2-distributed with 1 degree of freedom.

Looking first at the fixed effects, the time before the next trip is strongly related to whether a vehicle is charged at the end of a trip. For times up to three hours, the probability of charging increases with the waiting time. However, above three hours, there is essentially no change in the probability of charging. There are at least two possible explanations for this result. First, three hours is the approximate time needed to fully charge these vehicles, so it is possible that drivers would only want to plug in when they know they have enough time for a full charge. Alternatively, it is possible that three hours' worth of charging is the minimum that drivers are willing to accept in return for the inconvenience of plugging in. Distinguishing between these hypotheses would be more practical with charging data from some other types of plug-in vehicles.

The last trip of the day and one that ends at the location where the day began are each strongly correlated with a higher probability of charging. Combined with the substantial effect of a stop being longer than three hours, these results suggest that the probability of charging overnight is going to be relatively high, since overnight stops are likely to be longer than three hours, the last trip of the day, and to occur at the same place where the vehicle's day began. Trip length had a small effect, and weekends had no significant effect on the probability of charging.

The fixed effect estimate for SOC has the expected sign, indicating that the vehicles were less likely to be plugged in when the SOC was higher. When the battery was already full, the vehicles were much less likely to be plugged in. Surprisingly, an empty battery was associated with a lower probability of charging; it is possible that this is due to empty batteries being more common when vehicles are away from their usual charging infrastructure. Although statistically significant, this effect is relatively small compared with the effects discussed above. The fixed effects for times after noon were significant, indicating a modest reduction in the probability of charging after a trip that ends in the afternoon or, especially, in the late evening.

Turning to the random effects, there is heterogeneity evident in the effects of most variables on the probability of charging, which is significant in both statistical and practical terms. Interestingly, for some variables (ending on weekend, and several time-of-day dummies) there is no fixed effect, but there is a significant random effect. This indicates that although there is no effect of these variables on the probability of charging on average, the effect for some vehicles was positive and for other vehicles was negative.

Table 8.3 Parameter Estimates of Logit Model

	Fixed Effects, β (standard error)	**Random Effects, σ** (LRT statistic on nested model)
Intercept	-3.635 *** (0.113)	0.594 *** (60.3)
Battery State		
Battery SoC (percentage points SoC)	-0.0148 *** (0.0015)	0.009 *** (50.3)
Full battery (>90% SoC)	-2.762 *** (0.278)	0.948 (2.5)
Empty battery (<10% SoC)	-0.342 *** (0.064)	0.329 *** (15.8)
Next Trip		
Hours until next trip	1.007 *** (0.028)	
>3 hours until next trip	2.774 *** (0.081)	0.558 *** (70.3)
(Hours until next trip) * (>3 hours until next trip)	-1.007 *** (0.028)	
Current Trip		
Distance (miles)	-0.003 ** (0.001)	0.003 (0.3)
Last trip of day	0.972 *** (0.117)	1.143 *** (690.3)
Ends at day's starting point	0.655 *** (0.088)	0.840 *** (376.5)
Ends on weekend	-0.035 (0.067)	0.542 *** (71.3)
Trip End Time		
4 AM – 8 AM	0.053 (0.092)	0.551 *** (52.7)
8 AM – Noon	-0.075 (0.082)	0.365 *** (17.3)
Noon – 4 PM	-0.206 * (0.086)	0.395 *** (22.8)
4 PM – 8 PM	-0.202 * (0.096)	0.477 *** (22.6)
8 PM – Midnight	-0.285 + (0.152)	0.864 *** (40.9)
Model Summary Statistics		
Null Log-Likelihood L(0)	-37344	
Model Log-Likelihood L(β)	-16447	
Adjusted ρ^2	0.559	

+ Significant at 0.1 level * 0.05 level ** 0.01 level *** 0.001 level

Behavioral Changes, Design Changes, and Petroleum Displacement of PHEVs

Substantial policy incentives exist to increase the size of batteries employed in PHEVs. For example, U.S. Federal tax credits for PHEVs provide larger subsidies to vehicles with larger batteries. As shown in Figure 8.13, increasing battery size leads to greater petroleum displacement, but with diminishing marginal returns, especially above about 12 kWh (equivalent to about 55 km of electric-powered range for the vehicles in this study).

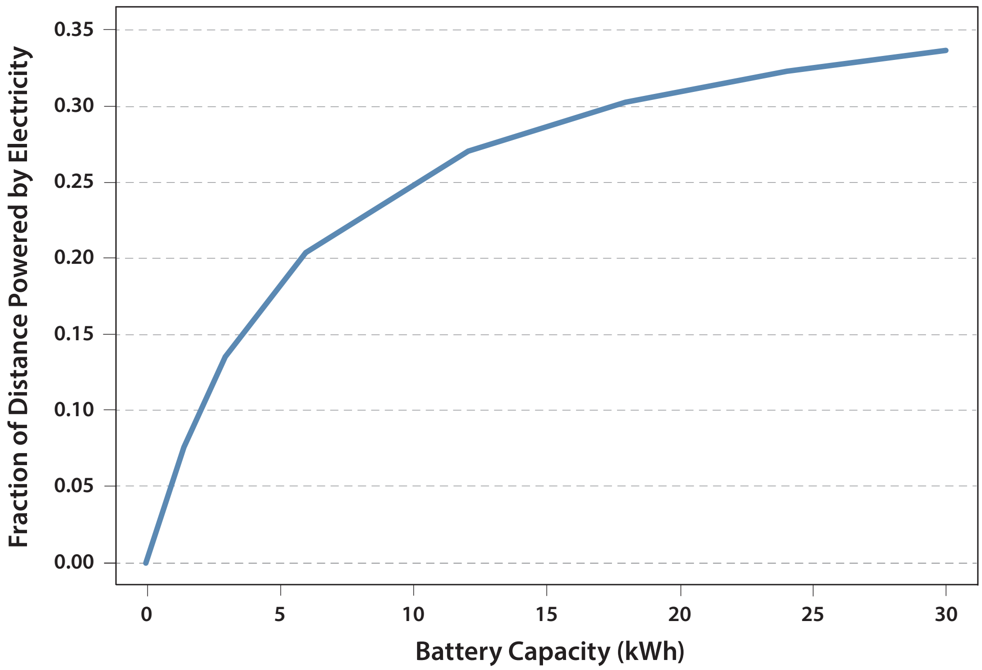

Figure 8.13 Effect of varying battery capacity on petroleum displacement factor, while maintaining travel and charging patterns for 125 PHEVs.

Increasing the frequency of charging can also substantially increase petroleum displacement. Figure 8.14 shows the petroleum displacement factors that would result from drivers charging whenever the dwell time between trips exceeds some threshold value. If drivers in this study had charged at every stop longer than three hours, the average petroleum displacement factor would have increased from 14% to 23%. If they had charged at every stop, petroleum displacement would have increased to 28%, even with a small, 3 kWh battery. This is about the same effect as would be achieved by quadrupling battery size.

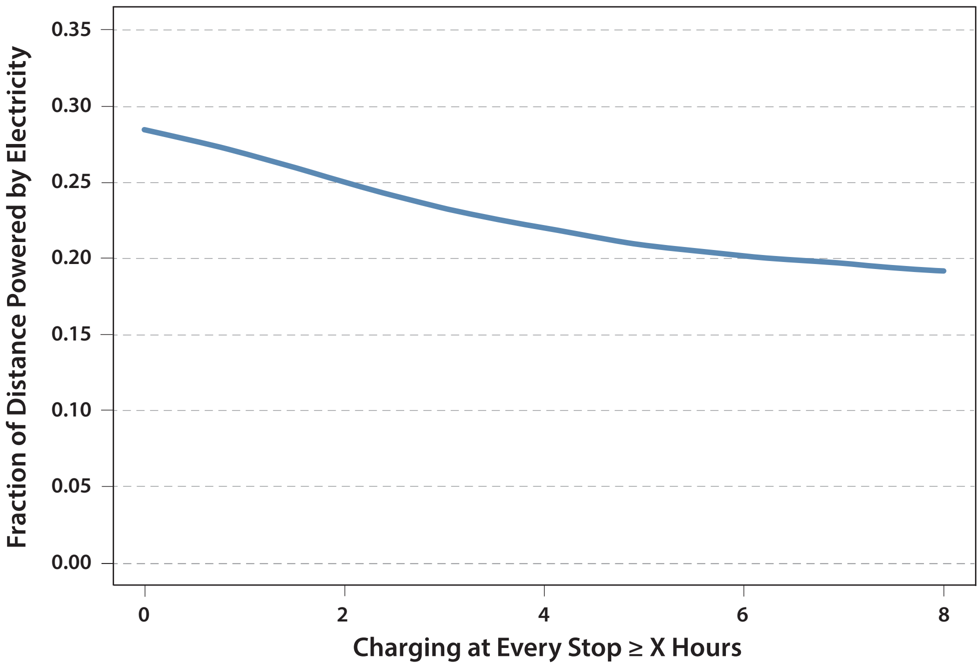

Figure 8.14 Effect of varying charging criteria on petroleum displacement, while maintaining battery size and travel patterns for 125 PHEVs. The X-axis represents a threshold length of stop, such that all stops longer than the threshold value include charging. The extreme left of the plot represents a limiting case in which vehicles are charged after every trip.

8.4 Summary: Traveler and Driver Behavior

Substantial opportunities exist to reduce petroleum consumption and emissions by modifying the decisions of travelers about where and how they travel, how they drive their vehicles, and with PEVs, when and where they charge them. Through 2050, vehicle kilometers traveled (VKT) could be cut by up to 15% by pricing travel and shifting travelers to alternative transportation modes. Operating light-duty vehicles less aggressively could cut energy consumption per mile by 5%–10%. With PHEVs, increasing the frequency of charging could potentially double the amount of petroleum that is displaced by electricity.

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9.0 Scenario Analysis Results

Over the past decade, our *On the Road* group has applied in-use vehicle fleet modeling to multiple regions around the world to project fuel demand and carbon dioxide (CO_2) emissions. These studies encompass the United States [e.g., Bastani et al., 2012a, Khusid, 2010, Chow and Heywood, 2014], major European countries such as France, Germany, Italy, and the United Kingdom [Bhatt, 2010], Japan [Nishimura, 2011], and China [Akerlind, 2013]. The work contained within this chapter draws together results of a number of papers and theses produced within the group over the past five years.

9.1 Scenario Analysis Methodology

The fleet model uses a large set of inputs to generate the four sequential outputs of vehicle stock, vehicle energy demand, vehicle fuel demand, and vehicle CO_2 emissions. In-depth data collection and analysis informs base year values. Other historical data on vehicle oil demand allow for model calibration. Thereafter, combining historical trends, new government policies, expert interviews, and our own analysis and judgments helps to define the future evolution of each input. The models generally encompass both fixed and variable inputs. The scenario analyses described below compare model outputs using various sets of the inputs many of which evolve over time.

Numerous individual inputs set up the fleet model appropriately for the region considered, and define each scenario.

- Type of vehicle: analyses assume one representative vehicle for each vehicle category, and different categories of vehicles and powertrains as appropriate in different countries or regions.

- Future vehicle sales: all analyses project future sales with sales growth rates; growth rates differ among countries.

- Future vehicle scrappage rates: analyses use two different methods to predict vehicle survival: survival curves that require data on average vehicle life span and fleet rate of decay or data that can be used to calculate annual scrappage as a fraction of annual sales.

- Future vehicle kilometers travelled per year (VKT): analyses use exponential decay equations to model VKT, projecting new vehicle VKT through annual percentage changes, and using an exponential mileage degradation rate to determine VKT as vehicles age.

- Future naturally-aspirated spark-ignition (NA-SI) engine vehicle fuel consumption: this is set as either an annual percentage change or by setting a ratio for fuel consumption in a given future year compared with the base year.

- Types of powertrains: Included powertrains are usually a mix of NA-SI engines, turbocharged gasoline engines, diesel engines, and the various types of electric powertrains.

- Future powertrain sales mix: Evolving annual percentage growth rate changes for sales market shares of all alternative powertrains allow the model to calculate sales market shares for all powertrains in any given year.

- Relative fuel consumption across powertrains: Usually determined by updating previous *On the Road* work [e.g., Bandivadekar et al., 2008]; this ratio generally changes little between different model years.

- PHEV utility factor: fraction of total vehicle miles/km driven by electricity.

- Electric motor efficiency.

- Fuels: fleet models have included gasoline, diesel, and other types of alternative fuels—compressed natural gas (CNG), methanol, various biofuels, and hydrogen.

- Fuel energy content: generally constant for each fuel across different studies.

- Fuel source efficiency: energy required to extract, produce, and distribute the "fuel" to the vehicle (well-to-tank [WTT] requirement), relative to energy supplied to the vehicle (tank-to-wheels [TTW] energy).

- Fuel CO_2 emissions or greenhouse gas (GHG) emissions intensity: total life-cycle GHG emissions for each fuel (usually as mass of CO_2 equivalent per unit of energy delivered).

9.2 Incorporating Uncertainty

Scenario analysis involves looking into the future. Many input variables, and their evolution over time, are needed to define a scenario. These variables and their evolution are uncertain. There are uncertainties of several different kinds, each of which increases as we move forward into the future. Many of the inputs to scenario analysis are "averages" which, once we move beyond the present, become less well defined. Thus, growing uncertainty with time is inherent. There is uncertainty in the scenario results due especially to uncertainties in the *rates* at which these inputs change over time. There are also uncertainties in the internal logic and equations of the models used—i.e., their internal workings. An important component of exploring the extent of these uncertainties is to determine the *sensitivity* of key scenario results to changes in the major input variables and assumptions, usually obtained by varying one (or a few) of these parameters in a systematic manner to quantify the degree to which key model output parameters change as a result.

We have employed several approaches to examine the extent of uncertainties and their impact in the various scenario analysis studies of different world regions discussed below. Comparisons between scenarios, where selected assumptions have been chosen to be different, can be used to provide "less-uncertain" information, since such comparisons generate numbers for the *differences* between the scenarios. Several of these aspects of uncertainty and sensitivity will be reviewed as we discuss a wide range of scenario analyses that we have completed over the past several years.

Our recent U.S. light-duty-vehicle (LDV) fleet analyses generated probability distributions for future fuel demand, and other outputs such as GHG emissions [Bastani et al., 2012a] based on distributions of the input assumptions. Our scenarios in Europe, Japan, and China generated sets of discrete projections. Specifically, these analyses created separate scenarios for the evolution of each input variable: usually a reference and a high and low projection [e.g., Akerlind, 2013]. The reference scenario was usually a middle-of-the-road, average, scenario. It presents future LDV in-use fleet energy demand, fleet fuel demand, and fleet CO_2 emissions using the reference set of all input values. In our China-focused studies [Akerlind, 2013], the scenario-based sensitivity analysis retains all input reference values save one which assumes either its high or low value. This generates a "delta" that illustrates the relative importance of each input assumption or driver in projecting future fleet energy demand and emissions. The goal of the sensitivity analysis is to assess the significance of a plausible change in one input relative to a similar change in another, in numeric terms. Therefore, this analysis can group inputs as having a small or large impact on future fleet fuel demand and CO_2 emissions.

The China analysis generates discrete scenarios that also include bounding scenarios that represent the extreme maximum and minimum future fuel demand and CO_2 emission projections by using all the high values or using all the low values for the various inputs generating these two bounding scenarios.

9.3 In-Use Vehicle Fleet Model

The fleet model is best described through a diagram (see Figure 9.1). The grey boxes denote fleet model inputs and the purple boxes denote fleet model outputs. The model generates four sequential outputs: stock size, energy and fuel demand at the vehicle level, then CO_2 emissions. These are then aggregated to give fleet energy, fuel demand, and GHG emissions. The first output, vehicle stock, corresponds with the *volume* component of the vehicle fleet impacts. The vehicle distance traveled input corresponds to the *use* portion of the vehicle fleet impacts, while fuel consumption and powertrain mix together correspond with the *energy efficiency* component. Together, these generate the energy demand output, which is then disaggregated by fuel to calculate the fuel demand output. Finally, specifying the different *fuels* used, and their GHG emissions intensities, then generates the final fleet CO_2 emissions output.

The bottom of the model diagram shows different ways to present the results: for example, total LDV stock, stock by component vehicle types, total fuel demand, fuel demand for different vehicle types, different vehicle fuels, or different vehicle powertrains. It may be relevant to know the amount of gasoline and diesel consumption that alternative fuels displace, even if total energy demand remains unchanged.

A series of equations underlies this schematic view of the fleet model. They follow here in this chapter:

$$\text{Stock}_{v,MY,CY} = \text{Sales}_{v,MY,CY} \times \text{Survival}_{v,MY,MY-CY}$$

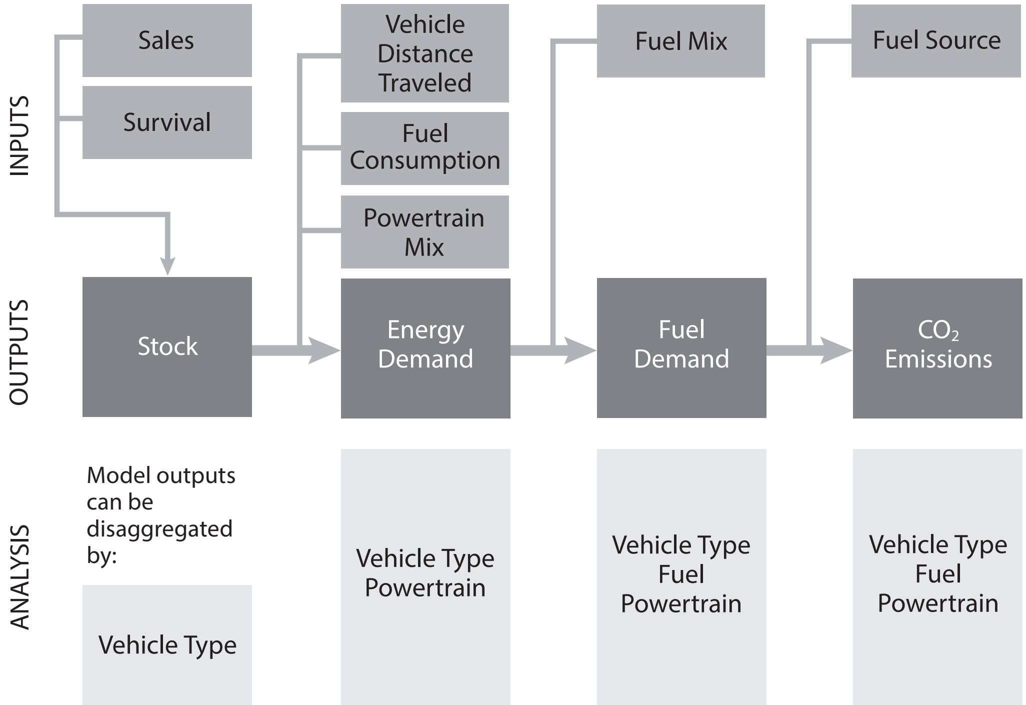


Figure 9.1 Schematic diagram of in-use vehicle fleet model.

The stock of vehicles for a given calendar year (CY), model year (MY) /age ($MY-CY$) and vehicle type (v) is calculated by multiplying the appropriate sales number by the appropriate survival ratio: the probability that a given age vehicle survives for the next year. This survival ratio is based on the average rate at which vehicles of a given age retire from the fleet:

$$\text{Survival}_{v,MY,MY-CY} = \exp\left[-\left(\frac{CY-MY}{T}\right)^{B}\right]$$

where T is the vehicle half life and B is the retirement rate. Survival ration versus vehicle age curves have varied modestly over time scales of a decade or more and differ between world regions. These differences, however, are not that large. Typically, the survival ratio curve is above about 90% for the first 8–10 years of a vehicle's life and falls to below about 10% at 17–20 years.

$$\text{Energy Demand}_{P,CY} =$$

$$\Sigma_{MY,v}\,\text{Stock}_{v,MY,CY} \times_{VKT} \Sigma_{MY,v}\,\text{Stock}_{v,MY} \times \text{VKT}_{v,MY-MY-CY} \times \text{Powertrain}_{v,P,MY} \times \text{FC}_{v,P,MY}$$

Overall energy demand per vehicle powertrain (P) for a given calendar year is determined by multiplying the number of vehicles in a year by how far each vehicle travels in a year (VKT) by the amount of fuel each vehicle consumes to drive unit distance. More specifically, the count of vehicles unique for a given model year, calendar year, and vehicle type is multiplied by the VKT associated with that count. The market share mix for different powertrains for a given model year and vehicle type divides this count and thereafter associates each count of vehicles with its appropriate fuel consumption (FC). Summing over model years and vehicle types gives energy demand per powertrain and calendar year.

$$\text{Fuel Demand}_{f,CY} = \Sigma_P \, \text{Energy Demand}_{P,CY} \times \text{Fuel}_{f,P,CY}$$

Annual fuel demand, broken down by fuel (*f*), is determined by multiplying fuel, the fraction of powertrain energy demand supplied by a given fuel, by the energy demand for a powertrain.

$$\text{Emissions}_{CY} = \Sigma_{f,i} \, \text{Fuel Demand}_{f,CY} \times \text{Source}_{f,i,CY}$$

GHG emissions are determined by classifying each source by fuel and carbon intensity (*i*) and multiplying each fuel's average carbon intensity for a given year with that given year's fuel demand to generate overall emissions.

While the LDV fleet models we used in our scenario analyses have evolved over time, their basic approach and structure have not changed that significantly. In our discussion of each set of scenarios, any additional details important to their understanding are highlighted and referenced.

9.4 Scenarios: USA

9.4.1 Background

Future energy consumption and GHG emissions from LDVs in the United States have been a major focus of our group's scenario studies. In 2011, the United States was the largest petroleum consumer in the world at 18.8 million barrels per day according to the Energy Information Administration (EIA). This accounted for some 22% of total global petroleum consumption. Approximately 70% of the oil consumed by the United States was used by the transportation sector in LDVs accounting for about 60% of the total transportation energy use. Furthermore, transportation in the United States accounted for about 28% of the total national GHG emissions of 6,702 Mt of CO_2 equivalent in 2011. This made it the second largest contributor of U.S. GHG emissions behind only the electricity sector. Transportation's GHG emissions have grown by approximately 18% since 1990 according to Environmental Protection Agency (EPA). These increasing levels of petroleum demand and GHG emissions pose a serious energy supply and global climate change problem. It is becoming ever clearer that one of the several major energy and GHG emissions challenges to which the United States must respond is reducing, as rapidly as possible, these LDV fleet impacts. Our U.S.-focused scenario studies have explored various promising, yet realistic, opportunities to do this.

We will focus here on the energy and petroleum consumption, and GHG emissions, reduction potential from the U.S. in-use LDV fleet over the next several decades. We will outline our mainstream "reference" scenario, characterized as a *realistic aggressive* scenario, which we project out to 2050. This was studied [Bastani et al., 2012a and 2012b] with our LDV fleet model with an approach that utilized a stochastic Monte Carlo methodology to examine the probability of achieving significant reductions in these fuel and GHG fleet impacts. This approach was also used to assess the potential for improvements and changes in powertrains, propulsion system, vehicle technology, size, and performance, to meet U.S. government regulatory "targets," related to the Corporate Average Fuel Economy (CAFE) requirements out to 2025. Several successively more optimistic scenarios were also compared.

The effects of increasing vehicle "electrification" through hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and (pure) battery electric vehicles (BEVs)—all alternatives to standard gasoline spark-ignition engine vehicles—on overall fleet impacts have been examined. The key question here was the effect that the rate of penetration of these more energy-efficient vehicles (especially PHEVs and BEVs), which add electricity to transportation's energy supply, has on the reduction in fleet energy consumption and GHG emissions. The additional impact of a potentially larger supply of biofuels, added to electrification, was also explored [Khusid, 2010].

We have used our LDV fleet model to examine a more focused and pragmatic question: would raising the anti-knock rating of standard U.S. gasoline, and the compression ratio of new gasoline engines in vehicles in parallel, have a significant impact on overall LDV fuel consumption and GHG emissions over the next couple of decades? This study [Chow and Heywood, 2014] additionally illustrates the value of input-driven scenarios using our fleet model.

We will now describe the major findings from these several studies. The primary emphasis will be on their results and their interpretation. Input details related to the fuel consumption and emissions characteristics of the various engine/propulsion system and vehicle technologies likely to be used are summarized in Chapter 3. The relevant characteristics of the various fuels and energy sources involved in these scenarios, and their GHG emissions intensities, are discussed in Chapters 3 and 6. The methodology and structure of the LDV fleet model has been summarized in Section 9.3 above (see Figure 9.1). The deployment rates over time of critical improvements in engine and transmission (or propulsion system), and vehicle technologies, are based on our previous studies of this important question as well as projections from the involved industries and other researchers, and historical trends. Note that the 2007–2011 recession and recovery in the automobile industry caused a significant "blip" in sales, scrappage, VKT, and deployment rates of new technology. We have included this in our fleet model and have assumed that post about 2013 "normal trends" have essentially returned. In our scenarios, we use projections and assumptions related to various time frames, as follows. *Current*, usually our starting point, is pegged to information corresponding to dates between 2008 and 2012, depending on the date of the study and data availability. We define the *near* (or *nearer*) term as the next decade or so (out to about 2025), the *midterm* as from 2025 to 2035, and the *long* (*longer*) term as beyond about 2035. We will show that different types of options or changes are likely to have very different degrees of impact depending on the time scale that we are considering.

9.4.2 Stochastic Modeling of In-Use Fleet Impacts

The work done by Bastani et al., 2012a, 2012b developed and used a Stochastic Transport Emissions and Policy (STEP) Model to analyze technology improvement and implementation, and petroleum and alternative fuel use pathways, including uncertainty, to explore the potential for reducing fleet fuel use and GHG emissions out to 2050. The stochastic approach used in this STEP model is illustrated in Figure 9.2. The 40 or so input parameters in the four categories across the top of the figure are each represented by a distribution with upper and lower bounds and a mode. The shape of the distribution with a given set of constraints was shown to be not that important, so a simple triangular distribution with the peak at the mode was used. The STEP model is effectively a vehicle fleet and technology penetration model (Section 9.3) which is exercised thousands of times using a Monte Carlo assignment process for each input variable value and carrying out thousands of individual fleet calculations. This produces distributions of output variables as illustrated. Also, Tornado Diagrams, which express the change in each output variable divided by a one-standard deviation increase in each input variable above its mean value (one at a time), display in rank order the magnitude of the sensitivities so determined.

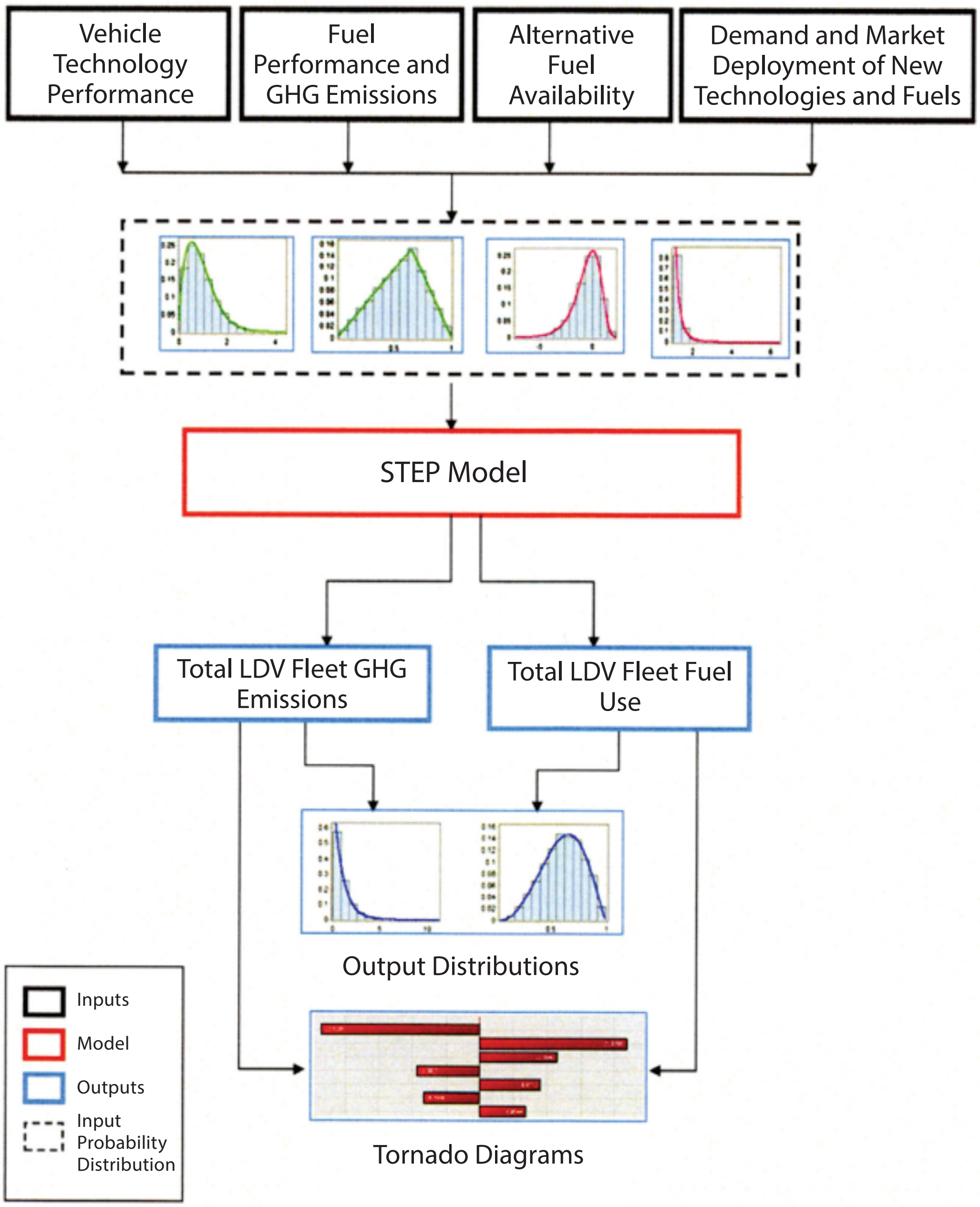


Figure 9.2 Schematic of STEP Vehicle Fleet Model [Bastani et al., 2012a].

The more important inputs for this "reference" *realistic aggressive* scenario are listed in Table 9.1. The logic behind these chosen input values (and the additional inputs) can be found in Bastani et al., 2012b. It is important to understand what these model input parameters represent. Many define the operating characteristics of the average vehicle of a given category and type: e.g., fuel consumption of the average gasoline engine passenger car. That is, variables such as this one represent the behavior of *all* the vehicles of this category and type. As discussed in Chapter 3, where the operating and performance characteristics of these vehicles with different propulsion systems are described and discussed, "all" such future vehicles will not incorporate all the technology improvements—some will include more, some less. In other words, the average vehicle will not have characteristics that are "as good" as the best (or optimum) vehicle.

Table 9.1 Important Inputs into STEP for *the Realistic Aggressive* Scenario [Bastani et al., 2012a].

Parameter	Min	Mode	Max	Mean	STD	COV	Values in 2010
Total light vehicles sales in 2030 ['000]	9,387	18,403	23,000	16,930	2,827	17%	11,500
Future scrappage rate (2011+)	65%	80%	105%	83%	8%	10%	80%
% Sales HEV in 2030	3%	10%	17%	10%	3%	30%	3%
% Sales PHEV in 2030	1%	5%	9%	5%	2%	35%	0%
% Sales BEV in 2030	0%	4%	8%	4%	2%	40%	0%
VKT-annual-growth (2006–2020)	0.26%	0.50%	0.74%	0.50%	0.10%	20%	0.50%
VKT-annual-growth (2030+)	-0.40%	0.00%	0.40%	0.00%	0.16%	N/A	N/A
ERFC Cars	40%	80%	100%	73%	12%	17%	50%
% Blend cellulosic ethanol in 2030	4%	14%	24%	14%	4%	30%	0%
% Electricity from clean sources in 2030	30%	50%	75%	52%	9%	18%	29%
Cellulosic Ethanol WTW in 2030 [gCO_2/MJ]	6	8	14	9	2	18%	10
Gasoline WTW in 2030 [gCO_2]/MJ]	81	92	103	92	5	5%	92
Electricity WTW in 2030 [gCO_2/kWh]	376	970	1,376	908	205	23%	1,078
FC-r NA-SI cars in 2030 (Relative fuel consumption)	0.44	0.70	0.96	0.702	0.105	15%	1.00
FR-r NA-SI light trucks in 2030 (Relative fuel consumption)	0.45	0.71	0.98	0.714	0.107	15%	1.00

Vehicle fuel or energy consumption characteristics are obtained from the relative fuel consumption data in Figure 3.3. This bar chart shows our estimates of the improvements in fuel consumption of a given type of vehicle (e.g., hybrid passenger car) over time, and compares our estimates of the performance of the various propulsion system technology vehicles, under the same circumstances. These relative fuel consumption values are converted to absolute values using the actual on-road (*called adjusted*) fuel consumptions of today's mainstream dominant technology. For a current (2010) NA-SI engine average passenger car and light truck, these calibrating fuel consumptions are 9.2 and 11.8 liters (gasoline)/100 km, respectively, giving a combined value of close to 10.5. These vehicle fuel consumption values are for the situation in which vehicle acceleration performance (characterized by the zero to 100 km/hr, 60 mph, acceleration time) remains essentially unchanged. This has not been the historical pattern (see Section 3.3 and Chapter 5), although the rate of increase in acceleration performance capability is decreasing. We have defined a parameter *Emphasis on Reducing Fuel Consumption* (ERFC) to quantify this trend. An ERFC of 100% corresponds to vehicle acceleration performance remaining the same: ERFC of zero corresponds to the case in which all the fuel efficiency improving technologies embodied into future vehicles are used to offset the negative impact of increased performance on vehicle fuel consumption, so the net result is no significant improvement in the actual fuel consumption. Figure 9.3 shows the estimated effect of ERFCs less than 100% on the fuel consumption of the mainstream technology, the NA-SI gasoline vehicle used in this study. The trend assumed is ERFC increasing from about 50% (in 2010) through 70%–80% in 2030 to 90%–100% in 2050. The worsening impact of this on average vehicle fuel consumption is some 10%, so it is a not-unimportant factor. With alternative powertrain vehicles, the impact of increasing acceleration is expected to be less due to the lower impact on powertrain efficiency as the relative load on the powertrain is changed.

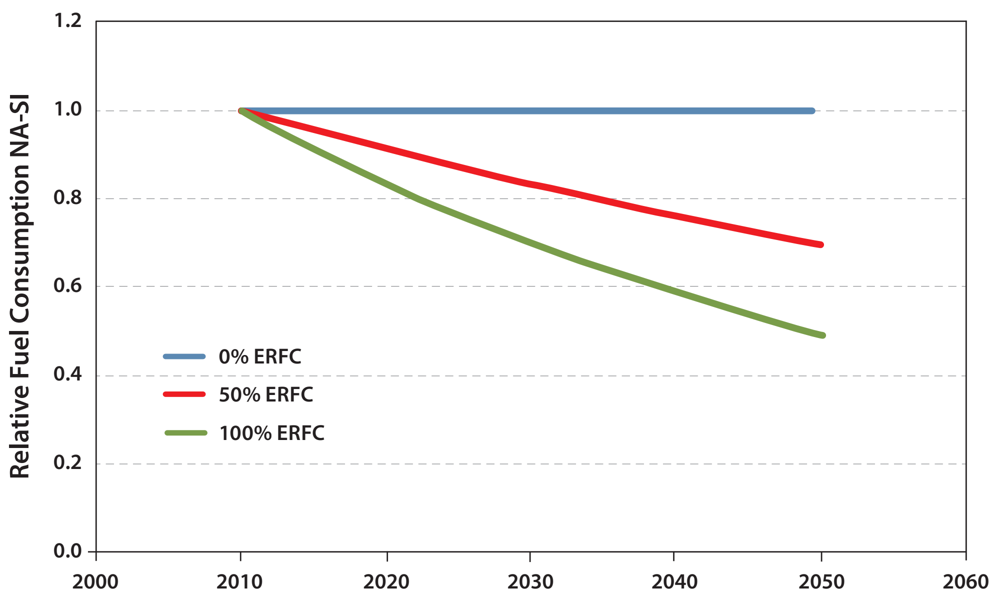


Figure 9.3 Impact of ERFC levels below 100% on relative vehicle fuel consumption (simplified FC-relative-ERFC map).

Figure 3.3 also shows the substantial differences in fuel/energy consumption between vehicles using different propulsion systems. When these per-vehicle fuel consumption numbers are combined with the sales mix among these different technologies an additional path is provided to decreasing fleet fuel consumption. The evolving sales mix over time assumed in this scenario is shown in Figure 9.4. Note that the radical alternative propulsion system vehicles are assumed to grow modestly over this time frame. Overall, "vehicle electrification" (HEV, PHEV, BEV, and FCEV) progresses significantly to about 40% in 2050. Turbocharged engines, gasoline and diesel, are assumed to grow to almost half of the total internal combustion engine vehicle sales (currently, in the United States, these are mostly standard NA-SIs). There is the question as to whether the automotive market would really evolve to this multi-technology state. Viewed as a decreasing internal combustion engine (ICE) based component and an electrified component, it is not really seven different propulsion systems, but a bifurcation. We have assumed that fuel-cell technology and hydrogen fuel, in the in-use fleet, grow slowly. Much will depend on the response that the initial rollout of fuel-cell vehicles (FCV), expected over the next decade or so, evokes from the vehicle-using public. An important issue is developing refueling infrastructure for alternative fuels. Our judgment is that the evolution of more than one major new fuel infrastructure is unlikely over the next few decades, and that new infrastructure is most likely (in the longer term) to be hydrogen. Thus, we do not view natural-gas-fueled LDVs as a significant component of the alternative vehicles and fuels mix. We have emphasized growth in PHEVs (developed from HEVs) as the larger electricity-using component, with BEVs more modest in sales and on-road use. Through their much greater vehicle recharging flexibility, PHEVs and Extended Range Electric Vehicles (EREVs) moderate the impact of electricity use on the electrical supply and distribution system, significantly. This is intended to be a *realistic* scenario.

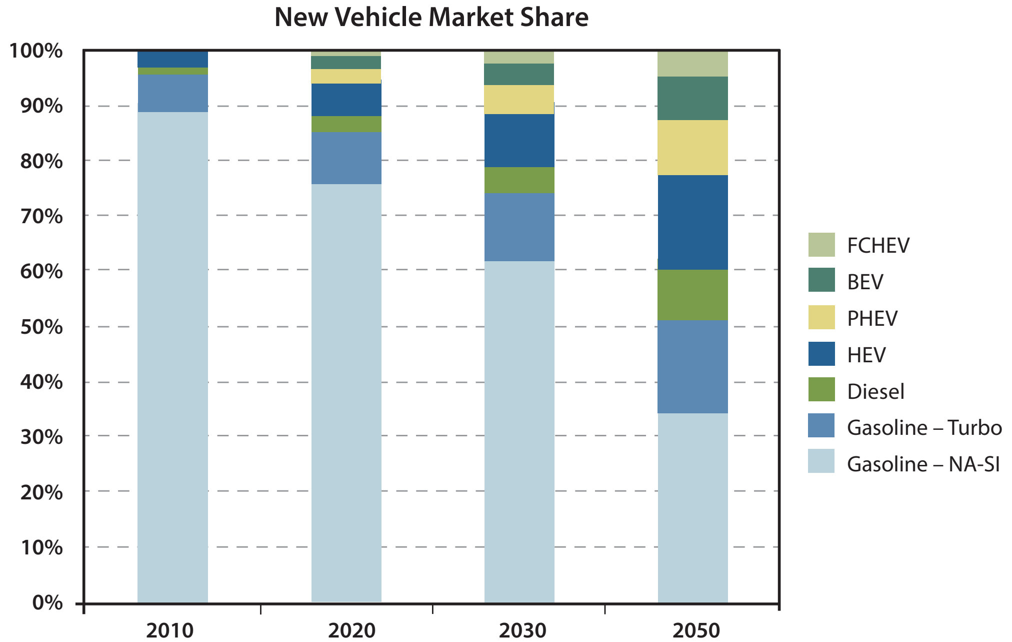


Figure 9.4 Powertrain market share input values 2010–2050.

We now summarize the results of this study (for additional details, see Bastani et al., 2012a). The methodology used generates probability distributions such as those shown in Figures 9.5a and 9.5b. The probabilities are scaled so the area under the curve equals unity. Figure 9.5a shows the total fleet CO_2 emissions in 2030: Figure 9.5b shows the distribution in 2050. The mean values shift lower with time: current (essentially maximum) fleet GHG emissions are 1,654 Mt CO_2 equivalent: the 2030 mean value is 1,367, and the 2050 mean value is 837—a reduction of close to 50%. The spread grows with time: the coefficient of variation, the standard deviation divided by the mean value, increases from today's value of zero (today's emissions are calculated from data), to 10% in 2030 to 27% in 2050. Note these are Well-to-Wheel (WTW) values in which the GHG emissions from the energy supply system have been added to the TTW emissions (WTW = WT tank + Tank TW). The probability distribution in 2030 is close to symmetric: by 2050 it has become significantly skewed toward the higher values.

The TTW fleet fuel consumption results behave similarly, but with some differences (again, see Bastani et al., 2012a). The rate of decrease in fleet fuel consumption (in equivalent gasoline liters/year) from the maximum (in 2008 and in 2014, with a modest dip in between due to the recession) starts relatively more slowly and in 2030 is about one-third of the reduction in GHG emissions (5%–6% from the maximum for fleet fuel consumed, relative to some 17% for GHG emissions). This faster reduction in GHG emissions is primarily due to ethanol biofuel counting as part of the fleet's fuel consumption (in gasoline equivalent liters), but having a lesser impact on CO_2 emissions due to the lower GHG intensity (gCO_2/MJ fuel energy) of corn-based ethanol (25% lower than gasoline in 2030) and cellulosic ethanol (90% lower). By 2050, the mean value of fleet fuel use has been reduced by some 40% from the current maximum level of 526 billion liters of gasoline equivalent per year: as noted above, the mean value of the fleet GHG emissions has been reduced 49% from the current maximum of 1,654 Mega tonnes CO_2 equivalent per year.

By generating the probability distributions for fuel and energy consumed, and GHGs emitted, by running this *realistic aggressive* scenario from today to 2050, we can lay out the overall evolution of these fleet impacts, as shown in Figures 9.6 and 9.7. Mean lines for LDV fleet fuel consumption and the 95%, 75%, 25%, and 5% probability lines are given in Figure 9.6: the same lines for CO_2 equivalent GHG emission are shown in Figure 9.7. The mean, 75% and 25% probability lines, defines the bulk of the Monte Carlo scenario simulations. (Note that 75% of the simulations fall below the 75% dashed line; 25% of the simulations are below the 25% line.) The middle half of the solutions can be viewed as indicative of the *spread* due to uncertainty while the 95% and 5% indicate the *extremes*. Note that the extent of these uncertainty bands depends primarily on the upper and lower bounds spelled out in the scenario inputs. All the important model input values are based on historical trends and data, assessments based on our studies and those of others, and our judgments.

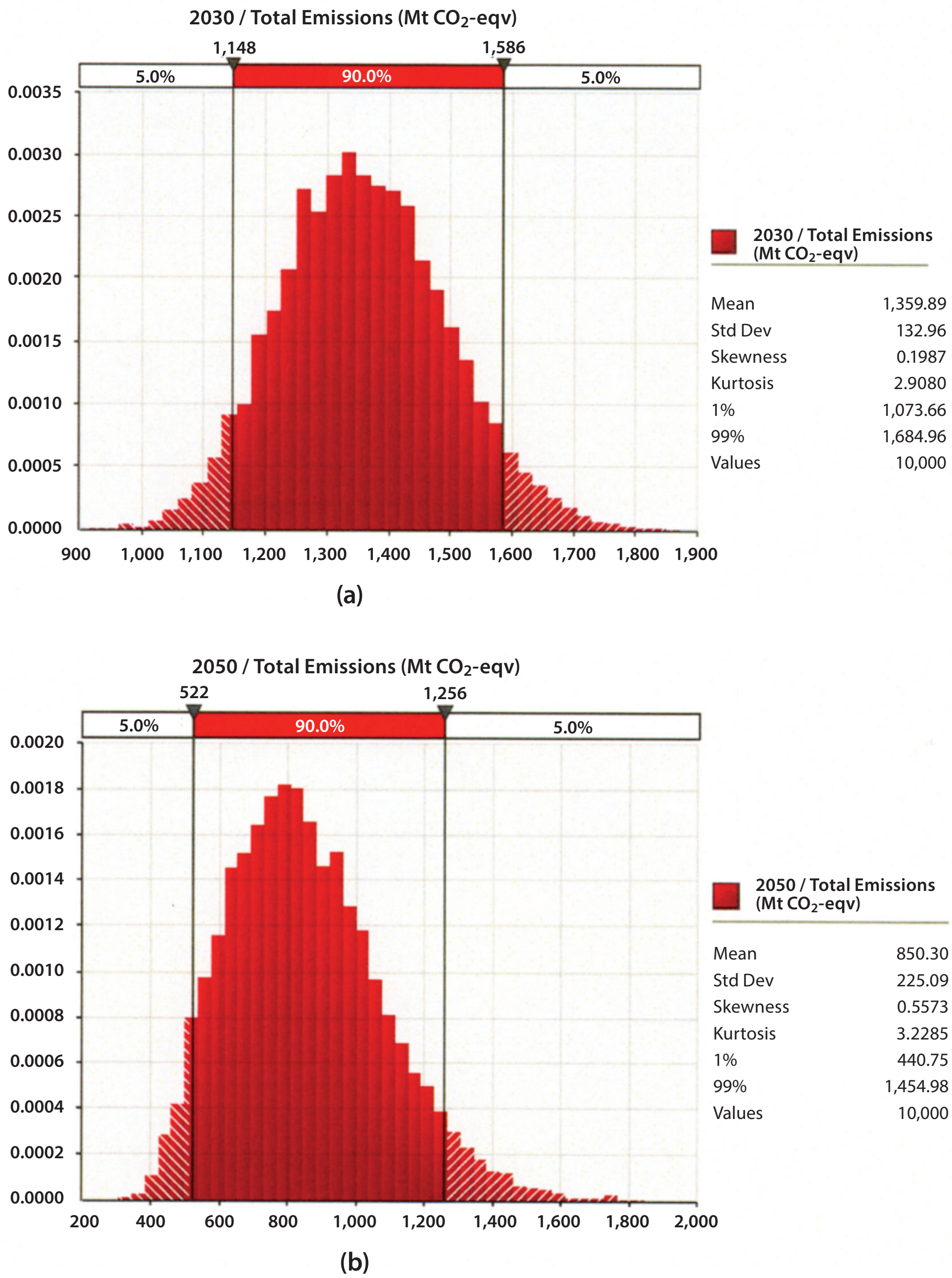


Figure 9.5 Probability profiles, U.S. LDV fleet GHG emissions (Mt CO_2 equivalent/year): (a) 2030; (b) 2050.

