On the Road in 2035

Reducing Transportation's Petroleum Consumption and GHG Emissions

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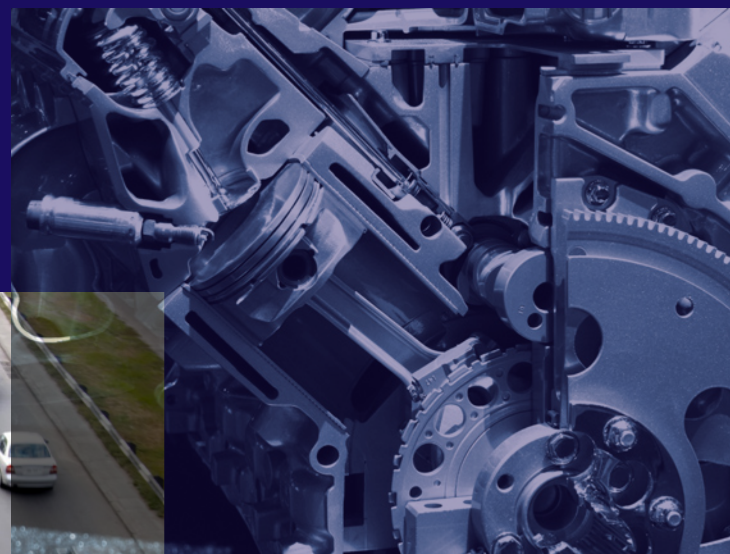

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Abstract

This report summarizes the results of a research program that assessed the technology of light-duty vehicles and fuels that could be developed and commercialized during the next 25 years. The research was done at the Massachusetts Institute of Technology from mid-2005 to mid-2008. Our objective was to assess and compare options for reducing fuel consumption, especially fuels from petroleum and greenhouse gas (GHG) emissions, during the production and use of both fuels and vehicles.

This is a successor to our 2000 report, “On the Road in 2020,” which addressed similar objectives. Since that report was written, the world has moved on with new vehicle and fuel technologies, and with inexorably increasing worldwide demand for all transportation services. That demand lends more urgency to curbing the growth of consumption of petroleum fuel and of GHG emissions.

Our research for the current report was confined to industrialized countries, with an emphasis on the United States but also including some western European countries. We first assessed the application of new vehicle and fuel technologies to the performance, cost, and life-cycle emissions of individual vehicles. We then considered the effects on the total on-the-road fleet of introducing those technologies using plausible assumptions about how rapidly they could be developed, manufactured, and sold to buyers to replace existing vehicles and fuels or to add to the total fleet.

We have concluded that a 30–50% reduction in fuel consumption is feasible over the next 30 years. In the short-term, this will come as a result of improved gasoline and diesel engines and transmissions, gasoline hybrids, and reductions in vehicle weight and drag. If these improvements are achieved, we estimate a $1,500–$4,500 increase in vehicle costs. Over the longer term, plug-in hybrids and later still, hydrogen fuel cells may enter the fleet in numbers sufficient to have significant an impact on fuel use and emissions.

Alternative fuels that replace petroleum fuels are unlikely to change GHG emissions significantly. The major near-term alternatives are based on fossil raw materials like the Canadian oil sands or coal, which increase GHG emissions. Some biofuels may prove beneficial, depending on the particular biomass feedstock and conversion technology. But the U.S. emphasis on corn-based ethanol is not obviously justifiable. It has high economic costs, questionable GHG advantages, and other unfavorable environmental impacts.

No single technology development or alternative fuel can solve the problems of growing transportation fuel use and GHG emissions. Progress must come from a comprehensive, coordinated effort to develop and market more efficient vehicles and benign fuels, and to find more sustainable ways to satisfy transportation demands.

Detailed discussions of our research conclusions and policy prescriptions can be found in the Executive Summary (pp. ES-2 to ES-11) and in Section 8 of the report (pp. 155-160).

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.

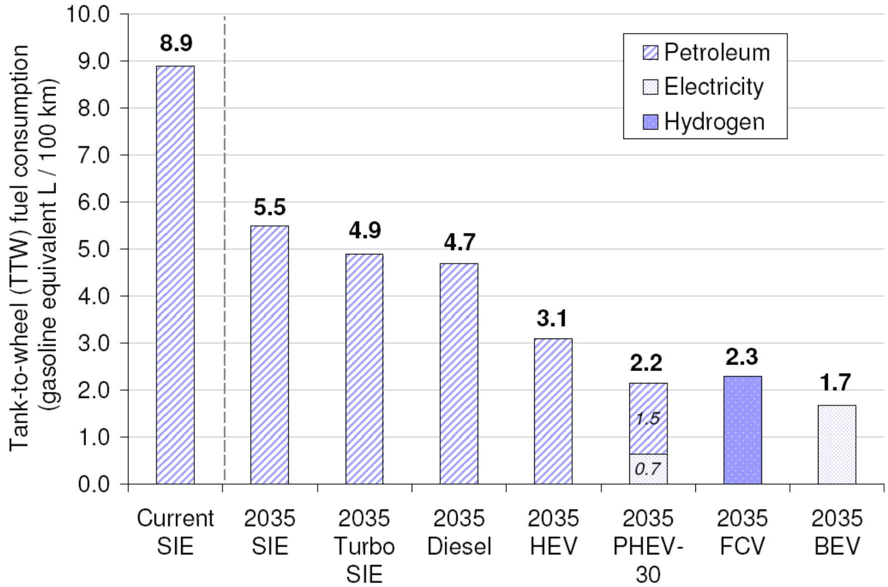
4. The plug-in hybrid electric vehicle (PHEV) offers important advantages over the two all-electric alternatives, fuel cell and battery-electric vehicles. It is no more range-limited than existing vehicles, and requires only modest changes to fueling infrastructure for battery recharging. The main technical 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.

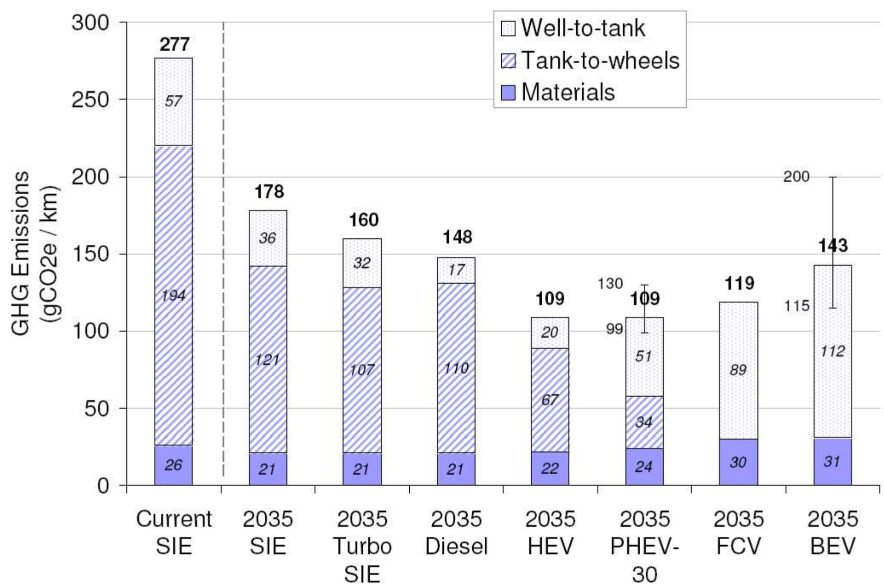
6. Our fuel cell vehicle (FCV) assessment is characterized by a high degree of technical and cost uncertainty with respect to both power plant and energy supply and storage. It is not yet clear that fuel cell vehicles will offer the real-world reliability and longevity that is commonly expected of general 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.

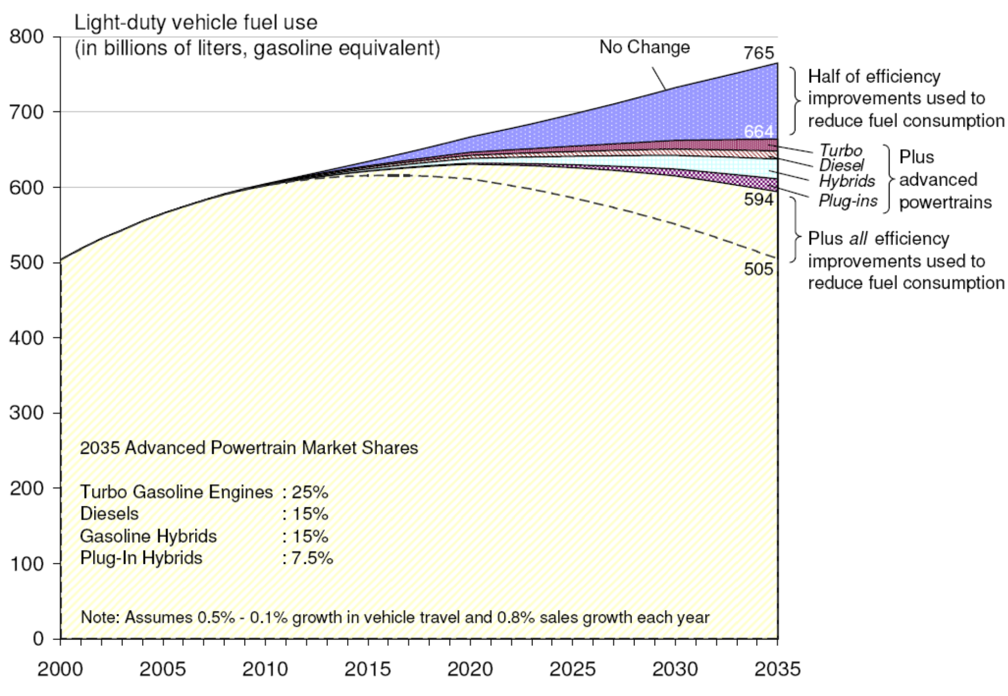


Figure ES-2: Representative scenario of light-duty vehicle fuel use with: (i) half of efficiency improvements used to reduce fuel consumption, then (ii) a two-thirds market share of advanced powertrains in 2035, and then (iii) *all* efficiency improvements used to reduce fuel consumption.

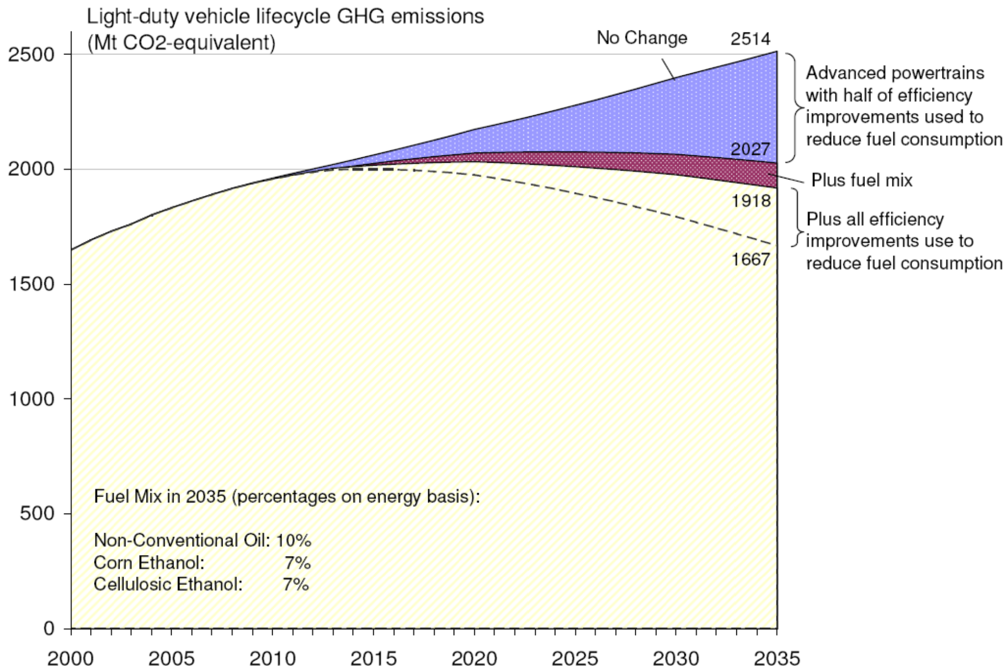


Figure ES-3: Same representative scenario of light-duty vehicle GHG emissions with a fuel mix of non-conventional oil, corn, and cellulosic ethanol.

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.

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1.0 Background, Objectives, and Context

1.1 Background

Personal transportation is highly dependent on the automobile. In the United States, there are approximately 240 million light-duty vehicles (LDVs). They comprise some 135 million cars and 105 million light trucks. The estimated fuel consumption[1] of LDVs in 2005 was approximately 530 billion liters or 140 billion gallons of gasoline. Gasoline use by U.S. cars (i.e., cars driven in the United States) and light trucks (pickups, SUVs, and vans) accounts for approximately 44% of U.S. oil consumption and some 10% of world oil consumption [Davis and Diegel 2007]. The U.S. Energy Information Administration (EIA) estimates that more than 60% of liquid fuels used in the country will be imported during the next 25 years. Moreover, an increasing fraction of this supply will come from the Middle East and from the Organization of Petroleum Exporting Countries (OPEC) [EIA 2007a]. Regardless of its countries of origin, pervasive use of oil means that the U.S. economy remains vulnerable to the price shocks in the oil market.

Increasing consumption of petroleum results in increasing emissions of greenhouse gases, which contribute to global climate change. The transportation sector is the largest contributor among the end-use sectors of the economy to the emissions of CO_2 in the United States. The emissions of CO_2 from transport have grown by approximately 25% during the period from 1990 to 2005. The tailpipe CO_2 emissions from LDVs in 2005 were estimated to be 1,260 million metric tons, or about 22% of total U.S. emissions of CO_2. LDV energy use had been projected to grow at a rate of 1.3% per annum, but recent fuel economy legislation and estimates of higher fuel prices have lowered expected growth to 0.3% per year [EIA 2007a; EIA 2008]. Even taking these factors into account, the unrelenting increase in the consumption of oil in U.S. light-duty vehicles presents an extremely challenging energy and environment problem. Effective measures will have to be taken to significantly reduce fuel consumption if risks to the economy and the environment are to be reduced.

In October 2000, our Massachusetts Institute of Technology (MIT) research group issued a report titled “On the Road in 2020” [Weiss, 2000]. That report explored the potential of new propulsion system and vehicle technologies for improving fuel consumption and reducing greenhouse gas (GHG) emissions over the next 20 years. The report expanded the life-cycle analysis methodology 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.

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

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[1] In this report, we refer to “fuel consumption” as the rate of consumption (in liters per 100 km or gallons per mile) of liquid fuels, expressed in gasoline-equivalent terms. Unless noted, this does not include energy supplied from electricity or hydrogen. Note that fuel consumption is the inverse of “fuel economy” (in miles per gallon), the more commonly used metric in the United States. “Fuel use” refers to total fuel used (in liters or gallons) by an individual vehicle or the larger vehicle fleet.

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 recently, there has been little action in the United States to develop strategies and policies that would decrease the petroleum consumption and GHG emissions from the in-use light-duty vehicle fleet.

Since our October 2000 report, our group has continued to work on this topic, as have many others. We have re-examined the potential for fuel cell vehicles and hydrogen [Heywood et al. 2003]. We have explained how a coordinated set of regulatory and fiscal policy measures is likely to be needed to ensure progress [Bandivadekar and Heywood, 2006]. We have estimated the likely time scales over which more efficient propulsion systems (both improved conventional systems as well as new technology systems) could be deployed. And in particular, we have focused our efforts on examining the impacts that the many more fuel-efficient technologies now being developed and deployed—and the changes in fuel supplies—might have on future total light-duty vehicle petroleum consumption and GHG emissions. We have examined these issues in the developed-world context, focusing primarily on the United States, but have also done similar analysis on major European countries. This report, "On the Road in 2035," describes the results of our work on these questions during the past three or so years. As our title indicates, we have extended our timeframe out to 2035, some 25 years from today.

