On the Road in 2035:

Reducing Transportation's Petroleum Consumption and GHG Emissions

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ES Executive Summary

ES.1 Introduction

In October 2000, MIT issued a report, “On the Road in 2020” [Weiss et al. 2000], that explored the potential of new propulsion system and vehicle technologies to improve fuel consumption and reduce greenhouse gas (GHG) emissions over the next 20 years. The report used a life-cycle analysis to include the energy consumed and GHG emissions produced in fuel and vehicle production, in addition to vehicle use consumption and emissions. It made explicit the well-to-tank, tank-to-wheels, and cradle-to-grave components of the overall vehicle impact.

This new report has been written because the world has moved on since 2000. Engine, transmission, and vehicle technologies have improved. The development of new technologies such as batteries and fuel cells has continued. Hybrids are now in production at modest volumes. Alternative fuels from oil sands in Canada and biomass are adding to our petroleum-based fuel supply at the few-percent level. Over the past few years, transportation fuel prices in the United States have increased sharply. Yet, until the recent increases in Corporate Average Fuel Economy (CAFE) standards, there has been little action in the United States to develop strategies and implement policies that would decrease the petroleum consumption and GHG emissions from the in-use, light-duty vehicle fleet.

Since our October 2000 report, we have continued to work on these topics. We re-examined the potential for fuel cell vehicles and hydrogen [Weiss et al. 2003]. We explained how a coordinated set of regulatory and fiscal policy measures is likely to be needed to ensure progress [Bandivadekar and Heywood 2006]. We estimated the likely time scales over which more efficient propulsion systems (both improved conventional systems as well as new technology systems) could be deployed. In particular, we focused on the impacts that more fuel-efficient vehicle technologies and alternative fuels could have on future total light-duty fleet petroleum consumption and GHG emissions. Our studies have examined these issues in the developed-world context, focusing primarily on the United States but including a similar analysis for major European countries. This report, “On the Road in 2035,” describes the results of our work over the past three or so years. We have extended our original timeframe of 2020 out to 2035, some 25 years from today.

ES.2 Study objectives and approach

The overall objective of our study has been to quantify the potential future petroleum, energy and environmental impacts of the new and improved technologies and fuels likely to be developed and deployed in light-duty vehicles. We have done this for the United States, and for several European countries where vehicle use patterns, the technologies deployed, and fuel prices are different. To quantify these impacts, we added estimates of production deployment schedules to vehicle-based technology assessments. We also estimated how much alternative fuel from non-conventional petroleum and from biomass would be supplied to consumers in the United States. And we have considered the marketing issue of whether vehicle buyers would continue their longtime preference for ever-increasing vehicle performance and size, or shift toward vehicles with lower rates of fuel consumption. Thus, our study involved the following steps:

1. Identifying the propulsion systems and vehicle technology areas that have significant potential for reducing fuel demand and GHG emissions over the next 25 years. Examples include improved gasoline engines, low-emission diesels, hybrids, improved transmissions, and weight and drag reduction.

2. Using engineering simulations to quantify the fuel consumption, performance, and GHG emissions of an average car and pickup truck in the United States over several standard driving cycles, assuming combinations of more promising technologies in current vehicles and in 2030 new vehicles. We also assessed the additional costs of these improved technologies.

3. Developing an in-use vehicle fleet model for light-duty vehicles in developed-world markets such as the United States and Europe, along with baseline assumptions for the key issues of growth in new vehicle sales, trends in average vehicle lifetime, and travel.

4. Developing and then examining scenarios with various combinations of propulsion system and vehicle technologies, the evolving production volumes of these technologies, and increasing amounts of alternative fuels. Different scenarios incorporated the trade-offs among on-the-road vehicle fuel consumption, vehicle performance, and vehicle size and weight.

5. Using these scenarios to identify options that would lead to a significant reduction of fleet fuel consumption and GHG emissions.

Our conclusions are summarized in the next two sections, ES.3 and ES.4.