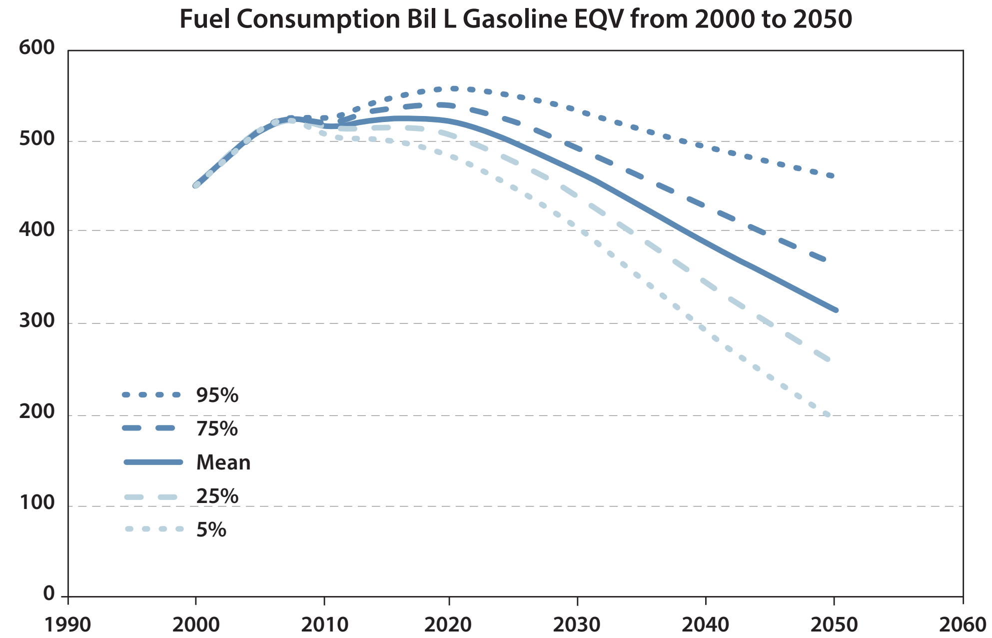


Figure 9.6 U.S. LDV fleet fuel use (billion liters gasoline equivalent/yr) over time, out to 2050.

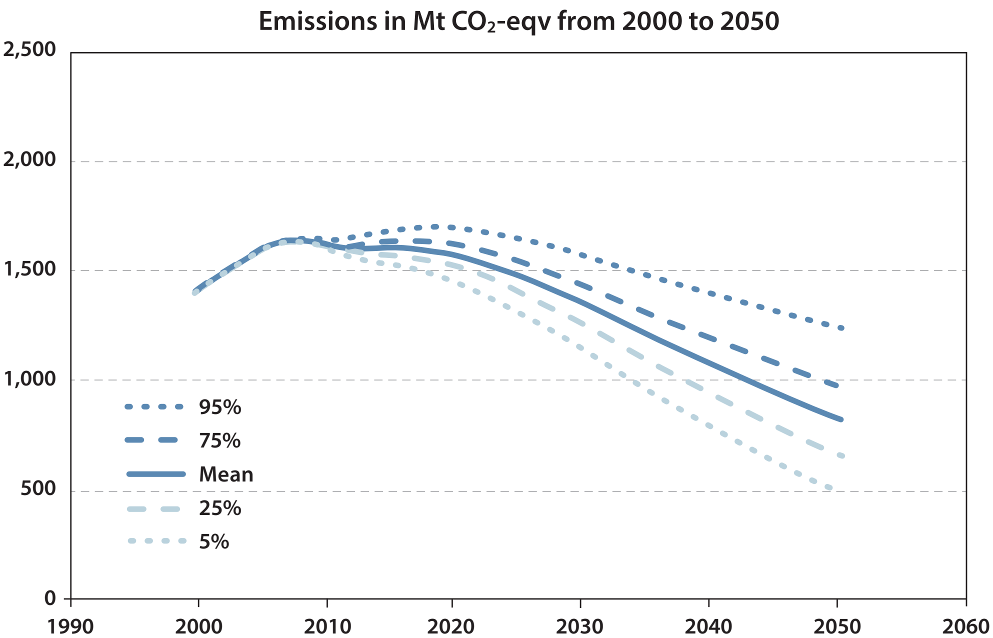


Figure 9.7 U.S. LDV fleet GHG emissions (Mt CO_2 equivalent/year) out to 2050.

With this perspective on uncertainties, we conclude the following: The spread between the 75% and 25% lines is not that large. All lines show an ongoing downward trend (ever lower fuel consumption and GHG emissions beyond about 2020). All of this is encouraging, and the Tornado diagram trends, discussed next, explain the major factors driving this steady progress.

Figures 9.8 and 9.9 show Tornado diagrams for the *realistic aggressive* scenario: Figure 9.8 shows the variable rankings for LDV fleet fuel consumption (TTW) for 2030; Figure 9.9 shows fleet GHG emissions variable rankings for 2050. Note each bar is the change in fleet fuel use or GHG emissions resulting from a one standard deviation change in that input variable divided by the standard deviation of that input variable distribution, arranged by priority—biggest at the top. Common to both impacts is the dominance of the fleet size (vehicle sales and scrappage rate), followed by the fuel consumption of the average dominant NA-SI engine vehicle (effectively how much does the embodied fuel efficiency technology in new vehicles improve over time), and ERFC. The fact that ERFC is ranked high on importance in this list indicates that the anticipated increases in vehicle acceleration performance over time should not be ignored. Specific to the fleet GHG emissions variable sensitivity is percent cellulosic ethanol: this is due to the fact that this does not affect *gasoline equivalent* fuel consumption, but does impact GHG emissions due to its much lower GHG emissions intensity (CO_2/energy) than gasoline. Note that variables that are in the higher sensitivity range on these Tornado diagrams are there due to their importance (in terms of magnitude) in the fleet model and/or due to their high uncertainty (high input variable standard deviation).

Overall, fleet growth, vehicle use growth (VKT), and mainstream engine and vehicle technology improvements are the most significant fleet fuel-consumption factors. With GHG emissions, we add the inherent GHG emissions intensity of the alternative fuels and energy sources to these three primary factors.

The benefits of both improving mainstream powertrain technology, and changing to more efficient propulsion systems, as well as reducing vehicle weight (and size) and resistances, are shown in Figure 9.10 where the decrease in average new vehicle fuel consumption over time is displayed. This decrease is due to both improvements in the standard gasoline and diesel engines and transmissions, and increasing sales volumes of HEVs, PHEVs, BEVs and FCEVs. Note that the change, 2006 to 2050, is substantial—a factor of three.

Figure 9.11 shows the breakdown of total LDV fleet GHG emissions by fuel and energy source. This breakdown incorporates both the *emissions intensity* of the fuel/energy-source, and the growth in its use, as well as the steadily improving efficiencies of the various technologies. Note that, with the assumptions used, the tar sands emissions grow by a factor of two, 2010 to 2050, while petroleum-based gasoline GHG emissions decrease by almost a factor of five. GHG emissions from electricity use increase by some 50% from 2010 to about 2025, and then remain almost constant to 2050, due to the anticipated reduction in GHG emissions intensity from the electricity generating sector over this time frame, offsetting growth in use of electricity in transportation.

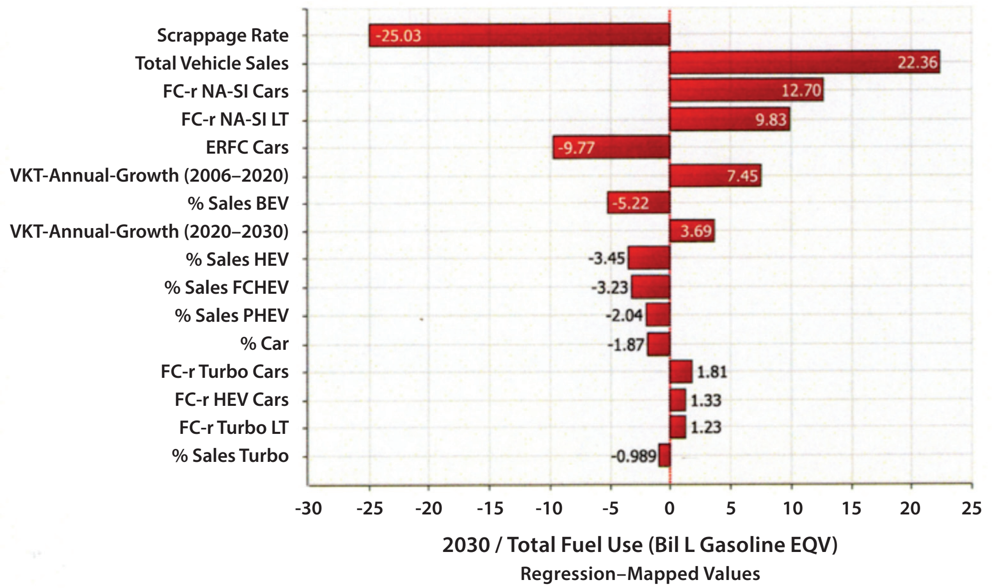


Figure 9.8 Tornado diagram for 2030 U.S. LDV fleet fuel use ranked by magnitude of influence (billion liters gasoline equivalent/year).

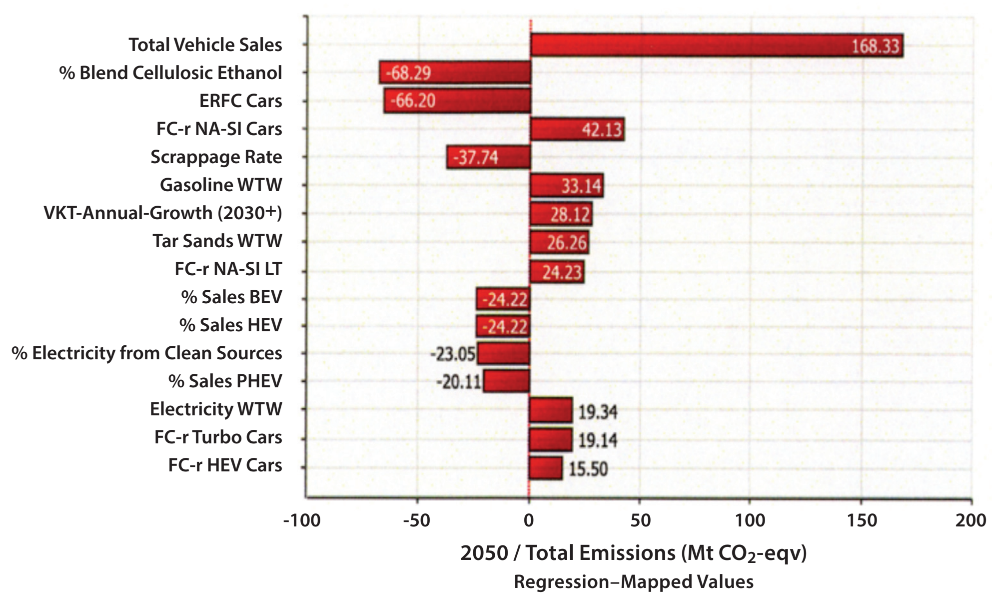


Figure 9.9 Tornado diagram for 2050 U.S. LDV fleet GHG emissions ranked by magnitude of influence (Mt CO_2 equivalent/year).

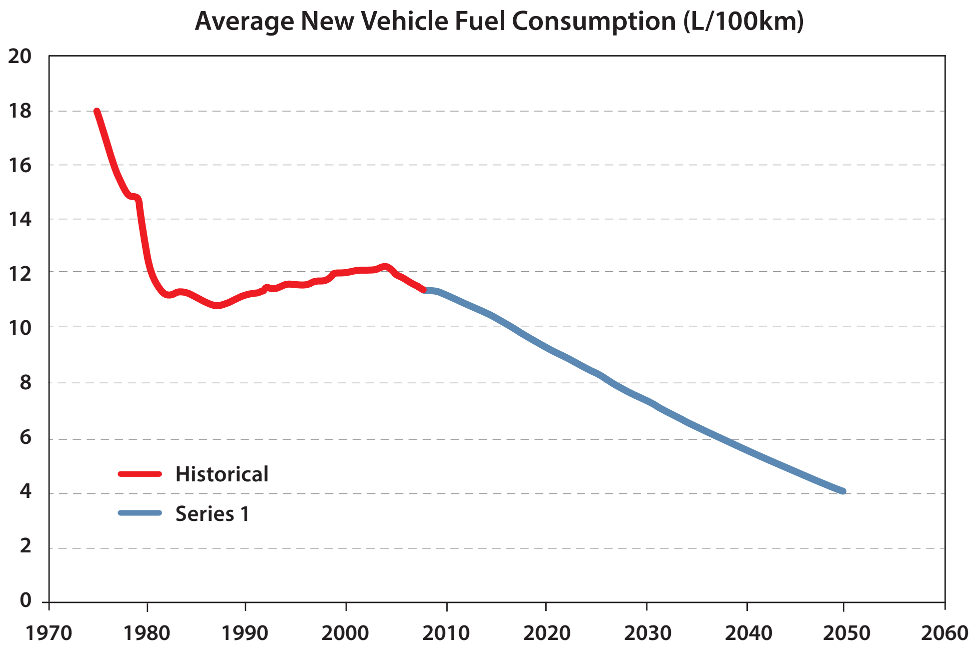


Figure 9.10 On-road mean new vehicle fuel consumption (liters/100 km) out to 2050.

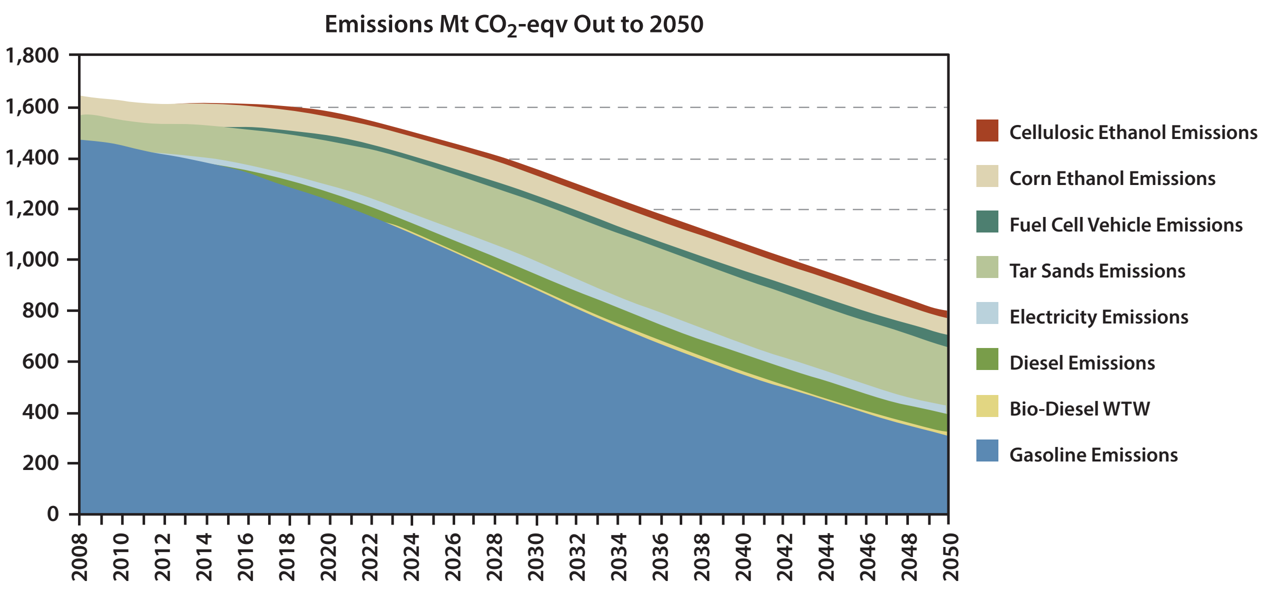


Figure 9.11 Mean lifecycle GHG emissions from U.S. LDV fleet (Mt CO_2 equivalent/year) by fuel type: Out to 2050.

Overall, the results and discussion here show that a *realistic aggressive* scenario for the United States projects substantial progress. The average new LDV sold could improve its on-road fuel consumption substantially. This more than offsets the negative impact of growth in fleet size and, possibly, vehicle use. This is a positive conclusion, but these assumed vehicle improvements will have to occur to realize these reductions. This will take ongoing, ever-stricter fuel economy regulation to force the pace, as well as policies that encourage the purchase of these more efficient but more expensive, lighter, and somewhat smaller vehicles, in the marketplace. This scenario will not happen without ongoing, steadily increasing “push and pull.”

9.4.3 Potential for Meeting Future CAFE Targets

In late 2011, the U.S. Department of Transportation (DOT) and EPA together announced their intention of proposing a rule making for LDV fuel-economy requirements (CAFE) for 2017 through 2025. The requirements that resulted from this rule-making process are based on vehicle-footprint size categories into which each auto manufacturer’s vehicle models are placed. As the footprint category becomes larger (and thus the vehicle models are larger and heavier) so the fuel economy requirement, miles per gallon (mpg), decreases. Vehicle model fuel consumptions are sales weighted within each footprint category, and then across each category to achieve averages for each manufacturer to assess compliance with the requirements. Both EPA and DOT have used future projections of the sales mix, first within each auto manufacturer, then across the several LDV manufacturing companies, to obtain “mpg targets” for the industry. These nominal targets have become well known as 34.1 mpg in 2016 (6.9 l/100 km) and 54.5 mpg in 2025 (4.3 *l*/100 km) with stepped values for each year in between.

We have used the STEP methodology described in the previous section to assess the prospects that these overall targets for 2016 and 2025 are within reach of plausible rates of development and deployment of engine and vehicle fuel-economy-enhancing technology [Bastoni et al., 2012c]. Note that these targets are not the CAFE requirements: rather they are our estimates of the average mpg that the new LDV mix would achieve (in 2016 and 2025) given the assumed, extrapolated sales fractions. Such a study provides useful information for the planned 2017 comprehensive assessment of progress toward, and prospects for meeting, the proposed standards looking ahead toward 2025.

It is unfortunate that these “nominal targets” (e.g., 54.5 mpg in 2025) have been so broadly used to quantify the nation’s fuel economy objectives because several “credits” have been negotiated which significantly reduce these mpg numbers. These credits include incentives for EVs, PHEVs, and FCEVs, also for applying certain novel technologies, hybridization of full-size pick-ups, and lower GHG impact air-conditioning refrigerants. These details are many and complex, and make realistic assessment of the effective targets challenging. Our assessment is that these credits effectively reduce the CAFE targets to 32.5 mpg in 2016 and 44 mpg in 2025. Other assessments of the effective targets are comparable. The current (2012) combined car and light-truck CAFE test cycle fuel economy is about 29 mpg. These target improvements correspond to 3.5% per year to meet the 2025 target over the 12 years from 2013 to 2025. These annual rates are somewhat higher than the historical record of close to 3% per year from technology improvements and sales mix changes [Schoettle and Sivak, 2013].

We analyzed three scenarios: our reference *plausible aggressive* scenario; that same scenario with almost all of the engine and vehicle fuel efficiency improvements targeted toward decreasing actual fuel consumption (ERFC approaching 100%); and the so-called EPA/DOT preferred (alternative) scenario, see below:

1. The **plausible aggressive scenario**: a realistic yet ambitious pathway that achieves close to a 40% reduction in fleet fuel use by 2050, developed in the authors' earlier study [Bastani, et al., 2012a]. This pathway includes significant improvements in the fuel economy of new vehicles through development of conventional powertrains (NA-SI) and introduction of downsized turbocharged (TC-SI) powertrains as well as hybrids and electric vehicles. These improvements are realized through both engine and vehicle developments, including weight reduction and aerodynamic drag, and tire rolling–resistance improvements. Better fuel consumption is achieved through these technology advancements, as well as by increasing the portion of the technical progress used to increase vehicles' fuel economy directly, rather than to offset increasing size, weight, and performance, which has traditionally been a major degrading factor in the United States. These scenario inputs are based on what we deem plausible, derived from engineering and vehicle simulation analysis and aggregated appropriately, rather than determined from what is required to meet some fuel economy target. Beyond this new vehicle CAFE target assessment in our in-use fleet analysis, the demand for vehicles and miles travelled is assumed to grow at a lower rate than the historical average along with a steady though moderate penetration of alternative powertrain vehicles into the new vehicles market.

2. The **high ERFC scenario**: a scenario with a strong *emphasis on reducing fuel consumption*, with essentially no increase in acceleration performance, with the same market assumptions as the plausible-ambitious scenario, but with more aggressive vehicle fuel consumption reduction from engine and powertrain technologies: ERFC is assumed to be close to 100% over time, indicating that all future technological progress is used to improve actual vehicle fuel economy instead of offsetting increasing vehicle performance, size, or weight.

3. **EPA/DOT preferred alternative scenario**: the agencies' proposed "preferred scenarios" are described in some details in the rulemaking document [NHTSA, 2011]. The scenario chosen here—often-labeled *preferred alternative*—is the one that the agencies used to support the proposed CAFE standards. It is significantly more aggressive in its rate of progress than our scenarios 1 and 2.

Additional scenarios were studied to assess the impacts of accelerated technology development and deployment, and specified demand reduction, on in-use fleet annual fuel consumption. Also, various technology and sales mixes that met the 2016 and 2025 CAFE targets on schedule were constructed and compared. These latter results provide insight as to what would need to happen to realize these targets on schedule. We now summarize the key results: see Bastani, Heywood, and Hope (2012c) for additional details.

Plausible aggressive scenario: calculations focus on the average new vehicle. Therefore, they involve input assumptions such as the relative fuel consumption of new vehicles over time for the different propulsion systems (as shown in Figure 3.3) calibrated with the actual CAFE test fuel consumption of the average standard gasoline-engine vehicle of today for cars and for light trucks—the two categories of vehicles are tracked separately since their relative proportions over time may well change. The relative deployment rates (sales fraction) of the various propulsion system vehicles then bring in the appropriate weighting to obtain the CAFE fuel consumption/economy of the sales mix for a given year. Figure 9.12 shows the combined (cars plus light trucks) CAFE mpg values from 2010 to 2025 in blue. The values for various probabilities (from the top, based on the stochastic model) of 95% below the short-dash line, 75% below the long-dash line, the mean (solid line), 25%, and 5%. The red line is the mean mpg for cars. The light-trucks mean line would be below the combined mean by a comparable amount, some 4 mpg since the current relative proportions of cars and light trucks are about 50:50.

With this scenario, the sales mix average reaches 35 mpg in 2025, but is well short of the 44-mpg CAFE target. The mpg has a strong upward slope and would likely reach 40 mpg in 2030 and 44 mpg a few years beyond that.

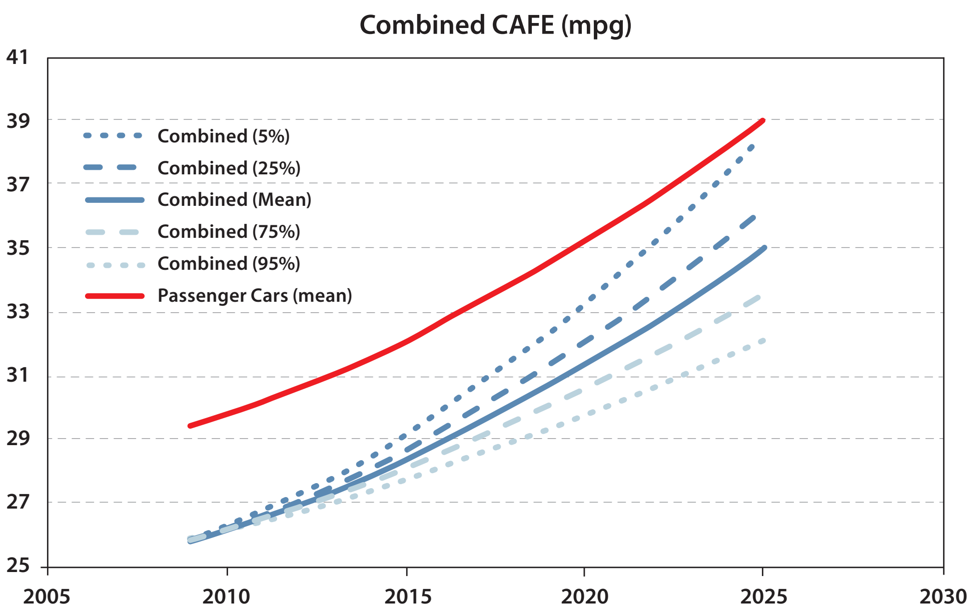


Figure 9.12 Combined new car and light truck CAFE mpg under the *plausible aggressive* scenario: top curve passenger cars only [Bastani et al., 2012c].

Figures 9.13 and 9.14 show the probability distributions of the CAFE fuel economies these average new vehicles would have in 2025: cars, light trucks (SUVs and other light trucks), and combined. The means are 39, 30, 28, and 35 mpg for cars, SUVs, other light trucks, and combined, respectively.

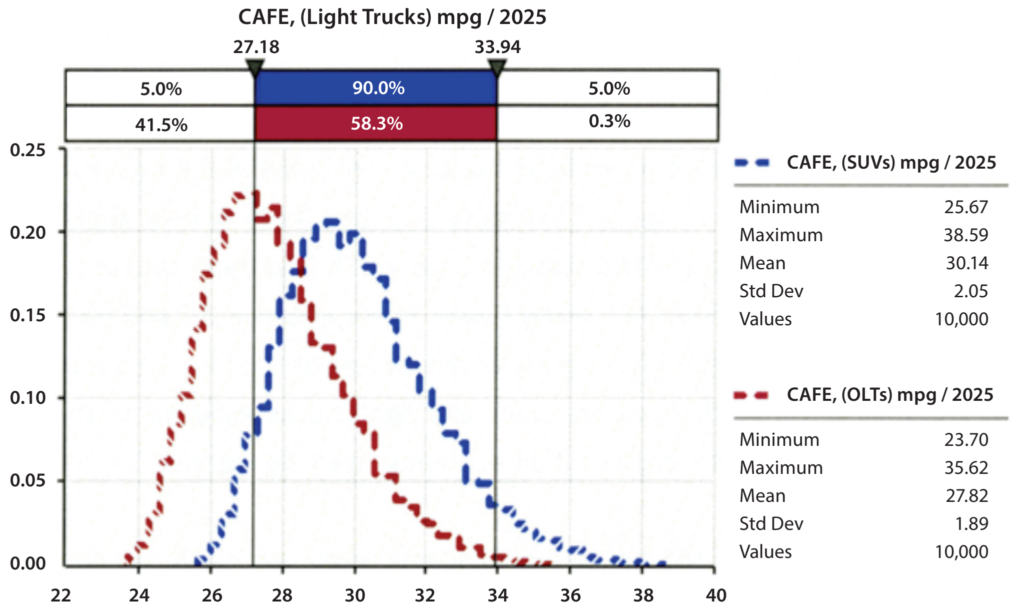


Figure 9.13 2025 CAFE (mpg) probability density function for light trucks (SUVs and other light trucks): *plausible aggressive* scenario [Bastani et al., 2012c].

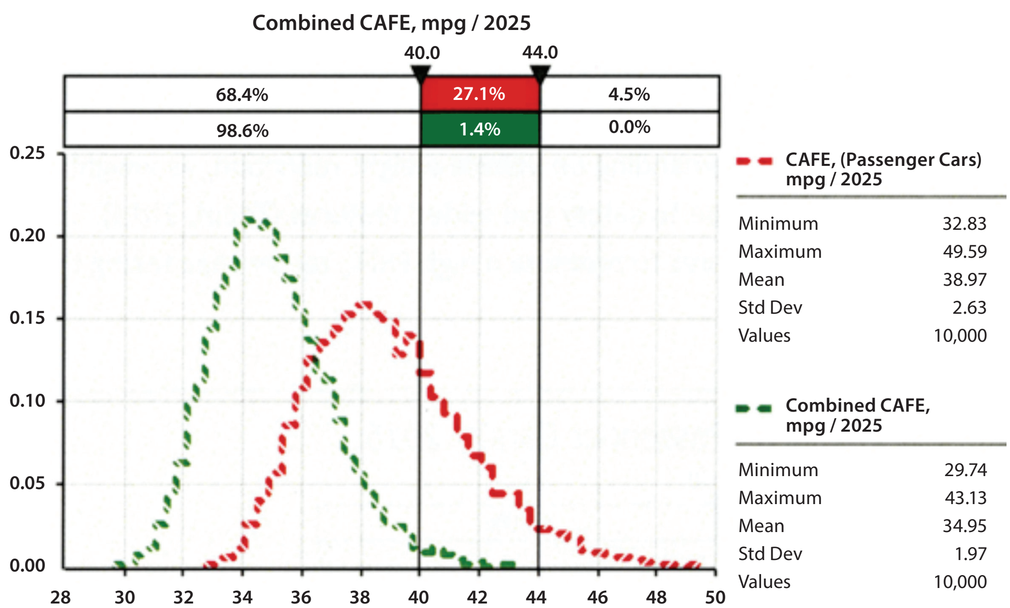


Figure 9.14 2025 CAFE (mpg) probability density function, passenger cars, and combined cars and light trucks: *plausible aggressive* scenario [Bastani et al., 2012c].

The standard deviations of these 2025 distributions are 2.63, 2.05, and 1.89 mpg for these three categories of vehicles, giving closely comparable coefficients of variation (stand. dev/mean). In our judgment, this spread due to uncertainty is relatively modest, despite the significant difference between the upper and lower bounds assigned to the input variables.

High ERFC scenario: The second scenario changes one important parameter, the emphasis on reducing fuel consumption (see Sections 3.3 and 5.2 for more discussion of why this parameter is important). An ERFC of 100% means that while fuel consumption/economy improve over time, vehicle acceleration performance stays the same. In the *plausible aggressive* scenario, ERFC for the new vehicle sales mix increased from about 50% today to some 75% in 2030. Thus, setting ERFC at 100% significantly improves (by some 5%–10%) the fuel consumption of new vehicles: the average fuel economy of the sales mix in each of the categories (cars, SUVs, and other light trucks) increases by 5% in 2016 and 9% in 2025. The combined CAFE test mean mpg for the *high ERFC* scenario in 2025 is 38.3 mpg compared with 35.0 mpg for the *plausible ambitious* scenario, but is still well short of the 44-mpg target.

EPA/DOT preferred alternative scenario: The third scenario is even more optimistic in terms of technological progress and deployment rates. This EPA/DOT *preferred alternative* scenario, is one of several proposed by these government agencies, and is the one used to support the rulemaking process. Vehicle performance is assumed constant (ERFC of 100%). The improvement in new vehicle fuel consumption in this EPA/DOT *preferred alternative* scenario is assumed to be somewhat higher and faster (and it is the NA-SI and TC-SI that are most important in this nearer-term time frame), but these seemingly moderate improvements compound to provide significantly higher mpg values, as shown in Figure 9.15. A comparison of Figure 9.12 (the *plausible aggressive* scenario) and 9.15 indicates the difference. This EPA/DOT preferred alternative path gives 17% higher mpg in 2025 compared to the *high ERFC* scenario (with which it shares the no increase in vehicle performance assumption) and 28% higher mpg than our base *plausible aggressive* scenario.

In summary, the probability of attaining the 44-mpg CAFE test value (that corresponds to the 54.4 mpg widely discussed target, with allowable credits) in 2025 is still only about 15% (i.e., 85% of the Monte Carlo scenario simulations fall below this 44 mpg target value and only 0.4% exceed the 54.5 mpg target value). The *high ERFC* scenario shows only 2.4% of the scenarios are above 44 mpg in 2025. For the *plausible aggressive base* scenario, the percentage of scenarios above 44 mpg is negligible.

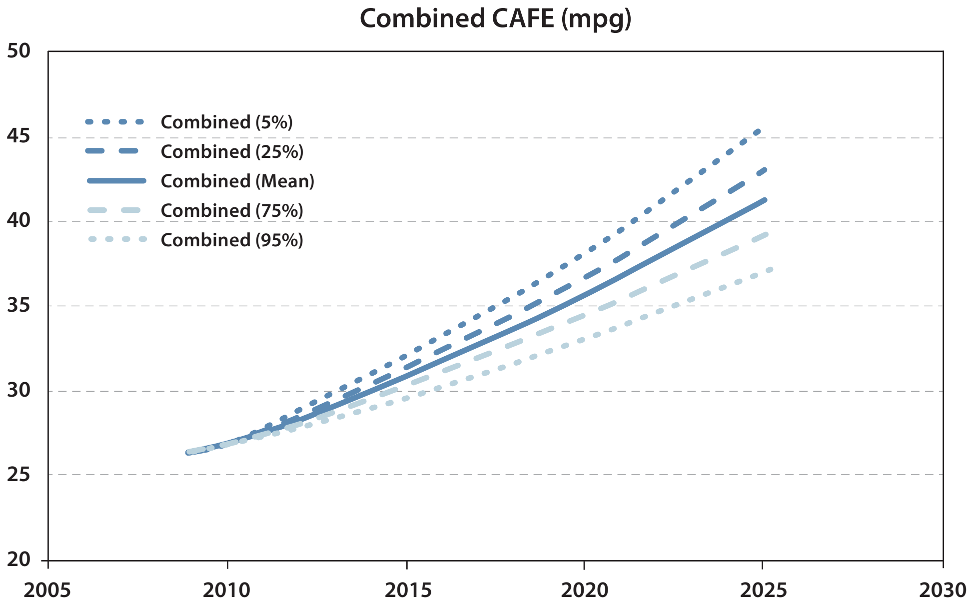


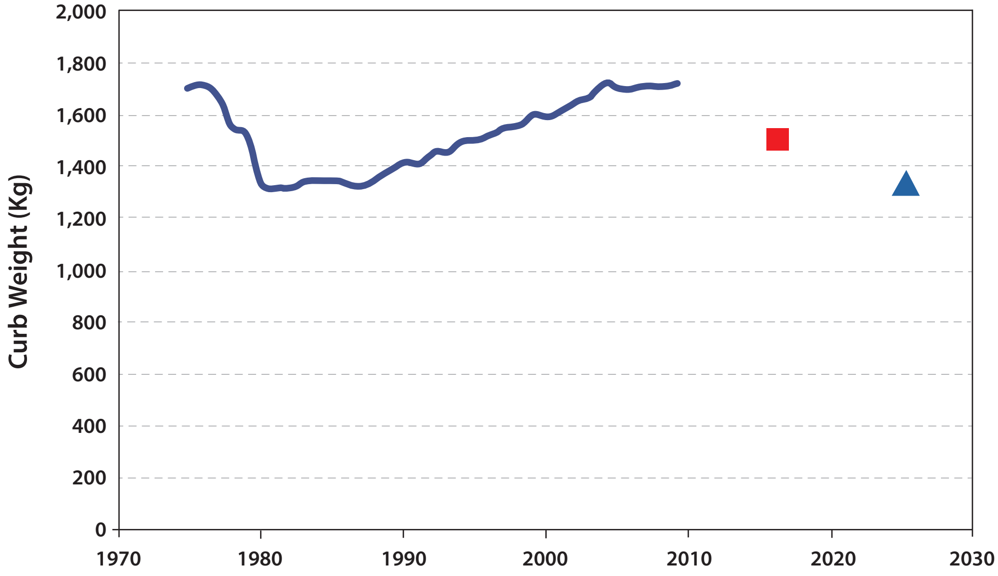
Figure 9.15 CAFE (mpg), 2010–2025, for new vehicles *EPA/DOT preferred* scenario: combined cars and light trucks [Bastani et al., 2012c].

Another part of this study [Bastani, Heywood, Hope, 2012c] works backward from the 2016 and 2025 overall mpg targets to identify a number of strategies that would come close to these targets. Table 9.2 provides illustrative examples of such strategies for 2016 and 2025 compared with the present context. Three alternative approaches are shown: strong emphasis on vehicle light-weighting and downsizing; high percentage of alternative powertrains (alternatives to the NA-SI standard gasoline engine vehicle); and a combination of these two and other approaches. We see that to approach 44 mpg (the 2025 CAFE target) would require high ERFC (little performance escalation), significant vehicle light-weighting and downsizing, a substantial increase in the proportion of cars versus light trucks (which provides additional vehicle weight reduction to that provided by lighter weight material and design efforts), and a much increased share of alternative (more fuel efficient) powertrain vehicles.

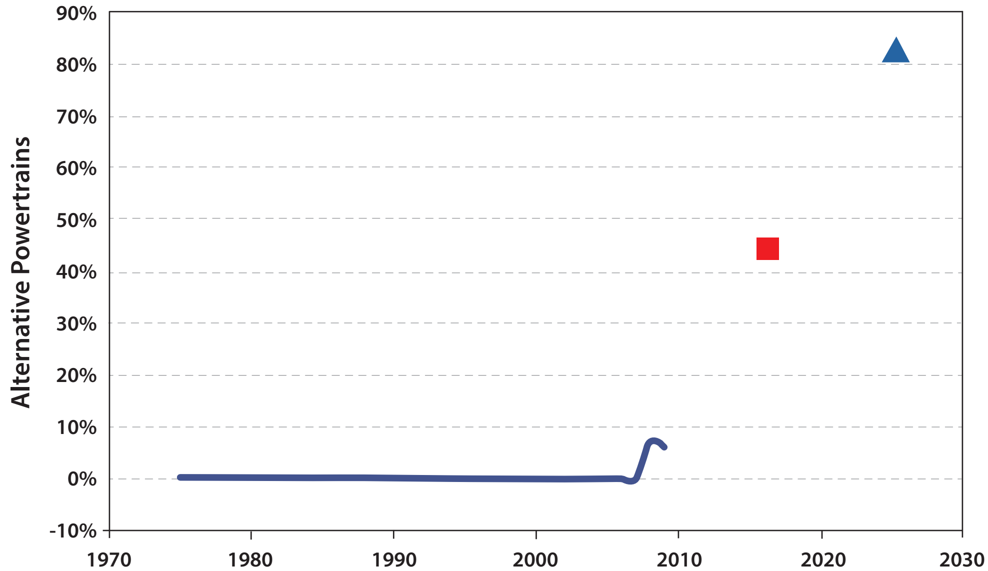
Table 9.2 Strategies for meeting the 2016 and 2025 CAFE targets, with 2009 baseline [Bastani et al., 2012c].

Strategies	% ERFC	% Curb Wt Reduction from 2009 (average new vehicle weight)	% Cars	% Market Share by Powertrains								On-road CAFE, mpg (test cycle)
				NA-SI	Turbo SI	Diesel	HEV	PHEV	BEV	FCHEV	Total Alt.	
2009	50%	...(1,727 Kg)	51%	94%	4%	0%	2%	0%	0%	0%	6%	21.04 (25.5)
2016												
Lightweight and Downsize	85%	19.5% (1,390 Kg)	90%	94%	4%	0%	2%	0%	0%	0%	6%	25.20 (30.5)
Alt. Powertrains	75%	7.5% (1,598 Kg)	51%	53%	30%	4%	9%	3%	3%	1%	50%	25.70 (31.1)
Combination	85%	12.5% (1,512 Kg)	65%	55%	21%	4%	15%	2%	2%	1%	45%	26.90 (32.5)
2025												
Lightweight and Downsize	85%	27.0% (1,261 Kg)	90%	46%	27%	9%	9%	4%	4%	1%	54%	34.30 (41.5)
Alt. Powertrains	75%	17.5% (1,428 Kg)	60%	0%	57%	7%	21%	6%	6%	3%	100%	34.80 (42.1)
Combination	85%	22.0% (1,350 Kg)	70%	22%	33%	7%	23%	6%	6%	3%	83%	36.40 (44.0)

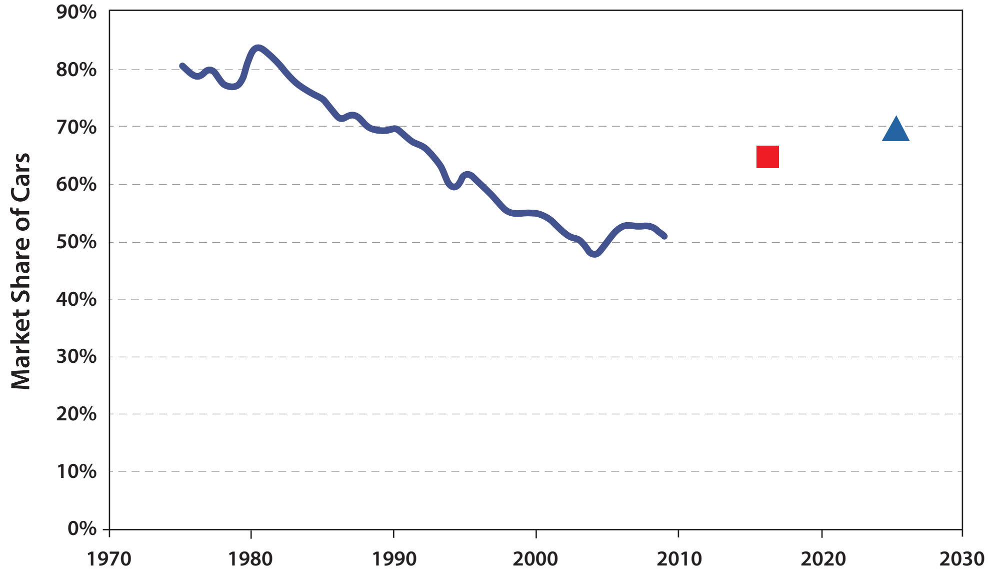
Figure 9.16 illustrates that all of these 2025 strategies have especially ambitious objectives: four critical vehicle and sales mix parameters for 2016 and 2025 are compared with the 1980 to 2010 historical context. It is clear that achieving these needed future weight reductions, vehicle market and technology shifts, and effective curtailment of the historical ever-increasing vehicle acceleration performance trend, required to meet the CAFE targets represent very challenging objectives.


Curb Weight (Kg)
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
1970
1980
1990
2000
2010
2020
2030

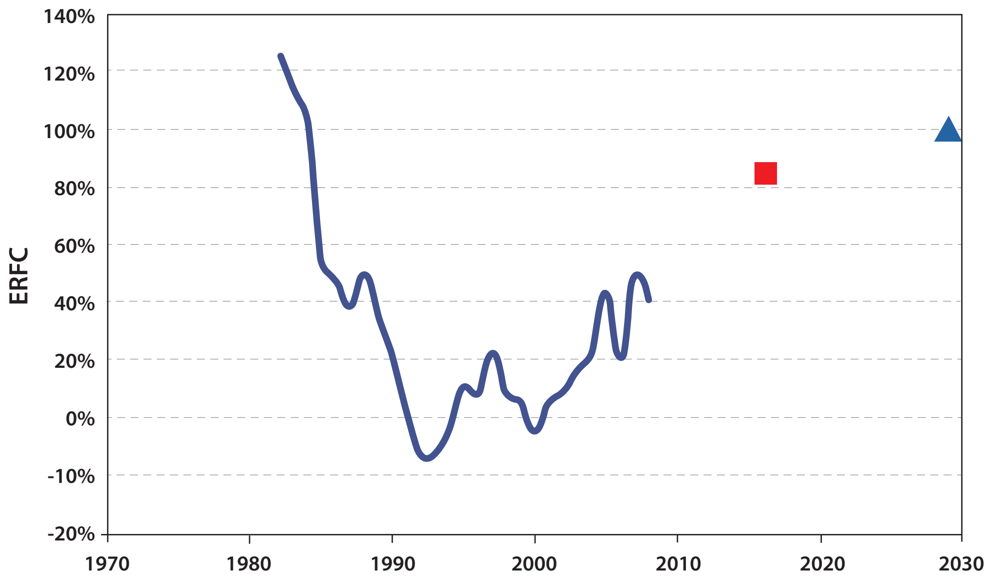
(a)


Alternative Powertrains
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-10%
1970
1980
1990
2000
2010
2020
2030

(b)



(c)



(d)

Figure 9.16 Historical trend, and combination scenarios over time, from Table 9.2 for 2016 and 2025. (a) Average vehicle curb weight: (b) Alternative powertrain (non NA-SI powertrain) vehicle market shares: (c) Market share of cars (versus light trucks): (d) Emphasis on reducing fuel consumption (ERFC) [Bastani et al., 2012c].

9.4.4 Emphasis on vehicle electrification and biofuels

A study with another set of scenarios focused on the impacts of increased sales of HEVs and PHEVs, and increased supplies of biofuels [Khusid, 2010]. In turn, these scenarios explore more efficient propulsion technology, introduction of electricity as a transportation energy source, and alternative liquid fuels from a potentially low-GHG-emitting source—cellulosic biomass. Table 9.3 couples the characteristics of these mainstream and alternative propulsion systems to the important questions of whether significant changes in propulsion system technology are required, and whether significant energy supply infrastructure changes will be needed.

Table 9.3 Overview of alternative transportation energy sources.

Emerging Automotive Propulsion Technology	Significant changes in vehicular technology required?	Significant infrastructure change required?
Advanced conventional vehicles (direct injection, diesel, turbocharging) using gasoline and/or ethanol	No	No
Hybrid electric and plug-in hybrid electric vehicles	Some	No
Non-conventional fuel (compressed natural gas, hydrogen) vehicles	Some	Yes
Battery Electric Vehicles	Yes	Yes

As we move down the table, we see that increasingly significant changes are required, which increase the cost and lengthen the time scales of any potentially positive outcomes. The challenges for natural-gas LDVs and BEVs in the United States have already been described in this chapter. In this study of various levels of vehicle electrification, we compare substantial market penetration of HEVs, with equivalent (high) market penetration of PHEVs, both embedded in what is essentially the reference *plausible aggressive* U.S. scenario already discussed. The sensitivity of fleet fuel consumption and GHG emissions impacts to high (essentially 80% of sales mix in 2050 as hybrid) dominated first by HEVs, and then (second) by PHEVs: We assume a negligible percentage of BEVs in these scenarios since, as Table 9.3 indicates, the battery technology performance market acceptance and cost demands, and the inherent range and recharging time limitations of this technology, downgrade their potential to a niche market status. A steady and substantial "greening" of the electricity supply system is assumed to occur.

The increasing volumes of HEVs and PHEVs still require significant liquid fuel. So, we also examined the consequences of increasing the biofuel ethanol contribution from its current 7% or so (on an energy equivalent basis) produced from corn grain, to about four times that level through the addition of second generation technology cellulosic-based ethanol embodied in the Renewable Fuel Standard (RFS) legislation of 2005 and 2007. This is based on the expectation that the technology for effective conversion of cellulosic biomass material will, in due course, be developed.

In the electrification study [Khusid, 2010], two specific scenarios were analyzed and compared. Both have hybrid vehicles rising from the current small fraction of sales (a few percent) to 80% of vehicle sales in 2050. In the first scenario, HEVs are the dominant hybrids rising to 67% of sales in 2050, with PHEVs constituting 13% (for a hybrid total of 80%). In the second scenario, PHEVs become the dominant hybrid vehicle type, starting at a low sales level in 2015 and rising linearly to 70% of sales in 2050. In parallel, in this scenario, HEVs initially rise to 15% in 2020, level off, and then drop to close to 10% in 2050. BEVs were not included in the electrified segment of the market due to our assessment that they will be a niche market of less than 5% or so of sales due to basic cost, driving range, and long recharging time constraints. FCHEVs were also omitted since the barriers to market entry are significant and are likely to delay substantial market penetration. In both cases, the market shares for cars and light trucks were assumed to be the same.

A PHEV-30 was chosen to represent that vehicle category (i.e., a PHEV having a 30-mile, 48-km, all-electric range), within the range of 10 to 40 miles expected for future PHEVs. EREVs were not included: they appear likely to be more expensive and less flexible. The overall objective of this study was to assess the impact of bringing electricity into the U.S. transportation energy source mix at an aggressive rate, and identify the key factors involved in thereby reducing liquid fuel consumption and GHG emissions. Note that these market penetration rates for hybrids are high. The Bastani et al. (2012a) base scenario (described as *plausible aggressive*) assumes that by 2050 market shares are: HEVs 17.5%, PHEVs 12%, FCHEVs 6%, BEVs 5%. That is, hybrids represent about 30% of the market, and an additional 10% or so is represented by fuel cell and battery vehicles.