1.2 Study objectives and road map

The overall objective of our study has been to develop a methodology that quantifies the potential future energy and environmental impacts of the technologies and new fuels likely to be developed and deployed in light-duty vehicles. This would be done for the United States, and several major European countries that have different vehicle use, technologies, and fuel price contexts. Quantifying impacts requires adding estimates of production deployment schedules to vehicle-based technology assessments. It also raises a critical market issue: how will the vehicle performance, size, fuel consumption reduction trade-off—which historically has favored vehicle performance over actual fuel consumption reduction—play out? It also requires an assessment of how alternative fuel streams from non-conventional petroleum sources and biomass are likely to augment petroleum-based fuels as the future unfolds. Thus, our study involved the following components:

1. Identifying the propulsion systems (improved gasoline engines, clean diesels, hybrids, improved transmissions) and vehicle technology areas (such as weight and drag reduction) that have significant potential for affecting the light-duty vehicles petroleum fuel demand and GHG emissions over the next 25 years.

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

3. Developing an in-use fleet model for light-duty vehicles relevant to the developed world, such as the United States and Europe, along with appropriate baseline assumptions for the key issues of growth in new vehicle sales, trends in average vehicles lifetime and vehicle miles (or km) traveled, and vehicle scrappage rates.

4. Developing and then examining scenarios that incorporate various combinations of propulsion system and vehicle technologies, the evolving production volumes of these technologies, and the anticipated growing alternative fuel streams that will augment petroleum fuels. These scenarios have incorporated and examined the trade-offs among on-the-road vehicle fuel consumption, vehicle performance, and vehicle size and weight.

5. Using these scenarios to identify those options that would have a significant impact on total fleet fuel consumption and GHG emissions, and thus identify those options likely to be most effective as we address these challenges.

6. Parallel studies of the factors that determine fuel and environmental impacts in the United States and in major European countries, which have different contexts.

These individual tasks are essential steps in estimating the potential for changing the impact of future light-duty vehicles. Only if vehicles with improved technology are out there being driven in large numbers will the impacts of those technologies on fuel consumption and GHG emissions be substantial. The performance, operating characteristics, and costs of the various propulsion system and vehicle technology options will determine their marketability, and thus the timeframe of their initial deployment. The subsequent ramp-up of production volumes will then depend on the market attractiveness of these improved-technology vehicles, the newness of the technology (and thus its potential for improvement), and the rate at which production capacity can be built up. It will then take several years, working at substantial production volumes, before a significant fraction of total vehicle travel will be with these better-technology vehicles. Of course, we do not know precisely how all these factors will play out. However, we can develop sets of plausible assumptions and build these into scenarios that we can compare—and thereby learn what it takes to make a difference.

The scale and timing of the impact of new and improved propulsion system, vehicle technologies, and fuels, on fleet fuel use and GHG emissions is contingent on the fuel consumption of individual vehicles embodying these technologies, their market penetration, and their utilization. An overview of our approach is shown in Figure 1, in which the contents of each report section are outlined. The remainder of *Section 1* provides the system context in which the U.S. LDV fleet operates.

Section 2 introduces propulsion system alternatives and describes their anticipated future performance characteristics, their fuel consumption and GHG emissions, and their costs.

Section 3 examines the opportunities for vehicle weight and size reduction, and the fuel consumption reductions and costs associated with these vehicle changes.

Section 4 evaluates the trade-offs among vehicle performance, size, and fuel consumption for different propulsion systems, and introduces the concept of Emphasis on Reducing Fuel Consumption (ERFC) for quantifying these trade-offs.

Section 5 explains the logic of the fleet model used to calculate life-cycle energy use, fuel consumption, and greenhouse gas emissions from light-duty vehicles. The fleet model is then expanded on in the next sections, where we fully explore the dynamics of the light-duty vehicle fleet.

Section 6 evaluates the impact of a changing fuel mix on the LDV fleet petroleum displacement and on GHG emissions. The section specifically evaluates the likely impact of increasing non-conventional oil and bio-ethanol content in the light-duty fuel mix, under different scenarios.

Section 7 details the supply- and demand-side constraints in building up production of advanced vehicle technologies, and their impact on fleet-wide fuel use. We develop three market penetration scenarios to illustrate the likely scale and impact of these technologies on LDV fleet fuel use over the next three decades. Additional scenarios are included which illustrate specific issues, such as the impact of delays, reducing 5% of light-duty fleet fuel use and GHG emissions by 2025, and doubling the fuel economy of new vehicles by 2035.

Section 8 summarizes the key conclusions of this report and outlines the agenda for the road ahead.

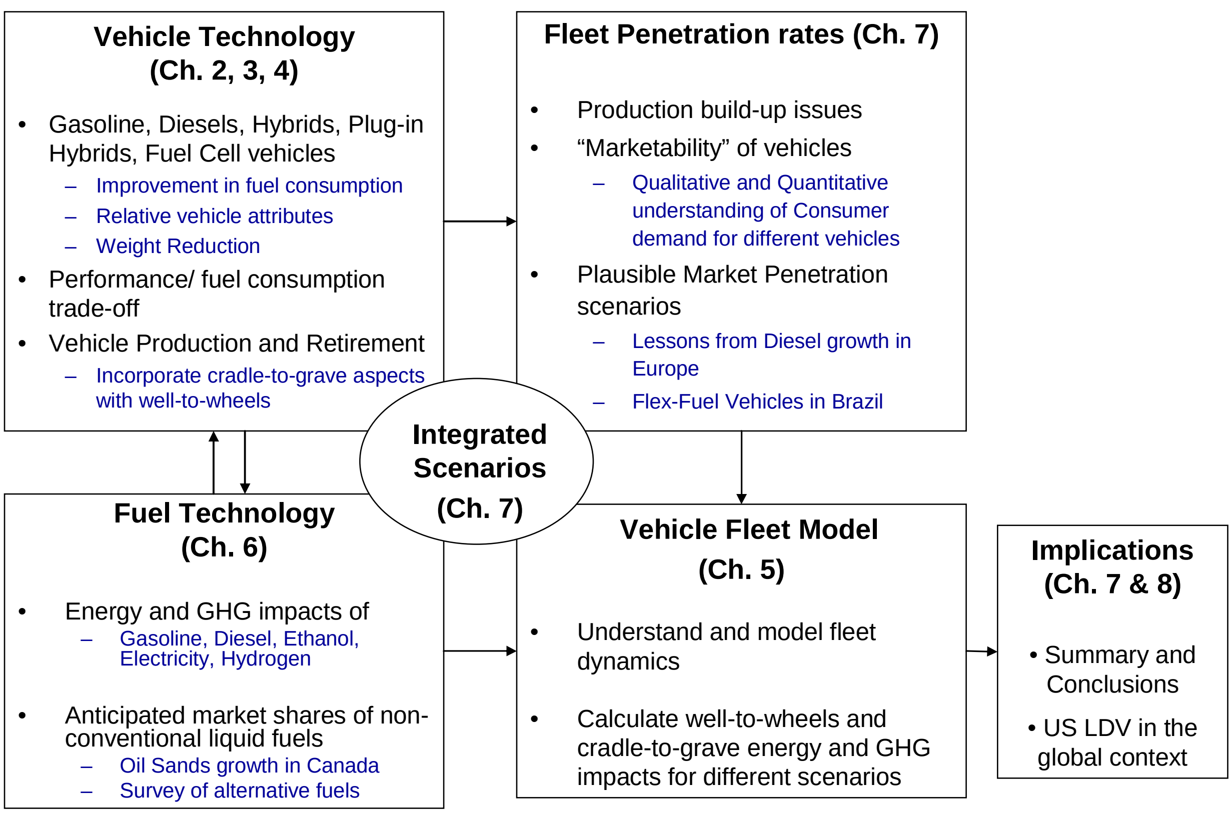

Figure 1 Report overview

1.3 The U.S. context

This section summarizes the context in which U.S. light-duty vehicle (LDV) technology and policy changes operate. Three topics are reviewed: 1) The factors that drive the growth in LDV fleet fuel use and greenhouse gas emissions, 2) the major stakeholders or actors involved in this arena, and 3) the policy alternatives available to affect the LDV fleet fuel use and greenhouse gas emissions. See Section 5.11 for a discussion of how these factors relate in a European context.

1.3.1 The factors

The fuel consumption from in-use motor vehicles depends on the efficiency of driving (LPK), and the total amount of driving (VKT). The greenhouse gas emissions resulting from that fuel consumption additionally depends on the GHG intensity of the fuel (FI) as shown by the following identity:

$$\text{GHG emissions} = \text{LPK X VKT X FI} \qquad (1.1)$$

Where,

GHG emissions = Greenhouse Gas Emissions (tons/year)
LPK = Liters per Kilometer (L/100km)[2]
VKT = Vehicle Kilometers Traveled (VKT in km/year)
FI = GHG Intensity of Fuel (GHG tons/liter of fuel)

All three factors, if reduced, contribute to reductions in GHG emissions; in addition, the three factors may interact with one another. For example, the carbon intensity of diesel fuel is slightly higher than gasoline, but diesel-powered vehicles are typically 30% more fuel efficient than gasoline vehicles. As a result, diesel-powered vehicles have a greater greenhouse gas reduction potential than gasoline-powered vehicles for the same amount of driving. As experience in Europe has shown, however, since diesel vehicles are more fuel efficient, they are likely to be driven farther than their gasoline counterparts. This “rebound effect” may reduce the GHG emissions benefit from diesel vehicles.

Vehicle fuel consumption

The average fuel consumption of new vehicles (as measured in liters of fuel consumed per kilometer traveled) was reduced considerably in 1970s and early 1980s due to federal fuel economy standards, as well as increased fuel prices in the aftermath of the oil shocks of 1973 and 1979. Since the mid-eighties, however, fuel consumption has stagnated at around 10 liters/100 km for new cars (23.5 mpg) and 13.5 liters/100 km for new light trucks (17.5 mpg) when adjusted for on-road performance [Davis and Diegel 2007]. The sales-weighted fuel consumption of new vehicles has been increasing during this period as a result of the increasing number of light trucks in the new-vehicle mix. As a result, the average fuel consumption for the light-duty vehicle fleet remained roughly constant, at 11.7 liters/100 km (20 mpg), as shown in Figure 2.

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[2] 1 liter/100 km = 235.2 miles per gallon (mpg)

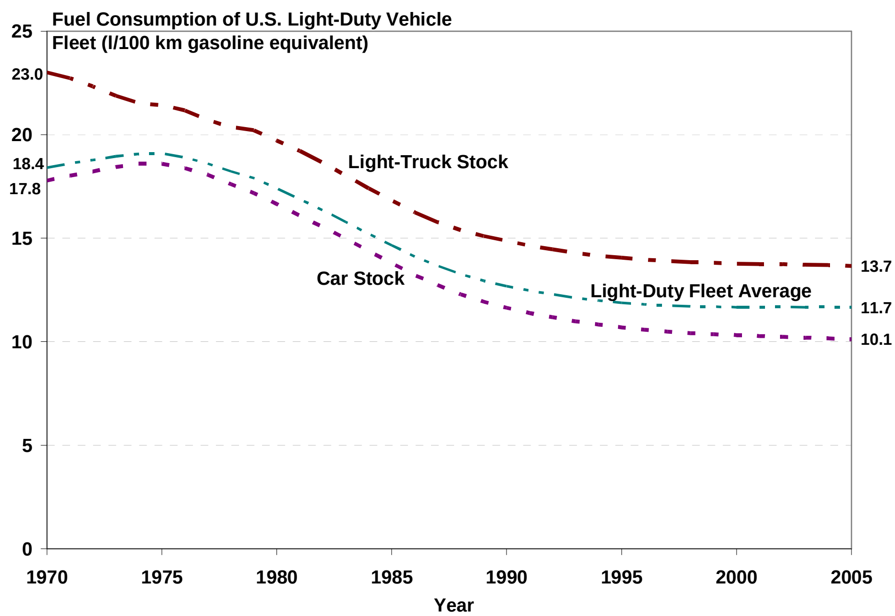


Figure 2 U.S. Light-duty vehicle fleet fuel consumption (1970–2005)

The lack of any significant reduction in vehicle fuel consumption during the last 25 years does not imply a lack of technology innovation. In fact, engine and vehicle technology improved steadily during this entire period. Technology improvements are "fungible," however, in that their efficiency gains can be used to enable other functions such as increased amenities, vehicle power, and weight, rather than directly improve fuel consumption [Plotkin 2000; An and DeCicco, 2007]. EPA analysis of vehicle characteristics during 1981–2003 indicate that if the new 2003 light-duty vehicle fleet had the same average performance and same distribution of weight as in 1981, it could have achieved about 33% higher fuel economy [Hellman and Heavenrich, 2003]. These trade-offs among performance, size, and fuel consumption are discussed further in Section 4.

Vehicle kilometers traveled

The total fleet vehicle kilometers traveled (VKT) in the United States has more than doubled in the past 30 years, as shown in Figure 3 [Davis and Diegel, 2007]. This growth has been steady except for the years 1974, 1979, 1980, and 1991. This large growth in VKT can be attributed to the following factors:

Increased number of vehicles. The number of vehicles in the U.S. LDV fleet increased from about 110 million vehicles in 1970 to over 235 million vehicles in 2005. Most of the growth has come in the light trucks segment, which now accounts for more than half of all sales, as compared to about 15% of sales in 1970.

Increased driving per vehicle. The average annual distance traveled per vehicle increased considerably from 1976–2005. This increased driving can be attributed to growing affluence, increasing urban sprawl and commuting distances, the low cost of driving, and changes in household demographics, such as age distribution. When adjusted for inflation, the cost of gasoline per liter or gallon has remained essentially constant for the past 35 years, except during the oil shocks of 1970s and since 2002, as shown in Figure 4.