ES.3 Conclusions from vehicle technology and fuels assessments

Here we summarize the results of our vehicle technology and fuels assessments:

1. Conventional naturally aspirated, spark-ignited internal combustion engine (SIE) technology offers a path for continuous improvements in vehicle efficiency for the next few decades. Realizing these improvements requires that technological advances be directed toward reducing vehicle fuel consumption rather than offsetting increases in performance or weight.

2. The efficiencies of spark-ignition and compression-ignition (diesel) technologies will become closer to one another in the future. In particular, the continued downsizing of gasoline engines that is enabled by higher power density will allow them to improve more rapidly than diesels. At the same time, diesel vehicles must contend with increasingly stringent emissions requirements, which currently carry a fuel consumption penalty. If knock limitations can be overcome, turbocharged gasoline engine vehicles have the potential to become almost equivalent in efficiency with low-emission diesel vehicles.

3. Over a time horizon of 20–30 years, the gasoline hybrid-electric vehicle (HEV) offers a promising path to cost-effective reduction in fuel use. Relative to conventional spark-ignition and diesel engines, gasoline hybrids are projected to offer increasing efficiency gains and a narrowing price premium. At the same time, other advanced technology vehicles, including hydrogen fuel cell or battery electric vehicles, will continue to suffer from high cost and other

limitations. Their limited market penetration means that their impact on fuel use and emissions is unlikely to be significant over the next few decades.

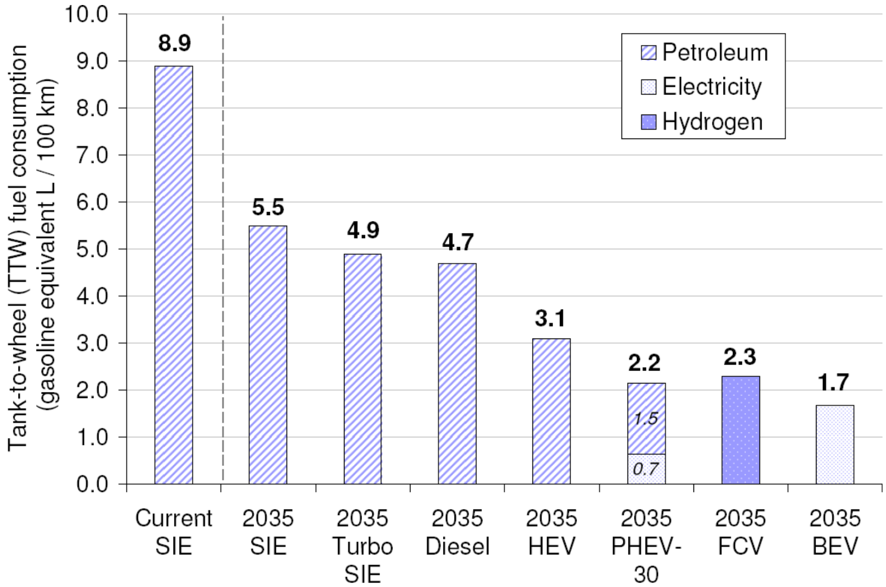
4. The plug-in hybrid electric vehicle (PHEV) offers important advantages over the two all-electric alternatives, fuel cell and battery-electric vehicles. It is no more range-limited than existing vehicles, and requires only modest changes to fueling infrastructure for battery recharging. The main technical challenges for plug-in hybrids are improving the energy storage capacity of lithium-ion batteries, demonstrating their reliability for automotive use, and reducing their cost. These are significant hurdles, but they are less daunting than the challenges facing fuel cell and battery electric vehicles.

5. Even with optimistic battery assumptions, the battery electric vehicle (BEV) is not competitive with other options on a mass-market level, particularly in comparison to the different plug-in hybrid configurations. Configuring a vehicle to offer a relatively modest 200-mile range would require a prohibitively large and expensive battery pack. And while the BEV completely displaces petroleum, the weight of the battery pack significantly increases the tank-to-wheel energy use compared to a plug-in hybrid operating in charge-depleting mode. With the current electric grid source mix, GHG emissions from electric power generation and grid recharging of batteries result in little or no reduction of well-to-wheels GHG emissions relative to improvements in more conventional technologies.