With the introduction of electricity into the transportation energy supply system, the GHG emissions intensity of electricity is a critical factor. Figure 9.17 shows the 2008 U.S. generating mix of which just under half is coal sourced.[21]

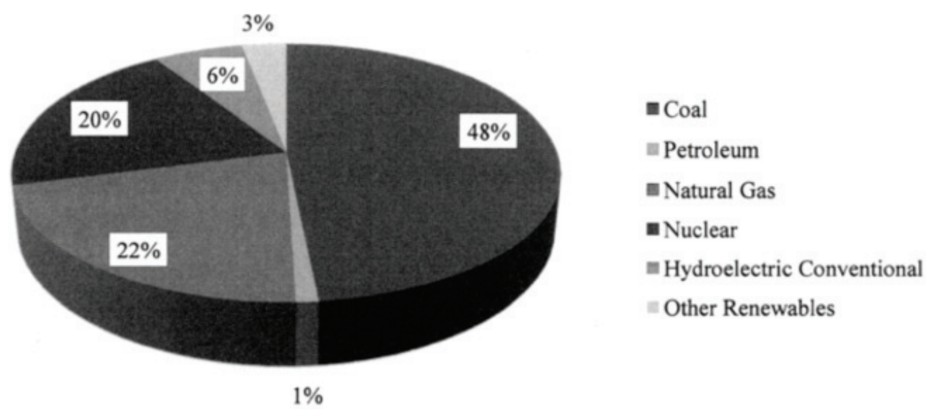


Figure 9.17 Average U.S. electricity generation by source in 2008: U.S. EIA, Electric Power Industry, 2008: Year in Review [2010].

[21]The changes, 2008 to 2014: some coal replaced by growing natural gas and increasing renewables, are significant but not yet that large in magnitude.

The assumed GHG emissions intensity, 2010 to 2050, is shown in Figure 9.18. An aggressive reduction in gCO_2 equivalent/MJ delivered is indicated: a reduction by a factor of 5. This would require, by 2050, a major renewable generating component, electricity storage, elimination of coal (or fully effective carbon capture and storage capability), reduced and clean natural generation, and substantive nuclear generating capacity. We have thus presumed a steady and major "greening" of the U.S. electricity supply system.

A final electricity factor is the vehicle's recharging pattern from the electricity grid. The simplest assumption is overnight recharging that occurs at home (though previous studies suggest this will limit the market for PHEVs/BEVs to about 50% of vehicle owners). An alternative [Kromer and Heywood, 2008] is so-called "opportunity charging" where the vehicle is recharged whenever it is parked (at a location with recharging outlets presumed to be widely available). The electric mileage percentage of total miles for a PHEV-30 (see Figure 3.2) are 57% and 74% for these two bounding situations, respectively. Then, the PHEV-30 electrical energy and petroleum-based fuel energy consumed (in liters, gasoline equivalent, per 100 km) are as given in Figure 9.19, where the ratios of electrical driving energy/total driving energy are 30% for home charging, and 55% for opportunity charging.

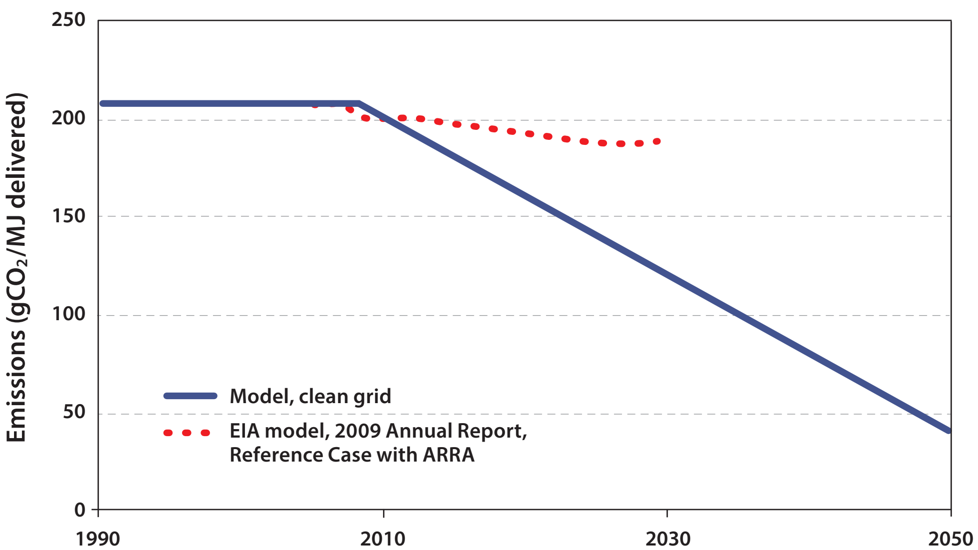


Figure 9.18 Assumed GHG emissions intensity (gCO_2 equivalent/MJ electricity delivered) by electric power grid to the vehicle.

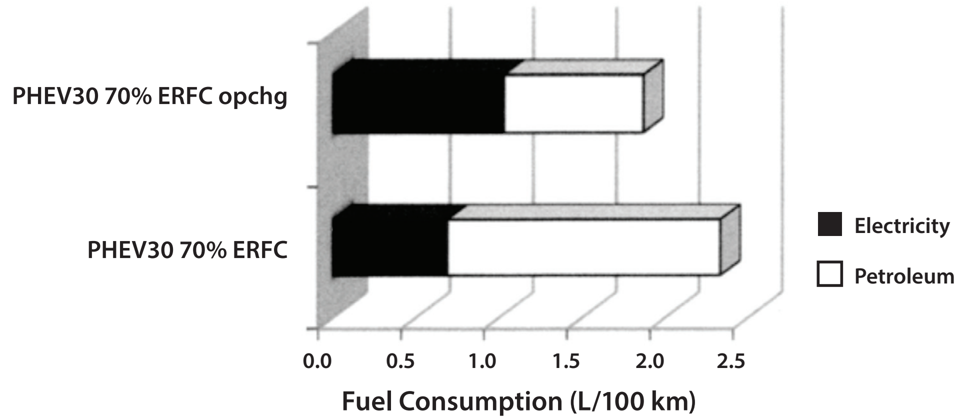
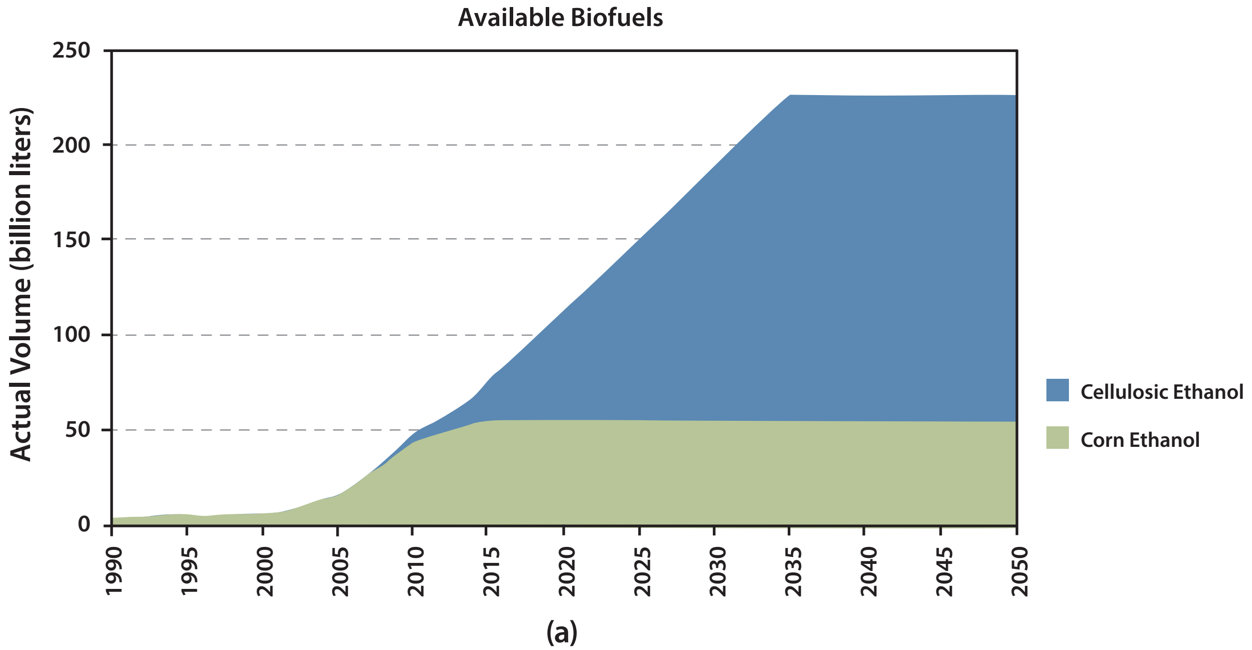


Figure 9.19 PHEV-30 energy consumption (electricity and gasoline) for home charging (lower bar) and opportunity charging (upper bar).

The final element in this electrification scenario comparison is expanding the biofuel component of the LDV liquid fuel supply. That fits with this major takeover of the market with hybrid vehicles since they would benefit from a lower-carbon-emitting liquid fuel. We examined three biofuel deployment strategies proposed by McAulay (2012): a baseline which assumes that corn ethanol production capacity reaches a limit in 2015, primarily based on the ethanol plants currently in operation or under construction. Also, advanced second-generation biofuels, interpreted here as cellulosic ethanol, do not become available in any significant quantities. The second scenario assumes that the RFS[22] was realized and extended from 2022 to 2035, rising from 140 to 225 billion liters per year: the *Extended RFS* scenario. The recent limited progress in developing cost-effective processes that convert cellulosic biomass feedstock into alternative fuels such as ethanol led to a third alternative fuels scenario: the *Delayed RFS* scenario. These scenarios are illustrated in Figure 9.20. Figure 9.20(a) shows the baseline scenario corn-ethanol supply scenario with the *Extended RFS* scenario added: Figure 9.20(b) shows the *Delayed RFS* scenario. Note that the maximum corn ethanol volume shown, some 57 billion liters/year, corresponds to about 40 billion liters/year on an energy content basis (converted to gasoline equivalent liters) and represents 7%–8% of the current (close to maximum) total in-use U.S. fleet fuel consumption of 525 billion liters gasoline equivalent/year (see Figure 9.6). Due to “lack of progress,” the *Extended RFS* scenario is now judged infeasible.

[22]The RFS originated with the 2005 Energy Policy Act and was expanded and extended by the Energy Independence and Security Act (2007). The RFS requires renewable fuel to be blended into transportation fuel in increasing amounts each year, escalating to 36 billion gallons/year by 2022 (about 140 billion liters/year).



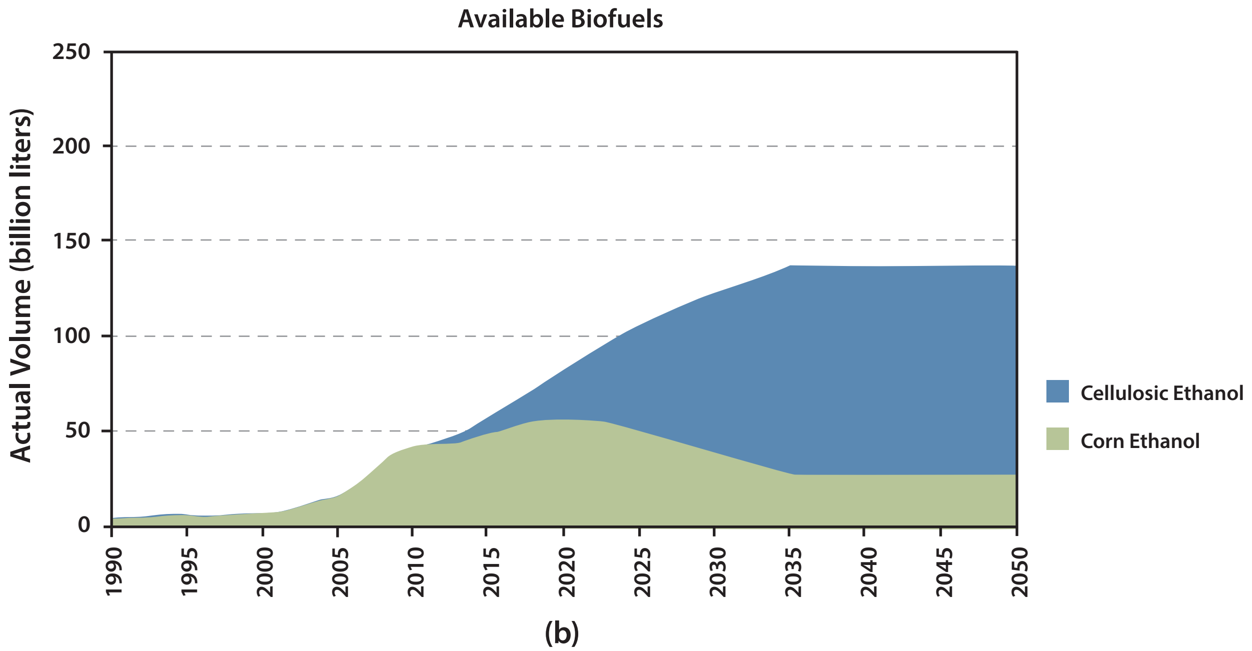


Figure 9.20 Biofuel availability in billion liters per year: (a) in the base (corn ethanol) and *Extended RFS* (cellulosic ethanol) scenario; (b) in the *Delayed RFS* plus reduced corn ethanol scenario.

The scenario results are as follows: The penetration of these new technologies into the in-use vehicle fleet is delayed in its overall impact due to the long lifetime of vehicles in the fleet (about 15 years). Figure 9.21 shows results for the PHEV scenario. The PHEV fraction in the in-use fleet rises rapidly from today to about half the in-use car fleet by 2050. Figure 9.21b shows the percentage of PHEVs in the new car sales and in the in-use car fleet. The lag for cars is about 10 years; for light trucks the lag is similar. By 2050, the U.S. LDV fleet size (stock) has grown to some 350 million LDVs: the PHEV fraction of this in-use fleet is about 50%. As noted previously, it takes a very aggressive expansion of PHEVs in each successive year's sales, starting in about 2020, to achieve this 50% penetration.

Predicted U.S. market shares of the various LDV technologies are shown in Figure 9.22: (a) shows the mix for the HEV scenario; (b) the PHEV scenario mix. Conventional (current technology) gasoline engines have been fully displaced by advanced conventional internal combustion engine and hybrid vehicles. Advanced conventional—improved NA-SI gasoline engines, turbocharged gasoline engines, and increased sales of improving diesel—are just under half the sales. From about 2015 on, these evolving improvements (out to about 2030) are the dominant reason for decreases in average vehicle fuel consumption. As hybrid sales increase, their better fuel consumption contributes to this decrease and then (in about 2035) becomes the larger factor in this reduction. The two scenarios have comparable market share mixes: note that the HEV technology leads the PHEV technology by some 5 to 10 years.

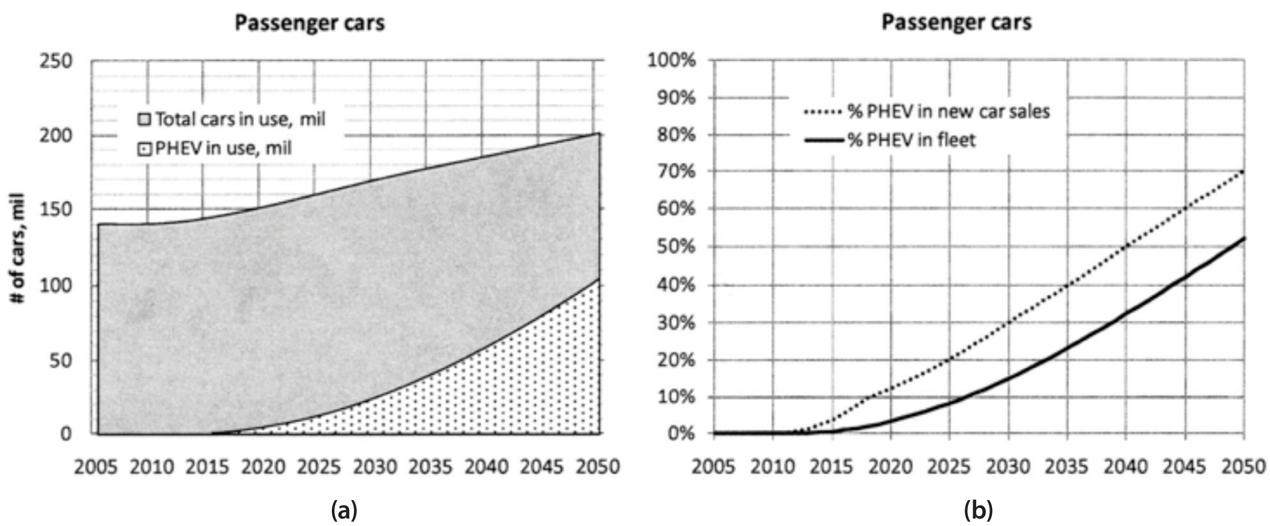


Figure 9.21 PHEV scenario: (a) in-use fleet passenger carfleet size, overall and PHEVs (b) PHEV as a percentage of new car sales, and percentage of the U.S. in-use vehicle fleet.

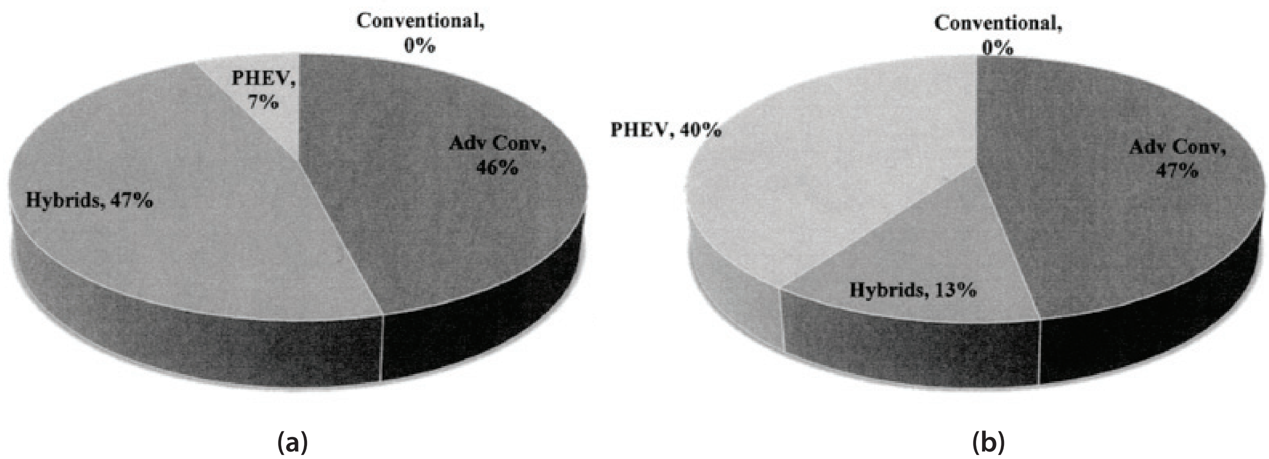


Figure 9.22 Technology mix in the U.S. 2035 new vehicle sales mix: (a) HEV scenario; (b) PHEV scenario.

The full scenario analysis results for the U.S. in-use LDV fleet's fuel consumption and GHG emissions are shown in Figure 9.23. The graphs on the left (a) show the fleet energy consumption (TTW) for the HEV (upper) and PHEV (lower) scenarios: the dotted lines show only the liquid fuel consumption impacts. For the HEV scenario, there is little difference between the total TTW energy and the TTW liquid fuel. For the PHEV scenario, the difference, due to the electrical energy consumed, is significant. On the right-hand side (b), the graphs show the fleet's evolving GHG emissions rate based on the fleet's energy consumption rate and the GHG emissions intensities of the various energy sources involved. (Note that the slight "upturn" in the upper graphs, starting in about 2045, is due to fleet growth more than offsetting the efficiency improvements in powertrain and vehicle technologies.)

Figure 9.23 shows that the PHEV scenario (rising to 70% market share in 2050) reduces both fleet fuel consumption (due to their reduced gasoline requirement, and their electricity use displacing gasoline) relative to the HEV dominant scenario. Table 9.4 provides a quantitative comparison of these two scenarios in 2040. The (high) HEV scenario reduces fleet fuel use to 0.74 of its (current) maximum, and GHG emissions to 0.76 of the maximum. The (high) PHEV scenario produces reductions to 0.69 of the maximum fuel use, and 0.65 of the maximum GHG emissions. Comparing the two scenarios shows that the PHEV scenario provides an additional 7% reduction over that of the HEV scenario's fuel consumption: for GHG emissions the additional reduction is twice that, 14%. Note that these hybrid scenarios are highly aggressive and do not, at this point in time, appear realistic. Also, the PHEV scenario assumes a comparably aggressive reduction in the GHG emissions intensity of the electricity supply system (reduction from current levels to about one-third by 2040).

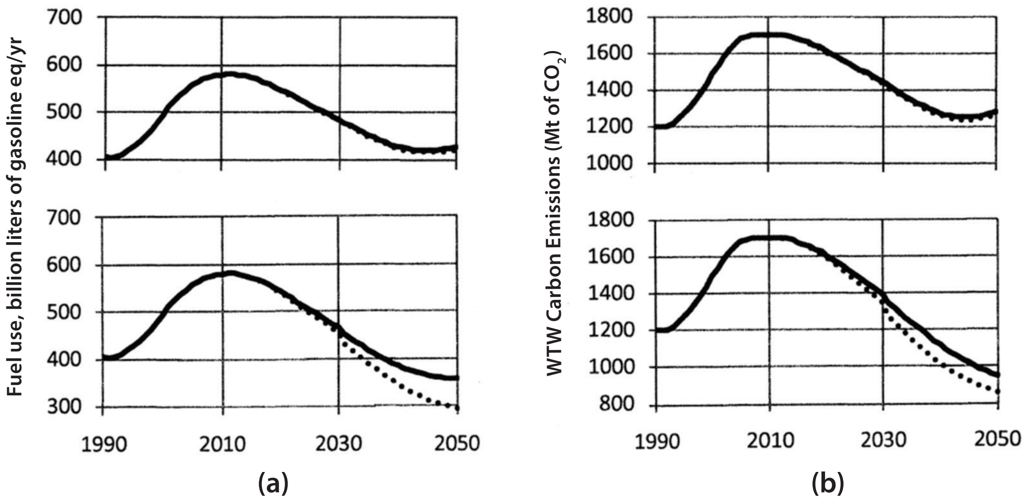


Figure 9.23 Technology mix in the U.S. 2035 new vehicle sales mix: (a) HEV scenario; (b) PHEV scenario.

Table 9.4 Comparison, in-use U.S. LDV fleet, 2040: Fleet fuel consumption, GHG emissions; HEV, PHEV, and Alternative Fuels scenarios.

	HEV Scenario		**PHEV Scenario**		**PHEV & Alternative Fuels**	
	Units	**Relative**	**Units**	**Relative**	**Units**	**Relative**
Fleet fuel use: (bill. Liters gas. equiv./yr.)						
2010 (max.)	579	1.00	580	1.00		
2040 (total)	429	0.74	397	0.69		
2040 (liq. fuel)	420	0.725	340	0.59		
Fleet GHG emissions: Mt Co_2 equiv./yr.)						
2010 (max.)	1,704	1.00	1,704	1.00		
2040 (total)	1,297	0.76	1,116	0.65		
2040 (liq. fuel)	1,255	0.74	984	0.58		
Fleet GHG + biofuels: Mt Co_2 equiv./yr.)						
2010 (max.)					1,704	1.00
2040 (delayed RFS)					936	0.55
2040 (Extended RFS)					778	0.46

The availability of increasing amounts of advanced biofuels would further reduce fleet GHG emissions, though not fleet energy consumption. Results from this study [Khusid, 2010] with the more realistic yet optimistic *Delayed RFS* scenario, and the much more optimistic (and, in our judgment, unrealistic) *Extended RFS* scenario, indicate additional GHG emissions reductions. In 2040, these additional reductions would be about 15% for the corn-based plus (rising) cellulosic-based ethanol to 140 billion liters per year in 2035 of the *Delayed RFS*: they would be almost 30% percent for the *Extended RFS* scenario which supplies close to twice as much ethanol per year than does the *Delayed RFS* scenario.

In summary, this electrification and biofuels study indicates the following: From a baseline of about a 20% reduction in fuel use (TTW) and GHG emissions (WTW) by 2040, from their maximum (current) levels, predominantly through improvements in mainstream powertrain and vehicle technologies [Bandivadekar at al., 2008], the additional reductions through aggressive hybrid vehicle deployments (sales fraction rising to 80% of total sales by 2050) were of the following magnitude: The aggressive HEV strategy further reduced fuel use and emissions by an additional 6% or so, and the aggressive PHEV strategy further reduced fleet fuel consumption by an additional 7% and GHG emissions by an additional 14% (beyond this 20%). Two levels of biomass-based ethanol were examined: one rising from the current supply rate of about 50 billion liters per year of corn-based ethanol to 140 billion liters per in 2035 (the additional ethanol being produced from cellulosic biomass), and the other rising twice as fast to 230 billion liters per year. These reduced the fleet GHG emissions in 2040 by 15% and 29%, respectively. (These numbers are based on the assumption that the land use changes in producing these substantial volumes of biomass-based ethanol do not result in significant CO_2 emissions from this land use change. This assumption is increasingly viewed as unrealistic. Thus these biofuels benefits could well be overestimated.) Also, the higher ethanol supply case, which extended the Renewable Fuel Requirements from about 140 billion liters in 2022 to 230 billion liters in 2035, is no longer judged to be feasible. Therefore, only the first of these two substantive alternative fuels scenarios is plausible. Moderate expansion of a biomass-derived alternative fuel supply remains a possibility.

Overall, these very aggressive hybrid and alternative fuels scenarios, when combined with significant improvements in mainstream powertrains and reductions in vehicle weight, drag and tire resistance, suggest that reductions in fleet energy consumption of about 30 percent with comparable reductions in GHG (WTW) emissions, might be approached by 2040. Extrapolating to 2050 (based on our several U.S.-focused scenario studies) suggests that additional reductions of about 15% (relative) might be attainable for an overall reduction by 2050 approaching 40% for fleet fuel consumption, and up to some 50% for GHG (WTW) emissions provided that important requirements such as major reductions in GHG intensity in electricity supply, and the availability of substantial volumes of low-GHG-emitting second-generation ethanol are met.

Figure 9.24 illustrates the fleet energy use in 2050 relative to 1990, 2000, and 2009 levels, broken down into electricity, and bio- and petroleum-based liquid fuel. Note that the 2009 line is close to the maximum level the current fleet is utilizing. The figure confirms the above summary: bringing significant electricity into the LDV energy mix (PHEV compared to HEV scenario) reduced petroleum-based fuel use by about 20%; the benefits from plausible biofuel production use are comparable.

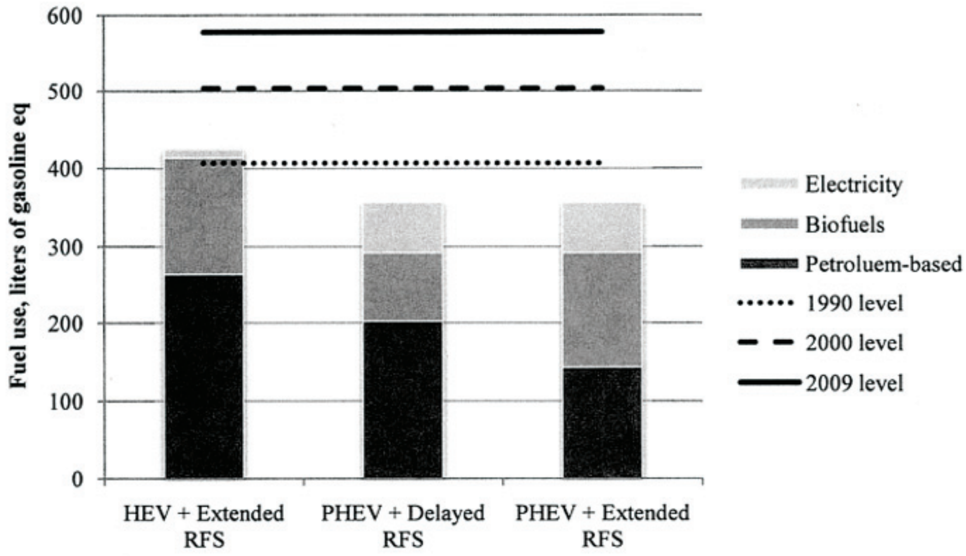


Figure 9.24 Annual in-use fleet energy use (billion liters gasoline eq. per year) in 2050, by energy source, the HEV plus *Extended RFS*, PHEV + *Delayed RFS*, PHEV + *Extended RFS* scenario. 1990, 2000, and 2009 energy-use levels are also shown.

A more realistic take on these overall impacts would be that some two-thirds of these reductions might be realized. Thus, while the impact of improving mainstream technology and steadily growing market share of HEVs over time is obviously the most important nearer-term impacting factor, increasing electrification of transportation's energy supply and building up biomass-based alternative fuels, would certainly displace a significant amount of petroleum-based-fuels. However, this diversification of energy sources would need to be accompanied by major reductions in the GHG emissions intensities of electricity generation and supply, and of low-carbon-emitting conversion of cellulosic biomass to fuels such as ethanol (see Table 3.6), for these benefits to be realized.

9.4.5 Benefits of higher octane gasoline

We will now report on a study that focused on the U.S. LDV fleet that examined the benefits of significantly raising the knock-resisting capability of standard U.S. gasoline. Knock, an abnormal engine combustion process, is caused by spontaneous ignition of the fuel-air mixture ahead of the flame inside the gasoline engine's cylinders. Knock onset limits the engine's compression ratio, as well as the boost levels in turbocharged gasoline engines, and thus the downsizing of the engine. A better knock-resisting fuel would delay the onset of this phenomenon, and thus enable engine changes that would usefully improve efficiency and performance. The knock resistance of a fuel is defined by its octane number, of which there are several definitions.

The most accurate octane number used in many world regions is the Research Octane Number (RON).[23] Regular gasoline in the United States is RON 91 or 92. Premium gasoline (RON 98) is about 10 percent of the U.S. gasoline market. In Europe, the standard RON is 95, higher than in the United States. Ethanol has a RON of 109, so it is an attractive anti-knock fuel, whether used in blends with gasoline or as a stand-alone fuel.

This study [Chow, Heywood, and Speth, 2014] evaluated scenarios in which the standard U.S. gasoline was replaced (over the next two to three decades) by a higher octane fuel (gasoline with some ethanol) with its RON raised to 98 or more. In parallel, new engines in LDVs would have their compression ratios raised and, if turbocharged, would have their boost levels raised and their displaced volume reduced appropriately (i.e., be downsized). This last point is important. If the output of an engine of given displacement is increased, that engine will generate more power. In a given vehicle, that engine would then provide greater vehicle acceleration capability. For equal acceleration performance, the engine should be *downsized*, i.e., its displaced volume reduced. As a result of any compression ratio increase, and especially due to engine downsizing in a given application, the engine's efficiency at part-load (where most normal driving occurs) is increased because the magnitude of the engine's friction and friction's relative importance significantly decrease. Depending on the impact on the petroleum refinery's energy consumption involved in producing this higher-octane "standard" fuel, this might be a worthwhile change to implement.

However, the time scales involved would be substantial. Joint decisions involving the petroleum and auto industries, and our national and state governments, would need to be made. Planning and implementing changes in refinery practice would need to occur. In parallel, engine design modifications would need to be made and carried into production. Vehicles that utilize the better gasoline must then be sold and, over time, penetrate the in-use fleet. This would take several decades. There are many constraints to overcome (e.g., vehicles must be able to be driven on the worst gasoline that is available). A workable transition strategy that allows a gradual buildup of the new fuel and a ramping down of the existing standard fuel must be worked out and implemented. For these (and other reasons), we analyzed the transition in the United States from today's standard *regular* gasoline (RON 91–92) to RON 98, today's *premium*. A critical reason for this specific transition was that upgrading to RON 98 (achieved in part with 10%–15% ethanol) has minimal refinery impacts [Speth et al., 2014], so essentially all the vehicle in-use benefits would be realized in a WTW sense.

On the gasoline production side, several assumptions were made to ease the refinery and engine design challenges. It was assumed that the supply of lower octane gasoline for high altitude use, primarily in Colorado, would be ended. (This helps the engine designer because the "worst" gasoline available would then have higher octane.) The primary parameter used to define gasoline's anti-knock quality would be its RON. Recent technical studies suggest that the Motor Octane Number (MON) could be lowered so that it constituted less of a constraint on gasoline production (as in Europe): that is, the gasoline's sensitivity could be increased. Ethanol would be available in

[23]In the United States an Anti-Knock Index (AKI) is used on gasoline pumps to specify the fuel's knock resistance. AKI is the average of the RON and a MON, usually some 8–10 octane numbers lower than the RON. This difference is called the gasoline's sensitivity. To convert AKI to RON, add about 5 octane numbers.

the 10% or so range (based on energy content) so that its blending octane benefit could be fully utilized. These implementable fuel-requirement changes help to simplify the refinery energy balance.

Engine (GT-Power) and engine-in-vehicle (Autonomie) simulations were used to estimate the improved vehicle fuel consumption realizable from higher compression ratio and boost levels, with appropriate engine downsizing, for this 6 RON fuel octane increase. We used our U.S. in-use LDV fleet model to assess the benefits of this transition to 98 RON standard gasoline. We essentially used the assumptions of our reference scenario defined in Table 9.1 [Bastani et al., 2012a], with minor changes and updates [Chow et al., 2014], as our base case. We also carried out a refinery analysis to assess the energy, GHG, and refinery product mix impacts of this change in standard fuel octane [Speth et al., 2014]. On this last point, the refinery changes were not significant up to a high-octane standard fuel of RON 98 (with the fuel specification modifications outlined above).

The critical issues needing quantification were the available compression ratio increase, the resulting engine efficiency increase at part-load in NA-SI engines, and the boost-level increase combined with the compression ratio increase realizable in turbocharged gasoline engines. Both of these changes would occur with the appropriate engine downsizing to forego increases in vehicle acceleration capability that would occur without or with less downsizing. The literature on this, and our own work, indicates that a 4 to 6 increase in RON is required for a unit increase in compression ratio. Thus, an increase of 1 to 1.5 in compression ratio would be realizable. This translates to a 3%–4.5% increase in part-load efficiency in NA-SI gasoline engines, and a 5%–7.5% increase for turbocharged engines, again allowing for appropriate engine downsizing. Note that these improvements are per vehicle, and occur in addition to the steady improvements in technology over time that we have discussed extensively in Chapter 3, and in Section 9.4.

Key LDV stock results are shown in Figure 9.25: the total U.S. LDV stock increases from about 250 million vehicles to 325 million in 2040. Figure 9.26 shows how the relative fuel consumptions of the various propulsion technology vehicles with 92 RON regular gasoline and high-octane 98 RON—the new standard gasoline—compared for NA-SI and turbocharged engine vehicles, and HEVs and PHEVs (for their gasoline-driven miles). The penetration of the higher-octane vehicles into the fleet over time is shown in the left in Figure 9.27. By 2030, 100% of vehicles sold have been designed for the high-octane fuel: as a consequence, these vehicles had penetrated to 69% of the in-use fleet. The fuel use of these same (new high octane, old low octane) vehicle technology categories is shown on the right of Figure 9.27 where, by 2040, almost 80% of the fuel used is the new high-octane gasoline.

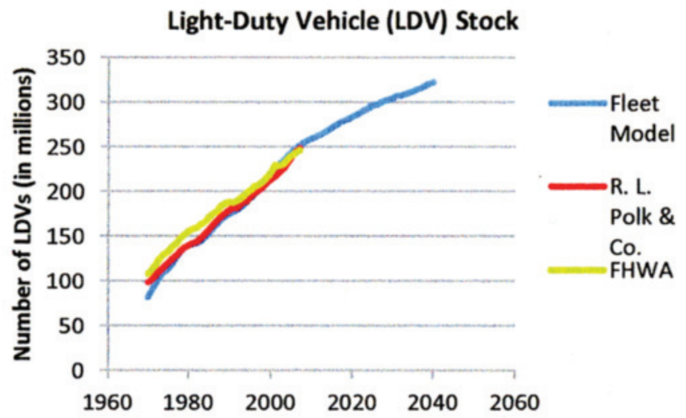


Figure 9.25 U.S. LDV stock size: historical record 1970–2005; fleet model simulation 1970–2040 [Chow et al., 2014].

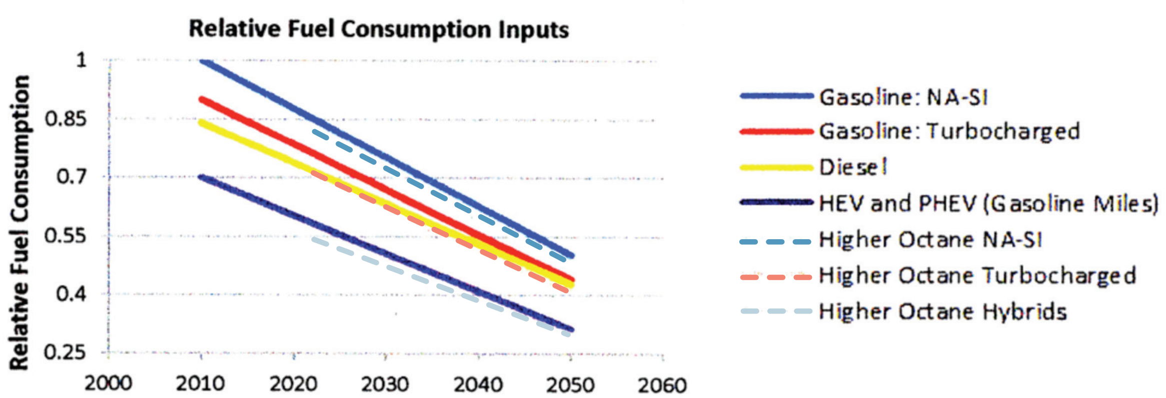


Figure 9.26 Relative (on-road) fuel consumption over time for different propulsion system vehicles: gasoline NA-SI, turbocharged, HEV, and PHEV (gasoline miles): current standard/regular gasoline, and high-octane gasoline.

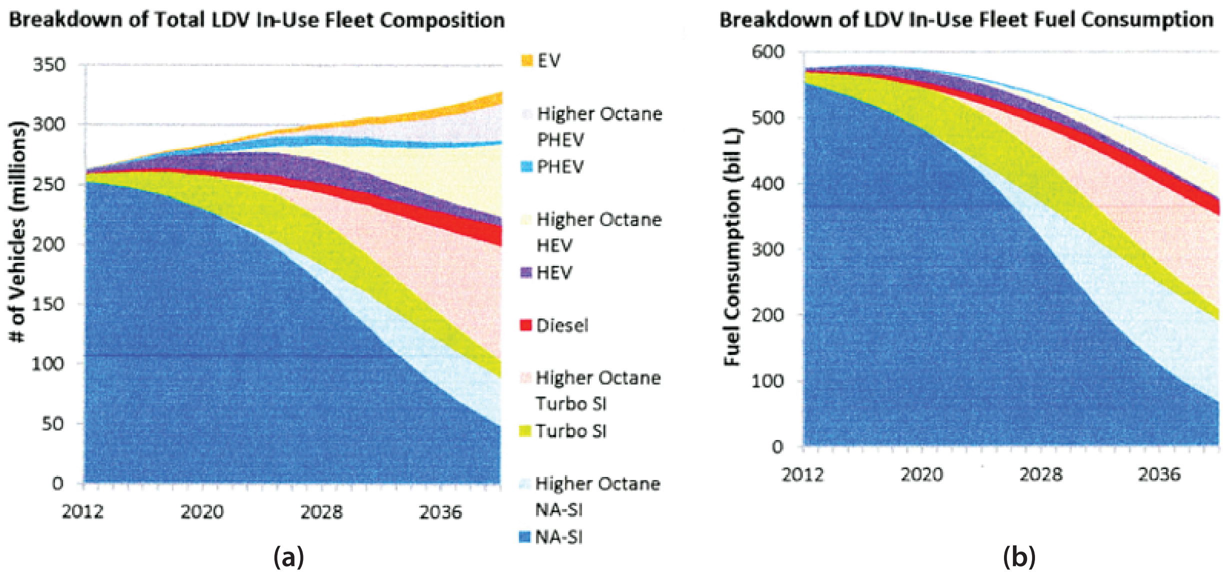
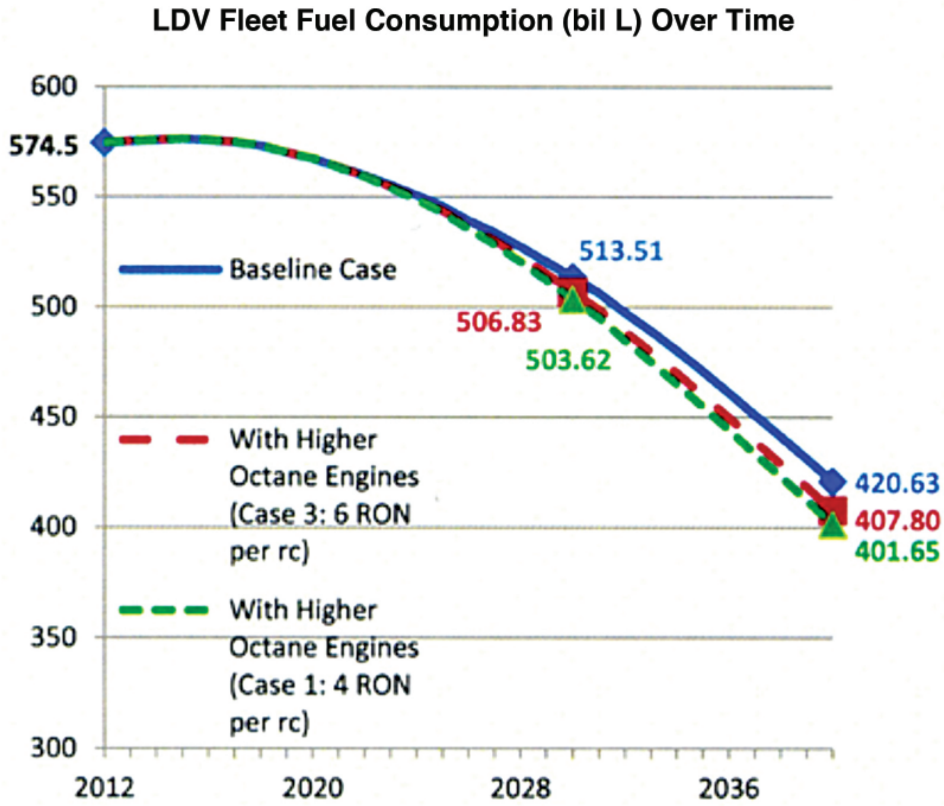
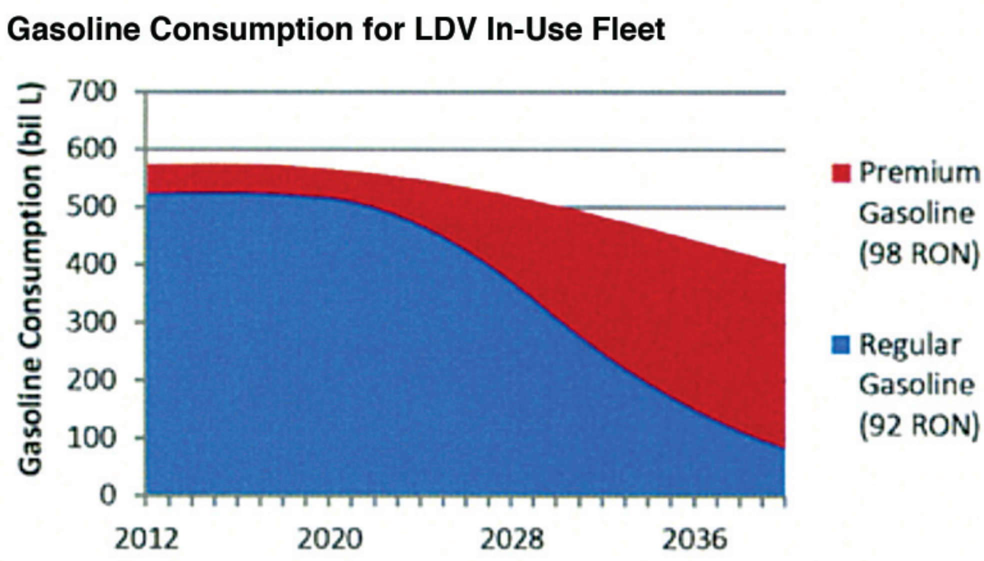


Figure 9.27 (a) Projected U.S. LDV in-use fleet composition by powertrain, and by standard and higher-octane gasoline. (b) Projected fleet fuel consumption by powertrain and fuel (Chow et al., 2014).

The overall scenario fuel-use summary is shown in Figure 9.28a. Fleet fuel use decreases in the United States from its current level of about 580 billion liters gasoline equivalent per year to 421 billion liters in 2040 in the baseline case. With 6 RON required per unit compression ratio increase, the 2040 level decreases further to 408 billion liters: with 4 RON per unit r_c increase, LDV fleet fuel consumption decreases to 402 billion liters. These represent 3% and 4.5% reductions from the baseline case, respectively: the baseline-scenario fleet fuel consumption reduction by 2040 from current levels is 27%. By 2040, almost 80% of the gasoline used by the fleet is 98 RON. Extrapolating these trends to 2050 (when almost all of the in-use vehicle fleet fuel use would be high octane) increases these percentage reductions, resulting from the transition to high-octane standard gasoline, to about 5% and 8%, relative to the reduced 2050 fuel consumption level of some 300 billion liters per year (baseline 325 billion liters). By 2050, the benefits of the higher-octane standard gasoline would be (in this analysis) essentially fully realized.



(a)



(b)

Figure 9.28 (a) Comparison of the total U.S. LDV in-use fleet fuel consumption (billion liters per year) for Baseline case; and with Higher Octane Engines, Case 1 with 4 RON increase required for unit increase in compression ratio, and Case 3 with 6 RON per unit increase in r_c. (b) Projected consumption of regular and premium (higher-octane) gasoline by the U.S. LDV fleet out to 2040 [Chow et al., 2014].

The broader implications of this specific *higher-octane gasoline* scenario are the following:

1. Fuel changes that also require vehicle changes are extraordinarily challenging: even this seemingly straightforward "premium becomes the new standard gasoline transition," with all its details and required coordination between the petroleum and auto industries, and governments, would be difficult to implement.

2. The overall benefits do not seem that substantial: less than 5% in 2040 and a maximum of some 8% in 2050. And these time scales seem far in the future. Yet other alternative fuels opportunities, with potentially higher impact, do not at this point in time appear promising.

3. We need to be working hard to realize any fuel opportunity that offers more than about a 5% fleet fuel-consumption reduction. Yet the degree of enthusiasm for undertaking this apparently straightforward opportunity, as the transition challenges become evident, is not yet clear.

9.5 Scenarios: Europe

9.5.1 Characterizing the European Union LDV Fleet

In 2009, the European Parliament passed a regulation to set GHG emission standards for new passenger cars registered in the European Union (EU). This measure was part of the EU's approach to reduce CO_2 emissions from LDVs. From 2015 onwards, the average CO_2 emissions from 100% of each manufacturer's newly registered cars should be 130 gCO_2/km or less. This target has been implemented in phases: 65% of new cars should have met the target by 2012 with the percentage rising to 100% in 2015. The requirements tighten to 95 gCO_2 km in 2020. Low-emitting vehicles sold (below 50 $kgCO_2$/km) counted as more than one vehicle: (3.5 vehicles in 2012 and 2013, decreasing to one vehicle, 2016 to 2019). Fines (increasing for each gram CO_2 above the requirement—5 Euro per car for the first gram of excess emissions, 15 Euro for the second, 25 Euro for the third, and 95 Euro for each subsequent gram) would be imposed on manufacturers that failed to meet the specified average emissions targets. The objective was to incentivize investment in new propulsion system and vehicle technologies by the car industry that would lead to significantly lower GHG emissions than from traditional technology vehicles.