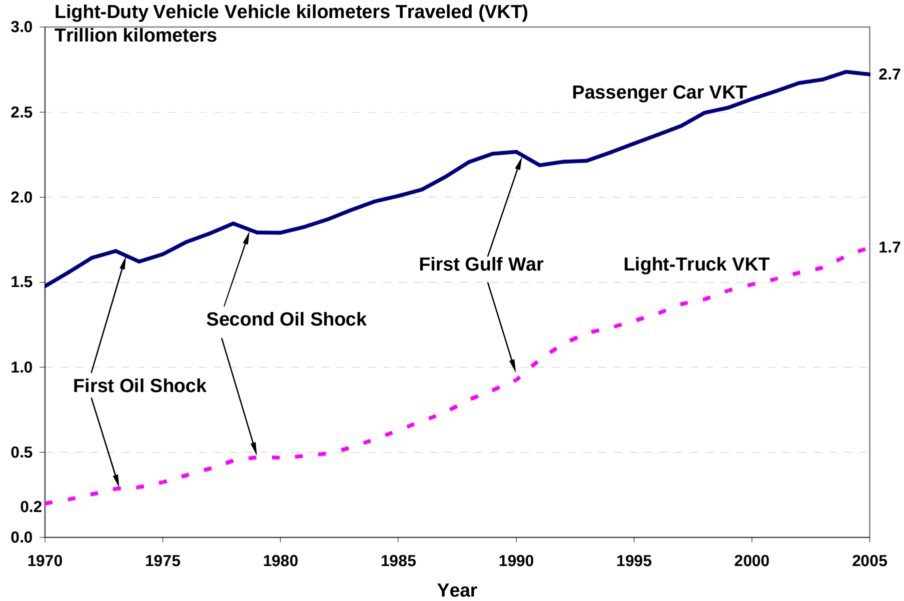
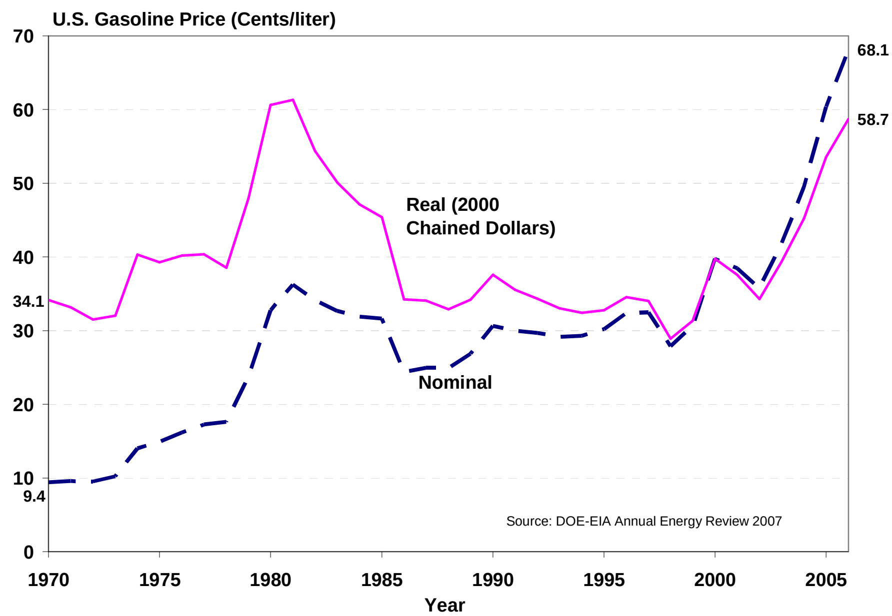
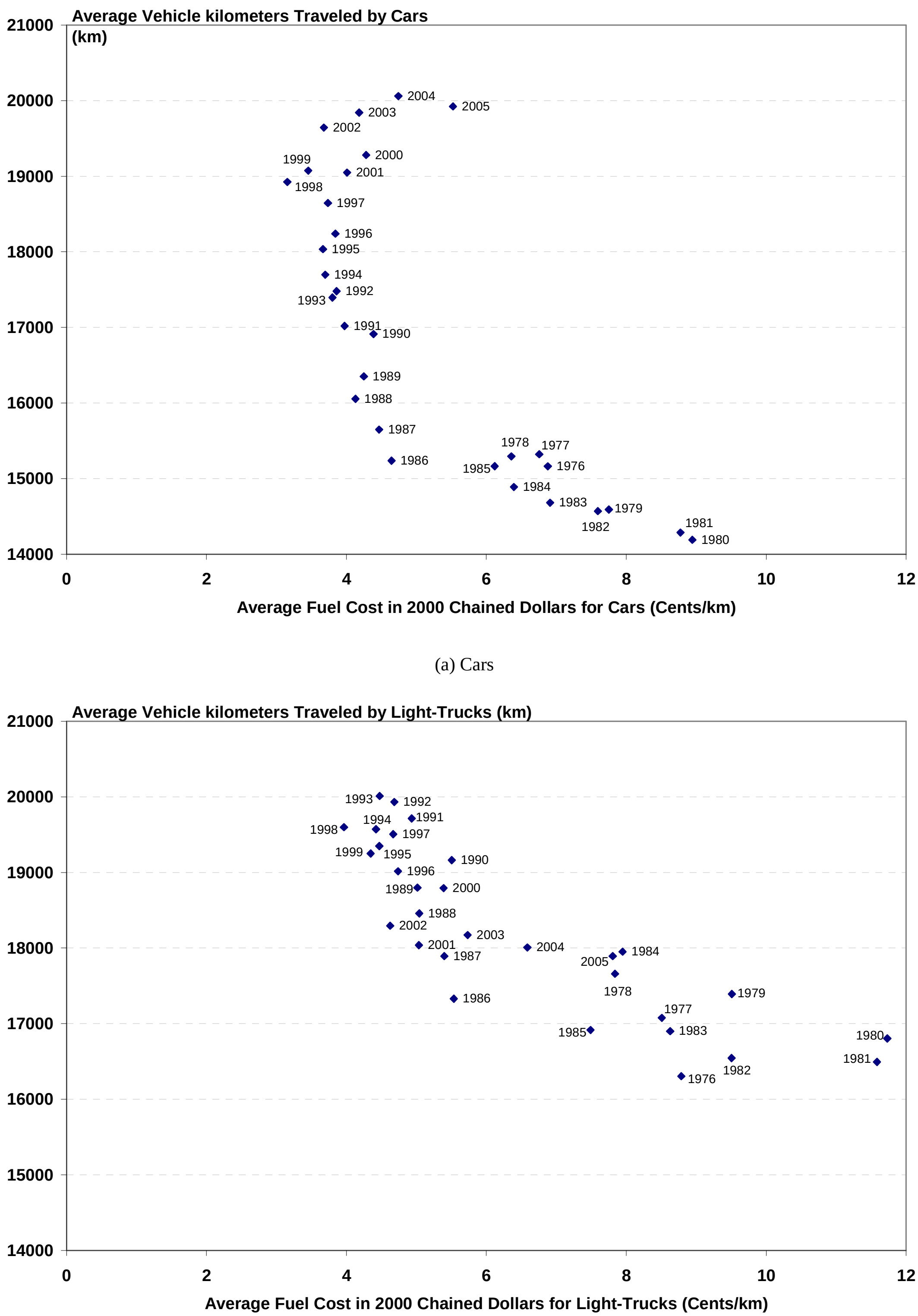


Figure 3 U.S. vehicle kilometers traveled, 1970–2005 [Davis and Diegel 2007]



Note: 3 dollars per gallon = 79 cents/liter; 2 dollars per gallon = 53 cents/liter

Figure 4 U.S. gasoline price in nominal and real terms, 1970–2006 [EIA 2007b]



(a) Cars

(b) Light-Trucks

Figure 5 U.S. average vehicle travel vs. average fuel cost per kilometer [EIA 2007b]

The average fuel consumption of cars and trucks decreased from 1976–2001. When combined with flat cost of gasoline over this period (inflation adjusted), the net effect is a drop in costs of travel per kilometer. The hypothesis that this has resulted in increased driving is known as the “takeback” or “rebound” effect. Figure 5 shows the increase in average annual distance traveled, while the average costs of driving every kilometer have declined for both cars and trucks. The rebound effect has been estimated to be on the order of 20%, based on historic data from 1970s and 1980s. More recent studies argue that the long-term rebound effect has declined to 10%, and may continue to fall as higher incomes and improved fuel consumption have insulated consumers from price changes [Greene et al. 1999; Greening et al. 2000; Small and van Dender 2007]. Figure 5 (a) also shows that while the cost of driving cars in real dollars has not changed much in the last 20 years, the average amount of travel per car has increased by approximately a one-third.

Greenhouse gas intensity of fuel

Greenhouse gas intensity of fuel used in the light-duty vehicle fleet in the United States has been essentially constant over time because most LDVs run on gasoline. The increasing amount of ethanol blended in gasoline is, however, altering the greenhouse gas intensity of the fuel. In Europe, diesel accounts for a third of fuel use in the light-duty vehicle fleet, since some half of these vehicles use diesel engines [CONCAWE 2007]. In the future, the use of diesel and/or electricity-powered vehicles, as well as different types of biofuels, is likely to increase. However, the greenhouse gas emissions intensity of the fuel may increase or decrease depending on the fuel/electricity production pathway. Sections 6 and 7 discuss the effect of a changing fuel mix on well-to-wheel energy and greenhouse gas emissions from light-duty vehicles.

1.4 Fiscal and regulatory policy options in the United States

In the past, regulation and oil prices have both played an important role in improving vehicle fuel consumption in the U.S. LDV fleet. The stagnation of reductions in vehicle fuel consumption and the relentless increase in vehicle travel since the early 1980s, however, suggest that policy changes will be required in the short- and longer-term future to achieve substantial reductions in fuel use and GHG emissions. Several of the options available to policy makers are reviewed in this section.

1.4.1 Fuel economy standards

Fuel economy standards are mandates placed on manufacturers that regulate the rate of vehicle fuel consumption. In the United States, vehicle fuel consumption is controlled by the Corporate Average Fuel Economy (CAFE) standard, which was first enacted as part of the Energy Policy and Conservation Act of 1975. These standards have established a binding limit on the fuel economy of cars and light trucks in the U.S. over the past three decades, as shown in Figure 6.

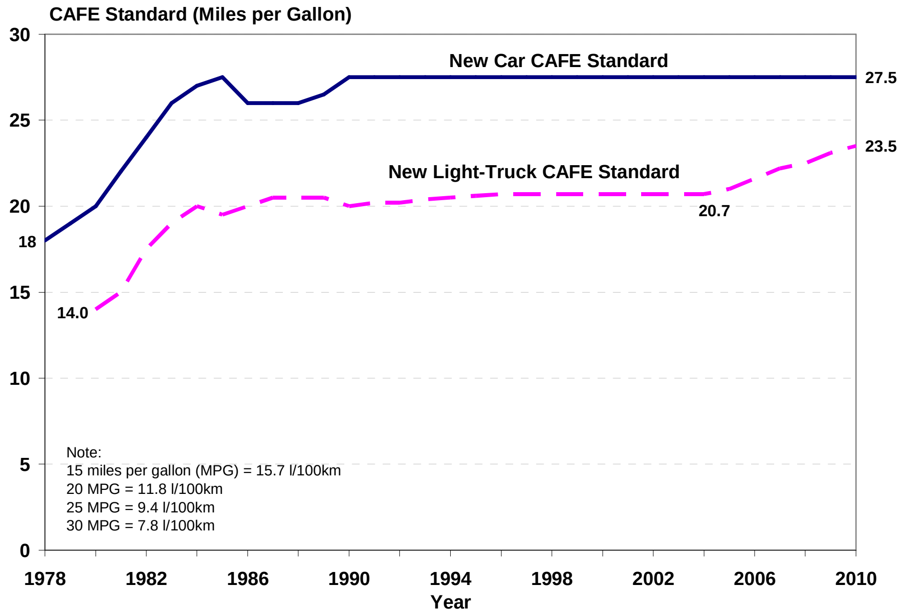


Figure 6 U.S. fuel economy standards for cars and light trucks [NHTSA 2006a; 2008]

Corporate Average Fuel Economy (CAFE) standards have been the dominant policy lever for reducing the fuel consumption of new vehicles in the United States. Since their enforcement, CAFE standards have played an important role in lowering the rate of fuel consumption during the period of high gasoline prices from 1975 to 1985, and in limiting a rebound in increased vehicle fuel consumption through the 1990s, when prices were low [Greene, 1990]. At the same time, they have been criticized for bluntly enforcing fuel economy standards while market forces have maintained a strong preference for larger, heavier, and more powerful vehicles at the expense of fuel savings. As a result, CAFE standards remained relatively constant for two decades, between 1987 and 2007, although light-truck standards increased slightly in the early 1990s. In 2003, the light-truck standards were increased substantially for model years 2005–2007. Proposed standards for 2008–2011 model year light trucks were handed back by the Ninth U.S. Circuit Court of Appeals for not going far enough in regulating fuel economy.

Recently, the Energy Security and Independence Act of 2007 (EISA) increased CAFE standards for both cars and light trucks to a combined average of 35 mpg by the 2020 model year. The new standards will be attribute-based, meaning that fuel economy requirements will be matched to related vehicle characteristics such as curb weight, interior volume, or "footprint"—the area covered by a vehicle's wheelbase multiplied by its track. Attribute-based standards were used in a previous National Highway Traffic Safety Administration (NHTSA) rule-making for light trucks, to address safety concerns by removing the option of downsizing as a way of meeting CAFE requirements, and to remove the incentive to categorize large cars as small light trucks (NHTSA, 2006a, p. 10).

The EISA 2007 legislation also introduced a credit-trading program as part of the CAFE regulations. Manufacturers that exceed the fuel economy standard for a given model year may earn credits that can be sold to those who fail to meet the requirements, provided that all manufacturers comply with a specified minimum standard for cars. Automakers may also transfer credits within their own fleets between cars that are made domestically, cars made non-domestically, and light trucks. For internal trading, credits may be used up to a limit that gradually becomes more lenient from 2011–2020.[3] It is believed that these measures will grant auto manufacturers more flexibility in determining how to achieve CAFE requirements within the mix of products that they offer to consumers.

1.4.2 Feebates

Feebates are financial incentives that use a sliding scale to adjust the retail price of cars and light trucks. Under a feebate system, a rebate is subtracted from the price of vehicles that consume fuel at a low rate, while a fee is added to the price of those that consume fuel at a high rate. In this way, consumers are free to choose larger, more powerful vehicles that consume fuel more rapidly, but they must pay an extra fee at the time of purchase. Others who select fuel-sipping vehicle models are subsidized through a rebate on the purchase price.

Applying fees and rebates in such a manner at the time of vehicle purchase induces a response from both consumers and from auto manufacturers. First, when fees and rebates are applied to the price of vehicles at the time of purchase, these price changes are visible to consumers, who shift their purchases towards vehicles with attributes that favor smaller fees or larger rebates (i.e., lower rates of fuel consumption or greenhouse gas emissions). Second, manufacturers can choose to apply technologies that reduce the rate of fuel consumption in order to lower the fee or increase the rebate assessed on a given vehicle.

The amount of the fee or rebate applied to a vehicle is determined by the *schedule* of the feebate. A linear schedule is the simplest type of feebate. Here, a flat rate is applied per unit of the attribute upon which the feebate is based (e.g., *x* dollars per liter/100 km, or *y* dollars per mpg, etc.). Feebate schedules may apply continuously across a full range of vehicle offerings, or they may be discretely applied across a limited range. Nonlinear feebate schedules have been suggested that increase the rate of fee or rebate across the range where most vehicles fall, increasing the impact of the policy without placing large feebates on the few vehicles with low or high rates of fuel consumption. Size-based schedules have also been suggested that would normalize feebates to some measure of vehicle size, such as interior volume [Davis et al. 1995].

An advantage of feebates is that they can be made revenue-neutral, such that the rebates disbursed to fuel-sippers balance the revenue collected from the fees minus administrative expenses. This is controlled by the *pivot point* or *zero point* of the feebate, or the point where the feebate is zero: vehicles that do better than this point receive a rebate, while vehicles that do worse than this point are levied a fee. Instead of a point, the pivot may be a band or range of values across which the feebate is set to zero. If revenue neutrality is desired, it is necessary to continually adjust the zero point downward as the fuel consumption of vehicles improves under a feebate system.

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[3] Credits may be used to achieve no more than one mile per gallon of fuel economy compliance between 2011 and 2013. This limit is relaxed to 1.5 miles per gallon between 2014 and 2017, and to 2 miles per gallon in 2018.

Another advantage of feebates is that they do not discriminate between vehicles that employ different technologies, but focus on improving fuel economy in a technology-neutral manner. One drawback is that they require oversight in how fees and rebates are calculated. Modeling studies of feebates have found that rates on the order of $200 to $500 for every liter per 100 kilometer reduction in fuel consumption are sufficient to incentivize lower consumption in new vehicles.

Surprisingly, these studies suggest that the largest share of the reduction in consumption comes not from consumers purchasing different vehicles, but rather from manufacturers who adjust their product mixes in order to take advantage of the feebate incentive against the retail price of their vehicles [Davis et al. 1995; Greene et al. 2005]. This may, to some extent, overlook the complex trade-offs manufacturers must make against vehicle attributes within a constrained budget [CAR, 2007]. Even with a feebate incentive, manufacturers may still prefer to direct technologies to improve the power and size of vehicles if the consumer willingness to pay for these attributes is higher than the feebate incentive for reducing fuel consumption.

1.4.3 Fuel and carbon taxes

Fuel taxes are taxes levied on the sale of gasoline, diesel, and other transportation fuels. They are typically applied as an excise tax, expressed in dollars per volume of fuel consumed. Governments levy fuel taxes for a number of reasons [Parry and Small 2005]. Primarily, they are seen as an efficient way of raising revenue, but can theoretically also correct for consumption-based externalities such as local air pollution and greenhouse gas emissions created in the consumption of gasoline and other fuels. By increasing the price of fuel, taxes also influence the price of travel, and can indirectly correct for externalities related to the amount of vehicle travel, such as congestion and traffic-related accidents that consumers might not otherwise take into account in their mobility decisions. Finally, taxes act as a user fee for the use of publicly provided roads and highways [Gordon 2005; Wachs 2003].

Carbon taxes are a charge on the environmental externality generated by the emission of greenhouse gases. In the transportation sector, greenhouse gas emissions are largely in the form of carbon dioxide released from the combustion of liquid fuels. Carbon taxes are used to incorporate the costs of climate change impacts into the price of activities that release greenhouse gas emissions, such as the combustion of transportation fuels. Typically, carbon taxes are expressed in terms of dollars per metric ton of carbon dioxide emissions, or simply in terms of dollars per metric ton of carbon. When applied to fuels, carbon taxes can be converted into a dollar-per-gallon amount that forms a portion of the fuel tax. Assuming one gallon of gasoline contains roughly 20 pounds of carbon dioxide, a carbon tax of $100 per metric ton of carbon (or $27 per ton of carbon dioxide) is equivalent to a fuel tax of 25 cents per gallon of gasoline.