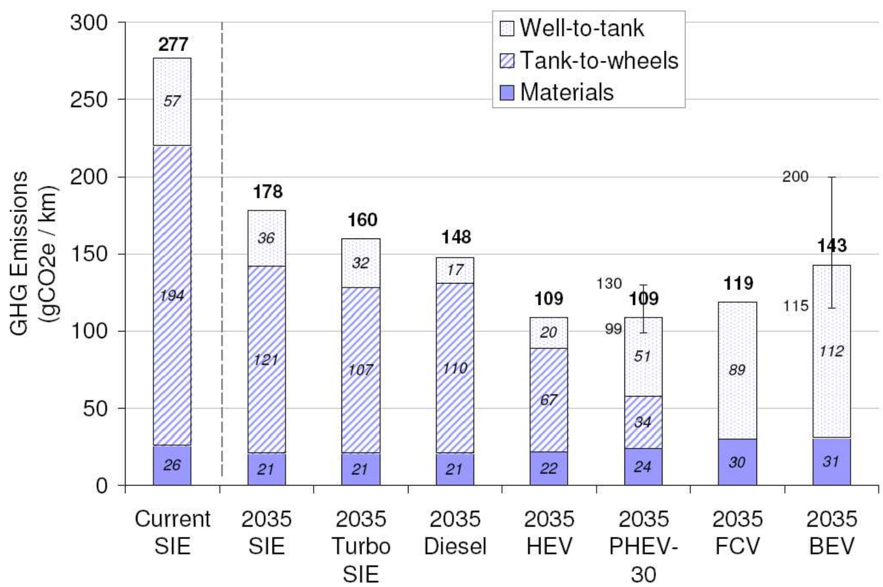
6. Our fuel cell vehicle (FCV) assessment is characterized by a high degree of technical and cost uncertainty with respect to both power plant and energy supply and storage. It is not yet clear that fuel cell vehicles will offer the real-world reliability and longevity that is commonly expected of general purpose vehicles, nor that the onboard hydrogen storage systems available will be satisfactory. However, automotive fuel cell systems are not a mature technology, and significant across-the-board improvements have been demonstrated over the past several years. If this pace of development continues, fuel cell vehicles could compete with gasoline hybrid or conventional technologies. The more daunting long-term challenge may arise from the need to develop marketable vehicles in parallel with deploying a new low-carbon hydrogen generation and distribution infrastructure.

7. Vehicle weight and size reduction could significantly reduce fuel consumption and greenhouse gas emissions. Direct weight reductions through the substitution of lighter materials as well as basic vehicle design changes (which, for example, maximize the interior volume for a given vehicle length and width) enable secondary weight reductions as other vehicle components are appropriately downsized. A shift in vehicle size distribution away from larger vehicles also reduces average weight and initially can be accomplished by changes in production volumes. Our estimates indicate that sales-weighted average vehicle weight could be reduced by 20% over about 25 years. The maximum potential vehicle weight reduction at plausible cost is 35%. These estimates allow for the additional weight of future safety requirements and convenience features. Vehicle weight reductions of this magnitude could alone result in some 12–20% reduction in vehicle fuel consumption.

8. Figure ES-1 illustrates the fuel consumption and GHG emissions levels from the various vehicle technology assessments described above, for the average mid-size car sold in the United States. The relative proportions for other vehicle types are similar.



(a) Tank-to-wheel gasoline-equivalent (GE) fuel consumption.



(b) Lifecycle greenhouse gas (GHG) emissions

Figure ES-1: Vehicle propulsion technology assessment for mid-size U.S. passenger cars. Well-to-tank energy consumption is not shown in (a) for the different fuel sources, but (b) shows the contribution of well-to-tank energy use in terms of GHG emissions.

All vehicles have same performance and interior size. 2035 vehicles have more efficient transmissions, 20% lower weight and reduced drag and tire resistances. Uncertainty bars denote well-to-tank GHG emissions for electricity generated from coal (upper bound) and natural gas (lower bound). FCV well-to-tank GHG emissions assume the hydrogen fuel is steam-reformed from natural gas at distributed locations and compressed to 10,000 psi.