Transport is the second largest GHG emitting sector (some 25%) and has historically been growing, while other sectors have not. Road transport emits about 70% of the total transport GHGs: LDVs account for two-thirds of the road transport emissions. The size of the LDV fleet in Europe is comparable to that in the United States, both being some one-third of the global total. Thus, assessing the potential for reductions in GHG emissions from the LDVs in Europe is an important topic.

The project summarized here assessed the feasibility of meeting these EU LDV CO_2 emission targets in the larger EU countries, through use of a powertrain-type and vehicle-weight based sales-mix model. Then, an in-use vehicle fleet model was used to assess the reductions in gasoline (petrol) and diesel fuel use and GHG emissions from the evolving fleet, again for the major EU countries and Europe as a whole [Bhatt, 2010]. An important difference between Europe and the United States is that, on average, vehicle sales split between gasoline and diesel engine

LDVs with about half of each, whereas in the United States, diesels constitute only a few percent of LDV sales. European car manufacturers' 2005 CO_2 emissions varied from about 140 gCO_2/km for the major manufacturers of lower-end, large-scale mass-produced smaller vehicles to about 165 gCO_2/km for mass producers with broader model offerings including larger vehicles. The higher-end German manufacturers had average CO_2 emissions in the 177 to 192 gCO_2/km range [Bhatt, 2010].

Developing an appropriate model for European sales is a necessary first step. The EU, with 27 member countries, is too complex from a data acquisition perspective to be workable. The 27 countries were compared on the basis of three factors: motorization, gross domestic product per capita, and population. Average values of these parameters per country were: motorization, 426 cars per thousand people, about half the U.S. value; GDP, $36,000 per capita; average population 18 million. Countries were categorized into three groups: (i) large, higher-than-average GDP/capita, highly motorized countries (Germany, France, the United Kingdom, and Italy), (ii) small, lower-than-average GDP/capita, lowly motorized countries (e.g., Romania, Portugal, Czech Republic, and Hungary; (iii) eclectic mix middle-layer countries (e.g., Spain, Poland, Netherlands, Greece, and Belgium). The *representative EU* for this study comprises nine countries: Germany, France, the United Kingdom, Italy, Spain, Netherlands, Portugal, Czech Republic, and Hungary. Collectively, these countries represent 72% of the EU population and 86% of the new car sales of the full EU-27 countries. We judge this an adequate representation of this major world region. See Bhatt (2010) for additional details.

9.5.2 Potential for meeting European Union LDV GHG emissions targets

Using the above definition of the EU, this study [Bhatt, 2010] assessed the likelihood of the vehicle sales mix embodying sufficient fuel-economy-improving technology to meet the European GHG emissions targets for 2015 and 2020. This was done through analyzing the nine representative countries listed in the previous section. The GHG emissions requirements must, of course, be met by the major auto manufacturers individually, and their sales are spread across Europe. Thus, we addressed "the likely availability of the needed technology" in a broader sense. The value of examining the sales mix in individual countries was in identifying important differences: e.g., in high-diesel sales-fraction countries like France and lower–diesel sales-fraction (and higher-performing vehicle) countries such as Germany.

Two key inputs to these calculations are the fuel consumptions of vehicles with different propulsion systems (e.g., NA-SI gasoline/petrol engines, HEVs, etc.) as they evolve over time. Figure 9.29 shows these vehicle fuel consumptions relative to the currently dominant NA-SI gasoline engine in 2010 and in 2020. These values are similar to those in Figure 3.3, although the set of propulsion system options has been expanded. The values represent the average new passenger-car fuel consumption on a relative gasoline-equivalent basis: values used for 2015 were halfway between the 2010 and 2020 values. Electrical energy for PHEVs and BEVs is not included.

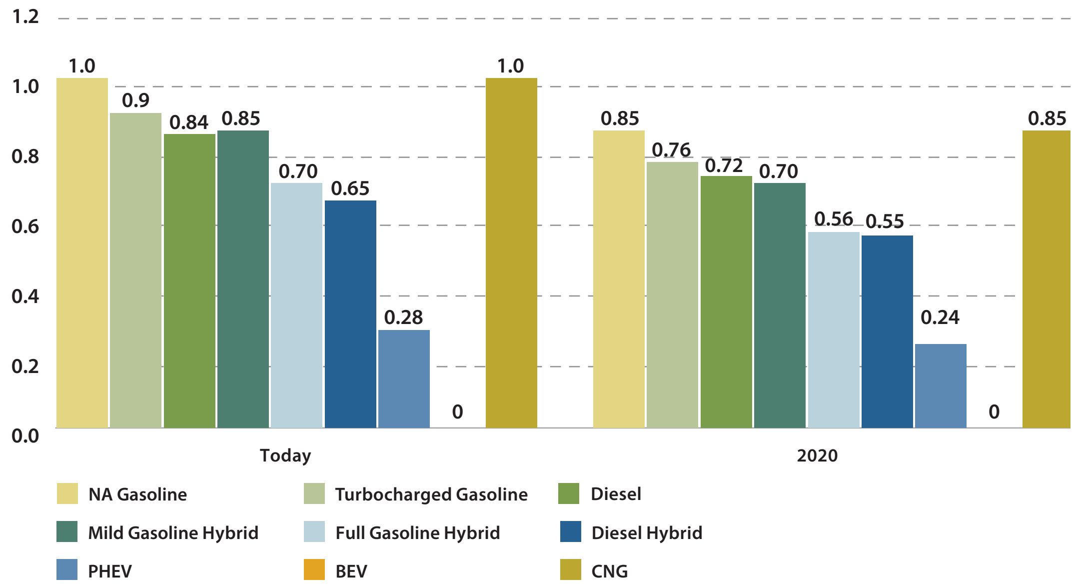


Figure 9.29 New vehicle fuel consumption, relative to average standard NA-SI gasoline engine vehicle, for the various propulsion system options: today (2010) and in 2020 [Bhatt, 2010].

Other key input assumptions are that the sales fraction of the various propulsion-system vehicles and the anticipated reduction in vehicle weight. These are shown in Table 9.5. Two 2020 scenarios were analyzed: an *Optimistic* and a *Realistic* scenario. These scenarios were developed based on our assessment of the anticipated shift toward a larger number of gasoline-fueled vehicles (relative to diesel) due to our judgment that the growing number of turbocharged, more efficient, gasoline engines would compete better with diesel passenger cars, and estimates of the (moderate) sales growth of the dominant alternative (various forms of hybrids). ERFC values in the table quantify the fraction of the potential fuel consumption improvements increasingly incorporated into new vehicles that actually improves the vehicle's fuel consumption. Thus, 75% ERFC means that 25% of this fuel consumption improving potential is used to offset the increase in vehicle acceleration performance. Our previous studies (see Chapter 5) indicate that a 10% decrease in ERFC results in about a 4% increase in fuel consumption. Thus, 75% ERFC results in a 10% increase in the relative fuel consumption values for the 2020 *optimistic* scenario shown in Figure 9.29 (which are for 100% ERFC). Similar scaling was done for all future years based on the estimated ERFC. Currently, for Europe's vehicle sales mix, ERFC is estimated to be about 50%. Our assessment is that ERFC appears to be increasing in the United States and elsewhere. Therefore, vehicle performance is increasing (and 0–65 mph acceleration times are decreasing), although at a diminishing rate. Auto manufacturers compete against each other for market share, of course, and consequently, when older models are reintroduced as refreshed or redesigned, poorer-performing older vehicles will come back as new designs with higher performance levels.

Table 9.5 Average European New Vehicle Sales Scenarios in Year 2020 [Bhatt, 2010].

	Today	Scenarios	
		Optimistic 2020	Realistic 2020
ERFC	50%	75%	50%
Weight Reduction (Total)		10%	5%
New Car Sales Mix			
Gasoline	**46.68%**	**34%**	**41%**
Non-turbo Gasoline	37.34%	14%	25%
Turbo Gasoline	9.34%	20%	16%
Diesel	**52.66%**	**42%**	**50%**
Hybrid	**0.5%**	**15%**	**6%**
Mild Hybrid		6%	4%
Full Hybrid	0.5%	6%	2%
Diesel Hybrid		3%	
Electricity	**0%**	**8%**	**2%**
PHEV		5%	2%
BEV		3%	
CNG	**0.16%**	**0.4%**	**0.4%**
	100.00%	100.00%	100.00%

Descriptive summaries of the three scenarios used in assessing whether the needed technology will be available to meet EU GHG requirements are as follows:

- **Realistic:** utilizes a realistic picture of vehicle sales mix, ERFC, and vehicle weight reduction that we anticipate would be achieved by 2020,
- **Optimistic:** a scenario that is more optimistic in nature and requires faster rates of change in technology, and
- **Fixed Sales Mix:** a scenario that provides the base case for comparison by assuming no change from today's powertrain sales mix, an ERFC constant at today's level of 50%, and no additional vehicle weight reduction above that achieved as part of the changing ERFC (about 4%; see Cheah et al., 2008).

It is important to note that these scenarios are not meant to forecast or predict. Instead, they are used to illustrate the relative ease or difficulty in achieving the emissions targets, and the sensitivity of improvements to rates of technology change. The *fixed sales mix* model was calibrated for the nine EU countries examined by comparing the "today" values with the EU CO_2 Monitoring Database (European Commission, 2010c). The difference was about 2%. Note that the input assumptions listed in Table 9.5 represent the *average* vehicle. Thus, for example, a weight reduction of 10% means that the total weight reduction achieved in the 2020 new vehicles sold is 10% of weight of all the vehicles sold the previous year.

Figures 9.30 and 9.31 show the projected CO_2 emissions in gCO_2/km for 2015 and 2020 for the nine countries, compared with the targets of 130 and 95 gCO_2/km, respectively. Figure 9.32 shows the vehicle-sales weighted average of these nine countries, indicating the overall EU situation. The *optimistic* scenario just meets the target in 2015, though not in Germany and the United Kingdom. Generally, higher diesel sales fractions result in somewhat lower average vehicle CO_2 emissions. The less optimistic scenarios fall considerably short (the *realistic* scenario by almost 10%).

The 2020 situation is less promising. The *optimistic* scenario falls short of the 95 gCO_2/km by 14%. The *realistic* scenario prediction for 2020 would be almost 40% above the standard. Note again, the actual requirements assess the sales-weighted CO_2 emissions level of each auto manufacturer's sales across Europe.

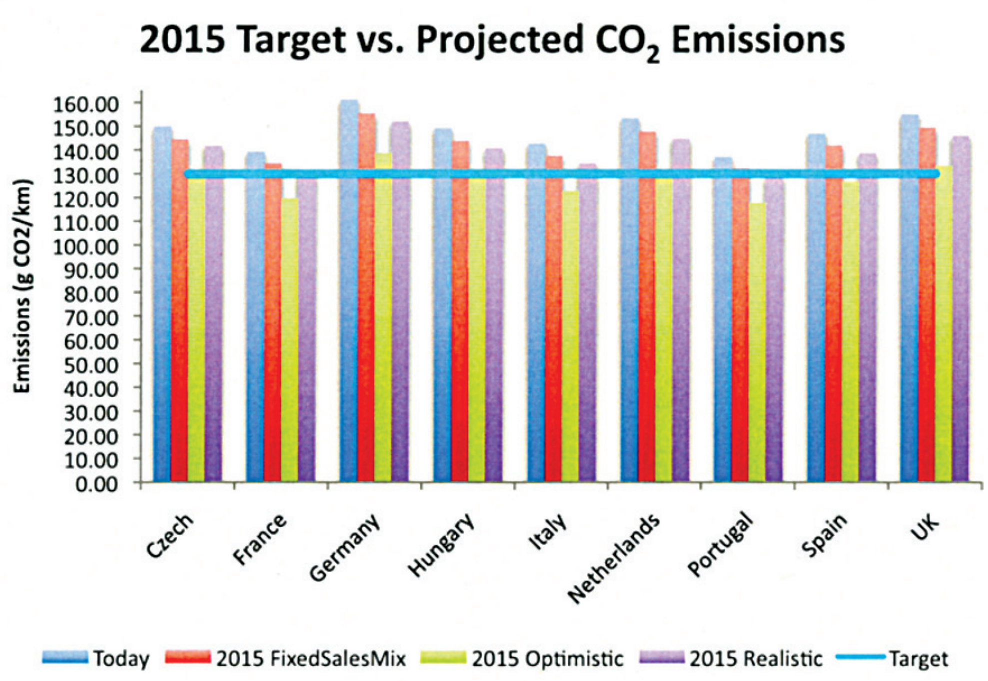


Figure 9.30 Projected average new-vehicle sales mix CO_2 emissions in 2015 for the nine European nations, compared with the gCO_2/km target [Bhatt, 2010].

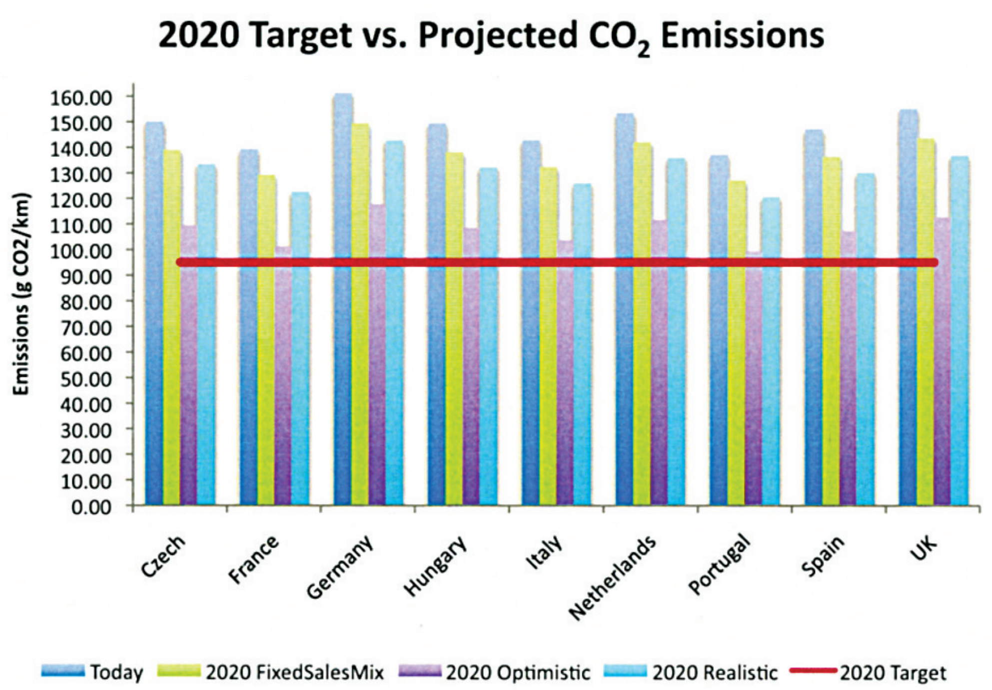


Figure 9.31 Projected average new-vehicle sales mix CO_2 emissions in 2020 for the nine European nations, compared with the 95 gCO_2/km target [Bhatt, 2010].

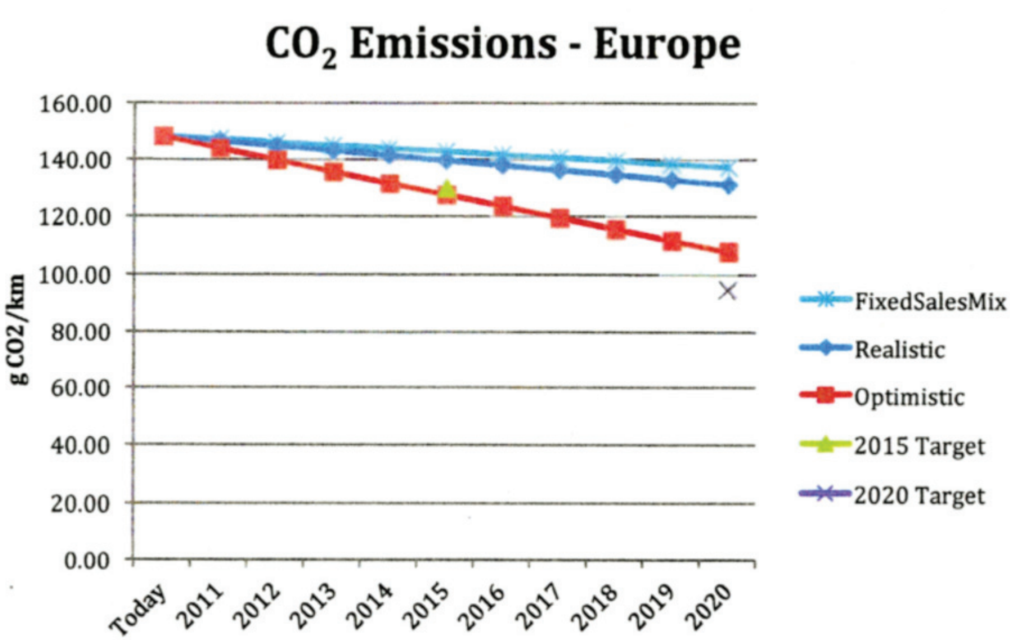


Figure 9.32 Projected average new-vehicle CO_2 emissions for the nine-country representation of EU for the three scenarios (*optimistic*, *realistic*, *fixed sales mix*), and 2015 and 2020 targets (130 and 95 gCO_2/km).

Moving forward from today, the key factors influencing the reduction in emissions are the rate of progress and the extent of implementation of the technologies that improve the fuel consumption of mainstream gasoline and diesel engine vehicles[24]; and the increase in deployment rate of electrified vehicles (HEVs, PHEVs, and BEVs). Fleet growth and increases in VKT over time are modest factors.

What would it take to meet these targets? The greatest benefits would come from increasing the market share of electrified vehicles, HEVs, PHEVs, and BEVs. The improvements needed for each of these three technologies would be a 0.17%, 0.4%, and 1% decrease in CO_2 emissions (in gCO_2/km) for each 1% increase in sales for HEVs, PHEVs, and BEVs, respectively. Thus, significant increases in the sales percentages of these electrified vehicles would be needed for both individual countries and the overall European sales-mix of new vehicles to have good prospects for meeting the 2020 targets. Note that the much higher impacts of PHEVs and BEVs are due to their greatly reduced gasoline/diesel fuel use since, in these Euro requirements, the GHG emissions released in producing the electricity used by these types of vehicles are not included in the TTW CO_2 accounting.

9.5.3 In-use LDV fleet fuel use and GHG emissions in major Euro nations

Here we review the impacts of these vehicle-improving technologies (both within a given powertrain-type vehicle, and through increasing the sales of more fuel efficient powertrains such as hybrids) on the sales-mix and in-use vehicle fleet's TTW CO_2 emissions and fuel consumption. The sales mix calculations were done for the nine European countries examined (see Figures 9.30, 9.31, and 9.32). In-use fleet models for the four larger countries were developed and used. Here we show results for three: Germany, France, and Italy. Of these, Germany has the lowest average fraction of diesel-engine vehicles sold, France has the highest, and Italy is in between these two. Other national fleet differences were included. The new-vehicle sales mix CO_2 emissions out to 2020 are shown in Figures 9.33, 9.34, and 9.35. The decreases in emissions in each succeeding year are quite similar: however, Germany has significantly higher current sales-mix CO_2 emissions levels (by close to 15%) so its challenges in meeting the 2015 and 2020 targets are much greater.

[24]Note that in the in-use fleet calculations summarized in the next section, it is assumed based on current driving patterns that diesel cars are driven significantly more per year than gasoline vehicles (by some 35% to 60%, depending on the country and, presumably, on the relative cost of these fuels in that specific country). Thus, a shift in the relative proportions of these gasoline and diesel cars results in a shift in annual VKT.

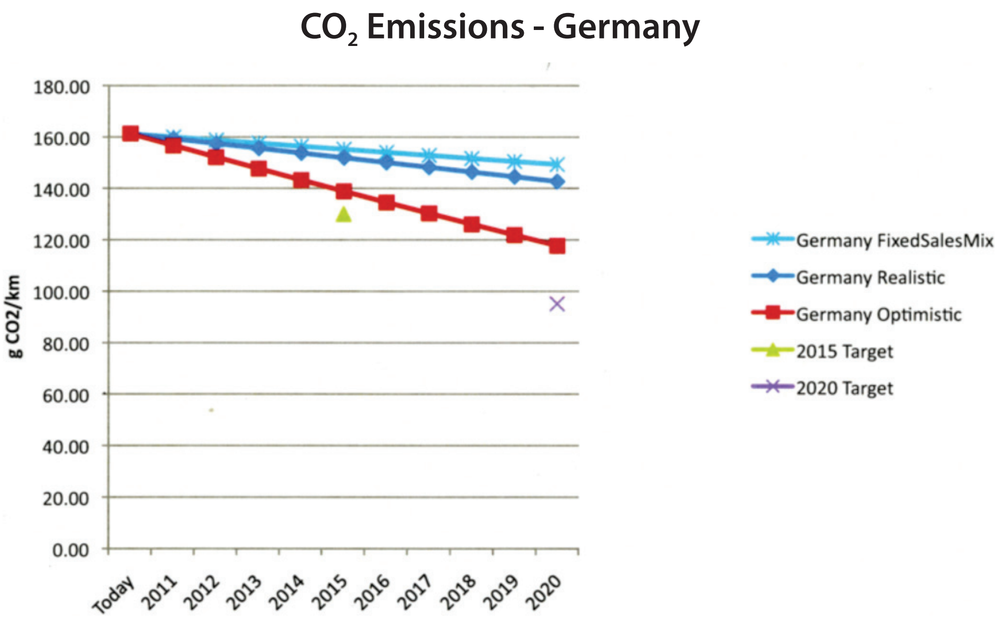


Figure 9.33 Projected average new light-duty vehicle CO_2 emissions (gCO_2/km), 2010–2020, for Germany for the three scenarios. 2015 and 2020 Euro-wide targets are 130 and 95 gCO_2/km.

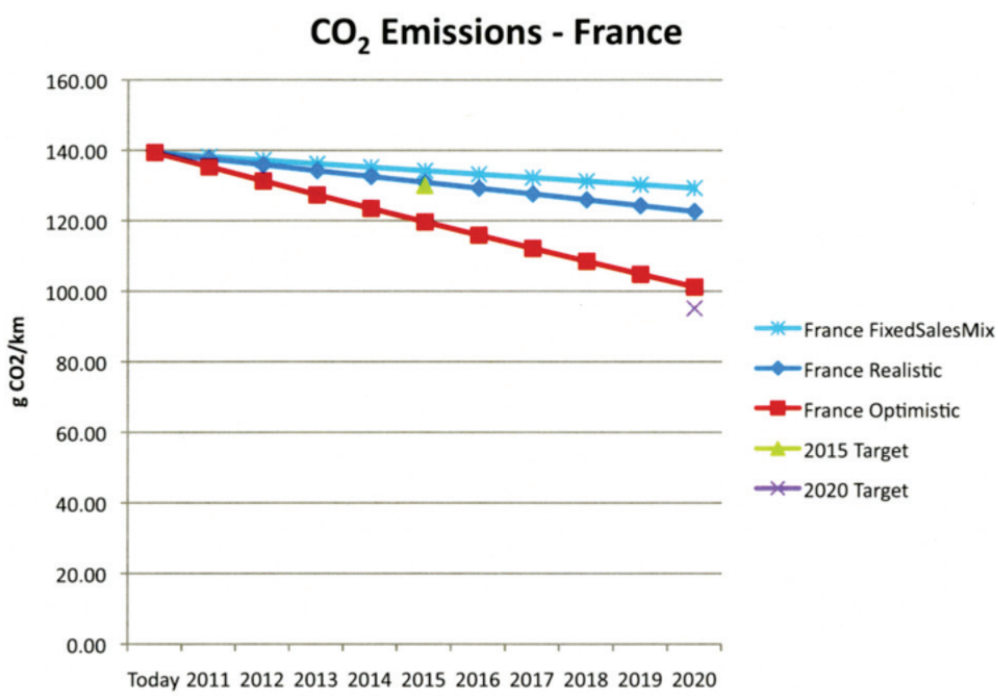


Figure 9.34 Projected average new light-duty emissions (gCO_2/km), 2010–2020, for France for the three scenarios. 2015 and 2020 Euro-wide targets are 130 and 95 gCO_2/km.

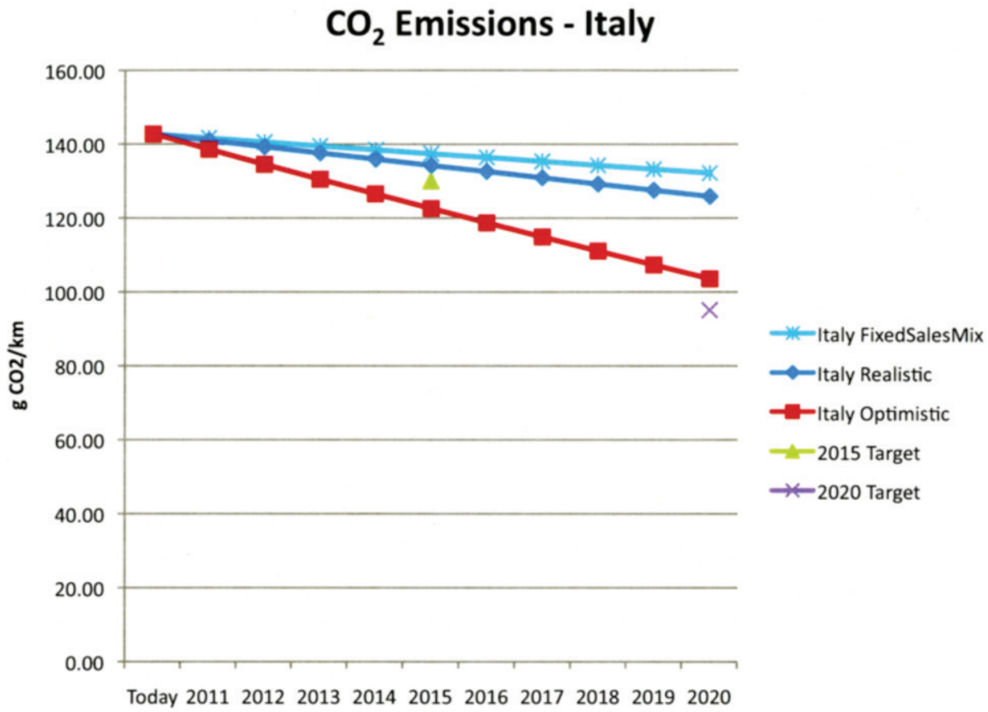


Figure 9.35 Projected average new light-duty vehicle emissions (gCO_2/km). 2010–2020, for Italy for the three scenarios. 2015 and 2020 Euro-wide targets are 130 and 95 gCO_2/km.

Tables 9.6, 9.7, and 9.8 provide critical input assumptions for the scenarios examined for Germany, France, and Italy. The diesel-to-gasoline engine sales ratio shifts over time from the current value in each country (in 2010) toward equal market shares at a given rate. Thus, Germany and Italy approach the same percentage: France does not reach that point because the current ratio is more than three-quarters diesel. The ERFC and weight reduction values, and the percentage of sales that are hybrid, PHEV and BEV, are the same in all the scenarios.

Table 9.6 Scenario Input Assumptions for Germany.

	Today/ Reference	Scenarios	
		Optimistic 2020	Realistic 2020
ERFC	50%	75%	50%
Weight Reduction (Total)		10%	5%
Due to ERFC		3%	2%
Additional	0%	7%	3%
New Car Sales Mix			
Gasoline	**55.46%**	**33.77%**	**44.77%**
Non-turbo Gasoline	44.37%	13.51%	31.34%
Turbo Gasoline	11.09%	20.26%	13.43%
Diesel	**43.71%**	**42.86%**	**46.86%**
Hybrid	**0.5%**	**15%**	**6%**
Mild Hybrid	0%	6%	4%
Full Hybrid	0.5%	6%	2%
Diesel Hybrid	0%	3%	0%
Electricity	**0%**	**8%**	**2%**
PHEV	0%	5%	2%
BEV	0%	3%	0%
CNG	**0.33%**	**0.38%**	**0.38%**
	100.00%	100.00%	100.00%

Table 9.7 Scenario Input Assumptions for France.

	Today/ Reference	Scenarios	
		Optimistic 2020	Realistic 2020
ERFC	50%	75%	50%
Weight Reduction (Total)		10%	5%
Due to ERFC		3%	2%
Additional	0%	7%	3%
New Car Sales Mix			
Gasoline	**22.37%**	**17.06%**	**28.06%**
Non-turbo Gasoline	17.90%	6.82%	19.64%
Turbo Gasoline	4.47%	10.23%	8.42%
Diesel	**77.13%**	**59.57%**	**63.57%**
Hybrid	**0.5%**	**15%**	**6%**
Mild Hybrid	0%	6%	4%
Full Hybrid	0.5%	6%	2%
Diesel Hybrid	0%	3%	0%
Electricity	**0%**	**8%**	**2%**
PHEV	0%	5%	2%
BEV	0%	3%	0%
CNG	**0%**	**0.38%**	**0.38%**
	100.00%	100.00%	100.00%

Table 9.8 Scenario Input Assumptions for Italy.

	Today/ Reference	Scenarios	
		Optimistic 2020	Realistic 2020
ERFC	50%	75%	50%
Weight Reduction (Total)		10%	5%
Due to ERFC		3%	2%
Additional	0%	7%	3%
New Car Sales Mix			
Gasoline	**48.54%**	**30.33%**	**41.33%**
Non-turbo Gasoline	38.83%	12.13%	28.93%
Turbo Gasoline	9.71%	18.20%	12.40%
Diesel	**50.58%**	**46%**	**50%**
Hybrid	**0.5%**	**15%**	**6%**
Mild Hybrid	0%	6%	4%
Full Hybrid	0.5%	6%	2%
Diesel Hybrid	0%	3%	0%
Electricity	**0%**	**8%**	**2%**
PHEV	0%	5%	2%
BEV	0%	3%	0%
CNG	**0.38%**	**0.38%**	**0.38%**
	100.00%	100.00%	100.00%

The in-use LDV fleet fuel use results in billions of gasoline-equivalent liters/year are shown in Figure 9.36, for both the *optimistic* and *realistic* scenarios. The reductions from the reference case achieved by each of the different propulsion system-type vehicles are identified individually. The changes over this ten-year time period are relatively modest. The reference cases (the *fixed sales mix* scenarios) change by less than + 5%.[25] The *optimistic* scenarios show reductions similar to the reference fleet fuel-consumption case of close to 6%, 2010 to 2020. Note that the figures for the *optimistic* scenarios imply that fleet fuel consumption (and GHG emissions) continues to go down at an increasing rate beyond 2020. The changes by 2020 are modest because the time available for technology and sales mix changes is short.

[25]Germany and France reference cases increase by 2.8% and 5.7%, respectively. Italy's reference case (due to negative growth) goes down by 5.5%.

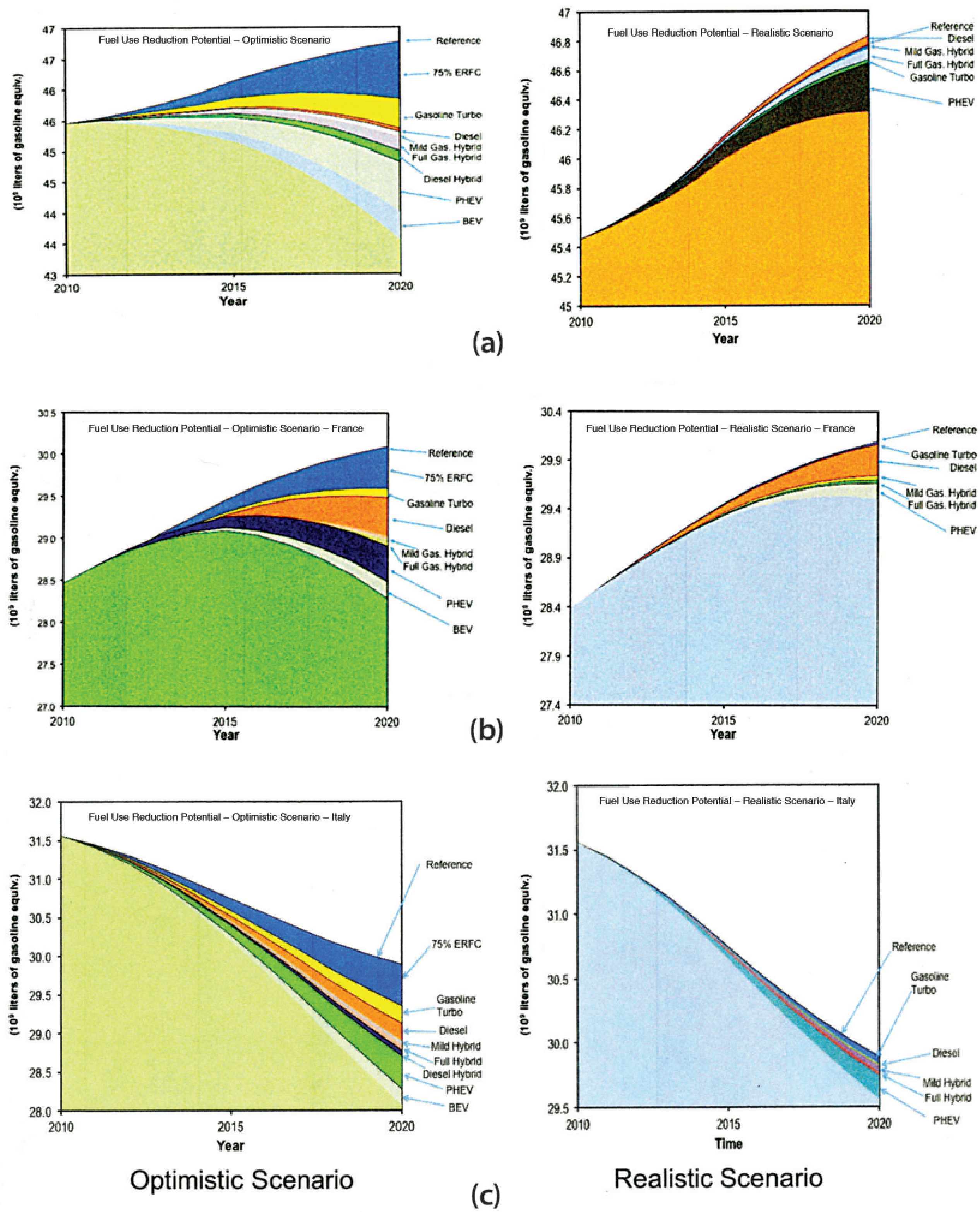


Figure 9.36 In-use vehicle fleet consumption (billions of liters/year, gasoline equivalent) for *optimistic* and *realistic* scenarios, for (a) Germany, (b) France, and (c) Italy. The reductions achieved by deploying the various powertrains and raising ERFC, from the reference *fixed sales mix* scenario are indicated [Bhatt, 2010].

One final topic important for Europe is the ratio of diesel to gasoline fuel demand. The current LDV sales mix between gasoline and diesel engine vehicles varies substantially country to country. It is high in France (77%) and low in the United Kingdom and Germany (44%). Thus, diesel fuel demand and gasoline demand for the LDV fleet are comparable, a situation substantially different from most other world regions. These LDVs (in Europe, largely passenger cars) consume about two-thirds of all road transport fuel. Of the additional one-third, most is diesel. Our in-use fleet model tracks LDV gasoline and diesel use, which in Europe are comparable in magnitude. The diesel-to-gasoline demand ratios tracked in these individual country in-use fleet impact assessments are shown in Figures. 9.37, 9.38, and 9.39 for Germany, France, and Italy. Most of the non-LDV fuel use (the remaining one-third) is for freight (not for passenger travel) and is diesel. Freight transport is growing significantly, almost everywhere, worldwide. Thus, overall transport diesel demand is currently about double the European LDV fleet diesel demand. Current diesel-to-gasoline volume ratios are 0.6 in Germany, about 2 in France, and between 1.0 and 1.1 in Italy, reflecting each country's fraction of diesel vehicles in the in-use LDV fleet. In all three cases, diesel fuel demand in this sector is rising, and the difference between the *realistic* and *optimistic* scenarios is modest. This rise is largely due to the fleet makeup moving toward an "equilibrium" in diesel vehicle fraction. Diesel vehicles sales have, until recently, been rising and, as higher numbers of diesel vehicles become ever "older," the diesel demand increases. The position of the reference scenario, in relation to the optimistic and realistic lines, depends on whether the diesel sales-mix fraction is increasing (Germany), decreasing (France), or not changing much (Italy), over time.

Overall, in Europe, achieving substantial changes in fuel consumption and GHG emissions from in-use LDVs is especially challenging. While growth in vehicle use is modest, fuel prices are high and vehicles are significantly smaller than in the United States. Thus, the weight reduction potential is more limited, and the higher-efficiency diesel powertrain is already in use on a large scale. On a TTW basis (only considering the vehicle), vehicle electrification through increasing deployment of PHEVs and BEVs offers the largest (at the individual vehicle level) reductions. But, on a full lifecycle analysis basis (WTT), these electrification reductions are much reduced if the electrical energy supplied to these vehicles is largely generated by fossil fuels.

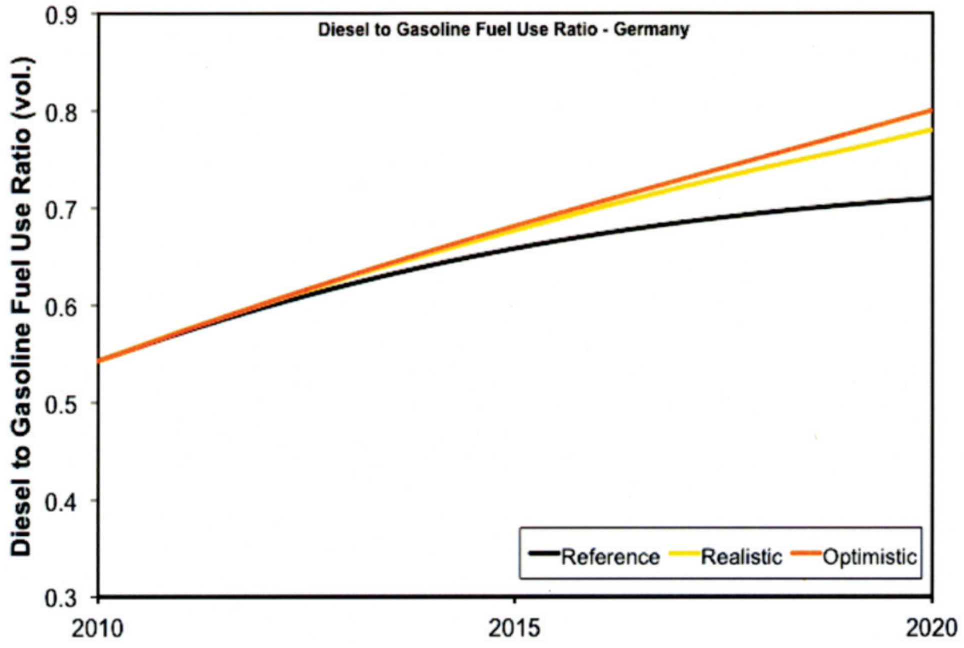


Figure 9.37 In-use LDV fleet diesel-to-gasoline fuel demand ratio, Germany: *Reference*, *Realistic*, and *Optimistic* scenarios.

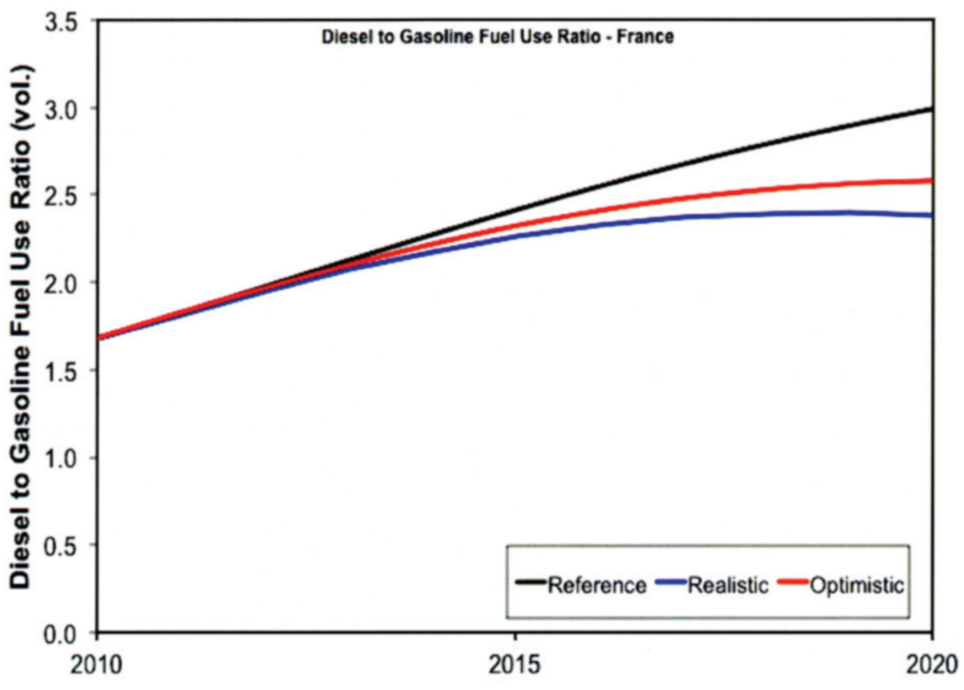


Figure 9.38 In-use LDV fleet diesel-to-gasoline fuel demand ratio, France: *Reference*, *Realistic*, and *Optimistic* scenarios.

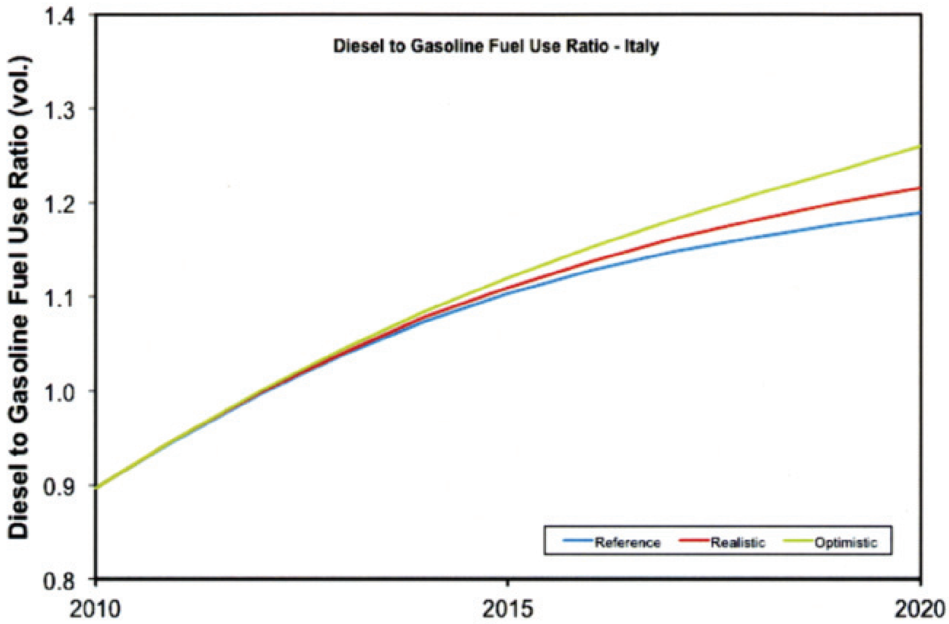


Figure 9.39 In-use LDV fleet diesel-to-gasoline fuel demand ratio, Italy: *Reference*, *Realistic*, and *Optimistic* scenarios.

9.6 Scenarios: Japan

9.6.1 Scenarios Definition and Assumptions

Under the Kyoto Protocol, adopted at the end of 1997 and entered into force in early 2005, Japan committed to reducing its GHG emissions by 6% below the 1990 level by 2012. Emissions had increased substantially from the 1990 levels, and in the transportation sector, that increase was 18%. Thus, substantial reductions in GHG emissions from the transportation area are required, particularly since transportation contributes about one-quarter of Japan's total GHG emissions.

The Japanese government has addressed this challenge in several specific ways: (1) Through promotion of environmentally friendly vehicles such as hybrids and BEVs; (2) By setting stringent targets for vehicle fuel economy based on best-available technology; (3) Through construction of a more "efficient" transportation system; (4) By implementing a more effective transportation infrastructure and traffic controls; (5) By promoting the use of public transport (trains and buses) instead of passenger cars. Also, Japan has high gasoline prices, which reinforce these government efforts, so people drive less than they did previously.

Given these concrete government actions, we felt that analyzing the likely evolution of the fuel consumption and GHG emissions from the in-use LDV fleet over several decades would be worthwhile. A part of the overall plan in Japan is substantial vehicle electrification, so an important question is what impact would significant electrification of transport have on transport's GHG emissions? Accordingly, a scenario-based analysis of this situation in Japan was undertaken by Eriko Nishimura (2011). Also, the transport situation in Japan is different than the situation in other major regions where we have done scenario analysis. Specifically, the population is large (128 million), the population density is high, and there is an extensive rail network, as well as a preponderance of smaller cars. Figure 9.40 shows the kilometers traveled per person per year in each transportation mode: public transportation carries a large share of passenger travel.

Accordingly, an LDV fleet model (see Section 9.3 and Figure 9.1) was developed for Japan. A quantitative model for assessing the impacts on Japan's GHG emissions of different evolving transportation technologies and fuel scenarios needs the following components: [Nishimura, 2011].

(a) A vehicle analysis capability that, for given propulsion system and vehicle technologies, can predict the vehicle's fuel consumption and GHG emissions over specified driving patterns.

(b) A model for the dynamics of the in-use LDV fleet, which includes vehicle sales and scrappage rates, and annual kilometers traveled.

(c) The specification of new, improved technology introduction time frames and the deployment rates of these technologies as a function of time.

(d) The resolution of the vehicle fuel consumption, performance, and vehicle size trade-off that, for given powertrain and vehicle technologies, affects the improvements in fuel consumption that are actually achieved.

(e) Quantitative scenarios for the fuel (or energy) streams expected to be available over the appropriate time frame and the GHG emissions intensities associated with the production and distribution of those fuels.

The LDV categories included in the fleet model are listed in Table 9.9.

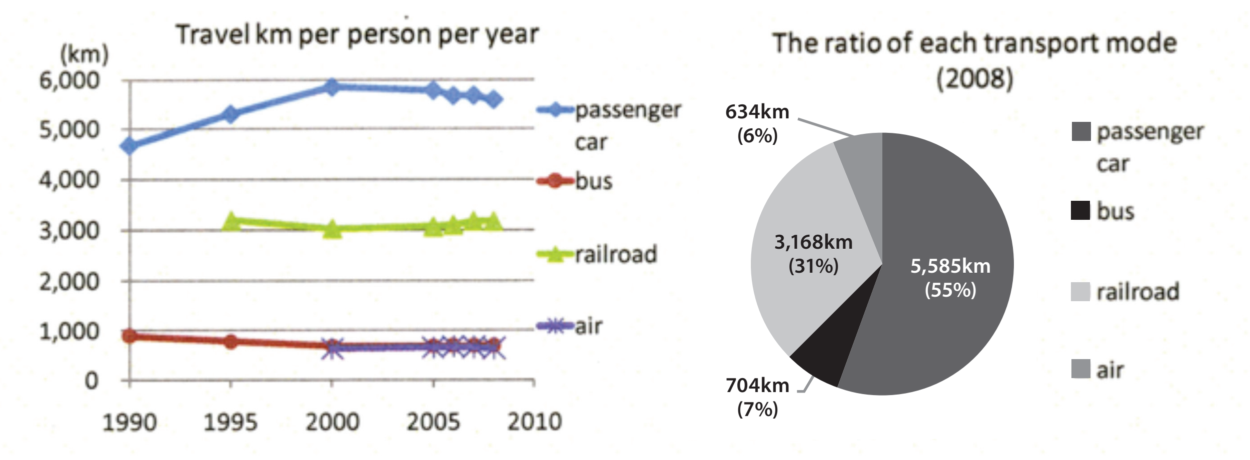


Figure 9.40 Kilometers traveled per person per year in each transportation mode: Japan [Ministry of Land, Infrastructure, Transport and Tourism (MLIT), 2010].