Increases in the fuel tax induce two types of response: 1) a change in the amount of vehicle travel, and 2) a change in the rate of fuel consumption in vehicles. As fuel taxes increase, consumers respond by reducing vehicle travel. This can be done by adding or eliminating inefficient trips, carpooling, and switching modes of transportation (e.g., shifting from private to public transportation). Recent literature suggests that income growth and improved rates of fuel consumption in vehicles have insulated consumers from short-term increases in fuel price, reducing this effect to as much as one-fifth of what it was in the early 1980s [CBO 2008].

When fuel price increases are sustained over a longer period of time, consumers begin to change their purchase decisions in favor of vehicles with lower rates of fuel consumption. Manufacturers respond to this demand by implementing technologies and vehicle designs that emphasize lower fuel consumption over other attributes. As long as prices remain high for sustained amounts of time (on the order of 10–15 years), studies have estimated that the magnitude of this response may increase by three to five times over the longer term [Small and Dender 2007; CBO 2008]. There is uncertainty in these estimates, and the level of response is likely sensitivity to a number of factors, such as income and the rate of fuel consumption in existing vehicles [Hughes et al. 2007].

It is argued that fuel taxes are the most effective way to limit fuel use and greenhouse gas emissions from vehicles. Fuel taxes influence both the amount of vehicle travel and the rate of fuel consumption in vehicles, and they act upon existing on-road vehicles as well as new automobiles entering the fleet. Studies have also estimated that fuel taxes are more cost-effective than CAFE regulations for saving fuel [Austin and Dinan 2005].

The disadvantages of increasing the fuel tax are that low-income and rural groups may be affected disproportionately by higher fuel prices. Increases are also politically sensitive, because small changes in the fuel tax generate a large amount of revenue for the government. At the same time however, studies have suggested that the current fuel tax is not sufficient to fully reimburse government expenditures on vehicle infrastructure and services [Delucchi 2007], nor is it enough to account for the various externalities associated with private vehicle travel [Parry and Small 2005]. This suggests that there are social benefits to raising the fuel tax, particularly if a portion of the revenue is rebated to lower-income groups to offset the regressive impact.

1.4.4 Pay-As-You-Drive and Pay-At-The-Pump charges

Motorists who drive often are more likely to get into an accident than others who drive less. Currently, automobile insurance is paid in an annual lump-sum amount that has been likened to an "all-you-can-eat buffet" [Bordoff and Noel 2008]. Once the lump-sum amount is paid, people tend to over-consume—in this case by driving further than they would if the price of insurance took into account their amount of travel relative to other consumers.

Measures that would roll the lump-sum cost of insurance into a variable rate based on the distance traveled or the amount of fuel used by a vehicle, could correct this to a certain extent. Figure 7 shows the costs of owning and operating an automobile in 2006. The cost of vehicle insurance is roughly equal to the cost of fuel. Since depreciation is not a cash transaction, insurance premiums have the greatest potential to impact driving costs, followed by registration and license fees.

A Pay-As-You-Drive (PAYD) system would correct this to a certain extent by rolling the up-front costs of annual insurance payments into a price per unit of distance traveled.

Under such a system, individuals who drive below average would pay lower premiums, while those who travel more than average would pay more; the premium of the average driver would remain unchanged. By calculating premiums on a *pay*-as-you-drive basis, rather than an *all*-you-can-drive basis, the approach would provide all drivers with a continuous price incentive to reduce vehicle travel.

An alternative approach, Pay-At-The-Pump (PATP) charges transfer a portion of the fixed costs of owning and operating a vehicle to a variable cost based on fuel use. Instead of an annual or semi-annual collection of charges such as insurance premiums, registration fees, and emissions-test fees, a PATP scheme collects these charges at the gas pump. The intent of PATP charges is to discourage low-value travel and promote the purchase of more fuel-efficient vehicles without raising the total costs of driving for the average driver. PATP proposals have been motivated more by efforts to reform auto insurance legislation rather than to correct the pricing of auto insurance.

A major advantage of a PATP insurance scheme is that all motorists would have insurance. Uninsured drivers, however, often come from low-income households, and some households will pay much more at the pump than they will save by not paying annual registration or insurance fees. Trial lawyers are also opposed to "no-fault" PATP program because they claim these programs would limit the ability of an individual to sue for non-economic damages [Wenzel 1995]. Finally, insurance and registration fees are state-dependent, so it would be difficult to coordinate a national-level PATP scheme. This makes such schemes an unattractive policy option at the federal level.

At the same time, although regulatory and cost barriers still exist, improvements in GPS technology and pilot programs conducted by insurance companies appear to have renewed interest in PAYD schemes. Under PAYD, the regressive impacts on lower income households may be less since these groups drive less than higher-income categories [Bordoff and Noel 2008; Figure 3, p. 9]. PAYD could more flexibly account for other important insurance risk factors, such as age, driving history, location, and time of day [Parry 2005]. Studies have estimated that substantial social benefits (on the order of $150 to $225 per insured vehicle) are offered by linking insurance premiums to annual travel. Suggested premiums are on the order of 6 cents per mile, or $1.20 per gallon[4] [Bordoff and Noel 2008; Parry 2005; Edlin 2003].

[4] Assuming the current average light-duty vehicle fleet fuel economy of 20 miles per gallon.

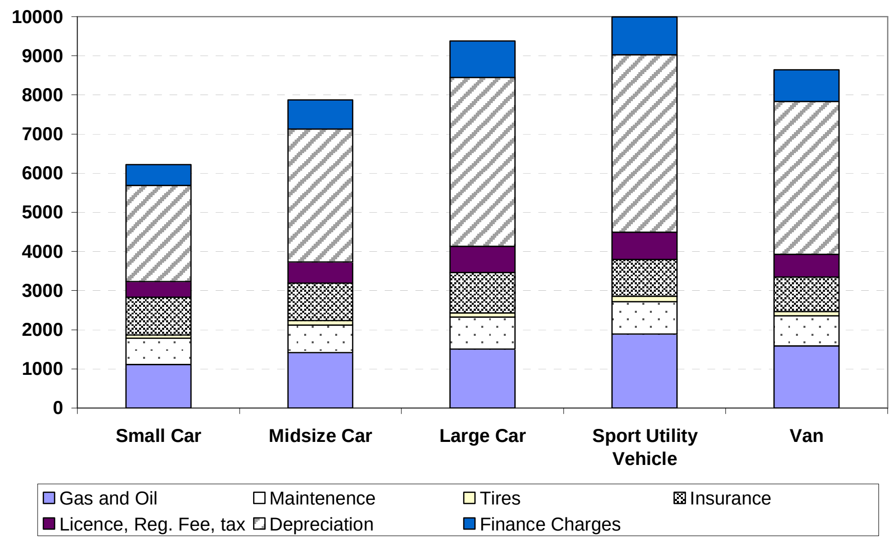

Figure 7 U.S. automobile driving costs in 2006 (dollars per year for 15,000 miles of travel) [AAA 2007]

1.4.5 Scrappage incentives

At the final stage of the vehicle life-cycle, *scrappage incentives* would provide a rebate to vehicle owners to promote earlier retirement of aging vehicles. To the extent that retired vehicles lead to new vehicle sales, and that these new vehicles travel farther on a liter of fuel, scrappage programs can increase the rate at which the on-road fleet achieves fuel consumption reductions. Early retirement also has a positive impact on local air pollution, as the oldest vehicles are responsible for a disproportionate share of total emissions.

Scrappage incentives can be combined with feebates or other differentiated vehicle taxes in order to promote the adoption of vehicles with lower rates of fuel consumption upon retirement of an older vehicle. For example, France's proposed feebate system includes a scrappage incentive for vehicles 15 years or older [Government of France, 2008].

Two drawbacks to scrappage programs are that they may increase the price of used vehicles, which can affect low-income groups that typically purchase older vehicles; also, that they may increase the migration of older vehicles into the area where the incentive is offered, thus offsetting some of the policy's benefits. One study in California found the regressive effect of a scrappage incentive to be smaller than expected, with average used car prices increasing by at most 5%, or $300 per vehicle. Local emissions reductions were very dependent upon the assumptions made regarding the age of vehicles which migrate into the area—under a worst-case assumption, the base-case emissions reductions predicted for the incentive were offset by two-thirds [Dixon & Garber, 2001: pp. 63-64; Table 7.2, p. 58].

2.0 Propulsion System Alternatives and Their Characteristics

2.1 Introduction

Advances in vehicle technologies and fuels are expected to contribute greatly toward reducing use of petroleum and CO_2 emissions from transportation. Figure 8 shows the possible evolution of vehicle propulsion systems over the next several decades. The current vehicle propulsion system is dominated by internal combustion engines (ICEs) that release the chemical energy in fossil fuels by combustion and convert it to mechanical energy. Gasoline-powered spark-ignition (SI) engines dominate the U.S. light-duty market, but diesel-powered compression ignition (CI) engines are widespread in European light-duty vehicles, and dominate the heavy-duty market globally.

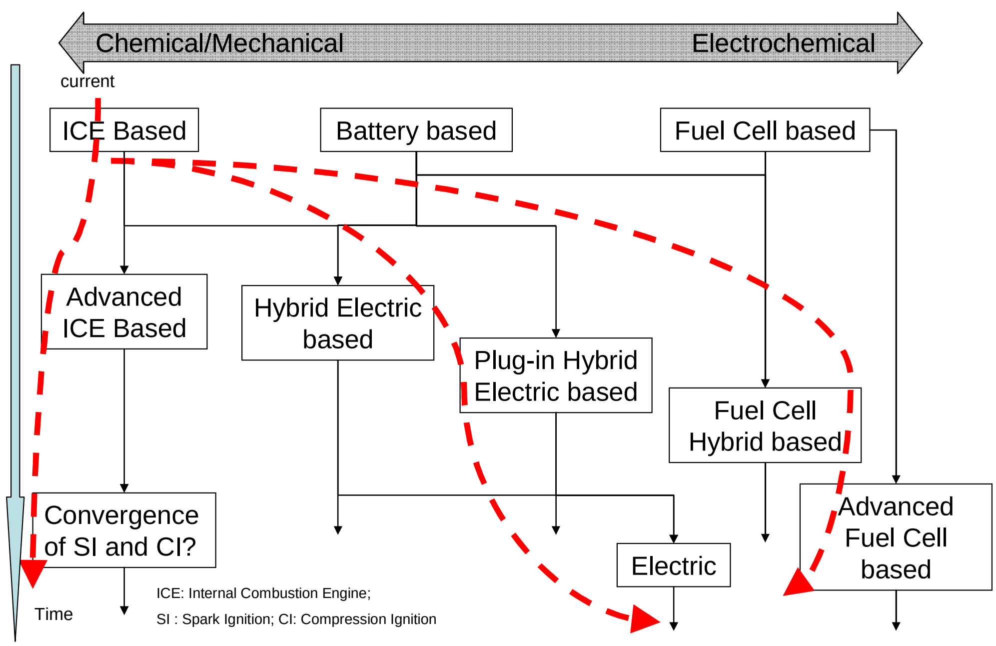

Figure 8 Possible propulsion system pathways

As shown in Figure 8, there are many different pathways along which vehicle technologies may evolve. It is not yet clear whether this evolutionary process will lead to continued use of ICE-based vehicles, or whether electric and/or fuel cell vehicles will replace them over time. While the basic architecture of ICEs has not changed dramatically over the last several decades, engine technology has improved steadily during this period. These improvements are likely to continue into the future. Because it takes 15-plus years for the transportation fleet to turn over, and alternative powertrains are only just penetrating the market, it is possible that mainstream ICEs will continue to dominate light-duty vehicle propulsion systems for the next few decades.

Gasoline hybrid-electric vehicles (HEVs) may act as a bridging technology to other alternative propulsion technologies, or offer a long-term solution in their own right. HEVs typically combine a high-power battery with a downsized ICE to capture additional energy efficiency benefits. The existing HEVs do not have to be charged from an external electric supply and have little or no ability to drive the vehicle in an all-electric mode. Plug-in hybrid vehicles (PHEVs) have a larger battery pack onboard that can be charged from an external electricity supply, and are typically capable of driving 20–60 kilometers on electricity alone. Because they obtain a portion of their energy from the electric grid, PHEVs move further along the path towards vehicle electrification; as such, successful deployment of PHEVs may pave the way for full electric vehicles in the future.

Fuel cell vehicles (FCVs), particularly those running on hydrogen, provide another non-ICE propulsion systems alternative. Initially, FCVs are expected to be hybrids with a powerful battery onboard, although non-hybridized versions might emerge several decades down the road.

This section projects the future energy use for these different vehicle propulsion systems using future vehicle technology under equalized performance conditions and using equivalent non-propulsion system components. We have used a 25-year period—from today until roughly 2035—to represent a plausible time scale for overcoming the barriers to technology diffusion and supply-side constraints necessary to achieve large-scale deployment of these propulsion systems alongside improved mainstream engines and transmissions.

2.2 Methodology

To compare fuel consumption reduction potential of different propulsion technologies on an equivalent basis, the size and performance of future vehicles were held constant at the level of representative 2005 models. The Toyota Camry, with a 2.5-liter engine, was used as a representative car, whereas the Ford F-150, with a 4.2-liter engine, was selected as a representative light-truck. This is because the Camry and the F-150 represent best-selling light-duty vehicles during the model year in question.

The vehicle system simulations were performed using ADVISOR® software. ADVISOR is a backward-facing simulation. This means that for every instant of a drive cycle, the required torque and rotational speed are first calculated at the wheel, and subsequently traced all the way to the engine.

Vehicle size was defined in terms of cross-sectional area—not vehicle weight. This is because evolutionary technical improvements could reduce vehicle weight for a given vehicle size. Performance was defined primarily in terms of 0–60 miles per hour and 40–60 mph acceleration time. Additional performance criteria, such as grade-climbing and towing capacity, are also very important in vehicle design. However, these tests are not well-defined in terms of vehicle and gear speed. As such, they were not rigorously equalized across powertrains; rather, vehicles were simulated to ensure that minimum top speed, gradeability, and towing requirements could be met.

To develop vehicle models, the evolution of individual vehicle components was first estimated using scaling laws. This evaluation entailed an assessment of vehicle characteristics—such as weight reduction, aerodynamic improvements, tire friction reduction, and engine and transmission improvements, as well as electrical system and architecture/control improvements for hybrids. The resulting vehicle system was subsequently simulated over driving patterns (drive cycles and performance tests) to yield the final results.

The following propulsion systems were studied: the naturally-aspirated spark-ignition vehicle (NA-SI); the turbocharged spark-ignition vehicle ("turbo"); the compression-ignition diesel vehicle ("diesel" or "CI")[5]; the gasoline hybrid-electric vehicle (HEV); the plug-in hybrid (PHEV-XX, where "XX" refers to the vehicle's electric range); the fuel cell hybrid vehicle (FCV); and the battery-electric vehicle (BEV).

Several propulsion system technologies were omitted from this evaluation because an initial review of the costs, benefits, and technical challenges indicated that they did not offer a high enough value proposition for a mass-market in U.S. and European contexts over an extended time horizon. These technologies include a fuel-cell vehicle using an onboard reformer, an internal combustion engine running on compressed natural gas (CNG), and a diesel hybrid-electric vehicle.[6] Finally, only an illustrative passenger car was evaluated for PHEV, BEV, and FCV systems. The light truck results for these propulsion systems were scaled from the passenger car results.

2.3 Opportunities for reducing vehicle fuel consumption

Figure 9 shows a representation of vehicle energy flows in a 2.5L 2005 Camry in an urban driving cycle. Vehicle fuel consumption can be reduced by reducing losses across propulsion and non-propulsion systems. Assumptions regarding these fuel consumption reduction opportunities are discussed below. (Details of these assumptions can be found in Kasseris and Heywood [2007] and Kromer and Heywood [2008].)