SIE = Spark-ignition engine vehicle / HEV = Hybrid electric vehicle / PHEV-30 = Plug-in hybrid with 30-mile all-electric range / FCV = Hydrogen fuel cell vehicle / BEV = Battery electric vehicle / Materials = Material lifecycle emissions.

9. Cost is a key factor in assessing the likelihood of technologies becoming widely adopted. Vehicles with turbocharged gasoline engines, diesel engines, and hybrids entering the fleet today are estimated to cost from 5–30% more than a baseline gasoline vehicle. Longer-term options such as plug-in hybrids and fuel cell vehicles would cost 25–35% more than a future gasoline vehicle. Battery electric vehicles are even more costly. Reducing weight by 20% in a future vehicle would cost an additional 5%; reducing weight by 35% would cost an additional 10% of today's baseline gasoline vehicle cost.

Table ES-1: Incremental retail price increase of current and future propulsion technologies, $2007.

VEHICLE TYPE	RETAIL PRICE INCREASE [$2007]	
	Cars	Light Trucks
Current Gasoline SIE retail price*	*$19,600*	*$21,000*
Increment relative to current Gasoline SIE:		
Current Diesel	$1,700	$2,100
Current Turbo Gasoline	$700	$800
Current Hybrid	$4,900	$6,300
2035 Gasoline SIE	$2,000	$2,400
2035 Gasoline SIE retail price	*$21,600*	*$23,400*
Increment relative to 2035 Gasoline SIE:		
2035 Diesel	$1,700	$2,100
2035 Turbo Gasoline	$700	$800
2035 Hybrid	$2,500	$3,200
2035 Plug-in Hybrid	$5,900	$8,300
2035 Battery Electric	$14,400	$22,100
2035 Fuel Cell	$5,300	$7,400

* SIE = spark-ignition engine vehicle

10. Relative to current SIE vehicles, only turbocharged SIE cars and diesel trucks currently recover their up-front retail price increase in fuel savings, assuming a fuel price of $2.50 per gallon and 7% discount rate over a 15-year lifetime. All current powertrains recover their retail price increase at higher gasoline prices of $4.50 per gallon. In the future, improvements in conventional gasoline vehicles are very cost-effective, with a payback period of four years at $2.50 per gallon relative to a current SIE vehicle. Relative to a future SIE, hybrid vehicles pay off at $2.50 per gallon over 15 years, but plug-in hybrid and fuel cell vehicles do not break even until fuel prices exceed $3.75 per gallon, assuming an electricity price of $0.05 / kWh and hydrogen fuel price of $3.50 / kg. Future diesel cars

remain expensive relative to gasoline cars, but diesel trucks break even relative to future gasoline trucks at fuel prices of $2.75 per gallon. Due to their high up-front retail price, battery electric cars require fuel prices upwards of $6.00 per gallon in order to break even over 15 years of operation, assuming an electricity price of $0.05 / kWh.

11. Alternative liquid transportation fuels are widely viewed as an important and growing contribution to reducing petroleum use and GHG emissions. Currently, the Canadian oil-sands reserves are supplying about 3% of total U.S. fuel use. This could expand to about 10% of total U.S. consumption in 2030, resulting in a 5% increase in well-to-tank GHG emissions. Ethanol displaces gasoline, by two-thirds volume for volume. The GHG emission reductions provided by different feedstocks are substantially different, however, with corn grain ethanol proving only modest GHG benefits and cellulosic biomass-based ethanol potentially providing large GHG benefits, since it provides all its processing energy requirements. Recent concerns about environmental penalties associated with biomass production due to land use changes suggest that presumed biofuel benefits may not be realized to the extent currently projected. While ambitious targets for ethanol production and use have been set in the United States and the European Union, it is unclear whether targets for cellulosic ethanol (comparable volumes to corn ethanol by 2035) can be met, and what the GHG emissions benefits will be.