Table 9.9 Japanese LDV Categories

Vehicle Category	Definition	Vehicle stock (2009)	Vehicle sales 1 yr. (2009)
Passenger Cars			
K-Car (light motor vehicle)	Maximum length: 3.4m Maximum displacement: 660cc	17.5 million	1.3 million
Compact Car	Maximum length: 4.7m Maximum displacement: 2,000cc	23.7 million	1.6 million
Normal Car	All larger passenger cars	16.7 million	1.3 million
Trucks			
K-Truck (light truck)	Maximum length: 3.4m Maximum displacement: 660cc Maximum load capacity: 350kg	9.2 million	0.4 million
Compact Truck	Maximum length: 4.7m Maximum displacement: 2,000cc (except for Diesel and CNG) Maximum load capacity: 2,000–3,000kg (ambiguous)	3.9 million	0.2 million
Normal Truck	All trucks other than above (mainly heavy-duty; not light-duty)	2.3 million	0.1 million

The categorization of Japanese vehicles, as shown in Table 9.9, is unique. There are three vehicle categories for passenger cars, and three categories for trucks. For passenger cars, vehicles are categorized based on their size and engine displacement. First come “K-cars,” so called because the pronunciation of K stands for “light” in Japanese. As for trucks, vehicles are categorized based on their size, displacement, and load capacity. The scope of this research is limited to LDVs. It includes the first five categories shown in Table 9.9, but does not include “normal trucks” because most of the normal trucks are heavy-duty vehicles which are mainly used for freight transport. Also, diesel fuel is used for most of these vehicles, so they do not use gasoline.

K-cars and K-trucks (both small in size and engine displacement) constitute some 35% of the LDV sales and of the LDV stock, a factor that makes the Japanese fleet unusual. Also, annual sales volume has been decreasing in all vehicle categories in Table 9.9 except K-cars, which have been modestly growing (some 1% per year). Figure 9.41 shows the LDV sales projections we have used for these Japan studies, out to 2030. Modest increases in K-car sales are assumed, along with decreases in compact and normal car sales over time, such that the total LDV sales decrease slightly from about 2020 through 2030.

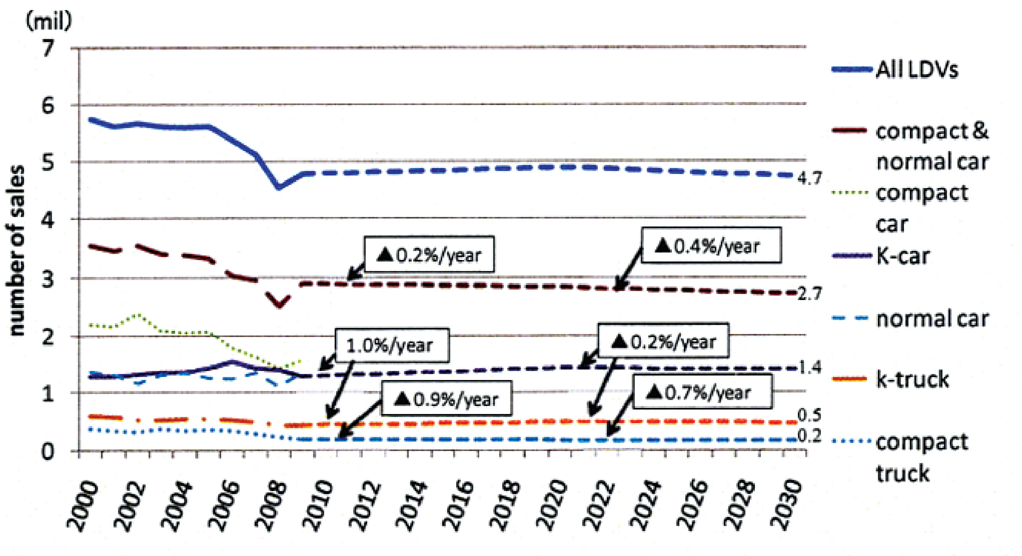


Figure 9.41 Vehicle sales data and projections in Japan for the various LDV categories, out to 2030.

Other stock parameters of importance are survival rates of vehicles as a function of vehicle age and average (or median) vehicle lifetimes (in years) projecting into the future. These data for Japan are not that different from other regions we have analyzed (United States and Europe). The average lifetimes for the various categories of LDVs have been increasing, starting in about 1995 [Nishimura, 2011]. This appears to be related to changes in in-use-vehicle inspection requirements.

The growth in VKT per vehicle (per year) for K-cars and K-trucks has been about 0.4% per year for the period 2000 to 2010. However, this K-car/truck VKT value (7,200 km/yr) is about three-quarters of the VKT of compact and normal cars (9,500 km/yr). The trends are slowly converging and our assumption is these two categories will have comparable VKT by about 2030. VKT, as in all our fleet model studies, decreases as vehicles age (from 14,000 km/yr for new vehicles to 4,000 km/yr for a 20-year-old vehicle).

In the scenario analyses to be described next, vehicles are divided into two groups to build up the sales mix by propulsion system type (e.g., NA-SI gasoline engines, HEVs, etc.). The first group is labeled *Standard Vehicles* and includes compact and normal passenger cars, and compact trucks. The second group includes K-cars and K-trucks, and is called *Light Vehicles*.

As is clear from earlier sections of this chapter, the fuel consumption values assumed for the various propulsion system vehicles, in the different vehicle categories, are important inputs for our fleet-model-based scenario analysis. The basic data used for developing these critical fuel consumption numbers are shown in Figures 9.42 and 9.43. These fuel consumption values are from the JC08 model Japanese test cycle. This relatively new test cycle has replaced the 10–15 mode cycle. It is intended to represent driving in city traffic, including idling periods and alternating vehicle acceleration and deceleration, with first a cold start and then a repeat warm start. Fuel consumption values (in liters/100 km) on the JC08 cycle are about 10% higher than equivalent fuel consumptions on the 10–15 mode, older, test cycle. [Ministry of Land, Infrastructure, Transport and Tourism MLIT, 2006]. It is anticipated that on-road, real-world vehicle fuel consumption values will be higher than the JC08 test cycle values due to the impact of more aggressive real-world driving, different ambient conditions, and the degree to which the vehicle has warmed up. In the United States, this on-road increase in fuel consumption (liters/100 km) above standard U.S. test cycle values is about 25%: in fuel economy terms, the shortfall is the reciprocal of this, 20%. It is plausible that Japanese test cycle results underestimate fuel consumption (overestimate fuel economy) by similar amounts. In these Japan focused scenarios, we have used the JC08 test cycle fuel consumption numbers.

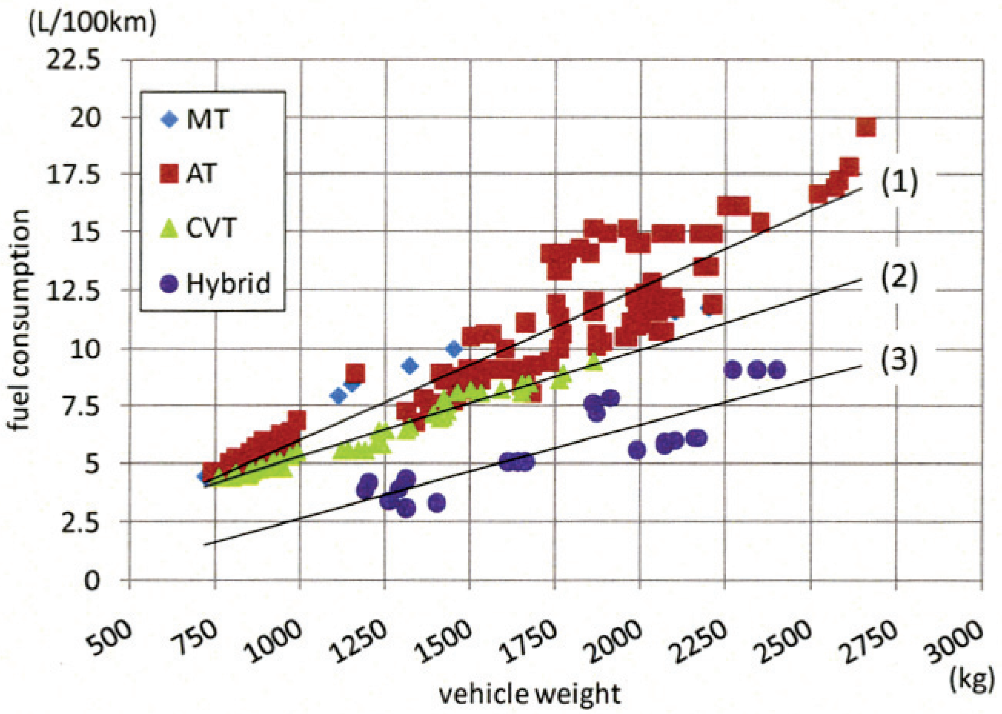


Figure 9.42 LDV fuel consumption (liters/100 km, JC08 test cycle values) as a function of vehicle weight (kg) in Japan, 2008 model year [MLIT, 2010].

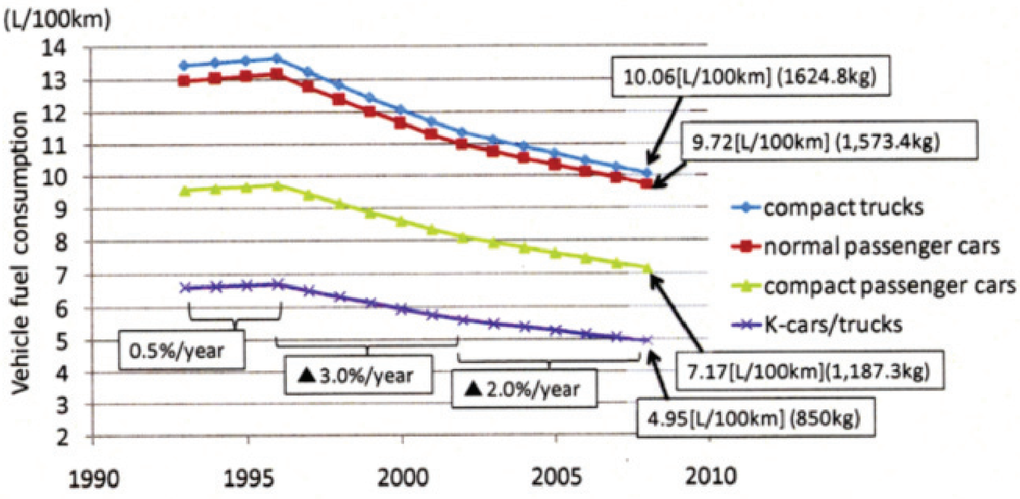


Figure 9.43 Trends in LDV fuel consumption (liters/100 km, JC08 test cycle) for the different vehicle categories, 1933–2008: current average fuel consumption and vehicle weight highlighted.

Figure 9.43 shows that vehicle fuel consumption has been decreasing since about the year 2000, at some 2% per year in each vehicle category. When weighted by sales fraction, the average fuel consumption of the new vehicles sold in 2010 was about 7 liters/100 km, close to the average value of compact passenger cars.

Figure 9.44 shows the relative fuel consumption values used in our Japan scenarios for the time period 2010 to 2030. They are based on our own studies of the technology improvement potential of mainstream internal combustion engines, multi-gear automatic transmissions in standard general-purpose vehicles (see Chapter 3) and of the various promising alternatives propulsion systems, as well as assessments from the Japanese Ministry of Environment [MOE, 2010]. These relative fuel consumption values are normalized by the fuel consumption of a current standard (NA-SI) gasoline engine vehicle. The values in Figure 9.44 include engine, transmission, and drivetrain improvements; vehicle weight and drag and tire rolling-resistance reductions; and allow (via MOE, 2010) for some increase in vehicle acceleration capability. These values (in the absence of clear evidence to the contrary) are applied to all vehicle categories (standard and light vehicles).

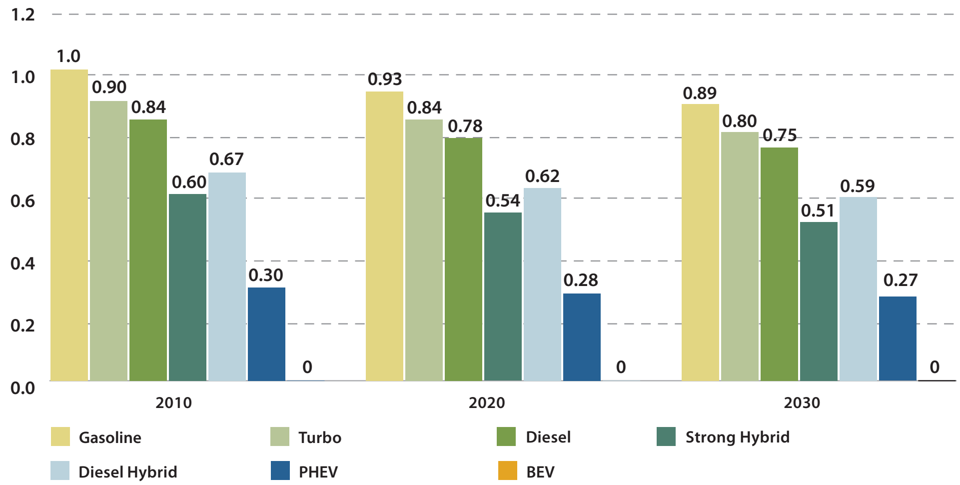


Figure 9.44 Relative fuel consumption for an average vehicle with the different propulsion systems: in 2010, 2020, and 2030 [Japanese Ministry of Environment (MOE), 2010]. Projected fuel consumptions are divided by fuel consumption of a 2010 standard NA-SI gasoline engine vehicle.

When compared to vehicle fuel consumption values for the United States (see Figure 3.3) and Europe (see Figure 9.29), the data for Japanese vehicles in Figure 9.44 show more moderate improvements. The reasons are:

(1) The mainstream gasoline engine vehicle in Japan already has lower fuel consumption than equivalent vehicles in Europe, and especially in the United States, so the potential for improving the fuel consumption of the dominant type of vehicle in Japan is thus less, especially in the weight reduction area.

(2) A strong-hybrid gasoline vehicle in Japan is well suited to the prevailing driving conditions in Japan, which include: low-speed driving, repeated acceleration and deceleration, and idling in congested traffic.

(3) The numbers in Figure 9.44 incorporate some increases in vehicle acceleration performance (through use of data from MOE, 2010). The fuel consumption numbers in Figures 3.3 and 9.29 are at constant acceleration capability: our ERFC parameter is 100%. The numbers in Figure 9.44 effectively incorporate an ERFC that is around 50% so these future Japanese relative fuel consumption values (relative to average 2010 standard gasoline-engine vehicles) will be higher than those in Figure 3.3.

9.6.2 Scenarios to 2030

As in the rest of this chapter, scenarios were used to project the fuel use and GHG emissions of LDVs under different market and policy conditions. The primary factor examined was the impact of different future sales mixes by propulsion system, mainstream and new. The propulsion systems included were: NA-SI gasoline engines, turbocharged gasoline engines, clean diesel engines, strong gasoline HEVs, diesel hybrid electric vehicles, PHEVs, BEVs, and FCVs. (Not all of these reach significant sales fractions by 2030.) The other factors in these scenarios are, as has been described above, total vehicle sales, fleet turnover behavior, and vehicle kilometers traveled per year per vehicle.

Four sales mix scenarios were defined:

(1) **Government Scenario**

In June 2008, then Prime Minister Yasuo Fukuda, talked about the government's vision that "An ambitious target to introduce Next Gen Vehicles (new propulsion technology vehicles such as hybrid vehicles and BEVs) at the ratio of half the total new car sales should be realized by 2020." Since the sales share of the new propulsion vehicles was only 11.8% in 2010, this *Government* scenario was obviously optimistic. The sales mix details of the *Government* scenario are shown in Figures 9.45 and 9.46 for *standard* and *light* vehicles, respectively [MOE, 2010]. Hybrid and FCVs were judged to be unlikely to be used in the light-vehicle group. The Japanese Government projected the number of sales of each propulsion vehicle, so the percentage is obtained based on future total sales projections.

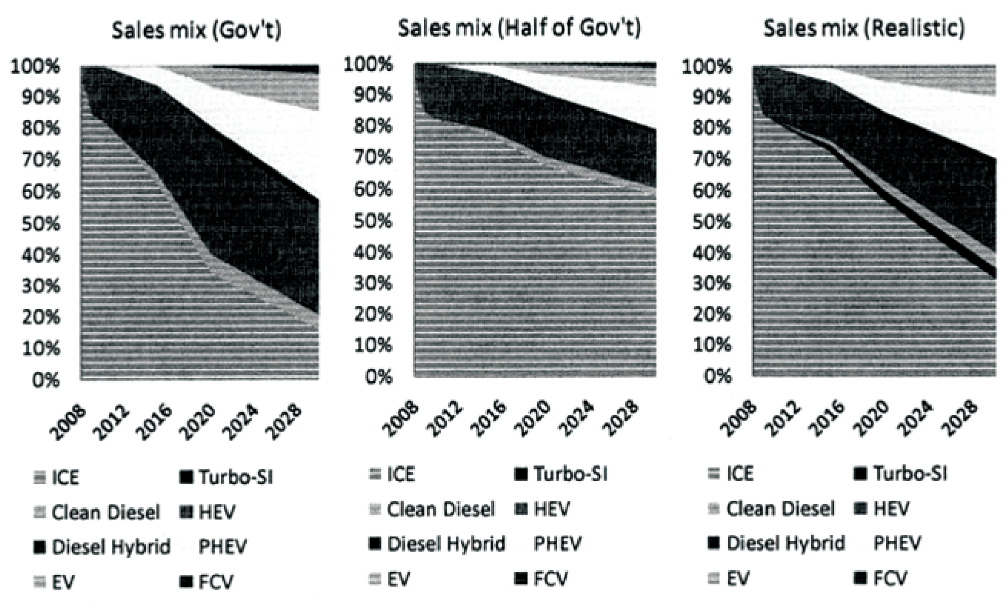


Figure 9.45 Sales mix by type of propulsion system out to 2030 for the different scenarios: Standard vehicles and normal and compact cars (and trucks).

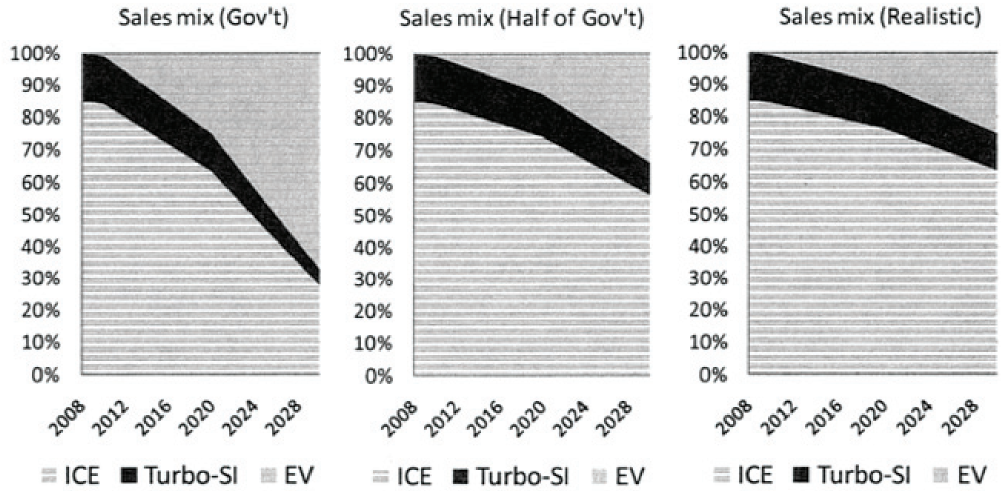


Figure 9.46 Sales mix by type of propulsion system out to 2030 for the different scenarios: Light vehicles, K-cars, and K-trucks.

(2) **Half of Government Scenario**

The sales percentages of new technology (all propulsion systems except for conventional gasoline vehicles) in each year in this scenario are half those in the *Government* scenario. This scenario was created because the *Government* scenario is extremely optimistic and thus a more plausible less-optimistic scenario based on the *Government* scenario objectives provides a useful comparison. The details of the *Half of Government* scenario are shown in Figures 9.45 and 9.46 [MOE, 2010].

(3) **Realistic Scenario**

This is an original scenario and was developed, based on our own judgments, future vehicle characteristics in Europe and the United States, and the opinions of others, to provide a more realistic alternative to the optimistic *Government* scenario. The details of the *Realistic* scenario are also shown in Figures 9.45 and 9.46.

(4) **No-change Scenario**

This scenario assumes that the sales mix, that is the sales share of hybrid vehicles or electric vehicles, etc., does not change in the future. Other scenario assumptions, such as the future relative fuel consumption improvements over time, are included.

More detailed information regarding the sales mixes shown in Figures 9.45 and 9.46 can be found in Nishimura (2011).

The rates of introduction of HEVs, PHEVs, and BEVs in standard vehicles in the *Government* scenario are very high, rising from 18% in 2010 to 74% of sales in 2030 at between 7% and 8% per year. The rate of increase in the sales of these electrified vehicles in the standard vehicle category in the *Half Government* scenario is 4% per year. In the *Realistic* scenario, it is 6% per year. In all the *Government* and *Half Government* scenarios, turbocharged gasoline engines were not included. In the *Realistic* scenario, the number of turbocharged gasoline vehicles grows to 11% of the standard gasoline engine vehicle sales by 2030. In the light vehicle category, turbocharged gasoline engine growth is higher (to 18% percent of light vehicles in 2030): since we assumed HEVs and PHEVs would not penetrate this small-vehicle market, the fraction is larger.

Vehicle weight is an important parameter in this type of vehicle fleet modeling. Available data were analyzed to obtain historical trends in average weight values for each vehicle category. Vehicle weight, of course, impacts fuel consumption. Values for these two characteristics in 2008 are shown in Table 9.10. Because these average vehicle weights are relatively low compared to the vehicles in other parts of the world, and fuel prices are high, only modest additional vehicle weight reductions are anticipated out to 2030. The impact of these weight reductions are included in average relative future vehicle fuel consumption values used in these scenarios, and are shown in Figure 9.44.

Table 9.10 Vehicle weight and fuel consumption for each vehicle category of Model Year 2008.

	Average Weight	Vehicle Fuel Consumption (JC08 mode)
Compact Truck	1,625 [kg]	10.06 [L/100km]
Compact Passenger Car	1,187 [kg]	7.17 [L/100km]
Normal Passenger Car	1,573 [kg]	9.72 [L/100km]
K-Car/K-Truck	850 [kg]	4.95 [L/100km]

The fleet model predictions of the size of the vehicle stock for each major vehicle category, 1995–2009, agree with fleet data for compact and normal cars (currently about 40 million), K-cars (about 18 million), compact trucks (4 million), and K-trucks (9 million). Projections indicate vehicle category stock values decreasing up to about 2020 with levels then remaining almost constant, except for K-cars which are projected to grow to about 22 million (about 20%) by 2030. Thus, Japan's vehicle sales mix and subsequent stock evolution are substantially different from the other world regions we analyze in this chapter. Several factors feed into this situation: Japan's long recession, high gasoline prices, decreasing population overall, and only modest growth in driver's license holders.

The results of the LDV in-use fleet fuel use from the four scenarios are shown in Figure 9.47. Fleet gasoline use is expected to decrease in the future in every scenario. In the *Government* scenario, the liquid fuel use in 2030 is 59% less than in 2008. Even in the *No-change* scenario, the 2030 fleet gasoline use is 36% less than in 2008. Remember that this scenario means "no sales mix change": the scenario does incorporate the fuel consumption improvements for the different propulsion systems shown in Figure 9.44. A modest fraction of "clean LD diesels" consumes an additional 2%–6% diesel fuel in 2030, relative to gasoline consumed (rising from a negligible fraction, currently). The data points shown in the figure (fleet data for 2008, and Government forecasts for *No Change* and *Government* scenarios in 2030) line up with this scenario and the *Realistic* scenario gives closely comparable numbers; though there are significant differences between these two scenarios, they effectively cancel out. These two plausible scenarios for Japan imply that by 2030, close to a 50% reduction from the 2008 fleet fuel consumption may be feasible. This results from growth rates in fleet size and VKT being close to zero or negative, and the more moderate (than Europe and the United States) fuel consumption improvements projected for Japanese LDVs are still significant.

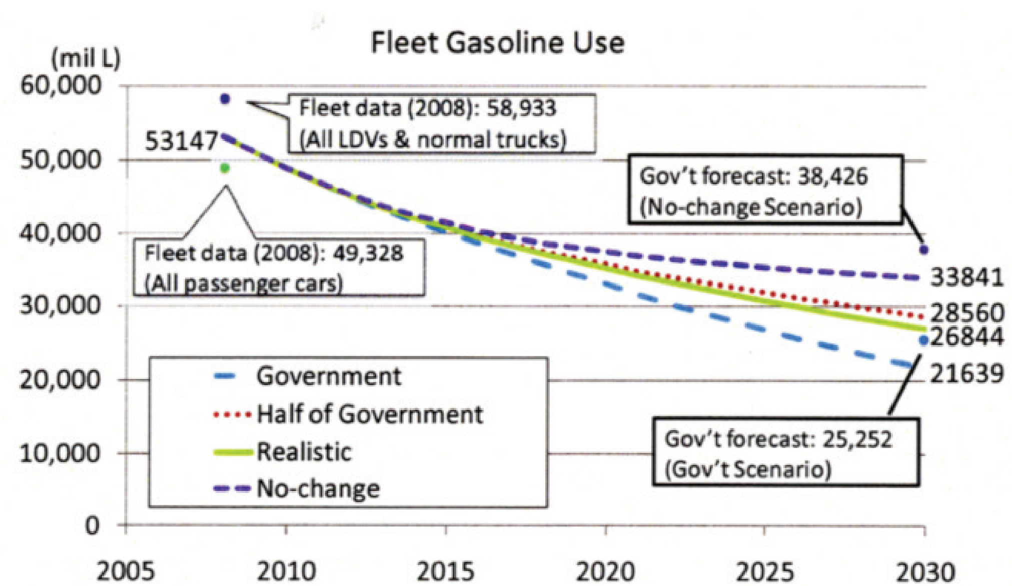


Figure 9.47 In-use LDV fleet gasoline use in million liters per year out to 2030 for the four scenarios analyzed. 2008 fleet data, and Government 2030 forecast also shown.

Figure 9.48 shows the same data as Figure 9.47, but with the fleet fuel consumption for Standard and Light vehicle groups noted separately. Note that the Light Vehicles group in-use fuel consumption, currently is about one-fifth the total, goes down only modestly with time since sales and thus VKT for this group grows. The decline in fuel consumed by Standard vehicles dominates the downward trend since their role (currently large) is declining. These scenario results underline that what happens to the higher fuel consuming (and GHG emitting) vehicle segment plays the strongest role in determining future fuel use and GHG emissions impacts.

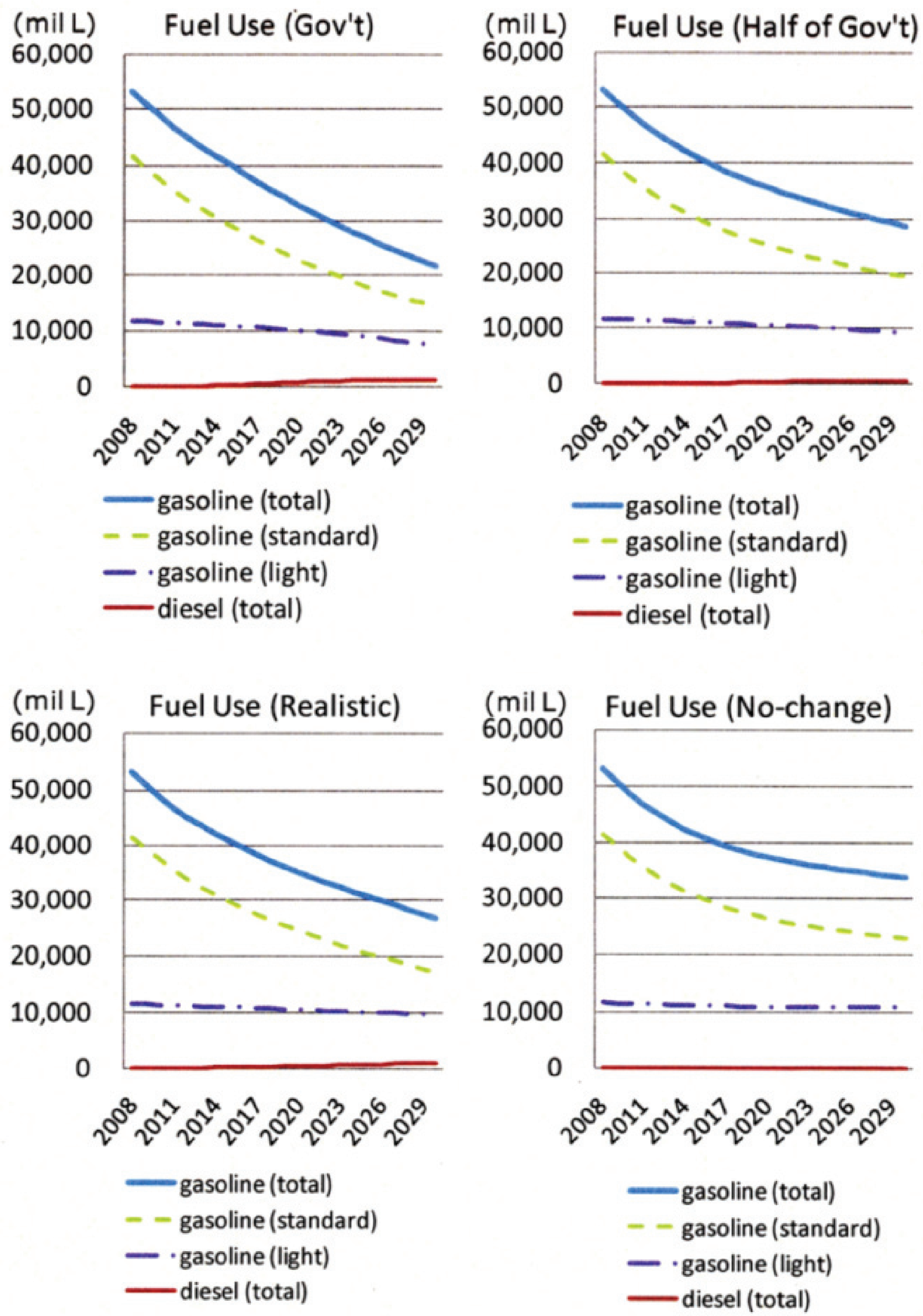


Figure 9.48 In-use LDV fleet fuel use (million liters/yr) for the four scenarios, for total, standard, and light vehicle categories, out to 2030.

Scenario results for the fleet's electricity use are shown in Figure 9.49. Electricity use increases fastest, at an increasing rate, in the *Government* scenario because of the much larger (two times) rate of increase in the sales of PHEVs and BEVs. Note that the units of the vertical scales in Figures. 9.47 and 9.49 are different: million liters gasoline/yr and GWh/yr, respectively. Using the conversion that 1,000 GWh of electricity has the same energy as about 110 million liters of gasoline, in the *Realistic* scenario the electricity use in 2030 is then 10,410 GWh/yr corresponding to 1,083 million liters gasoline/yr which is 4% of the gasoline use, 26,844 million liters/yr. We would expect this electrical energy flow into the vehicle to displace about four times that percentage of miles driven:[26] i.e., some 15%, which is significant.

The Government's forecast for 2030 BEV electrical energy demand is about 25% below our *Government* scenario prediction. This discrepancy results from different assumptions about vehicle electricity consumption per km in future vehicles. The Government forecast assumed that the efficiency of electric propulsion would increase at the same relative rate as gasoline engine propulsion. Our scenario assumed that electricity consumption was 0.15 kWh/km for Standard Vehicles and 0.124 kWh/km for Light Vehicles [Nissan, 2010], and both values remain constant. Our logic was that the potential for improving the efficiency of electric drive is significantly less than the potential for improving gasoline engine efficiency. Also, as yet, there are no targets or requirements for BEV energy consumption reduction. And, it is likely that the on-board demand for electricity (heating, cooling, electricity-requiring components and features) will increase over time. Thus a constant electrical energy drive requirement seemed appropriate.

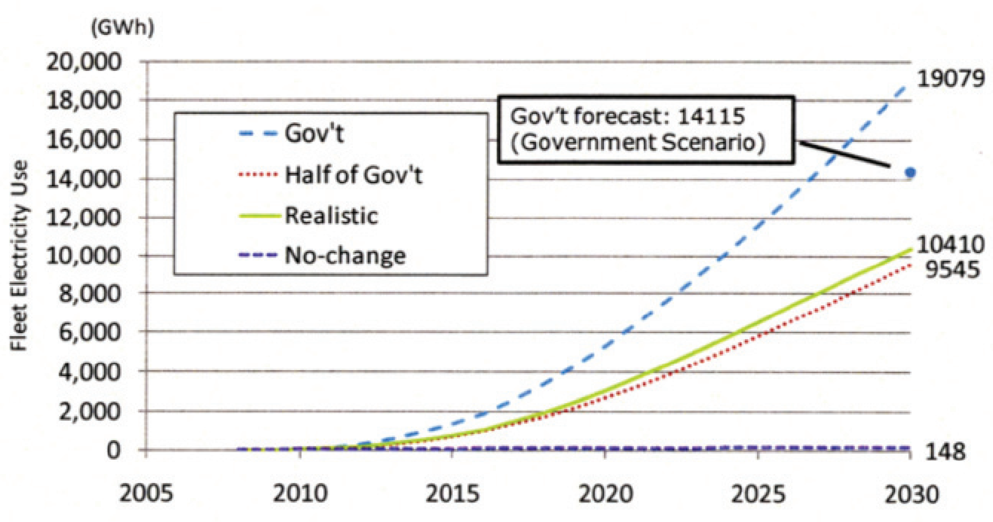


Figure 9.49 In-use vehicle fleet electricity use (in GWh/yr) for the four scenarios, out to 2030. (Government forecast from MOE, 2010).

[26]A BEV requires about 25%–30% of the energy per mile (as electrical energy) than the standard vehicle's gasoline (chemical) energy requirement to travel the same distance.

Fleet GHG emissions are calculated on a WTW basis, by multiplying the fuel/energy use by the WTT plus TTW GHG emissions intensity. These intensities are given in Table 9.11. Emissions intensities are given in gCO_2/MJ of fuel energy supplied. Note that, for electricity and BEVs, the energy required per km of vehicle travel is about one-quarter of the gasoline energy required: for hydrogen fuel cell vehicles, the energy required is about one-half that required for gasoline engine propulsion.

Table 9.11 Energy use and CO_2 emission factors. [MOE, 2010, METI, 2005; JHFC and JARI, 2006; IEA, 2009]

	Energy Use	GHG Emissions*		
		Fuel Cycle (Well to Tank) [g-CO_2/MJ]	Vehicle Operation (Tank to Wheel) [g-CO_2/MJ]	Total (Well to Wheel) [g-CO_2/MJ]
Gasoline	34.6 [MJ/L]	16.1 (JHFC)	67.1 (Gov's guideline)	83.2
Diesel	34.6 [MJ/L]	16.1 (JHFC)	68.6 (Gov's guideline)	77.2
Electricity (Average JPN mix)	3.6 [MJ/kWh]	122 (JHFC) 125 (IEA,data of 2007)	0	122 (JHFC) **125** (IEA, data of 2007)
Hydrogen	142 [MJ/kg]	74.9 ~136 (JHFC)	0	74.9 ~136 **105** (median for model)

*All emission factors are calculated on a lower heating value (LHV) basis.

For electricity, the TTW GHG emissions are zero: electricity generation is the emissions source. Electricity generation by source in Japan and the United States is shown in Figure 9.50: the average emission index for the Japanese electricity grid (125 gCO_2/MJ electricity, IEA, 2009) is much lower than the average U.S. grid value of 214 gCO_2/MJ due to less coal and more nuclear generation. Japan's electricity emissions intensity was assumed to be constant out to 2030.

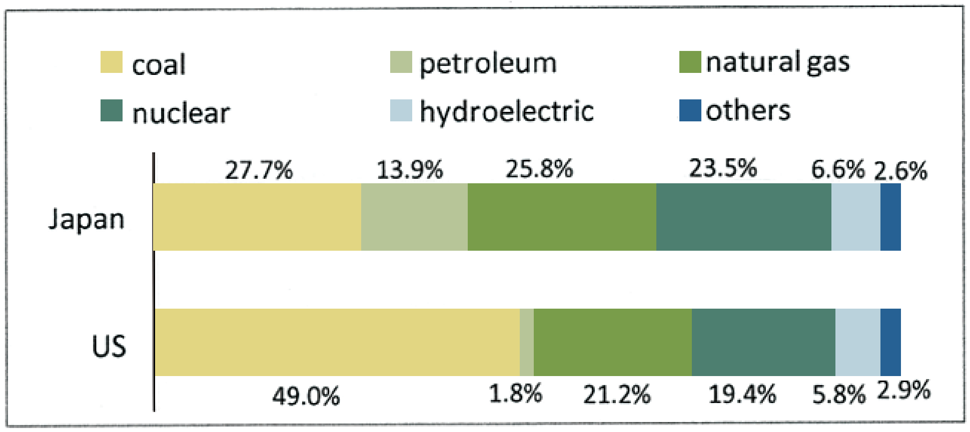


Figure 9.50 Japan and U.S. electricity generating mix by primary energy source [IEA, 2009].

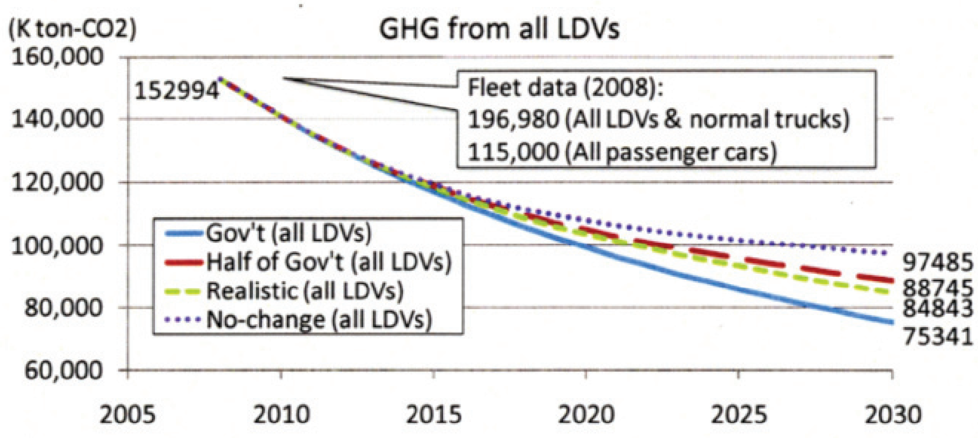


Figure 9.51 In-use LDV fleet WTW GHG emissions (in kilo-ton CO_2/yr) for the four scenarios, out to 2030.

Figure 9.51 shows the scenario results for WTW fleet GHG emissions. The curves are not that different from the fleet fuel consumption curves, even though those were TTW values. A major reason is that utilization of the alternative energy sources is modest and the emissions intensities of these alternatives are not yet that low. The middle two scenarios show about a 40% reduction from their 2010 value, a significant decrease.

Figure 9.52 shows how this reduction in GHG emissions is achieved, for the *Realistic* scenario. The electrification component by 2030 is still only about 7%. Almost all the reduction comes from the Standard Vehicle group of vehicles—roughly 40% normal cars and 60% compact cars in 2009. There is almost no reduction from Light Vehicles—K-cars. Again, the larger, heavier, vehicles are the prime opportunity for reducing fleet fuel consumption and GHG emissions through improvements in their technology (in this instance, aided by the steady reduction in sales volume of these Standard Vehicles).

More substantial vehicle weight reduction, especially in standard passenger cars (see Table 9.9), would increase these fuel and GHG emissions reductions. The vehicle weight trend for these normal vehicles up to 2010 has been flat: for compact cars it has been rising, but appears to have now moderated (and average compact car weight, now at about 1,200 kg, is 25% below average normal car weight). Every 100 kg of vehicle weight reduction results in about a 0.6 fuel consumption reduction. While some weight reduction (5%–10% over the next 20 years) is built into the relative fuel consumptions shown in Figure 9.44, additional weight reductions above this 10%, especially in larger vehicles, would further reduce fuel consumption and GHG emissions [Nishimura, 2011].

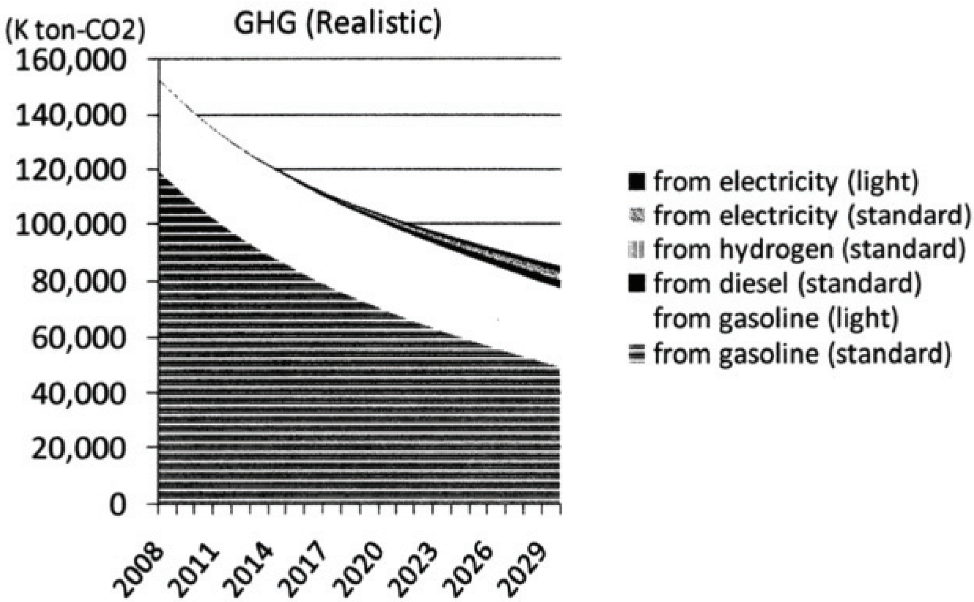


Figure 9.52 In-use LDV fleet WTW GHG emissions (kton CO_2/yr) for the *realistic* scenario, broken out into electricity, hydrogen (negligible for this scenario), diesel and gasoline, out to 2030.

9.6.3 Scenarios out to 2050

The final part of this study extended the scenario analysis to 2050. Substantial uncertainty is involved in laying out the needed assumptions from 2030 to 2050. The scenarios we developed through 2050 are based on the *realistic* scenario out to 2030. Two future sales mixes beyond 2030 were used:

(1) **Scenario A**: little change beyond 2030

This is the same as the *realistic* scenario before 2030, with little change beyond 2030. Here, the sales share of each propulsion system in 2050 is assumed to be almost the same as in 2030. Details are shown in Figures 9.53 and 9.54.

(2) **Scenario B**: significant change beyond 2030

Again this is the same as the *realistic* scenario before 2030, with significantly increased change beyond 2030 than in Scenario A. Specifically, the sales share of PHEVs and BHEVs, which use electricity, is projected to be 50% in 2050, thus achieving widespread adoption and use of EVs and PHEVs which together represent more than 50% of annual LDV sales [IEA, 2009]. The details of Scenario B are also shown in Figures 9.53 and 9.54.

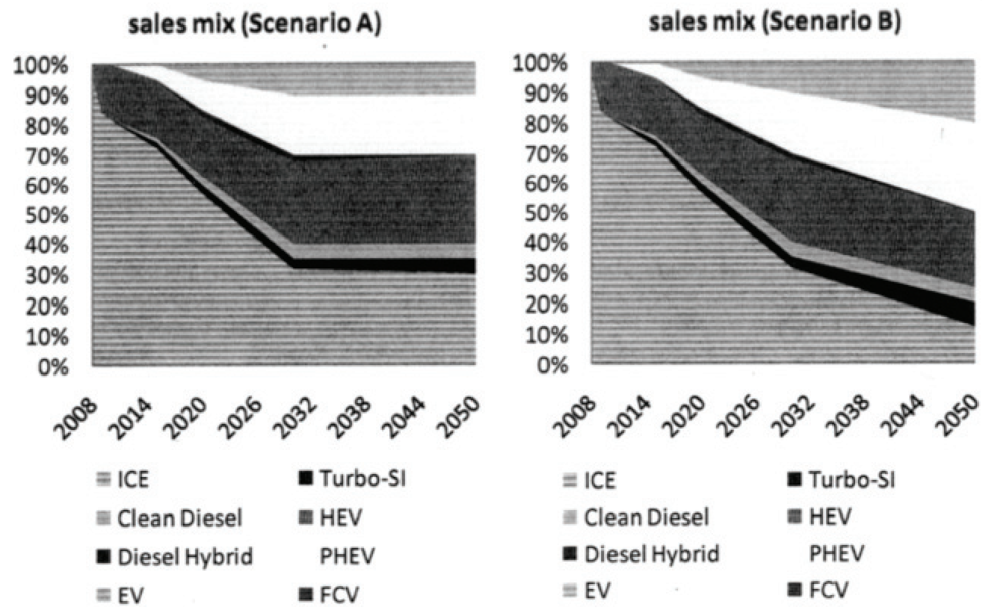


Figure 9.53 Vehicle sales mix by powertrain, 2010–2050, Scenarios A and B, for standard vehicles.

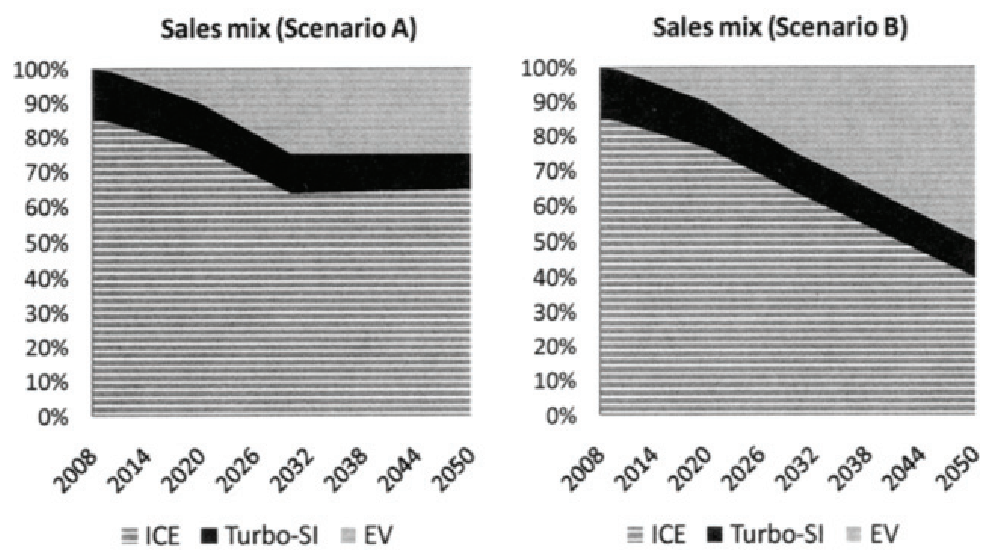


Figure 9.54 Vehicle sales mix by powertrain, 2010–2050, Scenarios A and B, for light vehicles.