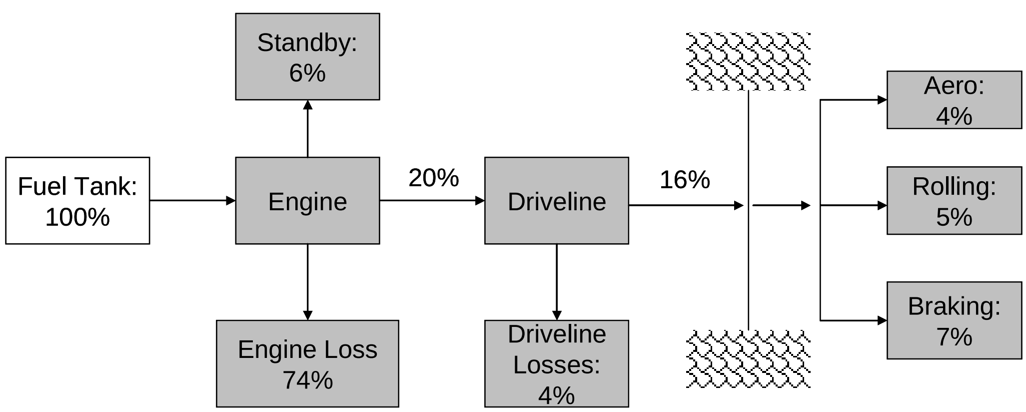

Figure 9 Representative vehicle energy flows in an urban driving cycle

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[5] Assumed to be a turbo-charged, high-speed direct injection diesel engine.
[6] In the case of the diesel hybrid, initial characterization showed only marginal benefit (~5%) compared to the gasoline hybrid. Further details on these results are found in Kromer and Heywood [2008].

2.3.1 Non-propulsion system improvements

Improvements in Vehicle Aerodynamics

Since vehicle cross-sectional area was assumed constant, reduction in aerodynamic drag comes exclusively from reduction of the coefficient of drag, c_D, through improvements in vehicle design. Estimated annual rates of reduction for c_D in the literature range from around 0.9% per year to about 2.5% [An et al. 2001; SAE 1992; Weiss 2000]. For this study, a linear annual rate of reduction of 1% was assumed for c_D resulting in a 25% reduction over 25 years.[7]

Improvements in tire rolling friction

Estimates of the rate of reduction of tire rolling friction as expressed by the coefficient of rolling friction (c_r) range from 1.1% per annum to 1.65% per annum [An et al. 2001; Weiss 2000]. A recent extensive study by the National Academy of Sciences concluded that a 10% reduction is feasible today [NRC 2006]. For the purposes of this study, a linear 1.65% per year reduction was assumed resulting in a 33% reduction over 25 years.

Vehicle weight reduction

Size and vehicle passive safety were held constant at present-day levels and plausible assumptions were made about the amount of technically-based weight reduction that can be achieved. A 20% reduction in curb weight was assumed for all the future gasoline engine vehicles at constant size and safety. Adjustments were made on this base assumption for the weight of the different powertrains. Further details on vehicle weight and size reduction opportunities are discussed in Section 3.

2.3.2 Propulsion system improvements

Transmission improvements

Transmissions will get more efficient by moving from four and five speeds to six and seven speeds. When coupled with improvements in bearings, gear sealing elements, as well as hydraulics, the efficiency of transmissions is projected to improve from around 89% today to 94% in the future. The logic of gear selection methodology is outlined in Kasseris and Heywood [2007].

Naturally aspirated spark-ignition (NA-SI) engines

Advances in future NA-SI engine technology were projected by extrapolating historical trends for the maximum brake mean effective pressure (normalized torque) versus mean piston speed curve, which have demonstrated improvements on the order of 0.5% per year for four

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[7] Although aerodynamic design is already quite sophisticated, there are still significant improvements that should be expected. Experimental prototypes have achieved drag coefficients that are 30–50% lower than the coefficients assumed for the future vehicles in this study, although these designs ride close to the road and sacrifice passenger comfort.

valve engines [Chon et al. 2000]. Technical improvements that could be postulated for continuing this trend include, but are not limited to, the following:

- Friction reduction opportunities, which include improved materials and piston ring design, camless valve actuation, synthetic lubricants, and electrically driven engine auxiliaries, among others.
- Smart cooling systems, which can reduce engine heat losses.
- Variable valve lift and timing (VVLT) systems, which can adjust the open time as well as the lift of the intake valve according to engine speeds.
- Cylinder deactivation or cut-out system, which deactivates some of the engine's cylinders at lighter loads.
- Variable compression ratio engines, which can operate at higher compression ratios at lower loads. They can be supercharged or turbocharged to provide increased power at high loads.
- Gasoline direct-injection (GDI), which allows for better control of combustion. Engine compression ratio can be increased using GDI due to the cooling effect of fuel evaporation, which protects against engine knock. Furthermore, GDI enables effective turbocharging of the gasoline engine.

Turbo SI engines

Turbocharging a gasoline engine significantly increases the maximum brake mean effective pressure. The frictional mean effective pressure, which scales mainly with engine speed, goes up only slightly. As a result, the resulting fuel consumption map has higher partial load efficiencies. Historically turbocharged engines have been limited by three important factors:

- Engine knock, which limits compression ratios and spark timing, reduces engine efficiency
- Low engine torque at low engine speeds
- Turbo lag

However, several technologies, such as Gasoline Direct Injection (GDI); E-boosting (i.e., coupling a small electric motor on the turbocharger shaft); variable geometry turbines; and variable compression ratio, offer solutions to these problems in the near-to-mid-term.

Diesel engines

Diesels engines, enabled by developments such as common-rail fuel injection, have improved rapidly since the 1980s. Several technologies could continue these improvements:

- Camless valvetrains for improved valve timing control
- Higher pressure fuel injection (more than 2000 bar)
- Improved thermal and exhaust gas recirculation management.
- Homogeneous charge compression ignition (HCCI)

Although control over diesel emission has been improving significantly, the pace of improvement may slow in the future relative to spark-ignition engine technology. In addition, meeting the U.S. criteria emissions standards is still a challenge. While particulate traps achieve the U.S. particulate emission requirements, they incur a small fuel economy penalty. Meeting NO_x standards will likely involve some degree of injection retard with an associated fuel consumption penalty. Other techniques to reduce diesel emissions include low temperature combustion with extensive exhaust gas recirculation (EGR), lower air-to-fuel ratios, and NO_x aftertreatment systems. These measures may directly impact fuel efficiency, while others affect the engine's power density; in addition, these aftertreatment systems may be costly, which will increase the diesel vehicle's price relative to gasoline engines.

Batteries

Each of the "advanced" technology vehicles—the HEV, the PHEV, the FCV, and BEV—are assumed to use lithium-ion batteries to provide either power assist capability, as in the case of the HEV and FCV; motive energy, as in the case of the BEV; or, in the case of the PHEV, both power assist and motive energy. Other energy storage technologies, such as ultracapacitors and nickel-metal hydride (NiMH) batteries, were considered. However, it was concluded that the primary barriers to lithium-ion battery deployment in automotive applications—notably safety and battery lifetime—are solvable in the near-term, and that they offer significant performance, weight, and cost benefits relative to incumbent battery technologies. Realizing these benefits is particularly important for widespread deployment of plug-in hybrid or battery-electric vehicles.

Although specific electrode and electrolyte materials are not postulated for the future battery system, the system is based on manufacturer data for the Saft VLE module, which uses a $Li[Co_{.2}Ni_{.8}]O2$ cathode and graphite anode [Saft 2006]. The future model includes several adjustments to the present-day performance characteristics. First, the future battery was assumed to maintain its rate capability at high depth-of-discharge—a development that is consistent with recent advances in phosphate-based chemistries [Thackeray 2002].

Second, the future models include evolutionary improvements in battery-specific power and specific energy. It is assumed that specific energy improves by a factor of 1.5 over present day lithium-ion battery packs—a rate of about 2% per year—for both high-power and high-energy batteries. It should also be noted that, in absolute terms, battery weight is a relatively minor factor for all of the vehicle technologies except the battery electric vehicle, as shown in Table 1.

Table 1 Battery weight as a function of electric range and specific energy

	Specific Energy (Wh/kg)				
Range (Miles)	**100**	**120**	**150**	**225**	
0 (HEV)	10	8	7	4	**Battery Weight (kg)**
10	32	27	21	14	
30	82	68	55	36	
60	165	138	110	73	
200	480	400	320	213	

For each vehicle propulsion system, the pack was sized to meet both a power and energy requirement. For hybrid systems, these factors are dictated by a sustained acceleration requirement of 20 seconds; for the plug-in hybrid and battery-electric vehicle, power is dictated by the acceleration requirement, while energy is dictated by the desired electric range. Battery weight and cost characteristics were calculated as a function of the battery's power-to-energy ratio, which follows a unique Ragone curve, as illustrated in Kromer and Heywood [2008].

Gasoline hybrids (HEVs)

The HEV model is configured as a single-motor parallel hybrid with an advanced transmission that can decouple engine or motor operation from the wheels and a control strategy that switches off the engine under low-load conditions. In addition, the vehicle braking system was configured to direct 90% of braking energy down the regenerative path. The motor and power electronics are assumed to meet U.S. Department of Energy performance and weight targets—both of which appear feasible for these components.

In order to investigate the effect of the size of the electric system the *hybridization ratio* is defined as the maximum motor power over the maximum engine plus motor power:

$$HR = \frac{P_{max,motor}}{P_{max,motor+engine}} \qquad (2.1)$$

The hybrid system (including battery, motor, and controller) was sized to be powerful enough to capture most of the vehicle's regenerative braking requirement under "typical" driving conditions. In practical terms, sensitivity analysis of the HWFET, FTP, and US06 drive cycles showed that a hybridization ratio of 25% was necessary and sufficient to meet this requirement.

An alternative to this "full" hybrid concept is a mild hybrid approach, using a start / stop system to eliminate engine idling, some regenerative breaking, and an electric drive at low loads and speeds. The benefits of a mild hybrid are about half those of a full hybrid and costs are significantly lower.

Plug-in hybrid vehicles (PHEVs)

The plug-in hybrid (PHEV) is defined as a gasoline hybrid electric vehicle with the ability to recharge from the electricity grid. The vehicle uses a lithium-ion battery pack in a parallel hybrid configuration similar to that assumed for the conventional hybrid. While a series plug-in hybrid architecture may be an attractive option, particularly for vehicles with a large driving range under electric power, this assessment adopts a parallel architecture as a natural outgrowth of the already-extant hybrid market. Above a threshold battery state-of-charge, the PHEV operates in "charge depleting" (CD) mode, in which it freely draws down the onboard battery to meet vehicle power demands. Once it reaches this minimum state of charge (SOC) threshold, the vehicle switches to "charge sustaining" (CS) mode. Charge-sustaining mode is functionally equivalent to vehicle operation in a conventional HEV.

The tank-to-wheels energy (E_{Total}), petroleum (E_{Petrol}), and electricity (E_{Elec}) use are calculated from the petroleum consumption in charge-depleting and charge-sustaining mode, and the energy use in charge-depleting and charge sustaining mode (PCCS, PCCD, ECS, and ECD, respectively):

$$E_{Total} = (ECD)\,(UF) + (ECS)\,(1\text{-}UF)$$

$$E_{Petrol} = (PCCD)\,(UF) + (PCCS)\,(1\text{-}UF) \qquad (2.2)$$

$$E_{Elec} = E_{Total} - E_{Petrol}$$

The plug-in hybrid's total power was fixed to meet the US06 drive cycle in both charge depleting and charge sustaining mode and to meet a minimum acceleration requirement in charge-depleting mode.

PHEV simulations are based on a vehicle with a 30-mile (50 km) electric range, which is estimated to capture approximately 50% of the vehicle's total miles.[8] The vehicle's electric range was defined as the distance the vehicle can travel under electric power over the combined, adjusted FTP/HWFET drive cycle. Specific trade-offs regarding how to size the system and use stored electric energy were explored by varying the hybridization ratio and the vehicle control strategy. The hybridization ratio was varied from 25%–55%. In addition, two different control strategies were evaluated: an all-electric strategy, in which the gasoline engine remains off during charge-depleting mode (necessitating a more highly hybridized vehicle); and a blended strategy, in which the engine is available to meet peak power demands during charge-depleting mode (allowing for a less-powerful electric propulsion system), but remains off at other times [Markel and Simpson, 2005]. During blended mode, engine operation was constrained by a minimum engine-on time as a way to minimize the number of cold engine starts.

Downsizing the electric powertrain (using a lower hybridization ratio) is desirable because it minimizes system cost and could have a performance benefit. To meet the same performance criteria as a vehicle using a blended control strategy, an all-electric drive vehicle would require electric propulsion that is powerful enough to meet the vehicle's entire driving load in addition to an engine that switches on during hybrid operation. On the other hand, all-electric operation minimizes the number of cold-starts and total engine operation time; as such, it minimizes both fuel-consumption and criteria pollutant emissions. A vehicle with a hybridization ratio of 45% using a blended control strategy was used for the plug-in hybrid vehicle configurations [Kromer and Heywood 2008].

Battery Electric Vehicle (BEV)

The battery electric vehicle sources all of its energy from offboard electricity and is charged from the electric grid. The BEV requires a significant tradeoff between cost and range. The 400-mile range vehicle seems implausible from a cost and weight perspective, and even the

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[8] Kromer (2008) estimated that the utility factor (UF)—or the fraction of vehicle miles traveled in charge-depleting (i.e. all-electric) mode—was approximately 50% for a plug-in hybrid with an all-electric range of 30 miles, based on the median values of a survey of several different studies of travel patterns in the United States [SAE J1711 1999 EPRI 2001, Markel 2006, ORNL 2004].

200-mile range vehicle is daunting. The vehicle with a 100-mile range is plausible from both a weight and cost perspective, but would require frequent recharge [Kromer and Heywood 2008].

The vehicle that was modeled is configured to offer 200 miles of electric range, which represents a compromise between the utility typically expected by consumers, and the prohibitive cost and weight of a vehicle capable of offering a 350–400-mile electric range.

Fuel Cell Vehicle (FCV)

The fuel cell vehicle projections are based on a vehicle that uses a proton-exchange membrane (PEM) fuel-cell system to power an electric motor in a series hybrid configuration. The battery characteristics are based on the same high-power lithium-ion battery used for the conventional hybrid vehicle model. Several different levels of hybridization were tested.

Fuel cell vehicles must overcome a number of technological challenges and greatly reduce system costs before they become marketable. In particular, power plant performance and durability is limited by the properties of present-day membrane materials, by catalyst effectiveness, and by the complex systems management needed to control fuel-cell operating conditions. In addition to improved fuel cell systems, developing an onboard hydrogen storage system that offers adequate vehicle range is problematic.

Onboard Hydrogen Storage. No significant breakthroughs in hydrogen storage technology were assumed. While various solid and chemical hydride storage solutions continue to be explored, barring a breakthrough, it seems unlikely that any of these will offer the combination of cost, simplicity, efficiency, and energy density needed to justify their deployment [NRC 2004, Schlapbach and Zuttel 2001]. Hence, the future fuel cell model is based on a vehicle that uses onboard gaseous compressed hydrogen storage. Although not ideal from either a cost or packaging point of view, gaseous storage is technically feasible with present-day technology.

The combination of improved vehicle and power plant efficiency enables a 10,000 psi storage system to offer a driving range on the order of 400 miles (combined, adjusted HWFET/FTP cycle) with a 150-liter tank.

Fuel Cell System. The vehicle power plant consists of a PEM fuel cell and a balance-of-plant (BOP) that manages the fuel cell's reactant flows and operating environment. The fuel cell operating map—defined by a polarization curve, or voltage vs. current density plot—was derived by postulating an improved version of a present-day, state-of-the-art system. The fuel cell stack is assumed to meet the DOE long-term (2015) performance target of 1500 mA/cm^2 at 0.65 V at rated power [NRC 2005].

The balance-of-plant includes a water management system (typically a pump and humidifier driven by a small motor); a heat-rejection loop (radiator and fan); a hydrogen pump; and a compressor/expander module (CEM) (for the baseline case) or a compressor (for the conservative case), which is used to boost operating pressure and manage air flows. The primary parasitic load comes from the CEM, which was assumed to follow efficiency and pressure ratio (PR) targets established by the DOE in Tiax, DOE [2003]. The system operating conditions and fuel-cell system characteristics are summarized in Table 2.