ES.4 Conclusions from scenarios of market penetration rates

By evaluating different market penetration rates of new propulsions systems and various scenarios of the light-duty vehicle (LDV) fleet fuel use, we find that:

1. Fleet fuel use responds with a lag of some 10 years to changes in the new vehicle market. Low rates of fleet turnover mean that the fuel consumption of mainstream technologies will determine the near-term fleet fuel use and GHG emissions. Directing efficiency improvements toward reducing in-use fuel consumption of high-sales-volume vehicle technologies is therefore critical. In Europe, the potential for impact through improved mainstream engines and weight reduction is significantly less than in the United States, due to the fact that about half of Europe's new fleet is already diesel, and vehicle size and weight are some two-thirds of average U.S. vehicle values.

2. As a result of high initial cost and strong competition from mainstream gasoline vehicles, market penetration rates of low-emission diesels and gasoline hybrids in the United States are likely to have only a modest, though growing potential for reducing U.S. fleet fuel use before 2025. Even with aggressive market penetration rates of new technologies, it will be difficult to reduce the 2035 fleet fuel use by more than 10% below fuel use in 2000.

3. The delay between the introduction of advanced vehicle technologies and their effects on total fuel use in the fleet is a necessary phase on the path to achieving long-term reductions. In the longer term (~50 years), the impact of advanced technology vehicles will indeed be far larger than the near term (~25 years) impact. To realize those deep reductions, advanced vehicle technology introduction needs to start as early as possible.

4. At similar levels of market penetration, gasoline hybrid vehicles look promising vis-à-vis diesels and turbocharged gasoline vehicles for reducing fleet fuel use. Thus it would require significantly greater penetration rates of turbocharged gasoline or diesel vehicles than gasoline hybrids to achieve similar fleet fuel consumption and GHG emissions.

5. Using half of all future efficiency improvements to reduce fuel consumption rather than emphasizing performance would alone reduce fuel use by 13% in 2035. Using *all* future efficiency improvements to lower fuel consumption would reduce fuel use by 26% in 2035. This is a slightly greater reduction in fleet fuel use than in a scenario with aggressive penetration of diesels and turbocharged gasoline vehicles that use half of future efficiency improvements to reduce fuel consumption. A scenario of aggressive penetration of hybrid and plug-in hybrid vehicles using all future efficiency improvements to reduce fuel consumption does better, and could lower total fuel use by 40% in 2035, relative to no change.

6. Developing scenarios that would halve the fuel consumption of the new vehicle sales mix in 2035 indicates that major changes would be required. To meet the target, two-thirds of the efficiency improvements must be used to reduce fuel consumption rather than emphasizing performance, alongside more than 20% vehicle weight reduction, and an 80% market share of advanced powertrains. Figures ES-2 and ES-3 summarize fuel use and GHG emissions from the light-duty vehicle fleet using representative scenarios based on our assessment of plausible vehicle technology penetration rates.