The annual vehicle sales forecasts from 2030 to 2050 are assumed to be constant. It is assumed that Japan's population and annual vehicle sale's volume stabilize. Vehicle lifetimes are assumed constant, also, over this 20-year time period.

The sales mix for Scenarios A and B, by propulsion system type are also shown in Figures 9.53 and 9.54, for Standard Vehicles (normal and compact LDVs) and Light Vehicles (small K-cars and K-trucks). The percentage of vehicles using electricity from the electricity supply system differ significantly. In Scenario A, in 2050, 20% of Standard Vehicle sales are PHEVs and 10% are BEVs. In Scenario B, the PHEV and BEV 2050 sales percentages for Standard Vehicles are 30% and 20%, respectively. For Light Vehicles, we assume there are no hybrid (HEVs or PHEVs) sales because there are propulsion system space limitations in these smaller vehicles. BEV sales in this Light Vehicle category constitute 25% and 50% for Scenarios A and B, respectively.

Two levels of vehicle fuel consumption were incorporated. One we judge as *conservative*, which extrapolates the improvements in relative fuel consumption in Figure 9.44 out to 2050: see Figure 9.55. The other, we label *optimistic*, based on the anticipated U.S. fuel consumption improvements [Bastani, et al., 2012a] is shown in Figure 9.56. The optimistic relative fuel consumption values for 2030 and 2050 are 20% lower and 35% lower, respectively, than the equivalent conservative values. Additional details of these scenarios out to 2050 can be found in Nishimura, 2011.

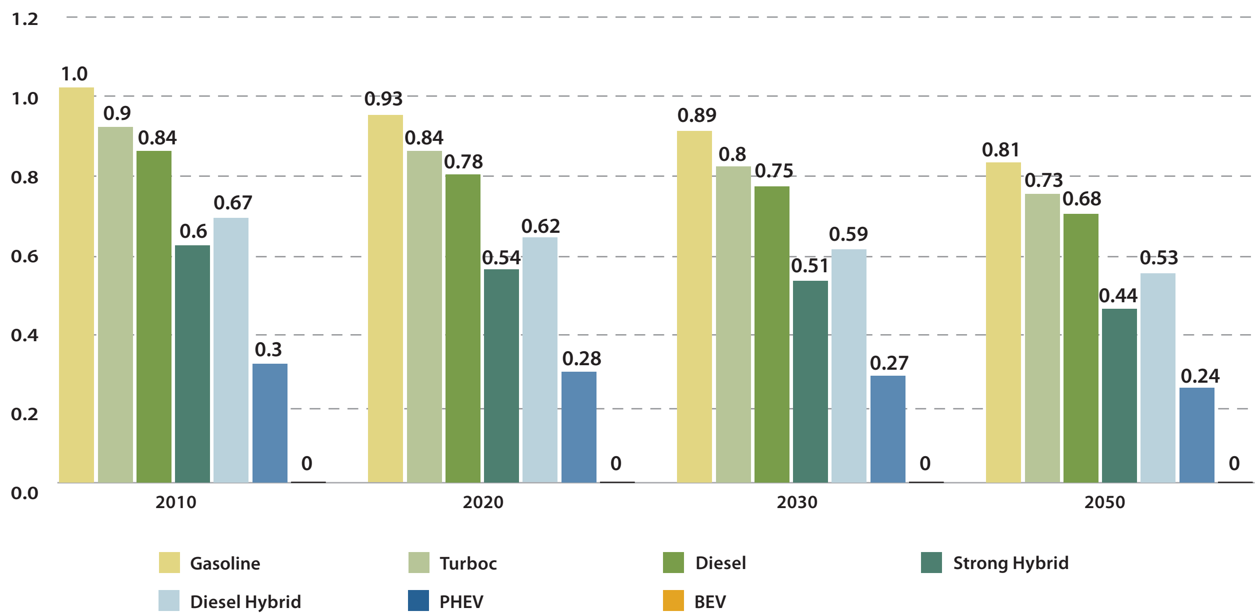


Figure 9.55 Relative vehicle fuel consumption for different propulsion systems, conservative scenario, by 2010 NA-SI gasoline vehicle value. (Japanese Government-based data.)

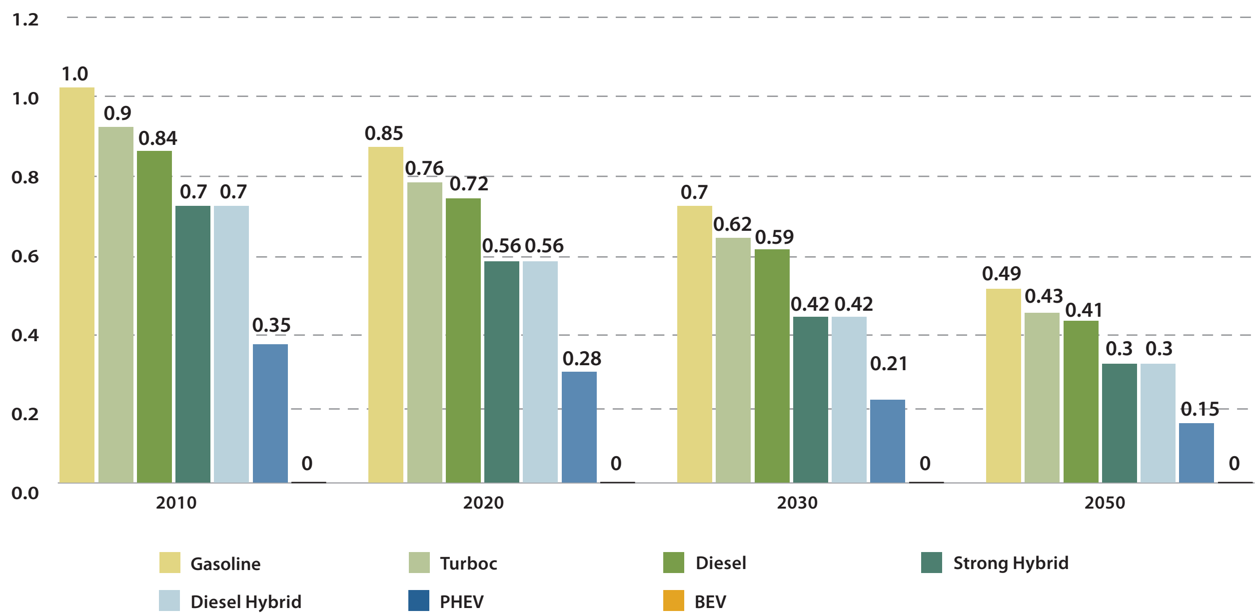


Figure 9.56 Relative vehicle fuel consumption for different propulsion systems, normalized by 2010 NA-SI gasoline vehicle value. (U.S.-based) [Bastani et al., 2012a].

We now discuss the fleet results for these four scenarios: *conservative* (C) assumptions concerning the improvements in vehicle fuel consumption over time, with sales mixes A and B; *optimistic* (O) fuel consumption improvements assumptions (taken from U.S. scenarios: see Section 3.3, Figure 3.3), with sales mixes A and B.

Figure 9.57 shows the in-use light-duty fleet gasoline use out to 2050. All of the scenarios start at close to 50,000 million liters/yr. in 2010. By 2050, the spread is to between a 56% and 73% reduction in fuel use, relative to 2010 values. Obviously, the more aggressive sales mix changes (B compared to A) and more optimistic assumptions regarding improvements in vehicle fuel consumption cause these differences. Diesel fuel use was also calculated: it was close to 900 million liters from 2030 to 2050, which is 4%–5% of the gasoline fuel use.

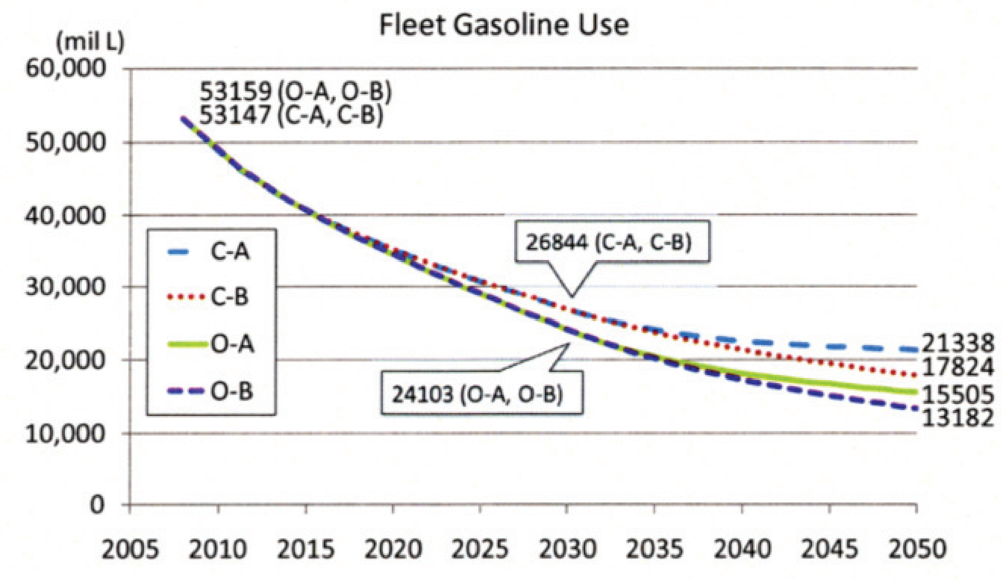


Figure 9.57 In-use vehicle fleet gasoline use, million liters/year, through 2050 for four scenarios: *conservative*, A and B; *optimistic*, A and B.

Figure 9.58 breaks down this fleet fuel use data by vehicle type (Standard and Light). The decrease in fleet fuel use over the next 15 years is dominated by the decline in standard vehicle fuel use. In 2010, standard vehicles represent 64% of the total LDV fleet and by 2030, they constitute 57%. This moderate decline in fleet vehicle fraction is greatly augmented by the assumed larger sales mix shift away from straight gasoline engines to hybrids and electrified vehicles (PHEVs and BEVs) for the Standard Vehicle category, whereas for Light Vehicles, transitions away from gasoline engines were only to BEVs: see Figures 9.53 and 9.54. Again, these results underline the importance of improving the fuel consumption of the larger vehicles in the total LDV fleet, and decreasing their sales volume and use.

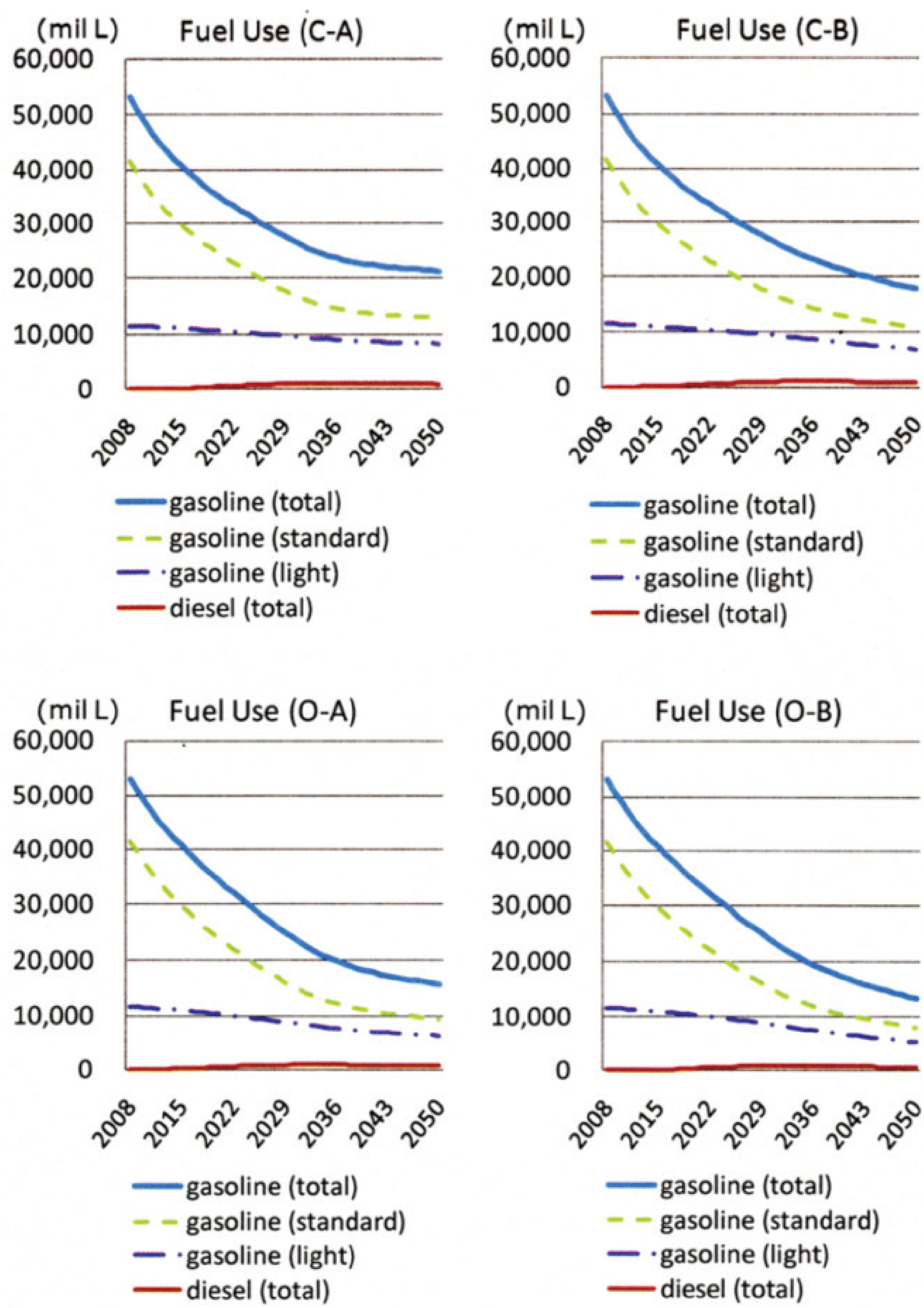


Figure 9.58 In-use vehicle fleet fuel consumption, total, standard and light vehicle categories, gasoline and diesel, for four scenarios: *conservative*, A and B; *optimistic*, A and B.

Figure 9.59 shows the growth in electricity use. The difference between scenarios A and B is, of course, due to the leveling off of sales of BEVs after 2030 in scenario A whereas in B, growth to 50% of sales by 2050 occurs. In 2050, scenario B's electricity consumption reaches 23,504 GWh/yr. This corresponds in energy equivalent terms to 14% of the fleet fuel use for the *conservative* scenario, and 18.5% of the fleet fuel use for the *optimistic* scenario.[27]

Note, again, that the electrical energy to drive an EV for one km is a factor of 3 or so less than the gasoline chemical energy required to drive a comparable IC engine vehicle one km. Thus, these electrical energy percentages correspond to much larger percentages of miles driven. The electricity use in the standard and Light Vehicle categories is roughly comparable: from about 2040 on, the Light Vehicles' electricity consumption is 70%–75% of the Standard Vehicles' electricity consumption.

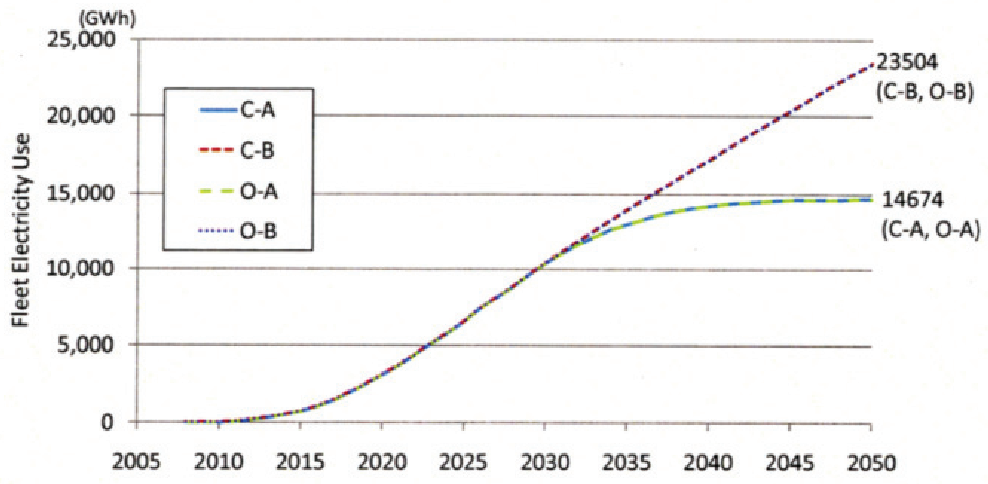


Figure 9.59 In-use fleet electricity use (GWh/yr), 2010–2050: for B, *conservative* and *optimistic*, and A, *conservative* and *optimistic*.

[27]Gasoline: 1[L] = 34.6 [MJ], Electricity: 1[kWh] = 3.6 [MJ]. Therefore, 1,000 [GWh] (electricity) = 3.6*109 [MJ], which is equivalent to 3.6*109[MJ]/34.6 [MJ] = 104.0 [mil L] (gasoline). Fleet fuel in 2050 is 17,824 Mliters/yr for scenario C-B, and 13,182 Mliters/yr for scenario O-B.

The GHG emissions from all LDV for the four scenarios, 2010–2050, are shown in Figure 9.60. These are WTW values, in ktons CO_2/yr. The spread between the four scenarios in 2050 (70,636 to 50,911 ktons CO_2/yr) corresponds to between a 51% and 36% reduction from the 2010 GHG emissions values. Thus, to reduce GHG emissions significantly below the "50% reduction by 2050" level, needs aggressive actions as exemplified by our *optimistic* scenarios. This is a broad finding in all the scenarios examined in this chapter. The major fuel use and GHG emissions reducing factors are improvements in the fuel consumption of mainstream ICE technology vehicles (which can grow more rapidly to high deployment levels), and the introduction of more efficient alternative propulsion system technologies in significant volumes with ever lower energy consumption and GHG emissions from their energy supply. These improving factors are offset by growth in vehicle fleet size and vehicle use. These normally offsetting factors in Japan are expected to act the other way—modestly reducing these impacts. Yet achieving reductions well beyond a 50% reduction is still extraordinarily challenging.

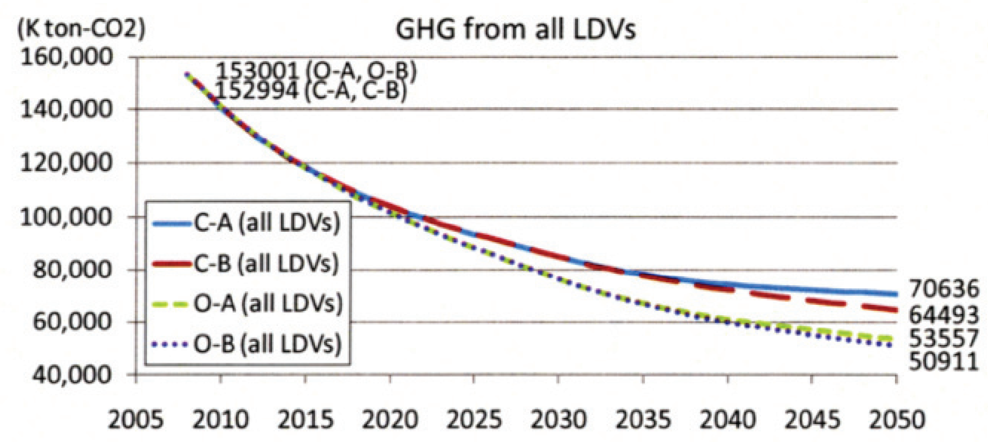


Figure 9.60 In-use vehicle WTW GHG emissions (kilo-tons CO_2/yr), 2010–2050, for four scenarios: *conservative*, A and B; *optimistic*, A and B.

The GHG emissions contributions from the different propulsion system vehicles, identified by their energy sources (WTW values) for Standard and Light vehicle categories are shown in Figure 9.61. For all scenarios, the enduring major contribution of gasoline fuel in NA-SI gasoline engines (including hybrids) is clear, though decreasing. Electricity's energy contribution varies from 9% in the C-A case to 21% in the O-B case. And again, the standard vehicle category dominates.

Effective measures to prompt the vehicle improvements and sales mix shifts represented by the *optimistic* scenario assumptions include the following, several of which are being seriously considered:

1. Subsidies or tax cuts for new propulsion technology vehicles such as hybrids. This approach is already being implemented and is, in part, responsible for the substantial rise in HEV sales in Japan.

2. Improving the infrastructure for PHEV and BEVs. This is an essential step to enable sales of these vehicle types to grow.

3. Higher taxes on older vehicles, such as vehicles over 15 years old. This would help prevent vehicle lifetimes increasing, which is the current trend.

4. Improving vehicle fuel consumption, and reducing vehicle weight and size. This is the most important nearer-term opportunity, and policies that support these changes at time of vehicle purchase will be essential to push progress in vehicle efficiency technology as rapidly as is feasible.

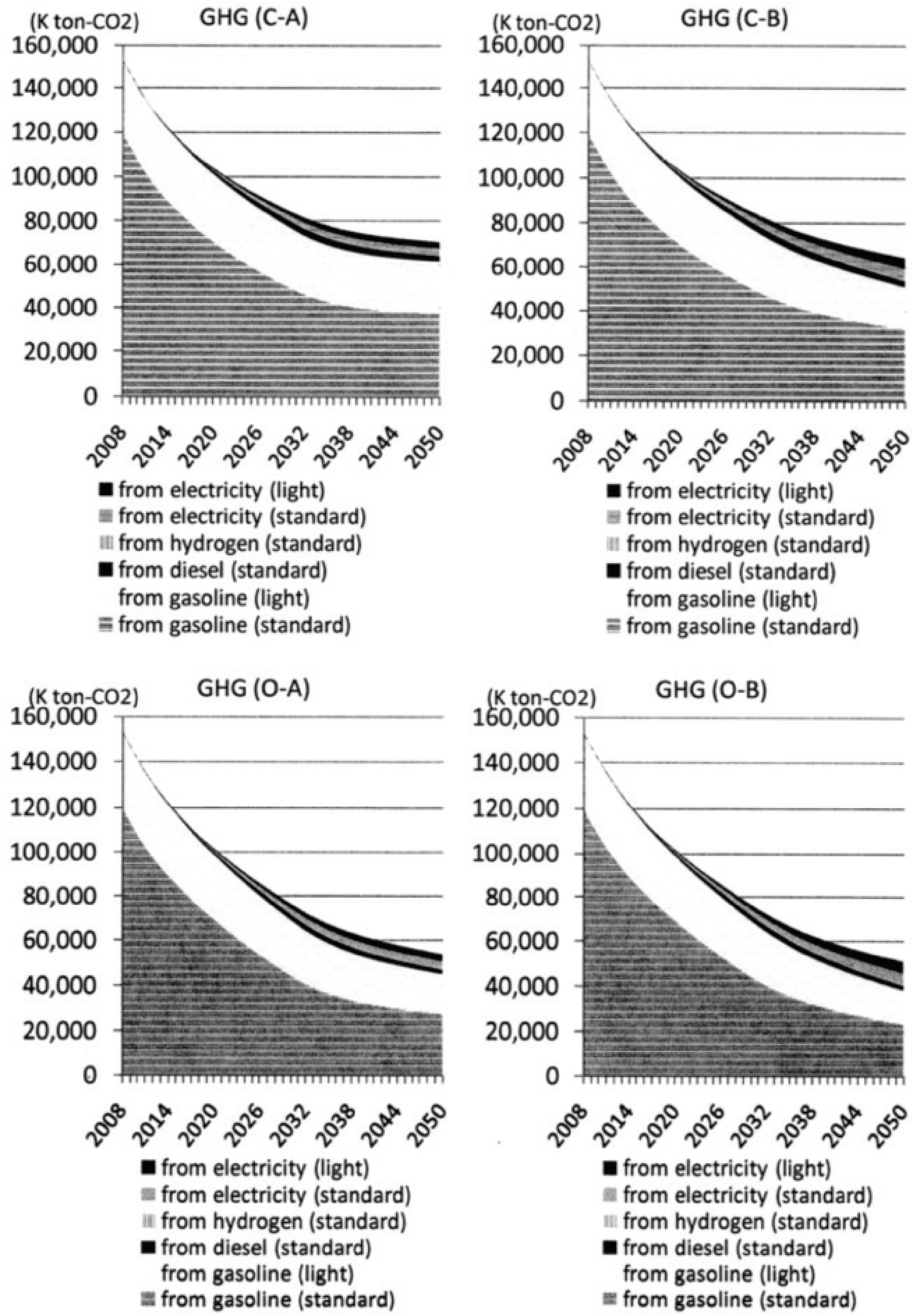


Figure 9.61 In-use vehicle fleet WTW GHG emissions (kilo-tons CO_2/year) for the four scenarios (*conservative*, A and B; *optimistic*, A and B) by energy source (electricity, hydrogen, diesel, gasoline) for the four scenarios.

9.7 Scenarios: China

9.7.1 Background and Focus

China's total energy consumption has ballooned over the past 30 years in both relative and absolute terms. China's energy consumption as a share of international energy demand grew from 10.5% in 1990 to 17.5% in 2010 [IEA, 2012]. In absolute terms, China's transportation energy demand has grown more than tenfold since 1971. Much of that road-transport growth is directly attributable to growth in passenger travel and the shipment of freight. Motor gasoline consumption has more than doubled since 1990 [IEA, 2012]. As a result, while China accounted only for 2.5% of international transportation energy demand in 1990, in 2010 it accounts for 7.5%. In addition, the portion of energy the transportation sector in China consumes as a share of total energy demand grew from 5.8% in 1990 to 11.6% in 2010. This is still far below the world average of 27% [IEA, 2012]. However, the transportation sector is one of the fastest-growing energy consuming sectors in China, so this fraction is expected to double before 2050 [Zhou et al., 2011].

This growth in transportation energy demand is partially attributable to ever-increasing vehicle sales (Figure 9.62). Mini-truck, minibus, and non-private car sales have all steadily increased since 2000, but private passenger cars have primarily fueled the overall LDV growth.[28] From 2000 to 2010, car sales increased from 0.6 million to over 9 million passenger cars per year, an annual sales-growth-rate increase of some 30%.

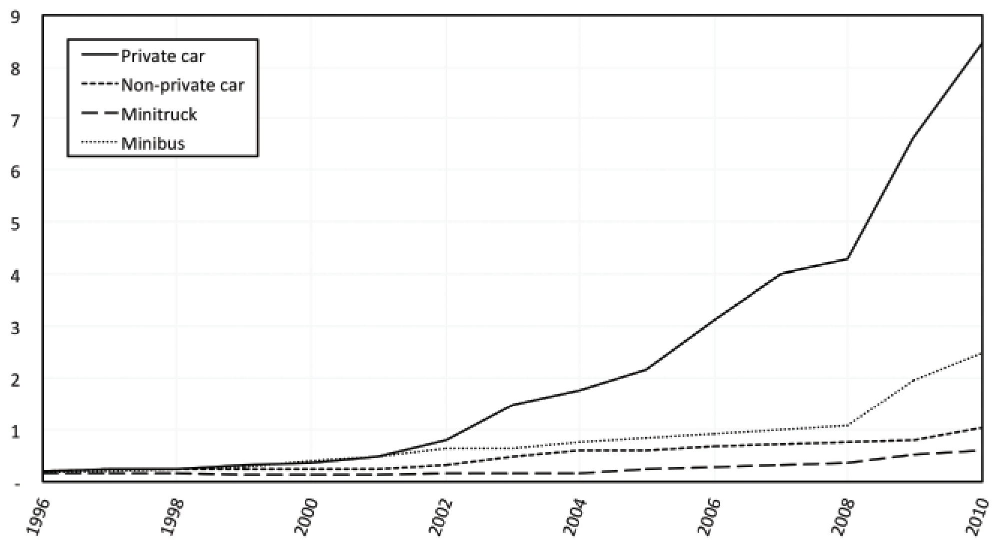


Figure 9.62 Historical LDV sales in millions of vehicles per year in China. [Source: China Automotive Industry Yearbook (2011), China Statistical Yearbook (2011), author analysis.]

[28] A mini-truck is a truck under 1.8 metric tons (Wang et al., 2006), the minibus car category corresponds loosely with the Japanese K-car. Industry associations and the government report sales for each category separately from passenger cars. Non-private cars include service vehicles, government cars, company cars, and taxis.

These increasing annual vehicle sales indicate that China's transportation energy demand will continue to grow for years to come. Nevertheless, the pace of growth has been variable: over 55% from 2002 to 2003 to less than 7% from 2007 to 2008. Several questions need to be answered. Can improvements in fuel efficiency and introduction of new technologies offset this rapid vehicle growth's contribution to rising energy demand and emissions? More importantly, which factors are the most important in determining China's future evolving fuel demand and GHG emissions?

By answering these questions, the China scenario analysis offered insights as to which of the various significant factors policy strategies should to target. The eight variable inputs examined were:

- Stock: automotive ownership per capita is currently low in China and will increase to as yet unknown future higher levels of ownership.
- VKT: the average annual distance traveled per vehicle in China is currently high compared with most developed countries. It could stay relatively constant or drop significantly.
- Turbocharging: today, turbocharged gasoline-engine vehicles make up a small fraction of vehicle sales in China, but the technology may gain quicker acceptance.
- Electrification: will the Chinese adopt HEVs, PHEVs, and EVs on an ever larger scale?
- EV or PHEV electricity use: will electrification focus on PHEVs or on EVs?
- Fuel consumption: will vehicle efficiency improve quickly or slowly?
- Natural gas: will natural gas become a widely used alternative fuel?
- Methanol: will methanol become a widely used alternative fuel?

9.7.2 Input Assumptions

The key input assumptions used for the China scenario analysis are listed in Table 9.12. This analysis assumed that several of these inputs were the same for all scenarios, including scrappage equation variables and mileage degradation rates. We assumed similar, though less rapidly decreasing with time, relative fuel consumption levels among liquid-fueled powertrains (NA-SI, turbocharged, diesel, HEV, and PHEV) as in our other *On the Road* fleet model studies. We also assumed that alternative fuels (CNG and methanol) achieve equal vehicle fuel efficiency on a per MJ basis as gasoline.[29]

[29]The work assumed the energy content for different fuels were 33.4, 18, and 35 MJ/L for gasoline, methanol, and diesel, respectively, and 38 MJ/m3 (at standard atmospheric conditions) for CNG.

Table 9.12 Input Assumptions for China Reference Scenario

Reference scenario; private car	2010	2030	2050	Varies?
Stock and VKT				
Vehicle sales growth (%)	10	1.5	0.5	Yes
Vehicle half-life (years)	14.5	14.5	14.5	No
Scrappage rate	4.7	4.7	4.7	No
Average VKT (km/year)	15,900	13,200	12,400	Yes
Mileage decrease (%/year)	5%	5%	5%	No
Fuel consumption				
NA-SI FC; on-road (Liter/100 km)	9.0	8.1	7.2	Yes
Electric efficiency (kWh/km)	0.2	0.1	0.1	Yes
PHEV utilization (% of energy)	30	50	60	No
Sales mix (% of sales)				
Turbocharged	7	42	46.4	Yes
Diesel	1	1	1	No
Total electrified	0	15	30	Yes
HEV	0	10.1	14.8	Yes
PHEV	0	2.9	8.2	Yes
EV	0	2.2	6.7	Yes
Fuels				
Methanol (% of energy demand)	0	3	5	Yes
CNG (% of energy demand)	0	2	4	Yes
Methanol CO_2 (g CO_2/MJ)	304	191	120	No
Electricity CO_2 (g CO_2/MJ)	265	179	122	No

Regarding the variable inputs, our analysis endeavored to be neither too pessimistic nor too optimistic: hedging future values with numbers from our studies of other countries (for sales and VKT inputs), assuming future progress more modest than the aggressive Chinese government targets but more optimistic than no progress (for fuel consumption and alternative powertrain sales percentages), or assuming some but not substantial adoption of alternative fuels. Not surprisingly, the vehicle sales growth and VKT growth assumptions for our China analyses differ from those made for other countries. Car sales growth rates in China are currently very high, and VKT has historically been high. The result is an "S"-shaped growth curve from 2000 to 2050 for vehicle stock size (Figure 9.63).

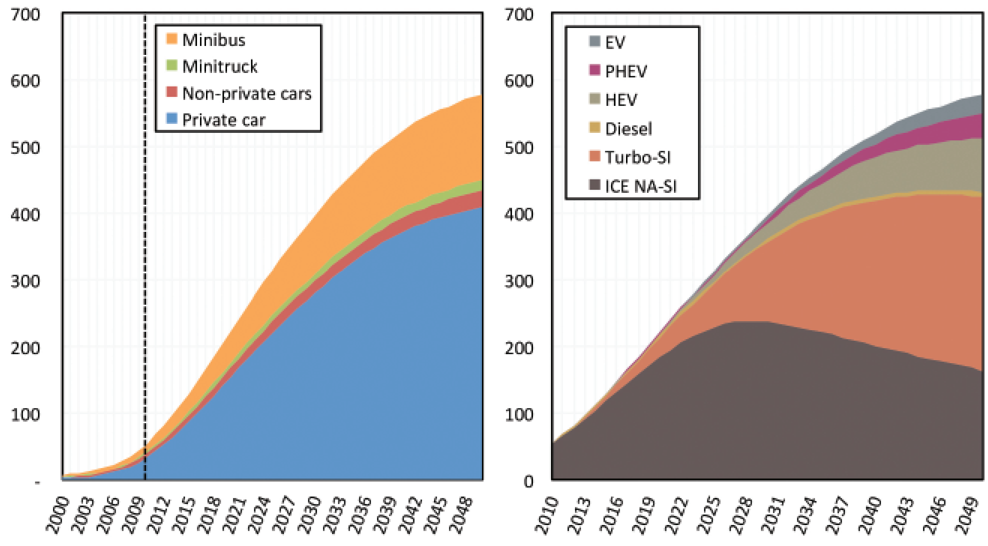


Figure 9.63 Vehicle stock projection, millions of vehicles: Left, disaggregation by vehicle type; Right, disaggregation by powertrain.

That said, appropriate fuel consumption, alternative powertrain sales market shares, and alternative fuel demand assumptions for China also differ from the assumptions we have used for other countries. While future fuel consumption mandates in China are as strict as those in the developed world, the ability or desire to achieve such targets is more questionable. Joint venture manufacturers (producing foreign vehicle brands through enterprises jointly owned by foreign companies and Chinese) dominate with 70% of passenger vehicle sales. The 30% of vehicles Chinese manufacturers produce tend to have simpler technology for the same vehicle weight. Thus, the Chinese government's dual goals of simultaneously raising the Chinese manufacturer market share and improving fuel consumption standards appear especially challenging. In addition, the average vehicle sold in China is less expensive than one sold in the United States. Meeting similar fuel consumption targets will likely involve similar increases in absolute cost, but the burden on Chinese manufacturers will be relatively heavier. Since it is uncertain how the government would prioritize these goals, it is unclear what policies will be implemented.

The Chinese government has strongly encouraged the development and deployment of EVs, and while acceptance to date has been lackluster, ongoing adoption of HEV and PHEV technology at a moderate rate is plausible.

Our study selected just two alternative fuels to model alongside conventional transportation fuels. Biofuel assessments for China vary across the map and there is little consensus, making it difficult to project forward. Second, CNG is already prevalent among non-private cars, and China is rich in coal reserves, which encourages the development of methanol. Modest growth in CNG and methanol use was included in the *reference* scenario.

9.7.3 Results: *Reference* Scenario

We use *reference* to denote a scenario that is aggressive, yet possible to achieve without an explicit environmental target in mind. Instead, it takes into account the comparable international evolution of vehicle technology, ownership, and use; the government's desire to develop an internationally competitive automotive industry; and concern over China's reliance on foreign oil.

China's LDV fleet energy demand, total fuel demand, and CO_2 emissions are projected to grow sharply until about 2030, after which growth levels off (see Figure 9.64). Levels peak in 2040 at some 370 Mtoe (million tonnes, oil equivalent) consumed (equivalent to 7.4 million barrels of oil per day), 499 billion liters of fuel consumed per year, and 1,700 mega million tonnes/yr CO_2 emitted. Subsequently, they begin to decline due to anticipated lower fleet growth and continuing technology improvement. Conventional ICE fuel demand of gasoline and diesel also increases rapidly up to about 2030, after which it peaks in 2038 at 453 billion liters and begins to decline. The contribution from new fuels surpasses 5% in 2024, continuously increasing to nearly 14% in 2050. The *reference* scenario assumes the combination of relatively small numbers of PHEVS and EVs, and that natural gas and methanol will be able to supply a modest amount of China's road transportation energy demand over this time frame. Energy demand, fuel demand, and CO_2 emissions in the Chinese LDV sector will increase more than fivefold in the reference case over the next 30 or so years, while conventional fuel demand will increase nearly fivefold. Moreover, because this scenario assumes certain efficiency gains, technology adoption, and fuel diversification, and these are uncertain, actual energy and emissions could be higher or lower. Transformations in Chinese travel patterns would also affect this evolution and significantly impact China's future oil imports.

The results do show, however, that China's vehicle energy demand, in the mid-and-longer term, will not continue to increase at a frenetic pace. Rather, as the vehicle market matures and technologies advance, China will eventually stabilize at a high but, given its population, not unexpectedly high, vehicle energy demand.

These results can be disaggregated by fuel or powertrain. Gasoline's continued dominance remains unchallenged although other fuels begin to contribute over one-tenth of energy demand and CO_2 emissions in the 2030s. Meanwhile, the dominance of the traditional NA-SI vehicle begins declining before 2030 as turbocharged SI vehicles proliferate. They eventually dominate the NA-SI engine category, even as new alternative powertrains such as HEVs account for larger fractions of total energy, fuel demand, and CO_2 emissions. Diesel fuel is not currently widely used in the LDV fleet, and in this scenario, it continues to be uncommon in the future.

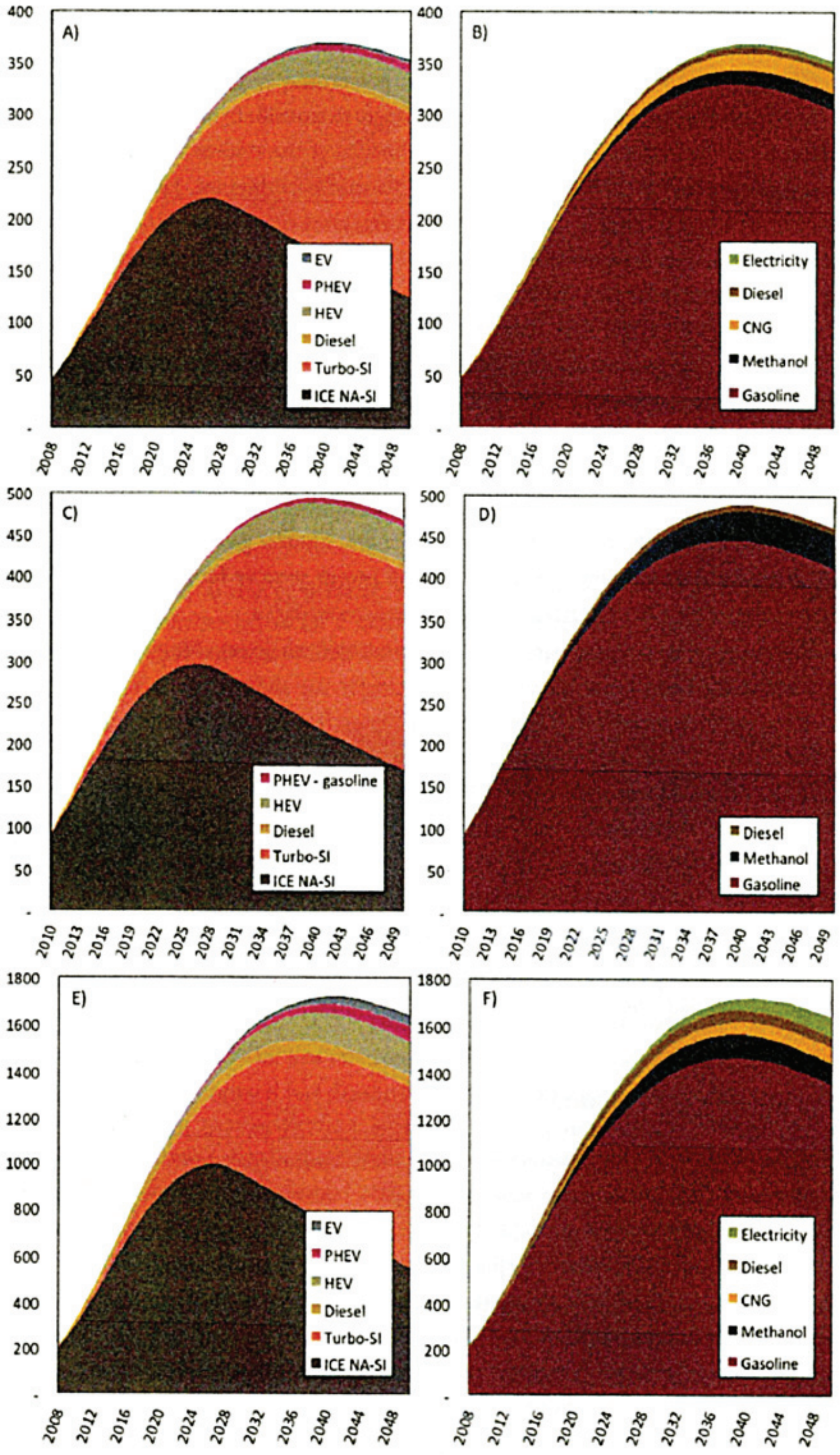


Figure 9.64 *Reference* scenario disaggregated by powertrain (left) and fuel (right). A) and B): LDV fleet energy demand in mega tonnes (oil equivalent) per year, Mtoe/yr (tank to wheels). C) and D): LDV fleet fuel demand (TTW) in billion liters fuel consumed/yr. E) and F): GHG emissions (WTW) mega million tonnes CO_2 equivalent/yr.

9.7.4 Results: Scenario Sensitivity Analysis

We next discuss scenarios in which the assumed values of key variables, one at a time, are changed from their reference value to a higher or lower value. For example, in relation to the fleet size in 2030, vehicle sales were assumed to be 39, 32, and 45 for the *reference*, *low*, and *high stock* scenarios. For 2050, these sales numbers were 47, 35, and 59. The high and low assumptions chosen were based on our assessment of the likely spread about the reference. As a percentage of the reference assumption, they varied significantly as one would expect since these variables each have a different function. See Akerlind (2013) for details. Figure 9.65 shows total on-road LDV fleet energy demand results for all scenarios in Mtoe/yr. Each scenario is identified by its high or low label in the figure. In addition, scenarios with all the variable assumed to be high and then all low, were run. (High and low natural gas and methanol are not represented in Figure 9.65 because implementing such scenarios would not change the energy demand.) Stock size (violet) is the most sensitive driver in both raising and reducing energy demand. Fuel consumption is a more significant driver in lowering energy demand than in raising it (green). This is logical because future fuel consumption (of the average new vehicle for each propulsion system) in 2050 is 60% of current fuel consumption in the *low-all* scenario, 80% in the reference, and 90% in the *high-all* scenario. Significant vehicle electrification proves itself to be an important driver especially after 2040 (blue). Surprisingly, significant electrification despite a significant HEV fraction, is a fairly promising means to lower future energy demand (turquoise) even though electricity supply in China currently has high GHG emissions. Targeting VKT is also a promising means to lower future automotive energy demand. The *high-all* and *low-all* scenarios show resulting energy demand if all inputs evolve along their predicted high or low values paths. These extremes differ widely: the projected peak in future energy demand varies between about 220 Mtoe per year to nearly 700 Mtoe.

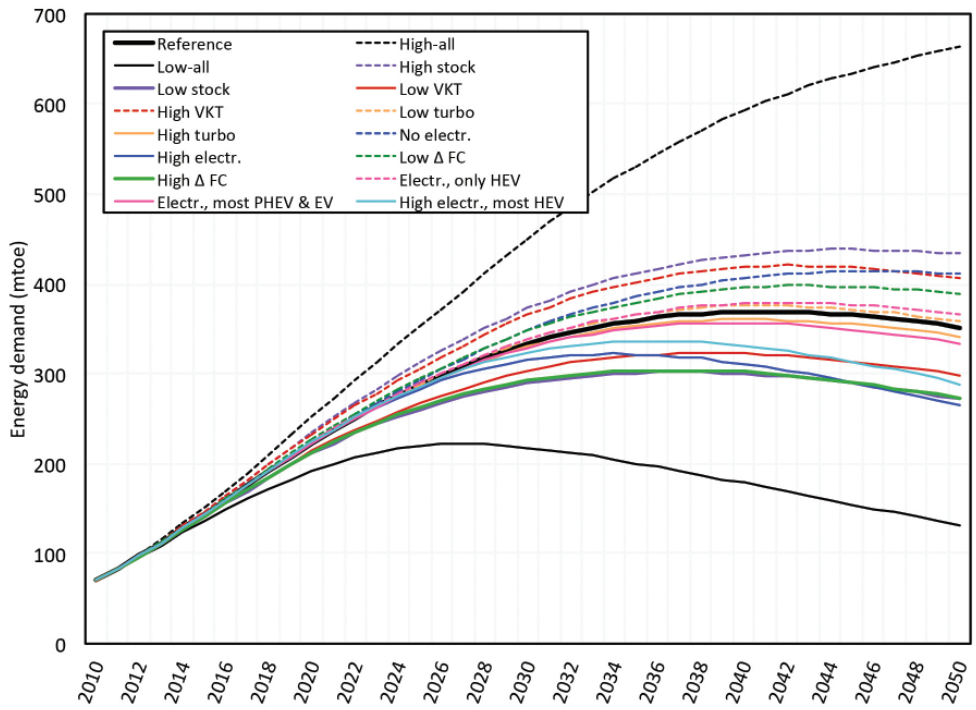


Figure 9.65 Future on-road energy demand results for China's LDV fleet (TTW) in mega tonnes oil-equivalent per year (Mtoe/yr) for all the sensitivity scenarios. Heavy black line is the *reference* scenario.

Figure 9.66 shows the conventional fuel demand future for the on-road LDV fleet, for all scenarios. The two high-all trajectories, one without any alternative fuel adoption and one with significant alternative fuel adoption, show that potential fuel demand savings could approach nearly 250 bil L of gasoline if all other drivers evolve per extreme values. The actual impacts of adopting methanol (olive) or natural gas (brown) are likely more modest and on the order of 50 bil L each. This figure illustrates how our approach differs from the wedge approach that other studies have used: the absolute impacts of changing any one driver are smaller in a median *reference* scenario as compared with an *extreme reference* scenario. They are subject to "diminishing returns" as society employs additional approaches to control automotive energy demand. CNG (brown) has a significant impact as a single driver in the nearer-to-mid-term, though its significance diminishes over time. Methanol has a modest impact in lowering energy demand, but a smaller one raising it (olive). Significant electrification and HEV-dominated significant electrification are even more sensitive for fuel demand (blue and turquoise). Nevertheless, stock (violet) and vehicle fuel consumption (green) are again especially important drivers in reducing conventional fuel demand, while VKT has a fairly large impact (red).