Table 2 Fuel-cell system specifications

Air Stoichiometry	1.50
Fuel Utilization	100%
PR (Bar)	1.0-2.75
Inlet Temp (^{O}C)	40
Outlet Temp (^{O}C)	80
Min. Voltage	0.65
η, peak (system)	52%
Spec Power (W/kg)	650
Balance-of-Plant	Includes Expander
Aux Power (% of Net)	~10%

2.3.3 Vehicle manufacturing and disposal energy and GHG emissions

Complete life-cycle consideration of energy consumption and GHG emissions from light-duty vehicles should include not just the well-to-wheel aspects which are associated with the fuel, but manufacturing and disposal aspects as well. Here, the vehicle-cycle impact is evaluated with Argonne National Laboratory's Transportation Vehicle-Cycle Model (GREET 2.7) [Burnham et al. 2006; Moon et al. 2006]. GREET 2.7 calculates the emissions and energy impact by different stages of vehicle life-cycle, namely material recovery and production, component fabrication, assembly, and disposal/recycling. The vehicle characteristics such as weight, battery, and fuel cell type are taken from representative vehicles modeled by Kasseris and Heywood [2007] and Kromer and Heywood [2008]. The distribution of materials by vehicle subsystem was set to default GREET 2.7 values. The corresponding energy and GHG emission factors associated with the manufacture and disposal of different vehicles are shown in Table 3.

Table 3 Energy and GHG emissions during manufacturing and disposal of LDVs

Vehicle	Cars		Light-Trucks	
	Energy (GJ/vehicle)	GHG (metric tons/vehicle)	Energy (GJ/vehicle)	GHG (metric tons/vehicle)
Current Gasoline ICE	96.9	7.7	124.6	10.0
Current Turbo ICE	95.9	7.7	134.3	10.8
Current Diesel ICE	99.0	8.0	128.4	10.4
Current Gasoline Hybrid	113.6	9.1	144.2	11.6
2035 Gasoline ICE	114.9	9.3	159.3	12.9
2035 Turbo ICE	113.7	9.2	159.3	12.8
2035 Diesel ICE	117.4	9.5	152.2	12.3
2035 Gasoline Hybrid	134.7	10.8	171.0	13.8
Future PHEV	137.8	11.1	174.9	14.1
Future FCV	158.2	12.9	203.4	16.6

For calculating the vehicle-cycle impacts of future vehicles, it is assumed that any weight reduction for future vehicles is realized through use of lightweight materials. Since lightweight materials such as aluminum and magnesium are more energy intensive than steel, the energy and GHG emission from vehicle-cycle for future vehicles will be higher than the current vehicles. In practice, part of the lightweighting can be realized through downsizing and enhanced vehicle design/reconfiguration. As a result, the energy and GHG factors in Table 3 represent upper-end—and therefore conservative—estimates of the GHG emissions associated with future vehicles. The energy and GHG emissions during the manufacturing of hybrid and fuel cell vehicles (FCVs) are larger due to use of energy intensive materials used in components such as batteries and fuel cell membranes.

For simplification purposes, all the energy and greenhouse gas emissions associated with vehicle manufacturing and disposal are attributed to the year in which the vehicle enters the LDV fleet. Thus, the new light-duty vehicles entering the fleet in year 2005 consumed 1.9 exajoules of energy (0.7 EJ for cars and 1.2 EJ for light-trucks), and the resulting CO_2 emissions were 152 million metric tons (59 mmt for cars and 93 mmt for light trucks).

2.3.4 Summary of assumptions

The main assumptions used in vehicle simulation are summarized in Table 4 and Table 5 [Kasseris and Heywood 2007; Kromer and Heywood 2008].

Table 4 Cross-cutting assumptions

Parameter	Units	2006 Value	2030 Value
Vehicle Parameters			
Area	*m^2*	2.49	2.49
Aero drag coefficient	--	0.28	0.21
Rolling resistance	--	0.009	0.006
Weight Assumptions			
Weight Multiplier[9]	--	1.5	
Specific Power, SI	*kW/kg*	0.74	0.925
Specific Power, Diesel	*kW/kg*	--	0.715
Specific Power, Motor	*kW/kg*	--	1.1
Efficiency Assumptions			
Engine indicated efficiency $\eta_{Spark\ Ignition}$	*%*	40%	43%
Engine indicated efficiency η_{Diesel}	*%*	44%	48%
Reduction in fmep, SI	*%*	--	25%
Reduction in fmep, diesel	*%*	--	15%
Improvement in bmep	*%*	--	12.5%
Peak $\eta_{Motor/Controller}$	*%*	--	95%
$\eta_{Transmission}$	*%*	89%	94%
Battery Assumptions			
Internal Resistance	*mΩ*	--	~4
Nominal Voltage	*V*	--	3.6
Minimum Voltage	*V*	--	2.7

[9] Additional weight beyond the 2030 base case incurs a 1.5X penalty to account for additional vehicle support structure, etc.

Table 5 Vehicle-specific specifications

	2005 NA-SI	2030 NA-SI	Turbo	Diesel	HEV	PHEV-30	BEV	FCV
Mass (kg)								
Vehicle[10]	1571	1284	1270	1320	1290	1338	1617	1320
Cargo	136	136	136	136	136	136	136	136
Engine/Exhaust	161	128	116	158	95	68	-	-
Motor	-	-	-	-	23	36	78	91
Chassis[11]	1125	929	927	935	935	947	1030	945
Transmission	114	91	91	91	91	91	40	40
Fuel Cell	-	-	-	-	-	-	-	93
Battery	-	-	-	-	10	61	333	14
Power								
Motor (kW)	-	-	-	-	25	40	85	90
Engine (kW)	119	95	94	95	70	50	-	-
Battery								
Energy (kWh)	-	-	-	-	1.0	8.2	48.0	1.3
Power (kW)	-	-	-	-	28	45	150	40
Mass (kg)	-	-	-	-	10	61	333	14
Sp En. (Wh/kg)	-	-	-	-	100	135	150	100
Pwr/En (W/Wh)	-	-	-	-	28	5.5	3.0	28

2.3.5 Vehicle simulation results:

The projected improvement in vehicle fuel consumption is shown in Table 6. As evidenced by the difference in fuel consumption between present-day and future technologies, holding performance and size constant enables significant improvements in fuel efficiency. Note that the relative improvement values for cars and light trucks are calculated based on the improvement in fuel consumption of a 2035 vehicle comparable in performance to a current ICE gasoline vehicle across the same drive cycle. Vehicles optimized for other applications, such as the subset of light trucks used for heavy towing, may have more limited opportunities for engine downsizing and hybridization that reduce their relative improvement in fuel consumption.

The advanced technology vehicles offer a number of feasible paths to greatly reduce petroleum consumption: the hybrid offers a 43% reduction over the 2035 NA-SI baseline, and a 63% reduction over the 2005 vehicle. The plug-in hybrid offers still greater potential for petroleum reduction, although the magnitude of this reduction depends upon the electric range of the vehicle, as well as the control strategy and degree of hybridization. The PHEV offers a 71% reduction in petroleum consumption over the NA-SI engine, and an 81% reduction over the 2005 vehicle.

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[10] Vehicle curb weight includes 136kg of cargo.
[11] Chassis includes the fuel tank; additional weight beyond the baseline NA-SI vehicle incurs a 1.5X penalty to account for additional vehicle support, etc.

Table 6 Projected improvement in vehicle fuel consumption, holding vehicle size and performance constant at current levels

Propulsion System	Cars			Light-Trucks		
	Fuel Consumption* (l/100 km)	Relative to current gasoline ICE	Relative to 2035 gasoline ICE	Fuel Consumption* (l/100 km)	Relative to current gasoline ICE	Relative to 2035 gasoline ICE
Current Gasoline	8.8	1	--	13.6	1	--
Current Diesel	7.4	0.84	--	10.1	0.74	--
Current Turbo Gasoline	7.9	0.9	--	11.3	0.83	--
Current Hybrid	6.2	0.7	--	9.5	0.7	--
2035 Gasoline	5.5	0.63	1	8.6	0.63	1
2035 Diesel	4.7	0.53	0.85	6.8	0.50	0.79
2035 Turbo Gasoline	4.9	0.56	0.89	7.3	0.54	0.85
2035 Hybrid	3.1	0.35	0.56	4.8	0.35	0.56
2035 Plug-In Hybrid	1.5 #	0.18	0.28	2.4##	0.18	0.28

* Gasoline Equivalent.

0.65 l/100 km of electricity usage in addition to gasoline not included

1.01 l/100 km of electricity usage in addition to gasoline not included

Battery electric vehicles (BEV) and hydrogen fuel cell vehicles (FCV) do not consume any petroleum-based fuel during vehicle operation. As a result, energy consumption per kilometer driven is a more appropriate comparison when these vehicles are included. Table 7 shows a comparison of tank-to-wheel energy consumption expressed in MJ per km of vehicle travel for different propulsion systems.

Table 7 Tank-to-wheel energy use, holding vehicle size and performance constant at current levels

Propulsion System	Cars			Light-Trucks		
	MJ/km	Relative to current gasoline ICE	Relative to 2035 gasoline ICE	MJ/km	Relative to current gasoline ICE	Relative to 2035 gasoline ICE
Current Gasoline	2.85	1	--	4.36	1	--
Current Diesel	2.38	0.84	--	3.25	0.75	--
Current Turbo Gasoline	2.54	0.89	--	3.64	0.83	--
Current Hybrid	2.0	0.7	--	3.05	0.7	--
2035 Gasoline	1.77	0.62	1	2.77	0.63	1
2035 Diesel	1.52	0.53	0.86	2.19	0.50	0.79
2035 Turbo Gasoline	1.56	0.55	0.88	2.34	0.54	0.85
2035 Hybrid	0.99	0.35	0.56	1.55	0.35	0.56
2035 Plug-In Hybrid	0.71	0.25	0.40	1.11	0.25	0.40
2035 Battery Electric	0.54	0.19	0.30	0.83	0.19	0.30
2035 Fuel Cell	0.74	0.26	0.42	1.13	0.26	0.41

1 MJ / km = 3.1 L / 100 km, gasoline equivalent

2.3.6 Future vehicle cost estimates

Technologies that improve the efficiency of future vehicles will come at extra cost to manufacturers. Production costs—and the associated increase in vehicle retail price—are a key factor in assessing the likelihood that advanced technologies will be widely adopted. Technologies that provide efficiency benefits in a relatively cost-effective manner will have an advantage in penetrating into the light-duty vehicle fleet.

The incremental retail price increases of different propulsion systems relative to current and future gasoline vehicles are shown in Table 8. These retail price estimates were based on production cost estimates summarized in Table 9 and Table 10. Production costs describe the costs associated with producing a vehicle at the manufacturing plant gate; they include vehicle manufacturing, corporate overhead, and production overhead. To account for distribution costs and manufacturer and dealer profit margins, production costs were multiplied by a factor of 1.4[12] to provide the retail price estimates.

Table 8 Incremental retail price increase* of current and future propulsion technologies

VEHICLE	CARS		LIGHT TRUCKS	
	Relative to current gasoline ICE	Relative to 2035 gasoline ICE	Relative to current gasoline ICE	Relative to 2035 gasoline ICE
Current Gasoline ICE	$0	--	$0	--
Current Diesel	$1,700	--	$2,100	--
Current Turbo Gasoline	$700	--	$800	--
Current Hybrid	$4,900	--	$6,300	--
2035 Gasoline ICE	$2,000	$0	$2,400	$0
2035 Diesel	$3,700	$1,700	$4,500	$2,100
2035 Turbo Gasoline	$2,700	$700	$3,200	$800
2035 Hybrid	$4,500	$2,500	$5,600	$3,200
2035 Plug-in Hybrid	--	$5,900	--	$8,300
2035 Battery Electric	--	$14,400	--	$22,100
2035 Fuel Cell	--	$5,300	--	$7,400

* Retail price increases here are drawn from the technology costs shown in Tables 9 and 10 below. They have been adjusted to *representative* retail price levels by a factor of 1.4, but do not represent the actual price that would be arrived at in a competitive auto market.

[12] The retail price factor of 1.4 was taken from Vyas, et al. (2000), based on our assumption that production costs include vehicle manufacturing, and corporate and production overhead. This adjusts the technology cost to representative retail price levels, but does not represent the actual retail price arrived at in a competitive auto market. Studies often refer to these estimates as Retail Price Equivalents, or RPEs.

If efficiency improvements provided by these technologies are directed toward reducing the rate of fuel consumption, vehicles will use less fuel and emit fewer greenhouse gas emissions over a given amount of travel. Table 11 and Table 12 provide a summary of the reduction in fuel use and greenhouse gas emissions of vehicles with alternative powertrains, relative to current and future gasoline vehicles.

It is important to note that a negative “net price” in Table 11 and Table 12 does not imply that a technology is “zero cost.” Instead of lowering fuel consumption, efficiency improvements can also be used to offset the effects of increases in the size and power of vehicles. The full cost of reducing fuel consumption would account for how changes in vehicle attributes such as fuel consumption, power, and size affect the value that consumers derive from these products.

(See next page.)

Table 9 Incremental production cost and vehicle weight reduction costs by powertrain type for cars ($US 2007[13])

CARS	Current Gasoline	Current Diesel	Current Turbo Gasoline	Current Hybrid	2035 Gasoline	2035 Diesel	2035 Turbo Gasoline	2035 Hybrid	2035 Plug-in Hybrid	2035 Battery Electric	2035 Fuel Cell
Engine											
NA-SI	$3,000	--	$3,000	$3,000	$3,700	--	$3,700	$3,700	$3,700	--	--
Diesel	--	$3,700	--	--	--	$4,400	--	--	--	--	--
Turbo	--	--	$500	--	--	--	$500	--	--	--	--
Motor / controller[14]	--	--	--	$1000	--	--	--	$600	$800	$1,500	$1,600
Fuel cell	--	--	--	--	--	--	--	--	--	--	$3,000[15]
Downsizing credit	--	--	--	-$100	--	--	--	-$100	-$200	--	--
Transmission											
Hybrid trans. & integration	--	--	--	$400	--	--	--	$300	$300	--	--
1-spd. trans.	--	--	--	--	--	--	--	--	--	$200	$200
Energy storage											
Battery[16]	--	--	--	$2,000	--	--	--	$800	$2,700	$12,000	$1,000
H_2 Storage[17]	--	--	--	--	--	--	--	--	--	--	$1,800[15]
Miscellaneous											
Exhaust	$300	$800[18]	$300	$300	$300	$800[18]	$300	$300	$300	--	--
Wiring	--	--	--	$200	--	--	--	$200	$200	$200	$200
Charger	--	--	--	--	--	--	--	--	$400	$400	--
Vehicle weight reduction[19]	--	--	--	--	$700	$700	$700	$700	$700	$700	$700
TOTAL[20]	$3,300	$4,500	$3,800	$6,800	$4,700	$5,900	$5,200	$6,500	$8,900	$15,000	$8,500

[13] Production cost assumptions in this table are adapted from Kromer 2007 (Tables 51–53, pp. 117, 118) based on sources noted by Kromer in Table 51, p. 117.
[14] $200 + $30 per kW for current hybrid vehicle; $200 + $15 per kW for 2035 vehicles (Kromer, 2007, Table 51, p, 117).
[15] Assumes fuel cell costs $50 per kW; hydrogen storage costs $15 / kWh (Kromer 2007, Table 51, p, 117).
[16] Assumes $2000 / kWh for current hybrid vehicle. For 2035 vehicles, assumed battery costs range from $250 / kWh for high energy batteries to $750 / kWh for high power batteries. Assumes 2035 hybrid battery costs $750 / kWh, 2035 plug-in hybrid battery costs $320 / kWh, 2035 fuel cell battery costs $750, 2035 battery electric vehicle costs $250 / kWh (Kromer, 2007, Table 52, p. 117).
[17] Assumes $15 per kWh storage (Kromer 2007, Table 51, p. 117).
[18] Includes NO_x after-treatment and diesel particulate filter (DPF).
[19] Assumes 20% weight reduction in 2035 vehicles; roughly 14% of weight reduction is achieved through material substitution at $3 / kg; the remainder is secondary reduction at no cost.
[20] Total incremental production cost relative to a baseline vehicle cost of $10,700. Total production cost of current gasoline car is therefore: $10,700 + $3,300 = $14,000.