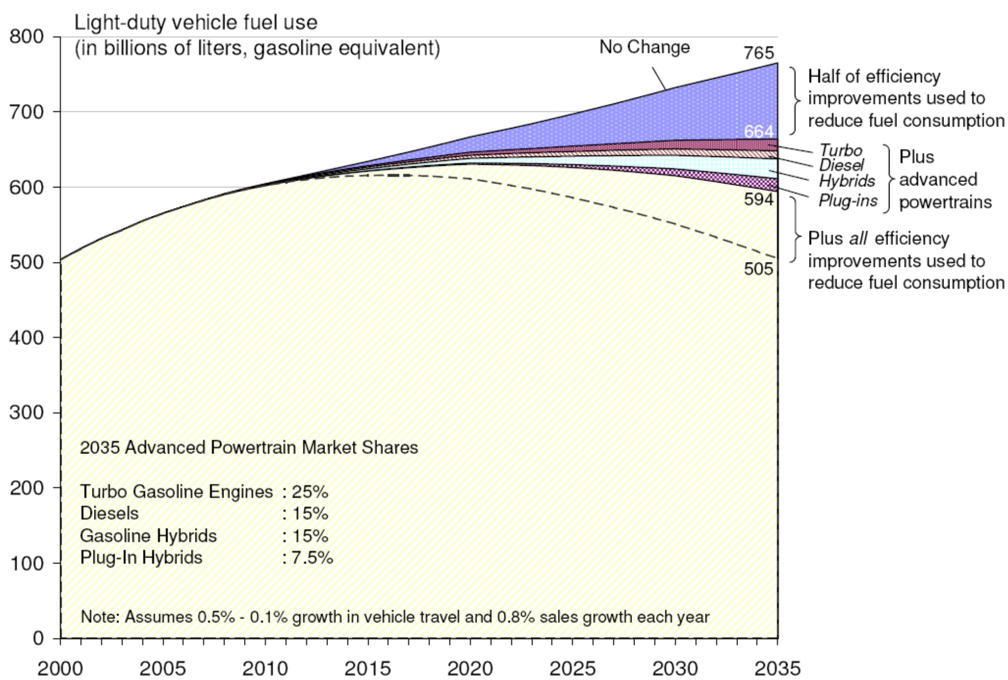


Figure ES-2: Representative scenario of light-duty vehicle fuel use with: (i) half of efficiency improvements used to reduce fuel consumption, then (ii) a two-thirds market share of advanced powertrains in 2035, and then (iii) *all* efficiency improvements used to reduce fuel consumption.

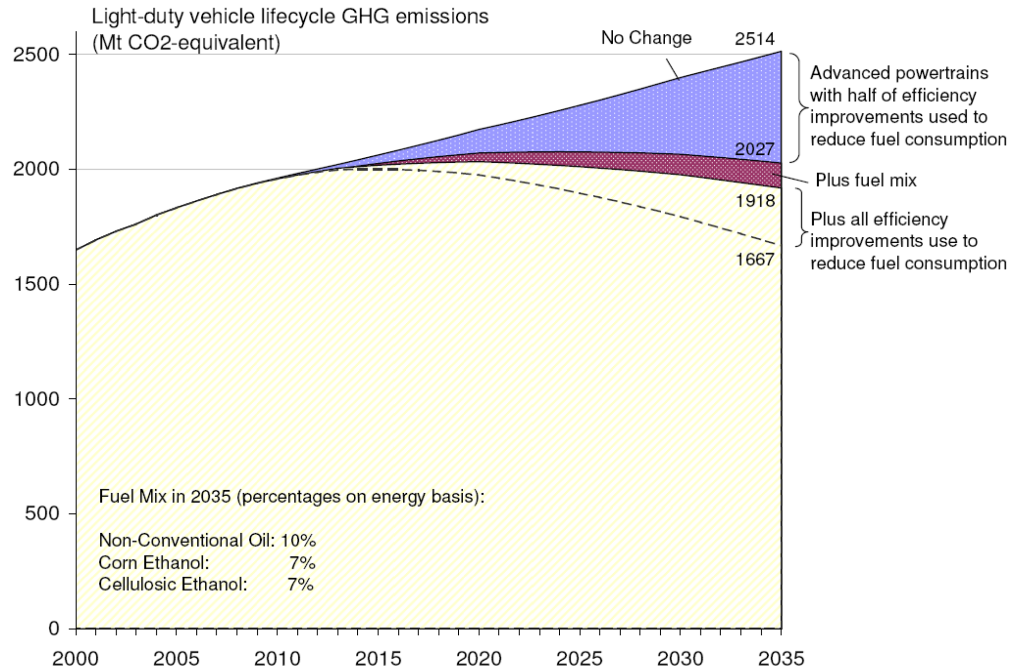


Figure ES-3: Same representative scenario of light-duty vehicle GHG emissions with a fuel mix of non-conventional oil, corn, and cellulosic ethanol.

7. Whether Europe continues further along its current dieselization trajectory or whether significant numbers of other advanced gasoline-fuelled propulsion system vehicles enter the fleet will have an important impact on the future ratio of diesel-to-gasoline fuel demand. For both of these scenarios, that ratio can be expected to continue to increase for at least the next 10 years. Given the fact that Europe's largest markets have historically emphasized improving fuel consumption over vehicle performance, the benefit from further increasing this emphasis is diminished when compared to the United States.