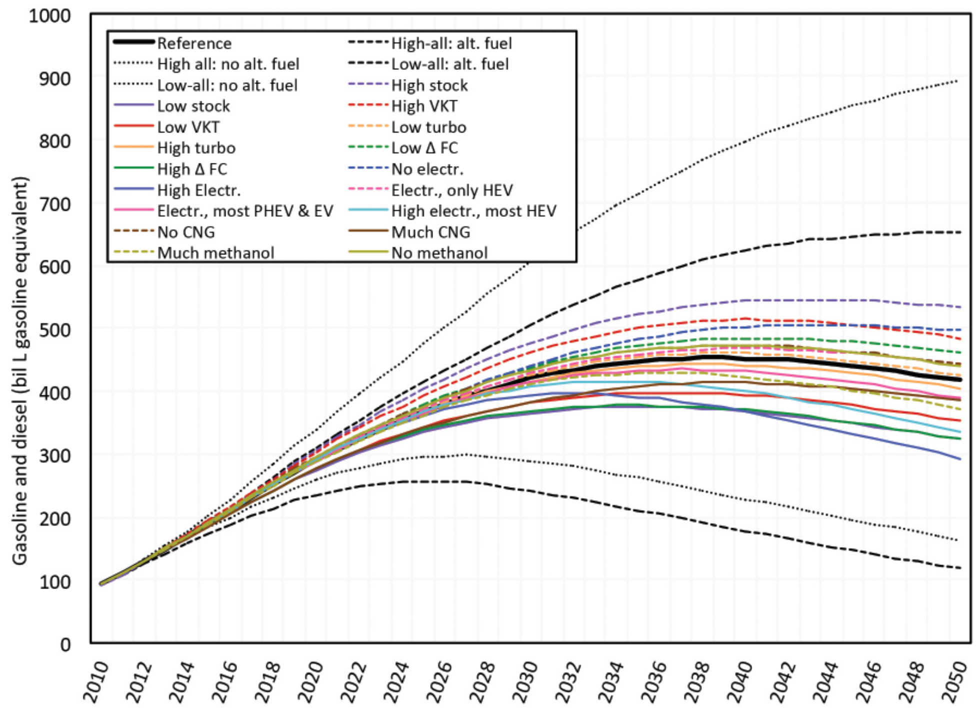


Figure 9.66 Future on-road conventional petroleum-based fuel demand (tank to wheels), China's on-road LDV fleet, 2010–2050, in billion liters gasoline-equivalent per year, sensitivity analysis all scenarios: heavy dark line is the *reference* scenario.

Figure 9.67 shows the WTW GHG emissions rates corresponding to Figures 9.65 and 9.66 (which are TTW energy and fuel demand). Alternative fuel adoption (olive and brown), composition of *reference* scenario electrification (pink), and turbocharged vehicle adoption (orange) have a small impact on future CO_2 emissions in Figure 9.67. It is also noteworthy that increasing amounts of methanol decrease conventional fuel demand but increase WTW GHG emissions. This is because methanol from coal, the primary source in China, is more CO_2 intensive than gasoline. Vehicle stock size is once again the most significant driver in terms of both increasing and decreasing the *reference* scenario emissions. It is closely matched by decreasing/increasing vehicle fuel consumption. VKT is the next most significant driver, ahead of electrification. However, because EVs are more efficient than their internal combustion engine counterparts, even though China's electric grid will remain more CO_2 intensive than gasoline, there is still some CO_2 emissions benefit from significant electrification.

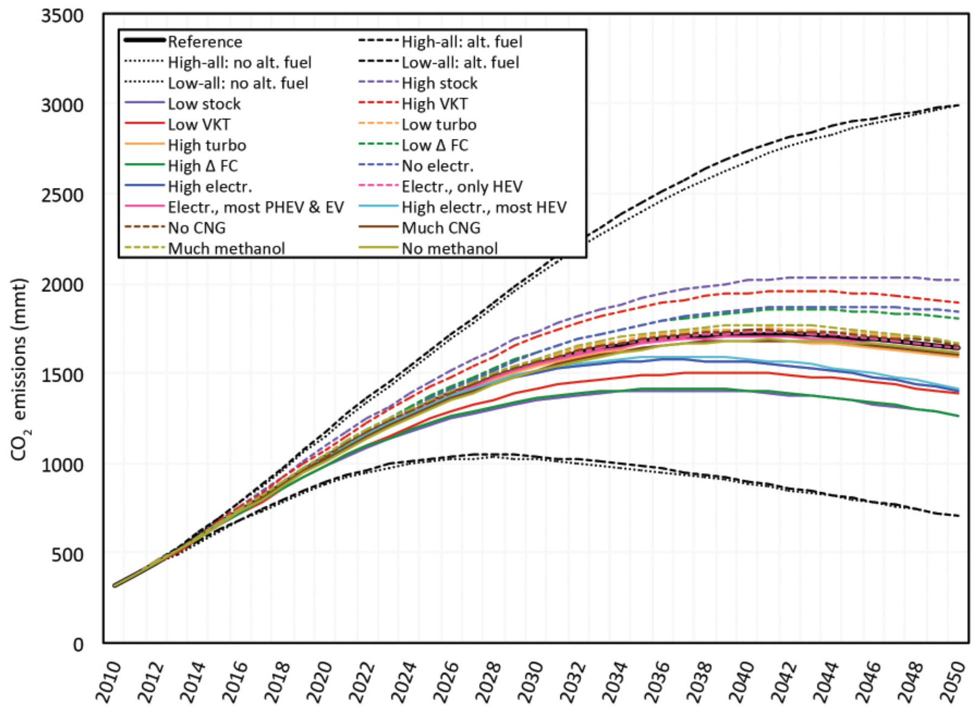


Figure 9.67 GHG emissions, (WTW) in MtCO$_2$-equivalent/yr from China's on-road LDV fleet, 2010–2050: sensitivity analysis all scenarios: heavy dark line is the *reference* scenario.

Table 9.13 compares the "deltas" discussed above (the difference between each sensitivity scenario and the *reference* scenario, at a given date) in percentage terms. Taking future energy demand, conventional fuel demand, and CO_2 emissions into account, vehicle stock has the greatest impact decreasing demand, or emissions. If significant gains can be made in lowering fuel consumption, it too can be an important tool in limiting future energy demand and CO_2 emissions. Significant vehicle electrification holds great potential for lowering energy demand and displacing conventional fuel. Moreover, this electrified fleet need not be wholly electric: significant HEV adoption can achieve comparable benefits to EVs in reducing CO_2 emissions, while achieving some three-quarters of their reductions in energy demand and conventional fuel demand.

Table 9.13 Difference between each Sensitivity Scenario and Reference Scenario

Change Over Reference Baseline	Energy Demand (mtoe)		Conventional Fuel (bil L)		CO_2 Emissions (mmt CO_2)	
Reference Baseline	334	352	421	418	1552	1637
Change	Δ 2030	Δ 2050	Δ 2030	Δ 2050	Δ 2030	Δ 2050
All High	+35%	+89%	+20%	+56%	+33%	+83%
All High (no alt. fuel)			+44%	+114%	+31%	+83%
All Low (high alt. fuel)			-43%	-72%	-33%	-57%
All Low	-35%	-63%	-31%	-61%	-34%	-57%
High Stock	+12%	+23%	+13%	+28%	+12%	+23%
High VKT	+9%	+16%	+10%	+16%	+9%	+16%
Low % Turbocharged	+1%	+2%	+1%	+2%	+1%	+2%
No Electrification	+4%	+17%	+5%	+19%	+4%	+13%
Electrification, only HEV	+1%	+4%	+2%	+6%	+1%	0%
Low Δ FC	+4%	+10%	+4%	+10%	+4%	+10%
No Methanol			+3%	+6%	-3%	-1%
No CNG			+3%	+6%	+1%	+1%
Low Stock	-13%	-23%	-13%	-23%	-13%	-23%
Low VKT	-9%	-15%	-9%	-16%	-9%	-15%
High % Turbocharged	-1%	-3%	-1%	-3%	-1%	-3%
High Electrification	-5%	-25%	-6%	-30%	-3%	-14%
Electrification, most PHEV & EV	-1%	-5%	-2%	-7%	0%	-1%
High Electrification, most HEV	-3%	-18%	-3%	-20%	-2%	-13%
High Δ FC	-12%	-23%	-12%	-23%	-12%	-23%
Much Methanol			-2%	-11%	+2%	+2%
Much CNG			-9%	-8%	-2%	-2%

9.7.5 Comparison results

Historically, China's transportation energy demand as a fraction of world energy demand has been relatively small (Figure 9.68). The United States and the rest of the OECD countries (mainly Europe) accounted for roughly a quarter each of global transportation energy use in 2010. Meanwhile, China accounted for almost no share of international energy demand in the early 1970s, but is quickly moving beyond 10% of international energy demand. As China's conventional fuel demand continues to grow, it will change the dynamics of the international oil market.

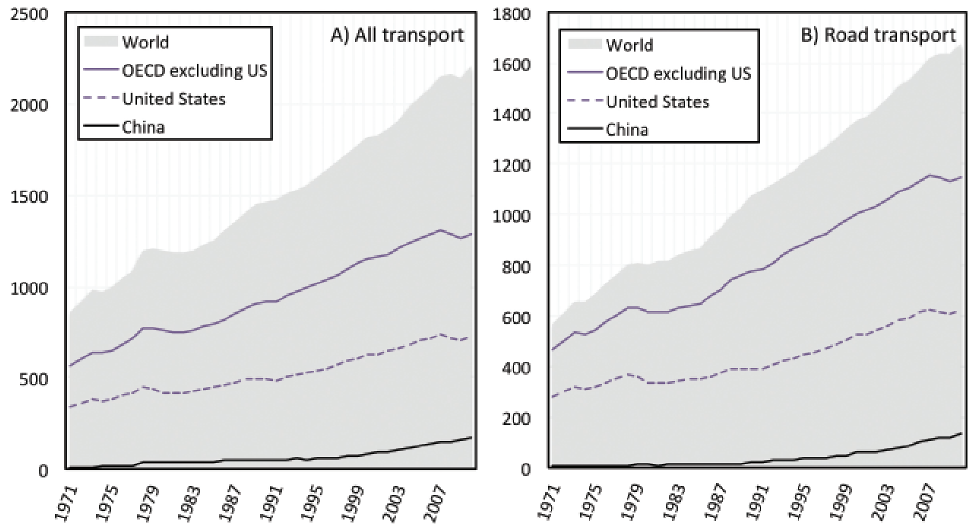


Figure 9.68 Global and regional total transportation and road transport energy demand in million tons oil equivalent per year (IEA).

Surprisingly, the China *reference* scenario peak in LDV annual fuel demand of close to 500 billion liters/year around 2040, closely matches the U.S. LDV fleet current fuel demand of some 525 billion liters/year (Figure 9.6). This coincidence is striking considering that the United States now has fewer cars than China will then have. Differences in VKT, fuel consumption, and the energy technologies deployed in volume combine to account for this result. Before U.S. fuel demand declines significantly, however, the two countries will together demand some 900 billion liters/year of fuel in 2030. These comparisons are valid because the fleet models for this China study and the Bastani et al. (2012) U.S. study originate from the same information sources, and many of the key assumptions (on future relative fuel consumption among powertrains, for example) are closely compatible.

9.8 Interpretation of Scenario Results

This chapter contains summaries of an extensive set of scenarios, focused on different major world regions: the United States, major European countries, Japan, and China. These different scenario studies, done with a common framework based on an in-use vehicle fleet model evolving over time into the future, have examined a wide range of options for reducing fleet fuel and energy use, and GHG emissions, through improvements and changes in engine propulsion system, and vehicle technologies over time, with various technology deployment rates, and with the introduction of other energy sources such as electricity and biofuels. Here, we identify the major findings that resulted from this body of work. Of course, there are many details and subtleties that qualify these broader findings and, as we are looking into the future, there are significant uncertainties. Nonetheless, as more research of this type is done, our sense of the more plausible evolving paths forward becomes clearer.

The key findings are:

1. The two variables that have the greatest impact on the extent to which fuel use and GHG emissions are reduced are those that control fleet growth (annual vehicle sales volumes and scrappage rates from the in-use fleet), and the rate of improvement in the on-road fuel consumption of mainstream technology vehicles (gasoline spark-ignition engine vehicles, and light-duty diesel vehicles in Europe). This is because growth in the in-use LDV fleet size governs growth in total kilometers (miles) driven, and because mainstream technology vehicles dominate the mix of vehicles in the in-use fleet through the near and at least the mid-term.

2. Mainstream technology improvements include more efficient gasoline (and diesel) engines, transmissions, and drivetrains; reductions in vehicle size and weight, and aero drag and tire resistances; and limiting vehicle power/weight ratio increases to hold down increases in vehicle acceleration performance. Note that reducing the fuel consumption of the largest (and thus heaviest) vehicle segment has much greater impact than similar reductions at the smaller end of the vehicle size distribution. This is especially important in the U.S. context because vehicles in North America are substantially larger than in the rest of the world, and thus both the potential for and the impact of weight reduction are greater.

3. In the nearer term, the impacts from EVs or FEVs and from biofuels will be modest. It is not yet clear how attractive these options will prove to be. Whether cellulosic biofuels have the potential to become market competitive and grow to substantial scale is unclear. Hybrid vehicle sales percentages are growing at moderate rates which is expected to continue and increase their impact. It is anticipated that PHEVs will follow (but lag) this hybrid growth. The broad attractiveness of BEVs is, as yet, unclear. Likely, deployment rates of these EV technologies are such that, due to the 15 or so year lifetime of vehicles in actual use, their impact prior to 2025 will be modest though it may continue to grow and, beyond 2040, become significantly more important. Note that decreasing the GHG emissions intensity (CO_2 emitted per unit of energy used) of the electrical supply system is an essential parallel evolution.

4. The scenario results for GHG emissions indicate that reducing the in-use fleet's emissions to about half of the peak levels in the United States, Europe, and Japan, by 2050, is a plausible though very challenging prospect. In regions where growth is modest (United States) or essentially absent (Europe and Japan), mainstream engine and vehicle technology improvements are already turning the aggregate LDV fleet emissions curve downward from its current peak. In China, the high recent fleet growth rates (sales increases of almost 10% per year) have started to decline, but are expected to remain large enough for the next decade or so for growth to more than offset vehicle technology improvements out to about 2040 when LDV emissions are likely to peak and then start to decline. Surprisingly, China's LDV fleet GHG emissions at that point in time will be close to the current value of the U.S. LDV fleet emissions that are now leveling off and starting to decline. Realizing these reductions in energy use and GHG emissions, through improving and changing vehicle technologies, reducing vehicle weight, and introducing new sources of transportation energy, would be a major accomplishment. We should not regard this seemingly slow-to-start wxrate of reduction as a failure!

5. However, the above is still an optimistic assessment, and measures to reinforce the purchase and use of increasing numbers of ever lower fuel-consuming vehicles are likely to be needed to achieve the overall reductions summarized above. Without substantive actions such as a significant carbon tax (see Chapters 10 and 11) to pull such changes, it is much less likely these substantial reductions will be achieved. We noted in this chapter that a more realistic expectation is that maybe two-thirds of this “50% reduction” might be realized. To go beyond this “50% reduction” would take more extensive and greater improvements in this vehicle segment’s fuel consumption technology and today’s petroleum-based fuels, and conserving actions on the demand side to reduce our use of transportation services, and major transformations to low GHG emitting energy sources (and, as noted, it is unclear which of our several options here are the most promising). This topic is further discussed in our final chapter (Chapter 11).

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10.0 A Comprehensive Policy Approach

10.1 Introduction

Achieving a low carbon road transportation system by 2050—and the set of solutions it employs—will depend on the incentives facing auto manufacturers, fuel providers, and vehicle users. If the past is prologue, the future vehicle fleet will be larger, heavier, and more powerful as well as still largely dependent on fossil fuels. Rising travel demand may be offset by gains in fuel economy, but without intervention, the desired aggressive reductions in fossil energy use or greenhouse gas (GHG) emissions are highly unlikely. This chapter considers how to move beyond the status quo. It focuses in particular on the role that public policy, by shaping technology and market developments, could play in encouraging conservation behavior in the near term, facilitating improvements in technology over the medium term, and enabling a transition to lower-carbon alternative fuels over the long term.

Before considering specific policy options, it is worth taking a step back to consider the role of transportation in an overall climate mitigation strategy. All GHG emissions, regardless of source, are equally damaging to the global climate. Globally, transportation services account for 23% of total GHG emissions, with around 10% due to travel in light-duty vehicles (LDVs) [Kyle and Kim, 2011; Fulton et al., 2013]. Policy makers must consider the role that LDVs should play alongside other opportunities to reduce emissions. Economists often point out that putting a price on the right to emit GHGs across all sectors would send a uniform signal and lead to emissions reductions where they cost least. Transportation would contribute part, but not all, of the solution, with significant contributions from other sectors where incremental reductions cost less. But such economy-wide policies have proven politically difficult. Policy makers have instead broadly pursued a range of measures more narrowly targeting vehicle technology, the fuel supply, vehicle fleet composition, or consumer purchasing behavior. Here we focus on policies that target LDVs, remaining mindful that it is important to assess transportation's contribution to carbon reduction in an economy-wide context.

To compare alternative policies, this chapter zooms out from the discussion in previous chapters to develop intuition about policy options that act on the LDV transportation system, and how these policies affect energy use, emissions, and the broader economy. This analysis focuses on an assessment of three of the most prominent policy options in the United States: fuel economy standards (FESs), renewable fuel standards (RFSs), and taxes on motor gasoline or diesel (referred to here as "gas taxes"). The second section briefly describes each policy. The third section describes the energy-economic model used to compare the different policies. The fourth section describes the results. The fifth section comments on how the results of the modeling analysis relate to the current policy situation in the United States. While the United States is the focus of this chapter, many of the insights developed through this analysis have relevance for policy in other countries.

10.2 Background on Policy Designs

LDVs account for around 43% of petroleum demand and 23% of GHG emissions in the United States [MacKenzie, 2013], and have long been the target of policy measures. Looking ahead, in the United States, as in other advanced industrialized countries, growth in demand for vehicle fuel is expected to slow given gradual ownership saturation and modest economic growth, while emerging markets account for most of projected global growth in petroleum demand [Fulton et al., 2013]. However, reaching ambitious targets for petroleum-based fuel use and GHG emissions reduction in the United States is still expected to require additional policy measures that bear on different parts of the transportation system. Table 10.1 summarizes the physical targets of several policy measures that are the focus of this analysis: RFSs, FES, and a gas tax (analogous to a cap-and-trade system or carbon tax, which effectively raises the fuel price).

Table 10.1 List of policies and primary target(s).

Policy	New ICE Vehicle Efficiency	Alternative Fuel Vehicles	Reduce Upstream Fuel Emissions Intensity	Increase Alternative Fuel Quantity or Share	Reduce VMT	Encourage Changes in Driver Behavior
1) Fuel Mandates Renewable Fuel Standard				X		
2) Vehicle Policies Fuel Economy (per-mile GHG emissions) Standards	X	X			-X	
3) Price Signals Gas Tax	X	X		X	X	X

10.2.1 Renewable Fuel Standards

An RFS mandates that a certain volume or percentage of the fuel supply be composed of a particular renewable fuel. In the United States, the Energy Independence and Security Act of 2007 mandates a volumetric target for blending biofuels into the fuel supply, reaching 36 billion gallons by 2022 (around half of which was initially expected to be derived from non-food crops and to deliver greater carbon savings than corn-based ethanol). For passenger vehicles, the near-term biofuel of choice has been ethanol, which can be blended into the gasoline supply up to an allowed percentage (currently 10% for non-flex fuel internal combustion engine (ICE) vehicles and up to 15% for approved model years).[30] The feasibility of this volumetric standard has been called into question, since it is not clear that a sufficient number of flex-fuel vehicles will be available to absorb the high volumes required [Blanco, 2010]. The RFS has been justified in part as a way to promote learning in the early stages of technology deployment, which is expected to bring down cost in the long run [Morris, 2009; Fischer & Newell, 2008]. However, this approach requires

[30] In 2011, the EPA determined that ethanol blends of up to 15% (E15) can be used in model years 2001 and newer vehicles [EPA, 2011].

a choice to support one technology over its alternatives. Therefore, there is a risk that the other technologies that were not chosen might have been less costly or more successful candidates for support.

10.2.2 Fuel Economy Standards

FESs have been implemented in the United States for several decades. Passed in 1975 to reduce gasoline use in the wake of 1973 Arab Oil Embargo, the Corporate Average Fuel Economy (CAFE) standards mandated increases in the fuel economy of cars and light-duty trucks starting in 1978 [Shiau et al., 2009]. These standards were tightened sharply through the early 1980s but remained constant over much of the 1990s and were not increased again until 2005 for light trucks and 2011 for cars.[31] In 2010, following classification by the Environmental Protection Agency (EPA) of GHG emissions as a pollutant under the Clean Air Act, the agency became involved in setting per mile CO_2 emissions standards. CO_2 emissions standards were harmonized with a more stringent version of the CAFE standard, which mandated a reduction in the combined average per mile CO_2 emissions to 250 grams per mile (which corresponds to an increase in fuel economy to 35.5 miles per gallon) over the period 2012 to 2016.[32] In late 2011, a new fuel economy standard for model years 2017 to 2025 was announced, requiring a 5% increase per year for passenger cars, and a 3.5% increase per year for light trucks for model years 2017 to 2021 followed by a 5% increase per year for model years 2022 to 2025 [EPA, 2012]. For model year 2025, this translates into a CO_2 emissions target of 144 grams per mile for passenger cars and 203 grams per mile for light trucks, equivalent to a combined new fleet average of 163 grams per mile. As discussed in Chapter 2 of this report, FESs have also been widely adopted in many countries and regions, including China, Japan, and the European Union.

10.2.3 Gas Taxes

In the case of a gasoline (or carbon) tax, a charge is levied based on the volume of gasoline or diesel fuel (or its carbon content), and passed along to consumers in the form of increased prices at the pump. Under a gasoline tax, the choice of fuel abatement strategy is determined by the availability and cost of the options. Options include fuel-saving technologies as well as consumer willingness to forego energy-intensive vehicle attributes in favor of higher fuel economy. Currently, the federal gas tax in the United States is 18.4 cents per gallon. Including state gasoline taxes, the average gasoline tax rate in the United States is approximately 49 cents per gallon [API, 2015]. In other advanced industrialized countries such as Germany, gasoline taxes are seven times higher.

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[31] In addition to passenger vehicles, the LDV fleet is comprised of cars and light-duty trucks owned by commercial businesses and government. U.S. federal regulations consider a light-duty truck to be any motor vehicle having a gross vehicle weight rating (curb weight plus payload) of no more than 8,500 pounds (3,855.5 kg). Light trucks include minivans, pickup trucks, and sport-utility vehicles (SUVs).

[32] The original vehicle fuel economy target under the Energy Independence and Security Act of 2007 was 35 mpg by 2020. The 35.5 mpg target is the improvement required if the corresponding per mile emissions target (250 grams per mile) is met by improvements in fuel economy alone.

Since a price signal targets either petroleum-based fuel use (e.g., a gasoline tax) or GHG emissions reduction (carbon tax), it does not *a priori* favor particular technological solutions. Assuming efficient markets, the price signal ought to encourage the portfolio of changes that cost least to achieve the desired reduction in petroleum-based fuel. It is worth pointing out that under these circumstances, political consensus may be more difficult to achieve in comparison to policies that deliver clear benefits to stakeholder groups. Attempts to introduce cap-and-trade legislation in the United States have included a broad range of provisions to make these policies more palatable to large and influential stakeholders, including large allocations of permits to parties likely to be most directly affected. Proposals involving taxes—based either on fuel volume or on carbon content—have been less successful in gaining broad public support [Levine & Roe, 2009].

10.3 Modeling Approach

Before describing the model used in this analysis, a brief discussion of the modeling philosophy is appropriate. To compare policy options, it is helpful to study not only the combinations of technology that produce a desired environmental outcome, but also the relative cost of achieving the outcome using different policy instruments. To do this convincingly, a model must capture both the primary leverage points that policies target and the impact that compliance has on the integrated energy and economic system. Therefore, we employ a model that represents the United States (including its energy system and advanced technology options) in both economic and physical quantities, albeit in a deliberately simplified way. Model predictions should not be viewed as precise forecasts, but instead as providing insight on the mechanisms and relative magnitudes of policy impact.

Specifically, this analysis employs a version of the MIT Emissions Prediction and Policy Analysis model version 5 (EPPA5) with a detailed representation of the light-duty passenger vehicle transport system. The EPPA model is a recursive-dynamic computable general equilibrium (CGE) model of the world economy developed by the Joint Program on the Science and Policy of Global Change at MIT [Paltsev et al., 2005]. The EPPA model captures both economic linkages across sectors and regions, including trade flows, and tracks energy and emissions quantities. These relationships are based on a comprehensive global energy and economic data set developed by the Global Trade Analysis Project (GTAP) network [Hertel, 1997; Dimaranan and McDougall, 2002]. The GTAP dataset is aggregated into 16 regions and 24 sectors including several advanced technology sectors for use in the EPPA model (Table 10.1).

10.3.1 The Passenger Vehicle Transport Sector in the *EPPA5-HTRN* Model

Several features were incorporated into the EPPA model to explicitly represent the passenger vehicle transport sector. These features include an empirically based parameterization of the relationship between income growth and demand for vehicle-miles traveled, a representation of fleet turnover, and opportunities for fuel use and emissions abatement. These model developments, which constitute the *EPPA5-HTRN* version of the model, are described in detail in Karplus et al. (2013a). The structure of the passenger vehicle transport sector in *EPPA5-HTRN* that includes these developments is shown in Figure 10.1.

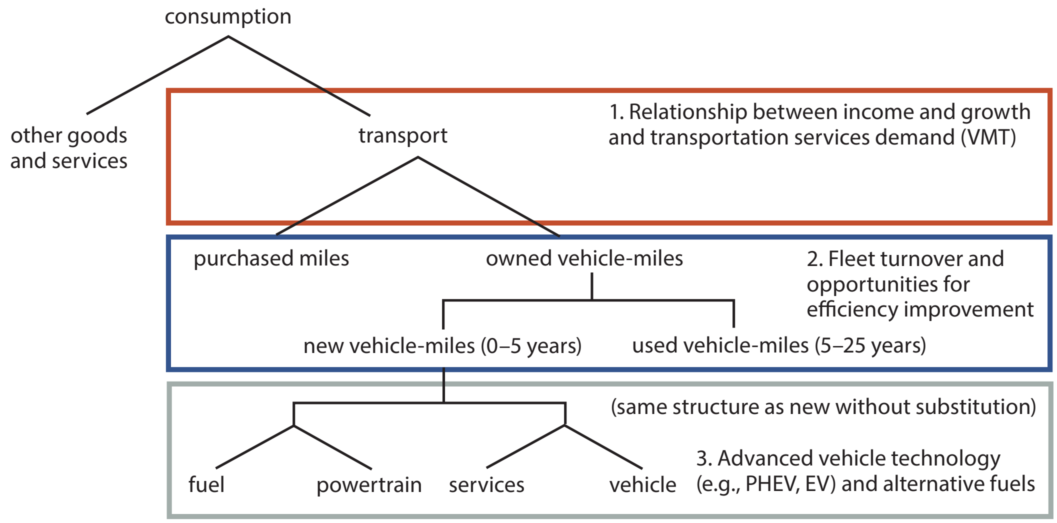

Figure 10.1 Structure of the passenger vehicle transportation sector in the EPPA model.

The main innovation in the *EPPA5-HTRN* model is the use of disaggregated empirical economic and engineering data to develop additional model structure and introduce detailed supplemental physical accounting in the passenger vehicle sector. First, to capture the relationship between income growth and vehicle miles travelled (VMT) demand, econometric estimates were used in the calibration of the income elasticities [Hanly et al., 2002]. These were implemented using a Stone-Geary utility function, which allows income elasticities to vary from unity within the Linear Expenditure System (LES) [Markusen, 1993]. The income elasticity in the United States was calibrated to reflect the long-run estimate of 0.73 given in Hanly et al. (2002), but after 2035 is set to diminish by 0.05 in each five-year period to simulate saturation of household vehicle ownership by further reducing the size of the household vehicle transport expenditure share. More details on model parameterization can be found in Karplus (2011).

Second, to represent fleet turnover and abatement opportunities in existing technology, data on the physical characteristics of the fleet (number of vehicles, vehicle-miles traveled, and fuel use by both new vehicles (zero to five-year-old) and used vehicles (older than five years), as well as economic characteristics (the levelized cost of vehicle ownership, comprised of capital, fuel, and services components) were used to parameterize the passenger vehicle transport sector in the benchmark year and vehicle fleet turnover dynamics over time [GMID, 2010; Bandivadekar et al., 2008; Karplus et al., 2013a]. Engineering-cost data on vehicle technologies were used to parameterize elasticities that determine substitution between fuel and vehicle efficiency capital [EPA, 2012].

Third, plug-in hybrid electric vehicles (PHEVs), as a representative alternative fuel vehicle, were introduced into the model, along with substitution between the fuel and vehicle efficiency capital (similar to the ICE vehicle) that represents fuel consumption reduction opportunities specific to the PHEV [Karplus et al., 2010]. The detailed structure of the powertrain-fuel bundle for new vehicles, which shows substitution between the PHEV and ICE-only vehicle, as well as opportunities to reduce the fuel consumption of each vehicle type through substitution with vehicle efficiency capital, is shown in Figure 10.2a.

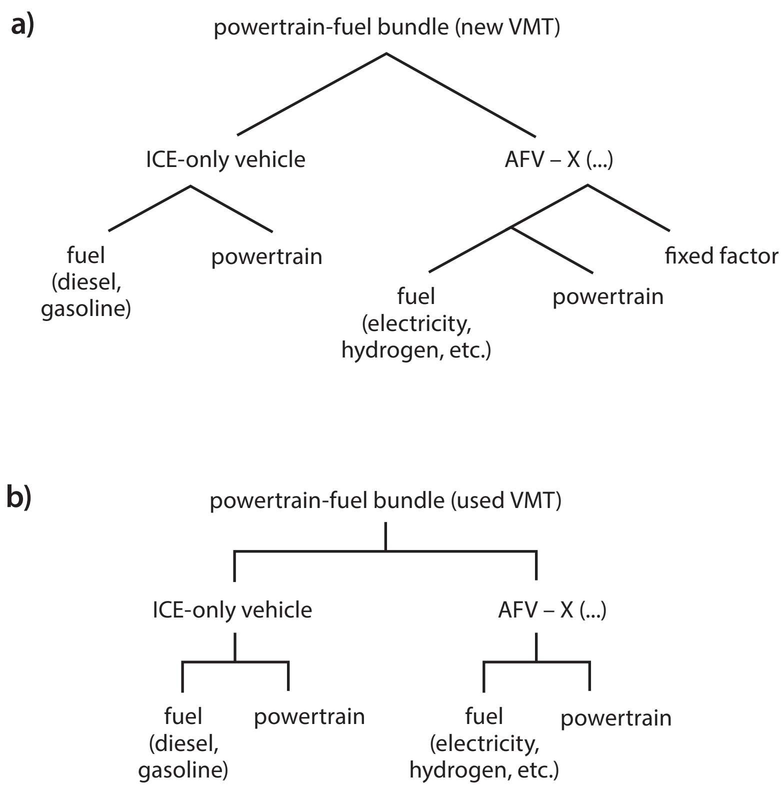

Figure 10.2 The inclusion of alternative powertrain types (denoted by AFV–X, where X could be a PHEV, EV, CNGV, and/or FCEV) in the a) new and b) used passenger vehicle transport sectors in the MIT EPPA model.

10.3.2 Description of Advanced Technology Options

The representation of technology and its endogenous response to underlying cost conditions is essential for analyzing policies, which typically act—directly or indirectly—through the relative prices of fuels or vehicles. Here we consider a PHEV, which is modeled as a substitute for the ICE-only vehicle which can run on gasoline in a downsized ICE or on grid-supplied, battery-stored electricity. The PHEV itself is assumed to be 30% more expensive relative to a new ICE-only vehicle, an assumption at the low end of the range of estimates from a recent literature review [Cheah and Heywood, 2010].[33] Vehicle characteristics and technology requirements are defined based on a mid-sized sedan, which relies on grid-supplied electricity for 60% of miles-traveled and liquid fuels for the remaining 40%.[34] ICE fuel economy assumes operation in hybrid mode, while the battery is sized for a useable all-electric range of 30 miles. As the levelized price per mile of ICE vehicle ownership increases over time (with increasing fuel cost and the introduction of efficiency technology), the cost gap is allowed to narrow and may eventually favor adoption of the PHEV. PHEVs are assumed to use grid-supplied electricity for the first 30 miles of travel, beyond which they run on the existing liquid fuel supply (gasoline and gasohol blends). The electricity sector in EPPA is modeled as a combination of generation technology mix in 2004 and any advanced low-carbon electricity production methods that are introduced over time in response to changing underlying prices or policy.[35]

In our modeling strategy we capture a single representative size class with average fuel economy for the both the new and used vehicle fleets. The characteristics of used vehicles, including their fuel economy, are a function of the surviving vehicles in each year, while the new technology is introduced largely through the sales of new vehicles. To capture the additional investment required to reduce fuel consumption, we represent substitution between vehicle efficiency capital and fuel that is based on an estimation of the costs of strategies for reducing fuel consumption in vehicles.

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[33] Specifically, we chose as a relatively optimistic scenario the estimate from Plotkin and Singh (2009) for a PHEV40 in 2015, which gives a markup over a conventional ICE car of US $6,000.

[34] This mileage split is a function of travel patterns in the United States and battery all-electric range, as discussed in Karplus (2011). The mileage share driven on electricity is referred to as the PHEV utility factor [Gonder & Simpson, 2006].

[35] We do not model hourly pricing or separately represent base load, peaking, and shoulder generation, nor do we represent regional differences in the electricity mix across the United States that could affect the marginal emissions rates for the PHEV fleet.

10.3.3 Policy Modeling Approach

Fuel Economy Standard

To simulate the U.S. CAFE standards, we developed an approach consistent with representation of technology and behavior in the model. Specifically, the FES is implemented as a constraint on the quantity of fuel required to produce a fixed quantity of vehicle-miles traveled. It is implemented as an auxiliary constraint that forces the model to simulate the adoption of vehicle technologies that achieve the target fuel consumption level at the least cost. Opportunities to improve fuel economy are described by a parameter that relates cost of technology to abatement potential, which is used to estimate the elasticity of substitution between fuel and powertrain capital as two substitute inputs to household vehicle transport. The model also captures how total VMT will then respond when fuel economy has been forced to high levels by the constraint, also known as the rebound effect. The form of the utility function, the input shares, and the substitution elasticity between vehicle and powertrain capital determines how much the marginal cost of a mile of travel changes in response to changes in the underlying fuel requirement and vehicle characteristics, which in turn determines the magnitude of the rebound effect.

We represent a fuel economy standard that roughly follows the trajectory for the United States through 2022, increases the stringency linearly through 2030, and then holds constant after that, in order to achieve a 20% reduction in petroleum-based fuel use over the period 2010 to 2050. More detail on how the FES has been implemented in the model can be found in Karplus et al. (2013b). The stringency of the fuel economy target is shown in Table 10.2.

Table 10.2 Stringency of the fuel economy target.

Year	Fuel Economy Standard			
5-year average	**% below 2010**	**UA (L/100 km)**	**A (L/100 km)**	**A (mpg)**
2005–2010	0.0%	9.1	11.4	20.6
2010–2015	12.5%	8.0	10.0	23.5
2015–2020	25.0%	6.8	8.6	27.5
2020–2025	37.5%	5.7	7.1	33.0
2025–2030	50.0%	4.6	5.7	41.2
2030–2035	50.0%	4.6	5.7	41.2
2035–2040	50.0%	4.6	5.7	41.2
2040–2045	50.0%	4.6	5.7	41.2
2045–2050	50.0%	4.6	5.7	41.2

Note: UA – unadjusted (regulatory target), A – adjusted (on-road fuel consumption).

Renewable Fuel Standard

To simulate an RFS, we introduced a constraint in the model to require that increasing volumes of advanced (carbon negligible) biofuels be introduced into the fuel supply through 2050. Biofuels are represented with an incremental cost of 3.1 times the cost of petroleum-based fuel on an energy basis [Paltsev et al., 2005]. The trajectory for the percentage of biofuels in the fuel supply (also on an energy basis) increases from 2015 to 2030, and achieves a cumulative reduction in petroleum-based fuel use of 20% over the period 2010 to 2050 (Table 10.3). The standard takes effect in 2015 to reflect the fact that currently, only near-term biofuels options with a higher carbon footprint are available to meet the RFS. The modeled and actual RFS policies differ in an important respect: in the model, an RFS is a percentage blend requirement, while on the books, it is a volumetric standard. This difference is not expected to strongly affect the results of the policy comparison.

Table 10.3 Increasing percentage of biofuels required under the RFS.

5-Year Average	Renewable Fuel Standard (% blend required)
2005–2010	N/A
2010–2015	12.50%
2015–2020	16.25%
2020–2025	20.00%
2025–2030	23.75%
2030–2035	23.75%
2035–2040	23.75%
2040–2045	23.75%
2045–2050	23.75%

Gasoline tax

In the EPPA model, a gasoline tax is modeled as an *ad valorem* (or constant percentage) tax that is implemented starting in 2010 and held constant through 2050. Given an underlying set of technology cost and behavioral parameters in the model, we iterate on levels of the tax until the targeted 20% reduction in cumulative petroleum-based fuel use is achieved. Under a scenario in which advanced biofuels are not available, the tax required to achieve the 20% reduction is 75 cents per dollar.[36] (With biofuels available at the 3.1 cost markup described above, the tax required in only 45 cents per dollar, because in later periods the tax incentivizes significant adoption of biofuels that displace a substantial fraction of petroleum-based fuel).

[36]The pretax price in 2004 is $2.23/gallon. All prices in the model are indexed to the 2004 price, and change over time in response to changes in underlying market conditions, including the direct and indirect impacts of policies.

10.4 Results

The results of the policy comparison show that the gas tax imposes the lowest total cost on the economy of the three policies, corresponding to the fact that it incentivizes broader changes in fuel economy, fuel type, and travel demand. The gas tax is significantly less costly than either the FES or the RFS. For the reduction paths assumed, a fuel economy is somewhat less costly than an RFS, but this also depends on the timing of reductions. Here we simulate policies that are as close as possible to current target trajectories through 2030 and also achieve a 20% cumulative reduction in CO_2 emissions. Under a different reduction trajectory that also achieved the same 20% emissions reduction, the cost ordering of these two policies could flip.

While the results do not represent predictions, they do provide insight into the relative cost of different policies and the source of the advantages and disadvantages of each. Table 10.4 shows the consequences of each instrument in a model that captures a range of real-world responses expected within the passenger vehicle transport system. For example, a gas tax has a modest effect on fuel economy of existing ICE vehicles. It also creates incentives to increase the share of PHEV miles in total miles driven. Finally, and perhaps most importantly, the penalty scales with miles of travel and thus results in the largest decrease in miles traveled in new and used vehicles of any policy by 2030 (-0.36%). With a price signal in place, this response reflects the optimal combination of fuel efficiency investment, reduced driving, and alternative fuel vehicle adoption, given the assumed costs of the various options available.

Table 10.4 Summary of forecasted travel demand and technology response under policies.

Scenario	Δ VMT in 2030	New ICE Fuel Cons. 2030 (L/100 km)	New ICE Fuel Cons. 2050 (L/100 km)	% PHEV in New VMT 2030	% PHEV in New VMT 2050	Cost ($ billion/year USD 2004)	Loss (%) Relative to Reference
Reference	N.A.	10.2	9.6	0%	14%	N.A.	N.A.
Gas Tax	-0.36%	8.9	7.2	19%	46%	1.7	0.03%
Fuel Economy Standard	+0.13%	7.2	8.4	14%	45%	10	0.20%
Renewable Fuel Standard	-0.24%	9.8	9.1	6.1%	26%	13	0.26%

In similar fashion, the simulated changes in the vehicle system help to explain why costs are projected to be much higher under an FEC or RFS. One reason is that both policies target a smaller set of responses—an FES must achieve the 20% cumulative reduction solely by reducing the per-mile petroleum-based fuel requirement, while an RFS must act solely by adding biofuels to the fuel supply. Indeed, an FES reduces new vehicle fuel consumption per mile far more than the other policies, and the PHEV also plays a significant role by 2050.[37] Furthermore, by reducing the per-mile fuel cost as a result of on-road vehicle efficiency improvements, an FES actually encourages a modest increase in driving, rather than a reduction.

[37]Even though the percentage of miles driven in a PHEV is lower in the FES case relative to the tax case, the absolute number of miles driven in a PHEV is higher because miles traveled are higher overall.

In all policy scenarios, targeting petroleum-based fuel use in LDVs only (or CO_2 emissions from LDVs only), resulted in the displacement of fuel use and associated CO_2 emissions to other sectors, as shown in Table 10.5. Both an FES and an RES induce this displacement through high-cost mandates, which puts a visible burden on the overall economy and results in reductions in fuel demand across the board. Use of petroleum-based fuel also increases in non-covered sectors. Meanwhile, in the case of a gas tax, the cost differential between using petroleum-based fuel in LDVs and in other sectors is larger, leading to a larger overall leakage effect, which shows up in a lower reduction in CO_2 emissions under the tax case, relative to either the FES or RFS cases. Indeed, a 20% cumulative reduction in LDV petroleum-based fuel use does not translate into a proportional reduction in national petroleum demand, as petroleum demand by other sectors (freight, household heating) increases and offsets this reduction.

Table 10.5 Total impact of policies on fuel use, CO_2 emissions, and cost.

Policy	Δ Emissions (mmt)	Δ Cost (billions/year, DR = 4%)	Cumulative Fuel Reduction from LDVs (%)	Cumulative Emissions Reduction (%)	Loss (%) Relative to Reference
FES	-16000	10	-20%	-4.4%	0.20%
RFS	-16300	13	-20%	-4.5%	0.26%
Tax – No Biofuels	-12100	0.70	-20%	-3.3%	0.03%

As a final exercise, we consider what happens when RFSs and FESs are combined, which is currently the case in the United States. We find that the modeled impact of combining the two standards is not strictly linear—instead, the simulated reduction is only 32%—while the cost is almost equal to the cost of each policy individually as seen in Table 10.6. This is in part a function of the fact that fuel economy improvements result in a reduction in total fuel demand, which means that a lower volume of biofuels is required to meet the RFS. However, compliance with an FES is not made easier by the presence of an RFS. Only the RFS is slightly easier to meet because of the FES, given the lower volumes of biofuels required. However, it should be noted that in reality the RFS is a volumetric standard, which means that the volume of biofuels required will not change with the stringency of the fuel economy standard. It may make compliance even more costly and difficult because of the need to introduce vehicles compatible with the required higher biofuels blends needed to absorb the volumetric requirement. This interaction underscores the importance of conducting policy impact assessments under the assumption that existing or proposed policies are also having an effect on fundamental properties (price, quantity) of the commodity or environmental externality they are trying to target.

Table 10.6 Total impact of combining an FES and RFS on fuel use, CO_2 emissions, and cost.

Scenario	Gasoline Use (billion gallons/year)	CO_2 Emissions (Mt/year)	Consumption (billion USD/ year)*	% Change Gasoline	Cumulative Emissions Reduction (%)	Loss (%) Relative to Reference
Reference (annual average)	138	7,300	14,120	N/A	N/A	N/A
RFS + FES	-44	-520	21	-32%	-7.1%	-0.41%

10.5 Conclusions

The modeling analysis performed in this work investigated three transport-specific energy policies. The objective of this analysis was to evaluate the costs of different policies and the impacts on technology, passenger vehicle gasoline use, and GHG emissions. Two important lessons emerge. First, in terms of the cost of achieving a fixed percentage of cumulative reductions in passenger vehicle refined oil use, the RFS and FES policies are at least six times more expensive as a gasoline tax (on a discounted basis, and depending on whether advanced biofuels are available). The FES and RFS are similar in cost. The analysis also showed that these policies produced very modest GHG emissions reductions. Second, the analysis showed that combining FES and RFS policies results in a smaller reduction in passenger vehicle gasoline use than the sum of reductions under each policy implemented in isolation, while the cost of combining policies is roughly additive.

It is worth noting that despite its being substantially lower cost, a gas tax has proven difficult to sell politically in the United States for many reasons [Karplus, 2013; Knittel, 2013]. Gradual but meaningful changes that start with today's policies and incorporate the most politically feasible principles of cost-effective design are perhaps the best way to ensure that aggressive targets for petroleum use and GHG emissions reductions can be achieved over the longer term. This discipline, it is hoped, will keep U.S. policy on a path that encounters fewer political obstacles to achieving energy security and climate goals, while encouraging a shift to more direct routes over time.

This analysis has suggested how energy-economic models can be helpful in comparing policy options on the basis of technological or behavioral requirements as well as economic impacts. Models currently used within the transport energy and environmental policy community to evaluate the impacts of policies typically do not take consumer preferences into account when forecasting policy compliance scenarios. These models often include considerable detail in their representation of the vehicle fleet, options for technological improvement, and the process of fleet turnover. They are applied to forecast the gasoline use and GHG emissions impacts of the introduction of new vehicle technologies, based on a view informed by both government and industry of what could be reasonably achieved. The model developed for this analysis includes important features of these relationships and further introduces economic logic. The method of calculating policy cost considers adjustments across the entire economy, and can be applied to consider interactions with policies imposed on the same or related sectors. Policy makers could usefully compare the aggregate policy cost estimates from fleet accounting approaches with those that emerge from economy-wide computable general equilibrium models that include a detailed representation of the passenger vehicle fleet to identify the sources of discrepancies as a step to improving on both approaches.

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11.0 Findings and Recommendations

11.1 Summary of Major Findings

This report consists of a set of chapters, based on our group's research over the past five or so years. Each chapter is effectively an essay that reviews major steps in the overall task of achieving major reductions in light-duty vehicle (LDV) energy consumption and greenhouse gas (GHG) emissions. Our group's focus has been on LDVs because they are the largest portion of our total transportation emissions in the United States, and thus have the greatest impact. Outside the United States, LDVs account for a large and growing fraction of transportation emissions in many nations. In this final report chapter, we highlight the key findings identified by the research described in each of the report's individual chapters. From these findings, we draw our conclusions and recommendations.

There are many options available for reducing the fuel, energy, and GHG emissions impacts of LDVs. As our understanding of these options improves, our ability to better prioritize their usefulness in moving toward significantly reduced impacts increases. We should continue to adopt policies to reduce transportation energy demand and emissions, while using our evolving information base to assess and reassess which options have the greatest leverage. While recommendations like ours can never be "proven" and will always be subject to some disagreement, the sequence of topics we have analyzed here constitutes, in our judgment, a valid basis for identifying pathways that are likely to have the greatest benefit. Achieving our overall goal—reducing fleet fuel and energy consumption and GHGs by three-quarters or more—will be extremely challenging. All of us involved in studying the ways in which we can move toward that goal have a responsibility to provide ever more useful and focused advice.

Here, we first summarize our major findings. The initial two chapters of this report develop the context within which our sequence of topics (which draw on a dozen or so individual research projects) are examined. The subsequent chapters then focus on this sequence of topics: the various technology options and their characteristics; vehicle weight and size reduction; vehicle performance, fuel consumption, weight trade-offs; fuel and alternative energy source opportunities; the diffusion rates of improved and new technologies; driver behavior and choice impacts; extensive future scenario analysis results; and policy opportunities.