Table 10 Production cost and vehicle weight reduction costs by powertrain type for light trucks. All costs in $US 2007.

TRUCKS	Current **Gasoline**	Current **Diesel**	Current **Turbo Gasoline**	Current **Hybrid**	2035 **Gasoline**	2035 **Diesel**	2035 **Turbo Gasoline**	2035 **Hybrid**	2035 **Plug-in Hybrid**	2035 **Battery Electric**	2035 **Fuel Cell**
Engine											
NA SI[21]	$3,900	--	$3,900	$3,900	$4,700	--	$4,700	$4,700	$4,700	--	--
Diesel[21]	--	$4,800	--	--	--	$5,600	--	--	--	--	--
Turbo[21]	--	--	$600	--	--	--	$600	--	--	--	--
Motor / controller[22]	--	--	--	$1,200	--	--	--	$800	$1,100	$1,900	$2,000
Fuel cell	--	--	--	--	--	--	--	--	--	--	$3,900[23]
Downsizing credit	--	--	--	-$100	--	--	--	-$100	-$200	--	--
Transmission											
Hybrid trans. & integration	--	--	--	$600	--	--	--	$400	$400	--	--
1-spd. trans.	--	--	--	--	--	--	--	--	--	$300	$300
Energy storage											
Battery[24]	--	--	--	$2,600	--	--	--	$1,000[25]	$4,000[26]	$18,000[26]	$1,200[25]
H_2 Storage	--	--	--	--	--	--	--	--	--	--	$2,700[27]
Miscellaneous											
Exhaust	$300	$900[28]	$300	$300	$300	$900[28]	$300	$300	$300	--	--
Wiring	--	--	--	$200	--	--	--	$200	$200	$200	$200
Charger	--	--	--	--	--	--	--	--	$400	$400	--
Weight reduction[29]	--	--	--	--	$900	$900	$900	$900	$900	$900	$900
TOTAL[30]	$4,200	$5,700	$4,800	$8,700	$5,900	$7,400	$6,500	$8,200	$11,800	$21,700	$11,200

[21] Gasoline, diesel and turbo engine costs scaled by a factor of 1.3 relative to gasoline/diesel cars, the ratio of current gasoline car to truck (1620 kg to 2,140 kg) vehicle weight (EPA, 2007).
[22] $200 + $30 for current hybrid vehicle; $200 + $15 per kW for 2035 vehicles (Kromer, 2007, Table 51, p, 117). Motor power calculated by holding power to curb weight ratio constant relative to car of same powertrain type; curb weight scaled relative to car by a factor of 1.3; share of power provided by engine and motor determined by degree of hybridization.
[23] Fuel cell power scaled relative to fuel cell car by a factor of 1.3.
[24] Assumes $2,000 / kWh for current hybrid vehicle. For future vehicles, assumed battery costs range from $250 / kWh for high energy batteries to $750 / kWh for high power batteries. Assumes 2035 hybrid battery costs $750 / kWh, 2035 plug-in hybrid battery costs $320 / kWh, 2035 fuel cell battery costs $750 / kWh, 2035 battery electric vehicle costs $250 / kWh (Kromer, 2007, Table 52, p. 117).
[25] Battery energy storage sized by a factor of 1.3 relative to 2035 hybrid car; same ratio of hybrid energy storage for trucks to cars determined by Kasseris (2006, pp. 180, 184).
[26] Battery energy storage scaled by a factor of 1.5 relative to 2035 car of same powertrain type. This is the ratio of energy required at the wheel by hybrid truck versus cars, based on ratio of fuel consumptions of hybrid light truck and car from Kasseris, 2006.
[27] Assumes $15 / kWh storage (Kromer, 2007, Table 51, p. 117). Hydrogen energy storage scaled by 1.5, ratio of energy required at the wheel by trucks versus cars; see footnote 26.
[28] Includes NO_x after-treatment and diesel particulate filter (DPF).
[29] Assumes 20% weight reduction in 2035 vehicles; roughly 14% of weight reduction is achieved through material substitution at $3 / kg; the remainder is secondary reduction at no cost.
[30] Total incremental production cost relative to a baseline vehicle cost of $10,800. Total production cost of current gasoline light truck is therefore: $10,800 + $4,200 = $15,000.

Table 11 Fuel and greenhouse gas emission savings of cars with alternative propulsion technologies relative to current and future gasoline cars. Assumes 240,000 km of vehicle operation over 15 years.[31]

CARS	RELATIVE TO CURRENT GASOLINE VEHICLE					RELATIVE TO 2035 GASOLINE VEHICLE					
	Current Gasoline	Current Diesel	Current Turbo Gasoline	Current Hybrid	2035 Gasoline	2035 Diesel	2035 Turbo Gasoline	2035 Hybrid	2035 Plug-in Hybrid	2035 Battery Electric	2035 Fuel Cell
Change in TTW fuel consumption [MJ / km][32]											
Petroleum	0.00	-0.47	-0.31	-0.87	-1.08	-0.24	-0.20	-0.78	-1.27	-1.77	-1.77
Electricity	--	--	--	--	--	--	--	--	0.21	0.57	--
Hydrogen	--	--	--	--	--	--	--	--	--	--	0.74
Total	0.00	-0.47	-0.31	-0.87	-1.08	-0.24	-0.20	-0.78	-1.06	-1.20	-1.03
Change in TTW fuel cost[33] [$]											
@ $2.5 / gal.	0	-1,539	-1,008	-2,855	-3,566	-806	-647	-2,568	-3,725	-4,556	-2,363
@ $5.0 / gal.	0	-3,077	-2,016	-5,709	-7,131	-1,613	-1,295	-5,136	-7,917	-10,381	-8,189
Net price [$][34]											
@ $2.5 / gal.	0	161	-308	2,045	-1,566	894	53	-68	2,175	9,444	2,937
@ $5.0 / gal.	0	-1,377	-1,316	-809	-5,131	87	-595	-2,636	-2,017	3,619	-2,889
Change in WTW GHG emissions[35]											
Emitted [tCO_2e]	0	-9	-7	-19	-24	-5	-4	-17	-18	-11	-18
Abatement price [$ / tCO_2e]	--	184	103	256	83	360	161	145	333	1,312	300

[31] Vehicle travel is taken from NHSTA (2006, Tables 7 and 8, pp. 22, 25) as the average of car and light truck annual travel over the first 15 years of vehicle life.
[32] Change in tank-to-wheel (TTW) fuel consumption for each propulsion system relative to current and future gasoline vehicles.
[33] Change in TTW fuel cost is calculated using a 7% discount rate (r), an electricity cost of $0.05 / kWh, and a hydrogen cost of $3.50 / kg (NRC, 2004). Change in fuel cost is calculated for two gasoline and diesel prices: $2.50 / gallon and $5.00 / gallon.
[34] Net price is equal to a propulsion technology's retail price increase (see Table 8) plus the change in TTW fuel cost. A negative result indicates that the fuel savings provided by the propulsion technology are greater than its increase in retail price.
[35] Well-to-wheel (WTW) greenhouse gas (GHG) emissions in metric tons of carbon dioxide equivalent (CO_2e). Includes emissions from upstream fuel production and downstream vehicle operation. Does not include the vehicle material cycle.

Table 12 Fuel and greenhouse gas emission savings of trucks with alternative propulsion technologies relative to current and future gasoline light trucks. Assumes 240,000 km of vehicle operation over 15 years.[36]

LIGHT TRUCKS	RELATIVE TO CURRENT GASOLINE VEHICLE					RELATIVE TO 2035 GASOLINE VEHICLE					
	Current Gasoline	Current Diesel	Current Turbo Gasoline	Current Hybrid	2035 Gasoline	2035 Diesel	2035 Turbo Gasoline	2035 Hybrid	2035 Plug-in Hybrid	2035 Battery Electric	2035 Fuel Cell
Change in TTW fuel consumption [MJ / km][37]											
Petroleum	0.00	-1.13	-0.74	-1.31	-1.61	-0.58	-0.42	-1.22	-2.00	-2.77	-2.77
Electricity	--	--	--	--	--	--	--	--	0.32	0.89	--
Hydrogen	--	--	--	--	--	--	--	--	--	--	0.74
Total	0.00	-1.13	-0.74	-1.31	-1.61	-0.58	-0.42	-1.22	-1.68	-1.88	-2.03
Change in TTW fuel cost[38] [$]											
@ $2.5 / gal.	0	-3,714	-2,441	-4,330	-5,306	-1,910	-1,380	-4,032	-5,880	-7,136	-3,701
@ $5.0 / gal.	0	-7,428	-4,881	-8,659	-10,612	-3,820	-2,759	-8,065	-12,480	-16,262	-12,827
Net price [$][39]											
@ $2.5 / gal.	0	-1,614	-1,641	1,970	-3,106	190	-580	-832	2,420	14,964	3,699
@ $5.0 / gal.	0	-5,328	-4,081	-2,359	-8,412	-1,720	-1,959	-4,865	-4,180	5,838	-5,427
Change in WTW GHG emissions[40]											
Emitted [tCO_2e]	0	-23	-16	-29	-36	-12	-9	-27	-28	-17	-28
Abatement price [$\$/tCO_2e$]	--	89	49	217	62	177	86	118	294	1,322	268

[36] Vehicle travel is taken from NHSTA (2006, Tables 7 and 8, pp. 22, 25) as the average of car and light truck annual travel over the first 15 years of vehicle life.
[37] Change in tank-to-wheel (TTW) fuel consumption for each propulsion system relative to current and future gasoline vehicles.
[38] Change in TTW fuel cost is calculated using a 7% discount rate, an electricity cost of $0.05 / kWh, and a hydrogen cost of $3.50 / kg (NRC, 2004). Change in fuel cost is calculated for two gasoline and diesel prices: $2.50 / gallon and $5.00 / gallon.
[39] Net price is equal to a propulsion technology's retail price increase (see Table 8) plus the change in TTW fuel cost. A negative result indicates that the fuel savings provided by the propulsion technology are greater than its increase in retail price.
[40] Well-to-wheel (WTW) greenhouse gas (GHG) emissions in metric tons of carbon dioxide equivalent (CO_2e). Includes emissions from upstream fuel production and vehicle operation. Does not include the vehicle material cycle.

2.4 Conclusions from vehicle technology assessments

The results of our vehicle technology assessment suggest the following conclusions:

1. Conventional naturally aspirated spark-ignition engine technology offers a path for continuous vehicle efficiency improvements for the next several decades. Realizing the potential for these improvements requires that technological advances be directed toward improving fuel consumption rather than vehicle performance or size.

2. The efficiency of spark-ignition and diesel engine technologies will converge in the future. In particular, continued downsizing of gasoline engines enabled by improved power density results in the gasoline engine improving more rapidly than the diesel; at the same time, diesel vehicles must respond to increasingly stringent emissions requirements, which carry a fuel efficiency penalty. In addition, assuming that knock limitations are addressed, turbocharged gasoline engines have the potential to become almost equivalent with low-emissions diesel engines in terms of efficiency, performance and GHG emissions.

3. Over the time horizon in question, the gasoline hybrid-electric vehicle offers a promising path to cost-effective reductions in fuel use and greenhouse gas emissions. Relative to conventional spark-ignition and diesel technology, gasoline hybrids are projected to offer substantial efficiency gains and a narrowing price premium. In the nearer term, other advanced technology vehicles will continue to suffer from high cost and a limited presence in the market, making it unlikely that they will have significant impacts over a 20- to 30-year time horizon.

4. The plug-in hybrid offers important advantages over both fuel cell and battery-electric vehicles with respect to fueling infrastructure, vehicle range, and technological risk. First, it does not require changes to the fueling infrastructure on the same scope as either the fuel cell, which would require extensive ramp-up in hydrogen production and distribution, or as the electric vehicle, which would likely require rapid-recharge electric fueling stations and major upgrades to the electricity generation and distribution infrastructure. Second, it is not range-limited in the same sense as an electric vehicle, for which increasing the electric range appears to be prohibitively expensive, or as a fuel cell vehicle, for which meeting consumer-driven range requirements is likely to require a large and expensive high-pressure storage tank. The key technical challenges facing plug-in hybrid vehicles revolve around demonstrating the reliability of lithium-ion batteries in an automotive context and reducing battery size, weight, and cost. While formidable, these hurdles appear far less daunting than those required to bring fuel cell or battery-electric vehicles to a mass market.

5. Even with optimistic battery assumptions, the battery electric vehicle is not competitive with other options in a mass-market context, particularly in comparison to the different plug-in hybrid options. Configuring a vehicle to offer a relatively modest 200-mile range would require a prohibitively large and expensive battery pack ($7,000–$10,000 incremental factory cost). 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.

6. The fuel cell vehicle assessment is characterized by a high degree of technical uncertainty with respect to both the power plant and energy storage. This technical risk manifests itself primarily in terms of uncertainty with respect to fuel cell system costs rather than system efficiency. It is also not yet clear that fuel cell vehicles will offer the real-world reliability and longevity that is commonly expected of general-purpose vehicles. However, automotive fuel cell systems are not a mature technology, and significant across-the-board improvements have been demonstrated in the last several years. If this pace of development continues, fuel cell vehicles could compete with gasoline hybrid or conventional technologies. Although not a focus of this report, the more daunting long-term challenge may arise from the combined need for developing a marketable vehicle in parallel with deploying a new hydrogen supply and fueling infrastructure.

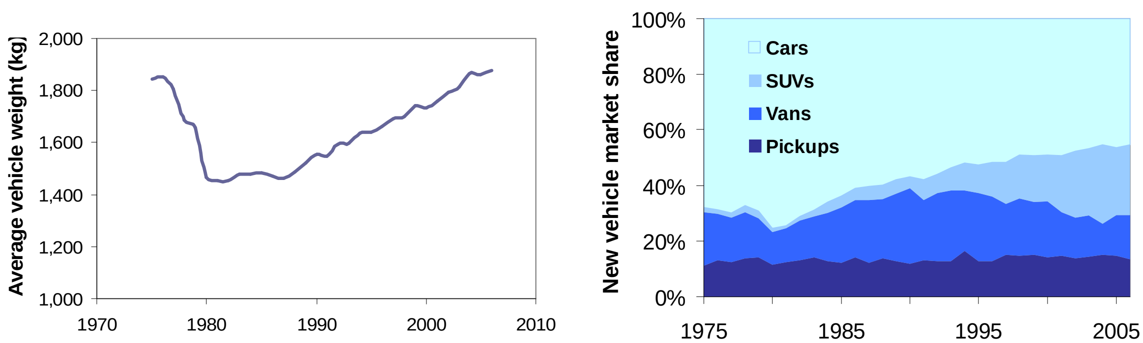
3.0 Vehicle Weight Reduction Options

3.1 Introduction

Vehicle weight reduction is a well-known strategy for improving fuel consumption in vehicles, and presents an important opportunity to reduce fuel use in the transportation sector. By reducing the mass of the vehicle, the inertial forces that the engine has to overcome are less, and the power required to move the vehicle is thus lowered. In this section, weight reduction as a strategy to reduce fuel consumption will be explored, primarily on the vehicle level. The effects of weight reduction on fuel use on the light-duty vehicle fleet level will be examined in Section 7.

3.2 Historical vehicle weight trends

In the United States, the sales-weighted average new light-duty vehicle weight is 1,880 kg (4,144 lb) today, and has been increasing slowly but steadily at a rate of about 1% per year since the early 1980s (see Figure 10 (a)). Since the mid 1980s, the popularity of larger and heavier light trucks, especially sport utility vehicles (SUVs), was partly responsible for the upward weight trend. The market share of SUVs has increased by more than a factor of 10, from less than 2% of the new light-duty vehicle market in 1975 to 27% of the market today. Conversely, the market share of new passenger cars and station wagons has decreased by more than 30% (Figure 10 (b)). [EPA 2007]



(a) sales-weighted average new U.S. light-duty vehicle weight (b) market share of new U.S. light-duty vehicles by segment

Figure 10 Historical sales-weighted average new U.S. light-duty vehicle weight 1975–2006 [Heavenrich 2006; EPA 2007]

While the shift from smaller vehicles to larger and heavier segments is partly responsible for the increasing average vehicle weight, weight increase within vehicle classes or segments is also taking place. For instance, the weight of a new Toyota Corolla recently introduced in the United States is about 100 kg heavier than the same model introduced 10 years ago (Figure 11). One reason for this is “feature creep”; the increasing number of new features that have been introduced into vehicles that improve utility such as comfort and safety, which also add weight. Examples include power folding seats, heated seats, navigation systems, additional speakers, and safety features like side air bags.