ES.5 Overall conclusions from the study

Petroleum use and greenhouse gas emissions are increasing steadily throughout the world due to seemingly inexorable growth in demand for passenger and freight transportation by all modes. Our challenge is to first offset this growth, and then to reduce fuel consumption and GHG emissions. This section summarizes our overall conclusions about how far future technologies might take us down this fuel-sipping, lower-carbon path.

1. At constant vehicle performance and size, a 30–50% reduction in the fuel consumption of new light-duty vehicles is feasible over the next 20–30 years. The greater uncertainty lies with the time necessary to achieve these changes, rather than the technological options available to realize them. In the near term, a combination of improved gasoline and diesel engines and transmissions, and gasoline hybrids, can achieve reductions on this trajectory. Vehicle weight and drag reductions can contribute in both the near and long term. Our longer-term options for moving beyond such improvements currently appear to be plug-in electric hybrids and electricity, and fuel cells and hydrogen. Compelling

visions of efficient low GHG-emitting ways for transportation to use these two energy carriers have yet to be developed.

These nearer-term changes, when combined in vehicles, result in cost increases between about $1,500 and $4,500 per vehicle if produced in significant volumes.

It will take longer (~20 years) for more complex or advanced technologies, such as hybrids, to result in significant overall reductions in fuel consumption and GHG emissions, due to their higher cost and slower deployment. Radically different technologies—such as plug-in hybrids and hydrogen and fuel cells—could take more than 30 years to be developed to the point where they are market feasible and deployed in substantial numbers. The additional costs of these advanced vehicles are uncertain but are anticipated to be significantly higher. The development and introduction of advanced technology vehicles needs to move forward as quickly as possible if we are to realize the long-term reductions in fuel use and GHG emissions that successful deployment would bring.

2. Policies developed to reduce vehicle fuel consumption will need to take into account the trade-offs among vehicle performance, size, weight, and fuel consumption. Vehicle purchasers and users have historically shown a clear preference for greater vehicle performance and size, providing market "pull" for these attributes. Automobile companies compete with each other by offering ever-increasing performance and vehicle size, providing the "push." In the United States, the emphasis on enhanced performance—and to a lesser extent, increases in vehicle size—have been so strong that no significant fuel consumption gains have been realized over the past 25 years. In Europe, the emphasis on performance has not been as strong, and some half of the fuel consumption improvements that could have been realized have already been achieved.

3. More alternatives currently exist for displacing the use of petroleum than for reducing greenhouse gas emissions.

    a. Plug-in hybrids, at present a costly and heavy option, might over the longer term have an important impact on reducing petroleum use. However, due to the likely GHG emissions from the electricity production required, the GHG emissions reduction that plug-ins would achieve in the nearer term are comparable to those available from change-sustaining gasoline hybrids at a lower cost.

    b. In the United States, ethanol might displace about 10% of gasoline by 2025. However, as explained above (ES.3-11), increasing the biomass-to-liquids supply in the nearer term might help reduce well-to-wheels GHG emissions, but increased use of non-conventional oil is likely to largely offset this effect. The contribution of biofuels is likely to be constrained by land availability, as well as by biomass yields, their environmental impacts, and costs.

It is therefore important that policy efforts focus simultaneous on measures that improve both energy security and carbon emissions.

ES.6 Looking ahead

We conclude that fuel consumption and GHG emissions of our light-duty vehicle fleet can be reduced significantly. How rapidly that reduction occurs depends on the determination of the major stakeholder groups—vehicle and fuel suppliers, vehicle and fuel purchasers and users, and governments—to vigorously undertake the actions required.