Paths Forward: We have identified three important paths forward—labeled *improve, conserve, transform*—which are of comparable potential impact, and which should all be pursued aggressively. Here *improve* means increasing the energy efficiency of propulsion system and vehicle technologies already in substantial production, including gasoline and diesel engines, transmissions and drivetrains, and hybrids. *Improving* has by far the largest and most certain potential impact in the nearer term. *Conserve* refers to changes in collective and individual behavior, such as reducing travel demand, shifting to less energy-intensive modes, and operating vehicles more efficiently. *Conserving* has the potential for ongoing benefits, nearer to longer term, across most of the in-use vehicle fleet. However, since the primary levers for change are economic and political, achieving and sustaining significant impact is especially challenging. *Transform* involves (over time) one or more major shift(s) in the energy sources used in transportation, from currently almost totally petroleum-based fuels (gasoline and diesel), to alternatives with significantly lower GHG intensities than these petroleum fuels. Usually this requires major changes in both vehicle technology and fuel supply, simultaneously. Exploring the attractive *transforming* options, while it has modest near-term impacts, is essential in the longer term and demands attention today due to the long lead times associated with these transitions.

A widely used useful framework for assessing options and progress is the identity

$$\text{GHG emissions} = \text{Person miles} \times \frac{\text{Vehicle miles}}{\text{Person miles}} \times \frac{\text{Energy}}{\text{Vehicle mile}} \times \frac{\text{GHGs}}{\text{Energy}}$$

where the GHG emissions are commonly expressed as mass CO_2 equivalent. The first two terms on the right-hand side indicate the impacts of *conservation*: reducing the need to travel, using vehicles more effectively, and shifting more travel to more energy-efficient modes. The third term represents the impact of *improvements* in the combined vehicle and fuel system. The final term, which for the GHG challenge is especially important, reflects the well-to-wheels GHG intensity of the fuel/energy source used, and is generally the target of *transformative* efforts.

Fuel Economy and GHG Requirements: Most major countries have set fuel economy (fuel consumption) and/or GHG emissions requirements (gCO_2—often equivalent—per mile or km) to 2020 or 2025, often with studies in progress to extend such requirements beyond 2025. Details such as test cycle used can differ country to country, making comparisons challenging. With efforts to adjust for these differences, current light-duty vehicle GHG requirements/levels range between about 110 g tailpipe CO_2/km (for Japan) to 175 g (U.S.), due in large part to different average LDV size and weight. By 2025, the targets converge some, to about 80 to 100 g tailpipe CO_2/km. The annual rates of decrease in these CO_2 requirements vary between about 2%/year (India) to close to 4% (U.S. and Europe).[38] These higher values are especially aggressive relative to historical rates of improvement reported here and in prior investigations.

The well-publicized light-duty vehicle U.S. 2025 fuel economy targets (Corporate Average Fuel Economy or CAFE) of 54.5 mpg (on the CAFE test cycle, which are some 20% higher than on-road values) relative to LDVs of today of close to 28 mpg (CAFE test values) would require a 5% per year reduction. This, however, is a “nominal value”: the 2025 CAFE target comes down to about 44 mpg (4% per year) after allowing for various credits—still a major challenge. Our studies of the feasibility of meeting these 2025 mid-40s mpg CAFE targets using available technology indicate that this is unlikely without some pullback in other vehicle attributes such as acceleration performance, though major improvements in fuel economy/consumption will still be realized. This discussion indicates that the required 2017 review of the 2025 CAFE standards, and the inherent complexity in the relevant mpg numbers, and what constitutes compliance, comprise a major public-education and communication challenge for both government regulators and auto companies.

[38]These are tank-to-wheel requirements, not well-to-wheels. For petroleum-based fuels the well-to-tank component is relatively modest, some 15%–20%. For several of the alternative energy carriers, such as hydrogen and electricity, the well-to-tank component is dominant.

Powertrain, Vehicle, and Energy Options: Chapter 3 reviewed the more promising options and summarized their current fuel consumption and GHG emissions characteristics, costs, and the expected improvements through 2050. These options include: spark-ignition engines (naturally-aspirated and turbocharged, NA-SI and TCSI); hybrid electric vehicle (HEV); plug-in hybrids (PHEV); fuel cell hybrids, and hydrogen, possibly as a plug-in with electricity recharging as well (FCHEV); battery electric vehicles (BEV); and spark-ignition engines using natural gas (NG). Figure 11.1 (also Figure 3.3) shows the fuel consumption of average vehicles with these various propulsion systems, where their liters/100 km values have been normalized to the current average value of a standard NA-SI gasoline engine vehicle.[39] This *relative fuel consumption* includes both propulsion system improvements and vehicle resistance (weight, aerodynamic drag, and tire rolling resistance) reductions over time. Note the factor-of-two reductions anticipated in this "realistic yet aggressive" scenario for each propulsion system, and the relative ranking of several promising propulsion systems in vehicles. Progress will be made by both steadily improving each propulsion system **and** by shifting increasing fractions of the sales mix each year to the more efficient alternatives.

Figure 11.1 shows tank-to-wheel assessments of vehicle energy consumption. The important next question is the comparative GHG emissions on a well-to-wheels basis. Table 11.1 (also Table 3.6) summarizes these characteristics for the different propulsion systems in an average new car, both absolute values in gCO_2 equivalent/km and relative to the standard NA-SI vehicle, in 2030. Ranges are given for non-petroleum fuels because GHG emissions intensity (gCO_2 equivalent per MJ of energy) depends on how the hydrogen or electricity is produced and distributed. For example, it is anticipated that the coal-generated electricity supply will decrease, the natural-gas electricity share will increase, as will renewable electricity generation (wind and solar), and also nuclear, but the rates of such changes are unclear. In the right-hand column in Table 11.1, the relative emission rates are significantly lower than those from the most efficient petroleum-based fueled engines only when the source of electricity or hydrogen is especially clean. Unless or until the supply systems for electricity and hydrogen are cleaned up, the propulsion system and energy options listed in Table 11.1 are unlikely to provide markedly lower emitting alternatives than will mainstream technologies. Whether this will happen by 2030, or even 2050, is far from assured, and warrants additional policy attention.

[39] The model years of "current vehicles" usually changed between our individual studies since they were done at somewhat different times. The range was 2009–2013: changes in vehicle characteristics over this period are modest.

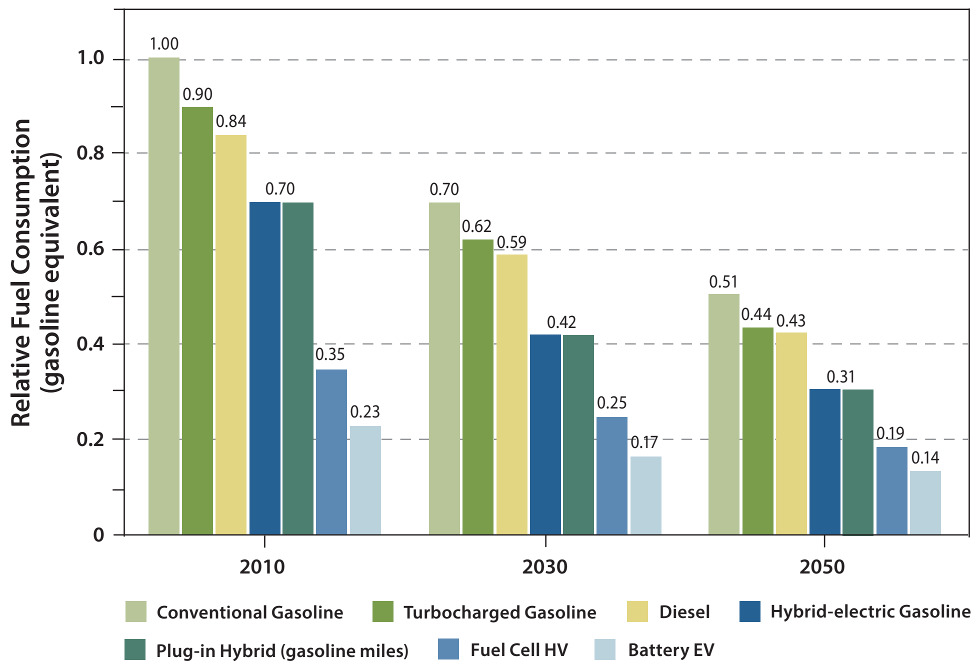

Figure 11.1 Average on-road fuel consumptions (tank to wheels) of the different propulsion systems in an average light-duty vehicle: 2010, 2030, and 2050. Includes vehicle weight reduction: at constant acceleration capability. Values normalized to standard naturally-aspirated gasoline engine vehicle.

One of our specific findings on the use of electricity in transportation is that, without additional technological breakthroughs, pure BEVs are likely to be limited to modest sales volumes. One major reason is the long recharging time for this technology, which better vehicle batteries will not significantly reduce. Drivers are accustomed to refueling gasoline vehicles for more than 400 miles of travel in about five minutes. Gasoline refueling occurs at a rate of chemical energy transfer through the pump outlet of about 10 MW. For the equivalent recharging rate (400 miles of range in five minutes) 2–3 MW of electrical power would be required.[40] This power requirement is more than an order of magnitude higher than even the fastest (Level 3) charging stations (~100 kW). Even if the associated battery cooling and durability challenges could be overcome, rapidly switching on 2–3 MW of charging power would place significant demands on the electricity distribution system: equivalent to the average power demand of more than 2,000 homes or 1 million square feet of commercial building space.

Therefore, BEVs, in our judgment, are unlikely to replace very many gasoline-fueled cars in the near- to mid-term, due to the combination of challenges from battery capacity, cost, driving range, and the practical constraints on recharging times. In contrast, PHEVs can get by with smaller, less expensive battery packs, and do not require rapid recharging. With the engine and

[40]The electric charging power is less than gasoline or diesel's chemical energy flow because the electrical energy required per mile of travel is about one-quarter of the gasoline (chemical) energy required per mile.

electric motor/battery pack combination of a PHEV, flexibility is built in and overnight recharging plus opportunistic recharging (at work, while shopping, etc.) should allow 60%–70% of miles traveled to be powered by electricity. PHEVs offer most of the benefits of BEVs without the large, expensive batteries or the need for fast recharging. Thus, evolving successful market-appealing PHEV technology appears to be the more promising path for increasing electricity's share of transportation energy consumption.

Table 11.1 Well-to-Wheels GHG Emissions Data: Average New U.S. Car in 2030

Vehicle Propulsion System/fuel	gCO_2e/km	CO_2/km Ratio
Gasoline NA-SI	213	1.00
Turbo SI Gasoline	191	0.90
Diesel	194	0.91
HEV	133	0.62
PHEV (10)–(30)[a]	103–77	0.48–0.36
FCEV[b]	150–74	0.70–0.35
BEV[c]	87–47	0.41–0.22
Natural gas NA-SI	169	0.79
Ethanol NA-SI[d]	167–80	0.78–0.40

[a]Dependent on the % miles electrical and electrical supply system
[b]FCEV—Lower number with Clean H_2 (with carbon capture and sequestration)
[c]Dependent on the CO_2 intensity of electricity
[d]Dependent on biomass GHG intensity

Substantial vehicle weight reduction now looks to be one of the important paths forward, as discussed in Chapter 4. It can be achieved in a number of ways: substitution of lighter weight (per unit strength) materials, such as aluminum for steel; vehicle and component design for lower weight and secondary weight savings; and reducing vehicle overall size. These weight reductions are additive, and are already in progress. An example is the 2015 Ford F-150 pickup truck (the best-selling vehicle in America at some 650,000 units/year) which is 700 lb (320 kg) lighter than the (2014) models it replaces which weighed (depending on the model) 4,800–6,200 lb (2,200–2,800 kg). In this example, vehicle weight was reduced by about 13% in a single redesign cycle.

Weight reduction has a high priority because its implementation is well understood and, with high-strength steel and aluminum, it can be readily implemented. But it is no panacea and incurs significant increases in vehicle cost. We anticipate that the *average* U.S. LDV has a total weight reduction potential of 30 plus percent (through material substitution, vehicle redesign, and downsizing) over the next 20–30 years (see Chapter 4). Given that a 10% reduction in weight in conventional vehicles results in a 6%–7% reduction in fuel consumption, this could correspond to a 20 plus percent fuel consumption benefit.[41] The potential for further weight reductions beyond these

[41]Note that production of aluminum is highly electricity intensive: thus to realize a corresponding GHG emission reduction though aluminum use requires both a low GHG emitting electricity supply system, and effective aluminum recycling.

levels is unclear, though the growing use of carbon-reinforced composite materials (lighter still than metals, but limited at present to high-end niche models) represents encouraging progress.

The trade-off between vehicle acceleration performance and fuel consumption should not be discounted. The evolving fuel consumption numbers in Figure 11.1 include steady improvements in powertrain efficiency, vehicle weight, and drag and tire resistance reduction, but assume constant vehicle acceleration performance. The seemingly inexorable escalation of vehicle acceleration capability over time (incrementally modest but cumulatively large) will likely reduce the fuel consumption benefits shown in the figure, and thus the GHG emissions reductions (see Chapter 5). Extrapolating the historical trend of decreasing 0–60 mph (0–97 km/hr) acceleration times, a steady increase in power/weight ratios and acceleration capabilities should be expected. From now to 2030, we anticipate a 10% decrease by 2030 in 0–60 mph acceleration times (from the current average of 8.1 sec to 7.2 sec) and to about 6.4 sec by 2050.[42] These represent 10% and 20% decreases relative to current practice. With a sensitivity of a 0.44% increase in fuel consumption per 1% decrease in acceleration time (see Chapter 5) these scale to about 5% and 9% worse average vehicle fuel consumption levels in 2030 and 2050, respectively. These fuel consumption losses are not negligible, and the historical record suggests that slowing or reversing this trend would be challenging.

Fuels and Energy Sources: Fuels are a major component of our energy and GHG challenge, and are proving to be an especially difficult area in which to make progress. In the alternative fuels arena it is not an exaggeration to say, “We really don’t yet know where we are going.” Accepting this reality has significant policy implications, pointing strongly toward a strategy focused on developing and maintaining an appropriately broad portfolio of options.

As Chapter 6 spells out, the problems with alternative fuels and energy include both fundamental technical challenges, and significant uncertainties in identifying the most promising alternatives. At the simpler end of the spectrum are improvements in fuels’ “cleanliness,” such as reductions in the concentrations of catalyst poisons such as sulfur. While the steadily improving technology paths are reasonably clear and well-defined, evaluating the overall benefits is challenging enough. More complicated are studies like ours focusing (in Chapter 9) on the impact of increasing the octane of the “standard” gasoline used in the United States from a research octane number (RON) of 91 (regular gasoline) to 98 (premium)[43]. Such a change could reduce in-use fleet fuel use by 3%–4.5% in 2040, and 5%–8% reduction in 2050, by enabling automobile manufacturers to increase gasoline engine compression ratios. However, a key assumption is that the refinery energy penalty associated with producing this new gasoline is minimized by relying on ethanol as the key to increased octane ratings [Chow and Heywood, 2014; Speth et al., 2014]. Most complicated and uncertain are alternative fuels such as electricity, hydrogen, and biofuels. The prospects for, and potential impacts of, these fuels are sensitive to consumer acceptance and to interactions with other economic sectors (agriculture, chemicals, electric power generation, etc.).

[42]Both of these are extrapolations of the average acceleration time data in Figure 3.4. Therefore, they should be viewed as indicative of the ongoing trend and not as “tight numbers.”

[43]The current sales volume ratio is 90% regular, 10% premium. This proposal would, over 25 years or so, reverse these numbers to 90% premium.

Expectations for the use of biofuels in transportation have cooled recently for several reasons:

1. Progress in the development of cost-effective technology to convert more sustainable biomass feedstocks into fuels that can be utilized within the existing fuel supply and distribution system has not met expectations.

2. Biomass is a distributed low-intensity (energy per unit land area) source of chemical energy limited to certain regions of the United States. Thus, its cultivation, processing into fuels, and distribution, especially at large scale, each pose major challenges.

3. When the GHG emissions that result from biomass cultivation and crop turnover (an emissions component that now appears to be substantial) are included in assessments, biofuels such as ethanol do not appear to be significantly better than petroleum-based fuels.

One positive opportunity is that current corn ethanol could be more effectively used to take advantage of its high-octane rating. This would expand its relative role and volume, moderately allowing it to become a useful component in our fuel system, even as it seems unlikely to become a major base source of transportation fuel.

The situation with fuel cells and hydrogen, a parallel non-petroleum-based path forward, is different. The propulsion system technology is moving forward faster than is our strategic vision of a hydrogen supply and distribution system. With a hybrid (and maybe, plug-in hybrid) architecture, this fuel-cell-based propulsion system is very energy efficient, but the production of hydrogen is not. So in energy conversion terms, the GHG emissions from this path are not much better than with our dominant petroleum-based approach (see Table 11.1). Nevertheless, hydrogen, like electricity, does at least address the challenge posed by hundreds of millions of dispersed GHG emissions sources. Subsequently, the key barriers to significant GHG emissions reductions are the need for low GHG-emitting hydrogen production approaches, convincing strategies for growing fuel cell vehicle sales volumes and growing hydrogen distribution and refueling infrastructure, so as to pull sales increases rather than holding back the expansion of this potentially promising vehicle propulsion technology. The major pieces of this hydrogen supply barrier are being aggressively studied: but so far, a *convincing* overall strategic plan and how its installation would be funded, has yet to be proposed. However, the fuel cell hybrid vehicle, fueled with hydrogen, is the new vehicle technology option most favored (and most invested in) by the major auto companies.

A recently revived alternative energy option for transportation is natural gas. Natural gas vehicles are used at modest volumes (up to 10%) in a few countries where the lower cost of natural gas (due, for instance, to proximity to supply and in some cases augmented by low fuel taxes) makes it economically attractive. However, on a worldwide scale, its use in LDVs is small. It is an “inconvenient” fuel: on-board storage as a high-pressure gas, compression before refueling, time required and complexity of refueling, leakage of methane (a potent GHG), reduced engine power, only modest CO_2 emission benefit (see Table 11.1), cost of gasoline vehicle conversion, NG refueling infrastructure. Thus, broad public use for private vehicles is unlikely. Natural gas is more likely to be used in local fleets where the economics are significantly more favorable. Such a step can be left to the market.

Potential for Conservation: Substantial opportunities exist to reduce petroleum consumption and emissions by modifying the decisions of travelers about where and how they travel, how they drive their vehicles and, with PHEVs, when and where they recharge them (see Chapter 8). Though we have not, to date, examined in detail the potential benefits of the many areas in which travel demand could be cut, our assessment of the literature on this topic suggests that, through 2050, VMT could be cut by up to 15% by appropriately pricing travel and shifting travelers to alternative transportation modes (see Cambridge Systematics, *Moving Cooler*, 2009). From one of our detailed studies on the demand side, we conclude that operating LDVs less aggressively could cut energy consumption per mile by 5%–10%. Also, in another study of user behavior with PHEVs, increasing the frequency of recharging could potentially double the amount of petroleum that is displaced by electricity, holding PHEV battery size constant. There appear to be several different demand reduction opportunities.

Fleet Scenario Analysis Studies: Many of our individual projects have used scenario analysis to explore our options for reducing the in-use petroleum and energy consumption, and GHG emissions, from LDVs. Our studies have used a *fleet model* of the in-use LDV fleet which follows the evolution of the various types of LDVs in actual use in a given country, through the vehicle sales mix and volume, and scrappage mix and volume, over time, out to 2050. The assumptions underlying each scenario are developed through the analysis of existing data, projections by ourselves and others, and judgment. Each study addresses specific well-defined questions, usually by comparing two or more different scenario versions developed for that purpose. These scenarios pull together information from all of the key areas summarized above (and discussed in detail in Chapters 3,4, 5, and 6): operating characteristics of the different propulsion systems in different vehicle types; vehicle weight reduction; the performance/fuel consumption trade-off; fuels and energy sources and their GHG emissions intensities; in-use vehicle fleet size and mileage driven; and sales mix by propulsion system and vehicle type. These scenarios have focused on the United States, Europe, Japan, and China. The key factors that influence the reductions in fuel, energy, and GHG emissions are growth in the in-use vehicle stock, annual mileage traveled, and changes in vehicle fuel consumption. In scenarios in which alternative vehicle sales become substantial, the sales fractions of these vehicles and the emissions-intensities of their fuels also become important.

The key findings from our scenario analyses include:

1. Stock growth is the most important worsening factor. In the different major world regions, China's growth rates are currently by far the highest, U.S. growth is moderate and, in Europe, growth in private vehicle passenger travel is small. Japan has slightly negative growth.

2. Improvements in mainstream engines and transmissions, and in vehicle technology through reducing weight, and aerodynamic drag and tire resistances, provide the largest fuel consumption and GHG emissions reductions for the next 20-plus years.

3. The alternative propulsion system vehicles (HEVs, PHEVs, BEVs, and FCHEVs) could by 2030 have increased to some 20% of the new vehicle sales mix (likely dominated by HEVs and PHEVs). However, with a 15-year average lifetime for vehicles in use in the vehicle stock, the fleet mix (which determines the fuel and GHG impacts) lags the sales mix by 5 to 10 years and would be about half that level. Since alternative technologies start from low sales volumes, they take much longer than mainstream technologies do to have significant impact.

4. As a consequence, the impact of alternative energy sources such as electricity and hydrogen, even going out 30 years or so, is modest, even if we assume that these alternative energy sources are attractive in the marketplace, and do become steadily "greener and cleaner" with ever-reducing GHG emissions intensity factors, as they must.

Policy options: In the policy arena, the work reported in Chapter 10 clearly indicates the economic efficiency advantage of market-based approaches such as cap and trade, introducing a broad carbon tax, and/or increasing fuel taxes. These approaches are more economically efficient, reducing the overall costs of achieving a given level of emissions reduction. It is less clear whether they will be politically feasible to the same extent as the Federal (and California) fuel economy and GHG standards that require auto manufacturers individually to meet sales-weighted mpg targets. Empirical evidence suggests that such regulations are easier to implement than are broader tax-based approaches. Nonetheless, work in this policy area indicates that "forcing the pace" through taxes or requirements is necessary to achieve rapid enough improvement in fuel consumption/fuel economy to offset the fleet growth factors, and force fleet fuel consumption and GHG emissions downward at a significant rate. A 2% per year reduction would decrease fleet GHG emissions in the United States from its current level to half that by 2050: 4% per year would bring emissions to one-quarter of today's level. The work summarized in this report suggests that the former objective (halving fuel consumption and GHG emissions by 2050) is plausible, though ambitious. The latter target (reducing these emissions to one-quarter) is definitely a very optimistic and challenging goal.

Summary: All these chapters support our overall description with *improving mainstream technology* as the path forward which has the greatest nearer-term impact on fuel use and GHG emissions. Even with these more immediate technology-improving opportunities, the time scales to major fleet penetration (e.g., 30%) into the in-use LDV fleet are long. For the alternative technologies, the time to impact is even longer. Table 11.2 lays out these time scales to impact through the essential steps involved. (Since each of these steps overlap, the *total time to impact* is less than the sum of the sequential steps.) Radical shifts in vehicle technology, in such a large system as the in-use vehicle fleet, will only gain major market share if the new technology vehicles are market competitive and successful, and production capacity is built up.

Table 11.2 Estimated time scales for alternative propulsion system technology

	Vehicle Technology				
Implementation Stage	Gasoline Direct Injection Turbocharged	High Speed Diesel with Particulate Trap, NO_x Catalyst	Gasoline Engine/Battery-Motor Hybrid	Gasoline Engine/Battery-Motor Plug-In Hybrid	Fuel Cell Hybrid with Onboard Hydrogen Storage
Market competitive vehicle	now	0–2 years	0–3 years	3–8 years	~ 10 years
Penetration across new vehicle production	~ 10 years (++)	~ 15 years (−)	~ 15 years (+)	~ 15 years (+)	~ 15–25 years (0)
Major fleet penetration	~ 10 years	10–15 years	10–15 years	~ 15 years	~ 20 years
Total time required	**15–20 years**	**25 years**	**25 years**	**~ 30 years**	**40–50 years**

(++) Very likely; (+) Likely; (0) Unclear; (−) Unlikely
[Source: Bandivadekar et al., On the Road in 2035 (2008)]

Our reference scenarios in the various major world regions incorporate changes in propulsion system and vehicle technology and energy sources, through the new vehicle sales mix. The assumed evolving U.S. new light-duty vehicle market in percent sales by powertrain out to 2050 is shown in Figure 11.2. Based on various inputs, it shows electrified vehicles (BEVs, PHEVs, FCEVs, and HEVs) growing from about 8% of sales in 2015 to 40% in 2050. Hybrids—HEVs and PHEVs—strongly lead this trend. Mainstream internal combustion engines improve, their sales mix diversifies, and they become significantly more efficient (see Figure 11.1). BEVs grow modestly. Fuel cells, with their need for hydrogen refueling infrastructure, either remain small or could grow more rapidly: i.e., their sales volume could remain small at the exploratory prototype stage, or be some twice the 6 or so percent shown if this technology proves attractive and the hydrogen supply and distribution systems develop rapidly. These are, of course, projections that are subject to the many uncertainties we have identified above.

In parallel with improvements in mainstream technologies, we should be inculcating lifestyle and behavioral changes that will conserve energy and reduce petroleum consumption in transportation. For example, less aggressive driving habits could reduce per-mile fuel consumption by 5%–10% in the near term, while shifting land use patterns and promoting alternative travel modes could cut local VMT by up to 15% by 2050. Introducing alternative powertrain technologies also creates new opportunities for conservation. Changing driving and charging patterns can lead to widely varying levels of petroleum savings even for the same PHEV design. While technology can facilitate some of these changes, they also require effective policies to stimulate conservation behaviors by millions of individual travelers.

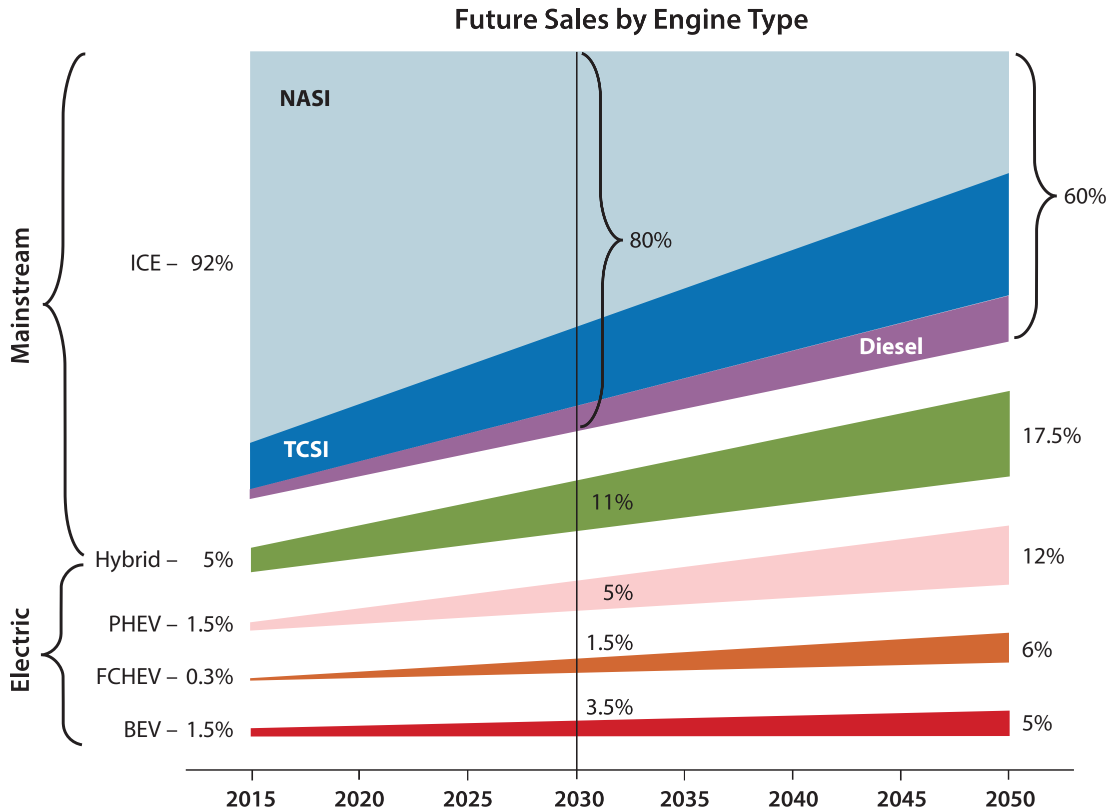

Figure 11.2 Evolving U.S. new LDV market: percent sales by powertrain type out to 2050. Other major regions likely to have similar evolution: diesel in Europe currently about 50% of the ICE sales, but that fraction is slowly decreasing.

Going beyond improvements in conventional technologies and conservation measures, a long-term transformation of the transportation energy system to one or more alternative fuels and energy sources is the ultimate piece of the puzzle of reducing petroleum consumption and GHG emissions. Today, it is possible to identify a number of potential alternative fuels, including electricity, hydrogen, biofuels, and natural gas. However, it is not yet clear that any one of these can fully assume the dominant position that petroleum has held as the preferred transportation energy source for the past century. More research, development, and demonstration studies are needed to lay the foundation for such a long-term transformation.

11.2 Recommendations

We end this report by making a set of recommendations. We do this to focus the extensive discussions and findings contained in each chapter of this report into five specific areas. Each one combines our major findings with our judgments as to "what needs to be done."

Six years ago, our group published *An Action Plan for Cars* (2009), which laid out a portfolio of policies that we concluded was needed to achieve significant reductions in U.S. petroleum consumption and GHG emissions from light-duty vehicles. That proposed plan is still relevant today. Only parts of our proposed set of "actions" have moved forward, and the Intergovernmental Panel on Climate Change's most recent report (IPCC, 2014) has stressed the urgency of taking actions that achieve real and substantial reductions in GHG emissions. Thus, that coordinated action plan for light-duty vehicles and the fuels they use is especially relevant now, and it is the basis for several of the recommendations we propose here.

1. **Since improving the fuel consumption of mainstream technology vehicles (ICEs, multi-gear efficient transmissions, reducing vehicle weight, etc.) is the primary nearer-term opportunity for reducing fuel use and GHG emissions, market-based incentives should be implemented to support the CAFE LDV requirements.**

The current CAFE requirements out to 2025 are already pulling improved and new technologies into mainstream and hybrid LDV powertrains, and initiating a substantial vehicle weight reduction effort. Since *improving mainstream technology* is the largest impact option for reducing LDV fuel consumption and GHG emissions over the next couple of decades, we should implement complementary market-based policies that would encourage the purchase and more effective use of vehicles with incrementally lower emissions. A "feebate" incentive system should be implemented to encourage consumers to place greater emphasis on fuel consumption in their vehicle purchase decisions, by providing rebates on the purchase of lower energy-consuming vehicles and assessing fees on higher-consuming vehicles. The fee or rebate amount, and the fuel economy level at which rebates change to fees, can be adjusted over time to keep the net overall cost impact small and continue to reduce fuel consumption. The range of fees/rebates could be up to some +/− $2,000.[44] We already have a rebate system in effect for alternative vehicles (tax deductions for purchases of electrified and fuel cell vehicles) of substantial magnitude. Applying feebates to all types of vehicles—mainstream and alternative—would achieve larger reductions and encourage alternative vehicle sales.

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[44]France, other European countries and Chile, have implemented such policies, and these have shifted the sales mix to achieve useful reductions in vehicle sales-mix fuel consumption.

A second strategy is to index the current fuel tax (at Federal and State levels) to the consumer price index and then raise that tax on gasoline, diesel, and maybe ethanol fuels. Today, the combined State and Federal fuel tax is about 50¢ per gallon, and while "raising taxes" is a challenging and unpopular objective, current discussions and actions show modest progress.[45] One primary objective of both indexing and also increasing the fuel tax is to generate the resources needed to maintain and improve our nation's road infrastructure, in the past largely done through the Highway Trust Fund which, due to shrinking fuel sales tax revenue (due to inflation and higher vehicle fuel economy) is almost out of funds. It would also offset the impact of steadily improving fuel economy, and reduce the likely rebound effect.

In our *An Action Plan for Cars*, we suggested that the fuel tax increase be in the range of 10¢/gallon per year, for 10 years. With current gasoline prices around $3 per gallon, 10¢ is a 3% nominal increase, and less after adjusting for inflation. The annual improvement in vehicle mpg is expected, over the next decade or so, to match that percentage, and thus the fuel cost per mile would be essentially unchanged. The overall objective here is to keep the cost of driving essentially constant assuming other factors than fuel remain unchanged, and to provide the resources needed to bring the state of our roads back to where they were (basic maintenance has been under-funded for decades), and then provide for needed improvements. Clearly delineating this underlying message will be essential to any substantial progress on this fuel tax/road infrastructure maintenance and improvement issue. While most recent attempts to raise taxes on transportation fuels have not been successful, incentives that prompt the purchase of more fuel efficient vehicles and encourage conservation in our use of these vehicles are a necessary part of a strategy to reduce GHG emissions on an urgent basis. Again, decreasing vehicle fuel consumption at the ongoing rate that we have estimated is technically feasible, and would significantly offset such fuel tax increases. Also, reductions in other taxes that would benefit the lower end of the income distribution could be implemented to make such increases in fuel tax less onerous to those likely to be impacted most.

[45]In Massachusetts, recent legislation has indexed the current state sales tax (24¢/gallon) to the Consumer Price Index (CPI), as have several other states. This would maintain the income that comes from the state fuel tax essentially constant (in constant dollars) rather than have it effectively decrease, year by year, if it remains at 24¢/gallon. However, Massachusetts' voters recently rescinded this regulation through a referendum.

2. **The CAFE standard targets for LDVs leading up to the 2025 model year need to be clarified in real-world terms. The normally quoted number of 54.5 miles per gallon is not what most new car buyers should expect to achieve in 2025. While knowledgeable professionals in this area understand this complexity, the broader public and most journalists do not. The responsible government agencies (U.S. Environmental Protection Agency, Department of Transportation, and the National Highway Transportation Safety Administration) need to address this misleading situation in order to maintain the public's confidence as 2025 approaches.**

The widely quoted fuel economy target of 54.5 mpg in 2025 is a much higher number than what consumers, on average, can expect to achieve in new vehicles in 2025. It is a target, based on specific test cycle numbers for new model vehicles that must first be adjusted for various credits that reduce its value to the upper 40s in test-cycle mpg. Real-world fuel economy is then estimated by reducing these numbers by approximately 20% to an on-road value of about 38 mpg. This is close to twice current new vehicle on-road fuel economy: a substantial achievement that would indicate real progress is being made. Nevertheless, the 54.5 mpg target makes the 2025 standards sound more challenging than they actually are. At the same time, repetition of this target may lead to disillusionment with the CAFE program when real-world performance fails to match the touted numbers.

There are additional complexities beyond those described above. BEVs, PHEVs, and FCEVs receive special treatment. CAFE is assessed on petroleum-based fuel consumption, tank-to-wheels, which for these technologies is assumed to be close to zero. However, for estimating progress on GHG emissions, the GHGs emitted in the production of alternative fuels (which nearer-term are going to be substantial) need to be included, as do petroleum-based fuel supply emissions (some 15 or so percent of the in-use emissions with gasoline and diesel fuels).

This problem of upstream emissions is complex and varies region to region. When these CAFE regulations were promulgated, the case for "keeping it simple" to avoid the need for a full life-cycle analysis (which was not then available) was the deciding factor. However, more realistic fuel and emissions accounting should now be developed and implemented to ensure that the incentives created by the standards are aligned with the expected benefits of each technology.

All these issues need to be spelled out carefully and clearly to the broader public. A review of the prospects for meeting the steadily stricter CAFE requirements over the next decade must be completed by 2017. That review, its report, and communications with the public about its findings provide an opportunity to clarify this complex situation.

3. **Vehicle electrification is a potentially promising alternative energy source and propulsion system technology to move us to lower fleet GHG emissions over time. We need to be more realistic about this opportunity and its impacts so we can better identify the barriers, and understand the more promising paths forward that would advance this option.**

From our studies of vehicle electrification, we have concluded that PHEVs offer the most viable path toward powering more vehicle miles with electricity. The market for pure BEVs is likely to be limited because their inherently limited driving range and long recharging times, and their high cost, make them less attractive to purchasers looking for an all-purpose vehicle. However, BEVs do appeal because their propulsion system is simpler than an ICE, and they do not dilute their "electric miles" with "gasoline miles," as does a PHEV. However, the flexibility and lower costs of PHEVs appear to trump this simplicity, certainly in the nearer term. Planning for electrification should be based on growth in the PHEV market over time in contrast to the more limited expected growth in the BEV market. Recharging requirements for PHEVs are not the same as for BEVs: especially, the demand for "fast recharging" stations is really not there.

The U.S. electricity supply system needs to evolve to become much less GHG intensive, if vehicle electrification is to have significant GHG reduction impact. Recently, natural gas has been steadily replacing coal as the primary energy source of electricity, and wind and solar generation have been growing (in the United States and elsewhere). These trends must continue if vehicle electrification can appropriately be described as a true "greening" of transportation's energy demand.

4. **The need to improve mainstream fuels, and to enable a transition to alternative fuels is both obvious and remarkably challenging. We should improve on conventional hydrocarbon fuels in the near term and accept that we do not yet have enough information to know where we are (or should be) going with alternative fuels in the long term. Also, we should continue to develop a portfolio that includes the more promising options, and refine our strategies as we learn more about the costs, benefits, and the viability of the pathways of different fuels.**

In the hundred-plus years since ICEs were first developed, petroleum-based fuels have been the dominant source of energy for vehicle propulsion. This persistent dominance is due primarily to the fact that they are liquids, have high energy densities, comparatively low prices, and are easy to produce, deliver and store. These properties set a high performance bar for any would-be alternative fuel to overcome. Moreover, the sheer scale at which we produce, distribute, and consume fuels around the world means that even incremental changes in fuel composition require coordination among several different stakeholders. By the same token, however, even small changes can have important aggregate benefits, due to the scale at which we use petroleum fuels. In the near term, we recommend that gasoline octane standards be increased, in the United States and elsewhere where the standards are relatively low, to enable the production of more efficient, higher-compression ICEs [Chow et al., 2014; Speth et al., 2014].

A fundamental problem of petroleum-based fuels is that they create hundreds of millions of mobile pollution sources. Transportation's GHG emissions problem cannot be fully mitigated without major reductions in fossil carbon emissions from vehicles, which necessarily means switching to an alternative energy carrier, be it electricity, hydrogen, or possibly non-fossil hydrocarbon fuels such as advanced biofuels. Such a transition is a necessary, but not sufficient, condition for deep reductions in GHG emissions from transportation. The alternative fuels must also be produced from low-carbon emitting energy sources.

We recommend continued research, demonstration, and data gathering with respect to a wide range of alternative fuels, including electricity, hydrogen, biofuels, and other promising options. Our primary conclusion regarding alternative fuels opportunities is that no single alternative is yet sufficiently compelling to justify a full-scale push at this time. Each potential alternative has its own set of strengths and weaknesses, as well as its supporters and detractors. The scale, and associated cost, of building out an infrastructure system for any one of these alternatives means that we cannot afford to get it wrong. We should seek a more sophisticated understanding of both the supply and demand sides of transportation fuels markets, which will allow us to understand the real potential of various alternative fuels and then develop effective strategies for expanding the supply and distribution systems for the most promising choices. In short, we need to become *wiser* in this fuels/energy source arena if we are to develop robust paths to lower GHG emitting fuel solutions.

5. **Any serious strategy to reduce fuel consumption and GHG emissions from LDVs should include components focused on conserving energy through changes in travel behavior, improving conventional technologies, and transforming the transportation system to increasingly use carbon-free energy sources.**

Through significantly *improving* the performance of mainstream LDV technology, and beginning the transformation with hybrids to increased vehicle electrification, our studies suggest that in-use fleet fuel consumption and GHG emissions in the United States could be reduced by 40%–50% below the current levels by 2050. Figure 11.3 illustrates the challenge. We will need to do the best we can with improving mainstream technology to achieve the lower edge of the blue "extrapolation scenarios" band. Realizing these improvements will require implementation of octane improvements in current fuels as we have outlined, as well as policy incentives for steady and sustained improvements in fuel economy beyond 2025, and would be a substantial positive achievement.

To go beyond this factor of two reduction—which we must do, we will need to encourage *conservation* and *transform* our transportation system to one that relies increasingly on low carbon sources of energy. Conservation through mode shifting and less aggressive driving can begin today, and it yields greater savings through changes in land use patterns and reduced travel demand in the longer term. While large-scale transformations are inherently slow in both transportation and energy, we must begin today to lay the groundwork for such a transition in the longer term. We will need to get significantly greater benefits out of hydrogen, electricity, and biofuels than our current scenarios anticipate, and these energy transformations will have to be "truly green," with low GHG emissions throughout the lifecycle.

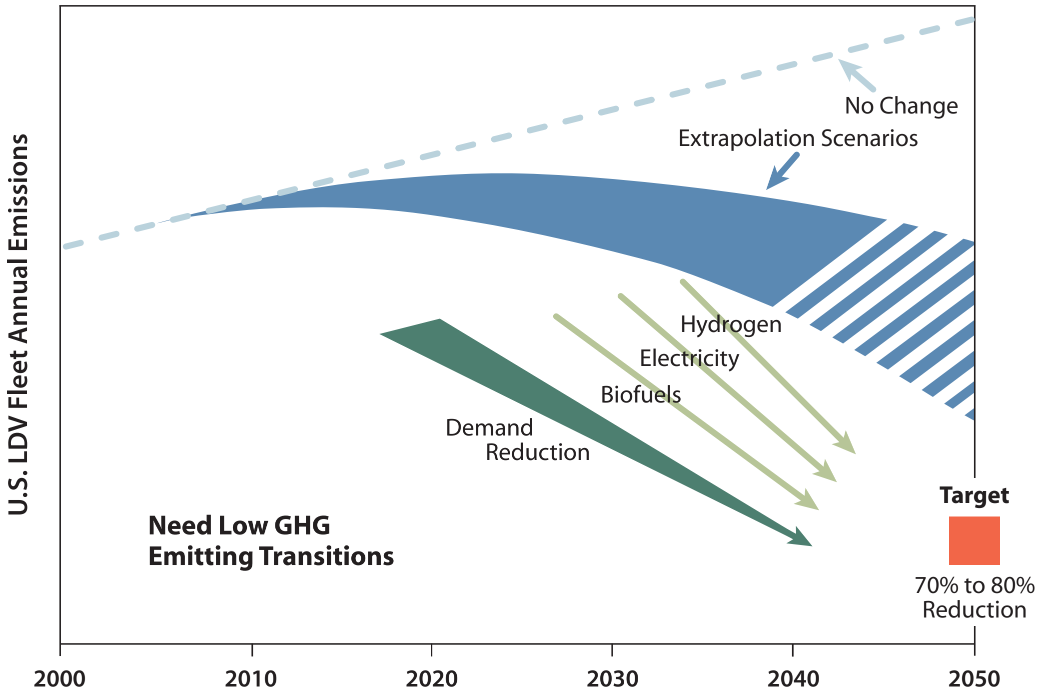

Figure 11.3 Strategic perspective on reducing greenhouse gas emissions from the U.S. LDV in-use fleet, 2010 to 2050.

Deep reductions in petroleum consumption and GHG emissions from personal transportation are within reach in the coming decades. We have already made meaningful progress toward reducing fuel consumption through improvements in mainstream technologies in recent years. In parallel with a continuing improvement trend, we must encourage energy conservation through more efficient behaviors and prepare to transform our transportation system to less carbon-intensive energy sources. This will take creative thinking, strategizing, determined implementation, and sustained focus. Are we up for this challenge?

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Acronyms

ABS	Acrylonitrile Butadiene Styrene
ACC	American Chemistry Council
AEO	Annual Energy Outlook
AFDC	Alternate Fuels Data Center
AFV	Alternative fuel vehicle
AKI	Anti-Knock Index
BEV	Battery electric vehicle
Bbl/d	Barrels per day
BOP	Balance of plant
BTL	Biomass to liquids
Btu	British Thermal Unit
CAFE	Corporate Average Fuel Economy
CBC	Canada's Online Information Source
CBTL	Coal-biomass to liquid
CCS	Carbon capture and sequestration
CD	Charging-depleting (mode)
CFRC	Carbon-fiber reinforced composite
CGC	Computable general equilibrium
CH_4	Methane
CI-ICE	Compression-ignition Internal Combustion Engine
CNG	Compressed natural gas
CO_2	Carbon Dioxide
CPI	Consumer Price Index
CTL	Coal to liquids
DCT	Duel clutch transmission
DI	Direct injection
DOT	Department of Transportation
E10	10% ethanol, 90% gasoline
E15	15% ethanol, 85% gasoline
E85	85% ethanol, 15% gasoline

ECE	Economic Commission for Europe
EERE	Energy efficiency and renewable energy
EIA	Energy Information Administration
EISA	Energy Independence and Security Act (2007)
EPA	Environmental Protection Agency
EREV	Extended range electric vehicle
ERFC	Emphasis on Reducing Fuel Consumption
EPPA5	Emissions Prediction and Policy Analysis Model version 5 (MIT model)
EU	European Union
EUDC	Extra urban driving cycle
EV	Electric vehicle
FC	Fuel consumption
FCEV	Fuel cell electric vehicle
FES	Fuel Economy Standards
FFV	Flexible-fuel vehicle
FHWA	Federal Highway Administration
FT	Fischer Tropsch
FTP	Federal Test Procedure
gCO_2e/km	Grams of carbon dioxide per kilometer
GDP	Gross Domestic Product
Gge	Gasoline gas equivalents
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation, Argonne National Laboratory's Model
GTAP	Global Trade Analysis Project
GTL	Gas to liquid
HDV	Heavy-duty vehicles
HEV	Hybrid electric vehicle
HOV	High-occupancy Vehicle
HSS	High-strength Steel
HWFET	Highway Fuel Economy Test
ICCT	International Council on Clean Transportation

ICE	Internal combustion engine
ISTEA	Intermodel Surface Transportation Efficiency Act
KWh	kilowatt hours
L	Liter
LD	Light duty
LDV	Light-duty vehicle
LES	Linear Expenditure System
LHV	Lower heating value
Li-ion	Lithium-ion
LLC	Limited liability company
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
Mbd	Million barrels per day
MJ	Megajoule
MLIT	Ministry of Land, Infrastructure, Transport, and Tourism
MOE	Ministry of Environment (Japanese)
MON	Motor octane number
MPa	Megapascal
MPG	Miles per gallon
MTBE	Methyl tertiary butyl ether
Mtoe	Million tonnes oil equivalent
NA-SI	Naturally-aspirated spark ignition
NAS	National Academy of Science
NEDC	New European Driving Cycle
NG	Natural gas
NGV	Natural gas vehicle
NHTSA	National Highway Safety Transportation Administration
NO_x	Generic term for the mono-nitrogen oxides NO and NO_2
NPC	Natural Petroleum Council
NRC	Natural Research Council
NREL	National Renewable Energy Lab

NVH	Noise, vibration, and harshness
PDF	Petroleum displacement factor
PEM	Proton-exchange membrane
PHEV	Plug-in hybrid electric vehicle
PHEV-30	Plug-in hybrid electric vehicle with a 30-mile all-electric range
Ppm	Parts per million
R&D	Research and Development
psi	per square inch
QAED	Quality Alliance Eco-Drive
RFS	Renewable Fuel Standard
RNG	Renewable natural gas
RON	Research octane number
Scfm	standard cubic feet per minute
SI-ICE	Spark-ignited internal combustion engine
SOC	State of change
STEP	Stochastic Transport Emissions and Policy Model
SUV	Sport Utility Vehicle
TC	Turbo Charged
TC-SI	Turbo-Charged Spark Ignition
TTW	Tank to wheels
UF	Utility factor
VKT	Vehicle kilometers traveled
VVT	Variable valve timing
WTT	Well to tank
WTW	Well to wheels
XTL	Shorthand for CTL and GTL
ZEV	Zero Emissions Vehicle Standard

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