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

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\text{GHG emissions} = \frac{\text{Person miles}}{\text{Person miles}} \times \frac{\text{Vehicle miles}}{\text{Vehicle miles}} \times \frac{\text{Energy}}{\text{Energy}} \times \frac{\text{GHGs}}{\text{GHGs}}
\]

where the GHG emissions are commonly expressed as mass CO₂ 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 (gCO₂—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 CO₂/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 CO₂/km. The annual rates of decrease in these CO₂ requirements vary between about 2%/year (India) to close to 4% (U.S. and Europe). 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.

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38These 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.

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\(^{39}\)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.\textsuperscript{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

\textsuperscript{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

<table>
<thead>
<tr>
<th>Vehicle Propulsion System/fuel</th>
<th>gCO₂e/km</th>
<th>CO₂/km Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline NA-SI</td>
<td>213</td>
<td>1.00</td>
</tr>
<tr>
<td>Turbo SI Gasoline</td>
<td>191</td>
<td>0.90</td>
</tr>
<tr>
<td>Diesel</td>
<td>194</td>
<td>0.91</td>
</tr>
<tr>
<td>HEV</td>
<td>133</td>
<td>0.62</td>
</tr>
<tr>
<td>PHEV (10)–(30)</td>
<td>103–77</td>
<td>0.48–0.36</td>
</tr>
<tr>
<td>FCEVb</td>
<td>150–74</td>
<td>0.70–0.35</td>
</tr>
<tr>
<td>BEVc</td>
<td>87–47</td>
<td>0.41–0.22</td>
</tr>
<tr>
<td>Natural gas NA-SI</td>
<td>169</td>
<td>0.79</td>
</tr>
<tr>
<td>Ethanol NA-SId</td>
<td>167–80</td>
<td>0.78–0.40</td>
</tr>
</tbody>
</table>

aDependent on the % miles electrical and electrical supply system
bFCEV—Lower number with Clean H₂ (with carbon capture and sequestration)
cDependent on the CO₂ intensity of electricity
dDependent 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

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41Note 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. 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). 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.).

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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 CO₂ 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

<table>
<thead>
<tr>
<th>Implementation Stage</th>
<th>Vehicle Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gasoline Direct Injection Turbocharged</td>
</tr>
<tr>
<td>Market competitive vehicle</td>
<td>now</td>
</tr>
<tr>
<td>Penetration across new vehicle production</td>
<td>~ 10 years (++)</td>
</tr>
<tr>
<td>Major fleet penetration</td>
<td>~ 10 years</td>
</tr>
<tr>
<td>Total time required</td>
<td>15–20 years</td>
</tr>
</tbody>
</table>

(++) 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.

45In 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.
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?

**Figure 11.3** Strategic perspective on reducing greenhouse gas emissions from the U.S. LDV in-use fleet, 2010 to 2050.
References