As worldwide demand for transportation services continues to grow, we foresee no single major development that alone can resolve the growing problems of vehicle fuel consumption and GHG emissions. Therefore, progress must come from a comprehensive effort to develop and market more efficient vehicles and more environmentally benign fuels, find more sustainable ways to satisfy demands for transportation services, and prompt all of us who use our vehicles and other transportation options to reduce our consumption. All of these changes will need to be implemented at very large scale to achieve significant reductions in petroleum, energy, and GHG emissions. Implementing these objectives will increase the cost of transportation to ultimate users, and will require government policies to encourage or require moving toward these goals while sharing the burdens more equitably and attempting to minimize total social costs.

The time scales for such changes vary, but all are long. Thus, a comprehensive program should include actions designed to achieve fuel and emissions reductions in the near term (up to 15 years), as well as in the mid-term (15–30 years), and also in the long term (more than 30 years). Mid- and long-term programs require preparatory work now (e.g., appropriately focused analysis, extensive technical research and development) to ensure they could be ready for implementation when planned.

An especially promising opportunity is the development and deployment of more efficient propulsion systems—engines and transmissions. Critical here is the need to use propulsion system efficiency gains to reduce real-world vehicle fuel consumption, rather than offset increasing vehicle power and size. This poses a serious problem of marketability to customers, given the long-term market trend toward increasingly powerful, larger, and heavier vehicles. Changing that trend may well require both manufacturer and government incentives.

A second important opportunity is vehicle weight reduction. This—along with reducing vehicle drag and tire rolling resistance—can be achieved as a result of vehicle redesign, vehicle size reduction, and the use of lighter materials. All of these methods will need to be implemented. While some aspects of vehicle functionality may be diminished, the basic mobility offered to consumers by personal transportation can be maintained.

Alternative fuels (fuels derived from raw materials other than petroleum) do reduce petroleum consumption, but they are more likely to increase than decrease GHG emissions, in the near term at least. The major near-term alternatives are derived from fossil raw materials (oil sands, very heavy oils, coal, natural gas). Their recovery and refining emissions range from high to roughly break even with petroleum, even using advanced technologies. In principle, biofuels can reduce GHG emissions drastically to the extent of potential biomass supply. Biofuel production is set by agricultural policy as well as energy and environmental policy, however, and the overall environmental and economic benefits of some biofuel approaches—notably corn-ethanol in the United States—are increasingly questioned, as are the benefits of other biofuels in

Europe. It is important that we encourage research and development on biofuels with promising environmental and economic prospects, and be realistic about their potential contribution.

We will need government policies that further the overall objectives of our road transportation system as well as reduce its energy and environmental impacts. Alongside regulatory instruments, we have reviewed the role that incentive-based policies such as feebates, taxes, pay-as-you-drive insurance, and scrappage incentives can play. These policies should be structured to achieve the following:

a. Push development and deployment of appropriate technologies—and generate market pull for those technologies—through policies that reinforce each other through synergies. Incentives should be for outcomes, and not be focused on particular technologies that put other vehicles with low fuel use and emissions at a competitive disadvantage. Such policies will need to be coordinated for the desired progress to occur.

b. Be transparent and appear fair to all stakeholders, especially those bearing the highest costs of the necessary transitions. Transportation-related taxes, fees, and credits can help balance the burden by clearly re-distributing revenue equitably among stakeholders and user groups.

c. Encourage conservation by users as they choose more efficient ways of using their transportation options, by, say, less aggressive driving, bundling of trips, and more carpooling.

Overall, this report reviews the many options available for reducing petroleum consumption and greenhouse gas emissions from private motor vehicles in countries like the United States. By exercising these options, current growth patterns can be leveled off and reversed. However, not much will happen without appropriate policies to push and pull improved technologies and greener alternative fuels into the marketplace in high volume.

Transitioning from our current situation onto a path with declining fuel consumption and emissions, even in the developed world, will take several decades—much longer than we hope or realize. We must focus our efforts on those changes that offer the potential for substantial impact, in both the nearer term and longer term. We will need much better technology, more appropriate types of vehicles, greener fuel streams, and changes in our behavior that emphasize conservation. We will need nearer-term results that get us out of our currently worsening situation. We will need to transition to much more sustainable pathways in the longer term. And we will need to pursue all these opportunities with determination.