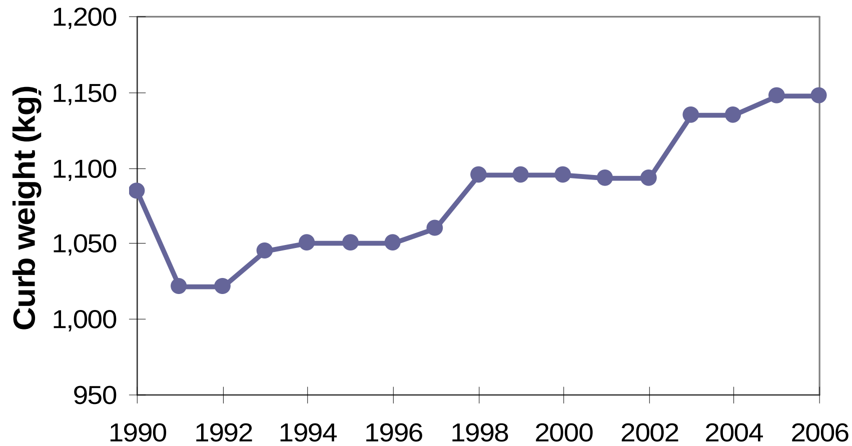


Figure 11 Curb weight of Toyota Corolla models introduced in the United States, model years 1990–2006

Increasing vehicle weight has not always been the trend. Between 1976 and 1982, automakers reduced the weight of the average new vehicle in response to the "energy crisis," which saw sudden increases in fuel prices, gasoline lines and rationing, and the enactment of federal Corporate Average Fuel Economy (CAFE) regulations. They did so primarily by downsizing the fleet and by shifting from heavier body-on-frame to lighter-weight unibody designs.[41] With new U.S. CAFE standards now legislated, interest in vehicle weight reduction is expected to intensify.

3.3 Effectiveness of vehicle weight reduction

It is clear that vehicle weight reduction has the potential to reduce fuel consumption, but the precise relationship is not so obvious. Figure 12 plots the adjusted, combined city/highway (55/45) fuel consumption and curb weights of all model year 2005 light-duty vehicles offered in the United States, revealing a general positive correlation. On average across all available vehicle models, every 100 kg weight reduction will achieve a reduction of 0.69 L/100km in fuel consumption. While these figures are useful to detect a general trend, they are not normalized for performance, size, or other attributes.

[41] The body-on-frame involves mounting the separate vehicle body to a weight-bearing rigid frame, which also supports the engine, driveline and suspension. In contrast, the unibody has the vehicle body integrated into a single unit with the chassis.

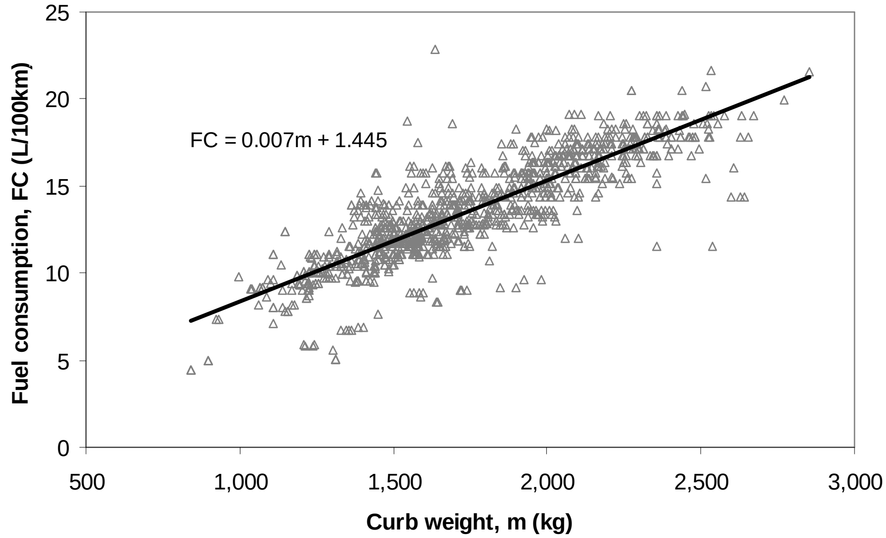


Figure 12 Curb weight and fuel consumption of U.S. model year 2005 vehicles

Many studies describe the vehicle fuel consumption reduction benefit associated with lightweighting [Wohlecker et al. 2007; NRC 2002]. The reported improvement in fuel consumption varies widely, from 4.5–8.0% for every 10% reduction in vehicle weight. Other studies report the benefit in absolute gains, where the improvement in fuel consumption ranges from 0.15–0.70 L/100km for every 100 kg of weight reduction. Factors that affect this relationship include the size and type of vehicle, the drive cycle used to evaluate the vehicle, and the powertrain.

We are primarily interested in the effect of vehicle weight reduction on its fuel consumption, at constant performance and size, for the average new vehicles being driven in the United States. To estimate this, simulations of representative vehicle models were run using AVL© ADVISOR vehicle simulation software. We selected the model year 2005 Toyota Camry and the Ford F-150, the best-selling vehicles in the United States, to represent the average car and light truck. The fuel consumption of these gasoline internal combustion engine vehicles were estimated from simulations that combine both city (FTP-75) and highway (HWFET) drive cycle results.[42] The combined fuel consumption results were adjusted with the same correction factors used by EPA to better reflect expected on-road results.

The simulations revealed that leaving vehicle acceleration performance and size unchanged, for every 100 kg weight reduction, the adjusted, combined city/highway fuel consumption could decrease by 0.40 L/100km for cars, and 0.49 L/100km for light trucks in the United States (see Figure 13). In other words, for every 10% weight reduction from the average

[42] The Federal Test Procedure (FTP-75) is used by the U.S. Environmental Protection Agency (EPA) to certify the fuel economy and emissions performance of consumer vehicles for city driving. The highway fuel economy test (HWFET) driving cycle is used to simulate highway driving and estimate typical highway fuel consumption.

new car or light truck's weight, the vehicle's fuel consumption reduced by 6.9% and 7.6%, respectively.

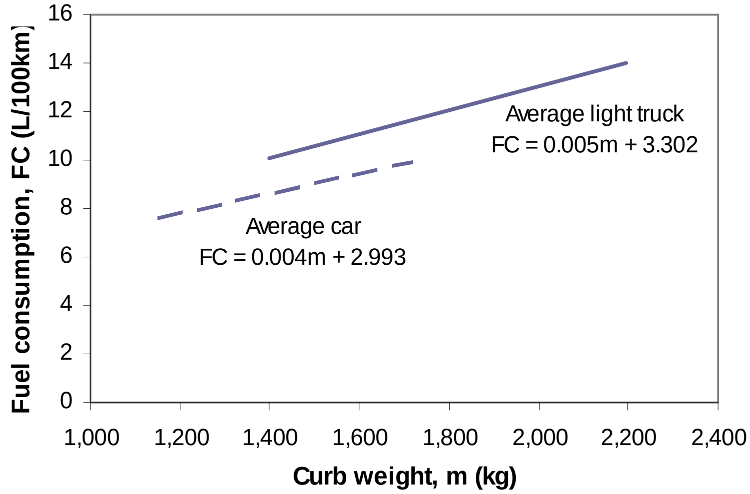


Figure 13 Simulation results: curb weight-fuel consumption relationship for today's vehicles

3.4 How vehicle weight reduction can be achieved

There are several ways to reduce the sales-weighted average weight of new vehicles sold in the United States. Weight reduction can be achieved by a combination of: 1) lightweight material substitution; 2) redesigning the vehicle to minimize weight; and 3) downsizing the new vehicle fleet by shifting sales away from larger and heavier vehicles. These approaches will be discussed in turn.

3.4.1 Vehicle weight reduction by lightweight material substitution

For an average vehicle, about three-quarters of its weight is incorporated in its powertrain, chassis, and body (Figure 14), and the bulk of this is made of ferrous metals. Other major materials found in an average automobile in the United States include aluminum and plastics or composites, as shown in Figure 15. This figure also shows how the use of aluminum and high-strength steel (HSS) as a percentage of total vehicle mass has been increasing over the past two decades, while the use of iron and mild steel has been declining.

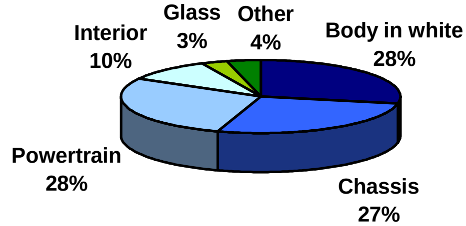


Figure 14 Vehicle mass distribution by subsystem [Stodolsky et al. 1995]

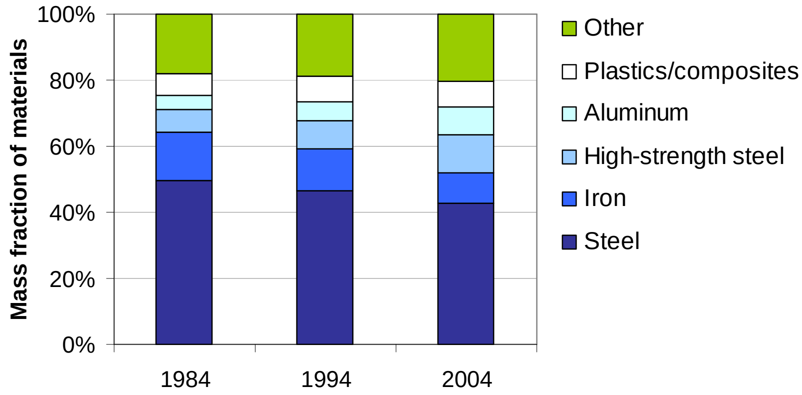


Figure 15 Material composition of the average automobile in the U.S. [Ward's 2006]

Aluminum and high-strength steel are two of several alternative lightweight materials that can be used to replace heavier steel and iron in the vehicle. Other material candidates include magnesium, and polymer composites such as glass- and carbon-fiber-reinforced thermosets and thermoplastics. The relevant properties of these materials are summarized in Table 13 below, and are discussed in turn. More costly and rarer alternative materials, such as metal-matrix materials and titanium, are not considered.

Table 13 Properties and prices of alternative lightweight automotive materials

Material	Density, g/cm^3 (relative)	Yield strength, MPa	Tensile strength, MPa	Elastic modulus, GPa	Relative cost per part [Powers 2000]
Mild steel	7.86 (1.00)	200	300	200	1.0
High strength steel (A606)	7.87 (1.00)	345	483	205	1.0-1.5
Iron (D4018)	7.10 (0.90)	276	414	166	-
Aluminum (AA6111)	2.71 (0.34)	275	295	70	1.3-2.0
Magnesium (AM50)	1.77 (0.23)	124	228	45	1.5-2.5
Composites - Carbon fiber - Glass fiber	1.57 (0.20)	Flexural: 200	810	190	2.0-10.0

High-Strength Steels (HSS). High-strength steels are manufactured using a combination of alloy compositions and processing methods to achieve high strength with almost the same formability as mild steel. HSS are a popular alternative automotive material because they make use of existing vehicle manufacturing infrastructure, and there is OEM support for near-term use. The challenge is to develop manufacturing technologies to make the production and use of these new materials economically viable on a high-volume scale, such as using tailored blanks and tube hydroforming. Today, one-fifth of the steel used in the average automobile is HSS, and this fraction has been increasing steadily. Using mostly dual-phase steel, the International Iron and Steel Institute's Ultralight steel Auto Body (ULSAB) Program demonstrated mass savings of 25% for a C-class (compact) car's body structure. HSS is an attractive nearer-term option, due to its relatively low cost and its accessibility.

Aluminum. Nine percent of the mass of the average automobile in the United States is aluminum. Most of the aluminum is cast, and used mainly in the engine, wheels, transmission, and driveline. The stamped-sheet aluminum body of a car is more difficult to form than steel, and has to be handled with care to prevent scratches, because it is softer. Aluminum is a better conductor than steel, making it more difficult to spot weld, so it is more likely to use more laborious adhesive bonding rather than spot welding. Ducker Research projects that aluminum use in automotive applications will reach 144 kg per vehicle by 2010, but is unlikely to overtake steel, due to the higher cost of aluminum.

Magnesium. Magnesium alloy is 30% less dense than aluminum and 75% lighter than steel components. It is also easier to manufacture, having a lower latent heat (it solidifies faster, and die life is extended), and being easier to machine. However, it has a lower ultimate tensile strength, fatigue strength, modulus, and hardness than aluminum. Promising automotive applications include structural components in which thin-walled magnesium die castings may be used. About 40% of magnesium in vehicles today is cast into instrument panels and cross car beams. Other applications include knee bolsters, seat frames, intake manifolds, and valve covers. Magnesium content in vehicles is expected to grow from 3.5 kg today to 7.3 kg in 2010 [Ducker 2002]. The U.S. Automotive Materials Partnership (USAMP) announced an ambitious goal of raising this to almost 160 kg by 2020. However, factors limiting the growth of magnesium by the automotive industry include the development of creep-resistant alloys for high-temperature applications, improvements in the die casting quality and yield, corrosion issues, and the production of magnesium in sheet and extruded forms.

Polymer composites. Plastics and polymer composites currently make up about 8% of a vehicle by weight and 50% by volume, and these numbers are expected to increase slowly. The main factors restricting the growth of polymer composites in vehicles today are the long production cycle times and the cost of the fibers. The most common type of automotive composites is glass fiber reinforced thermoplastic polypropylene, which is applied to rear hatches, roofs, door inner structures, door surrounds, and brackets for the instrument panel. Other types include glass mat thermoplastics, sheet molding compounds made of glass fiber reinforced thermoset polyester, and bulk molding compounds or glass fiber reinforced thermoset vinyl ester. Carbon fiber reinforced polymer (CFRP) composites are more expensive and less popular, although they offer significant strength and weight-saving benefit. The Rocky Mountain Institute's mid-size concept Hypercar used CFRP to achieve a body-in-white weight that is 60% lighter than a conventional steel one [Lovins and Cramer 2004]. However, carbon fibers cost an inhibiting $13–$22 per kilogram, compared to $1–$11 per kilogram of glass fibers [Das 2001]. Use is typically restricted to low-volume applications in high-end luxury vehicles. One successful application in production vehicles is the carbon fiber drive shaft. Other technical challenges of using CFRP include the infrastructure to deliver large quantities of materials and the recycling of composites at the vehicle's end of life.

To summarize the lightweight material candidates, a comparison of these options is given in Table 14. Of the candidates, aluminum and HSS are more cost-effective at large production volume scales, and their increasing use in vehicles is likely to continue. Cast aluminum is most suited to replace cast iron components, stamped aluminum for stamped steel body panels, and HSS for structural steel parts. Polymer composites are also expected to replace some steel in the vehicle, but to a smaller degree given high cost inhibitions.

Table 14 Comparison of alternative lightweight automotive materials

Material	Current use	Merits	Challenges
Aluminum	130 kg/vehicle, 80% are cast parts e.g. engine block, wheels	- Can be recycled - Manufacturers familiar with metal forming	- High cost of Al - Stamped sheet is harder to form than steel - Softer and more vulnerable to scratches - Harder to spot weld, uses more labor-intensive adhesive bonding
High-strength steel	180 kg/vehicle, in structural components e.g. pillars, rails, rail reinforcements	Makes use of existing vehicle manufacturing infrastructure; there is OEM support for near-term use	- More expensive at higher volume scale - Lower strength-to-weight ratio compared to other lightweight materials
Magnesium	3.5 kg/vehicle, mostly thin-walled cast parts e.g. instrument panels and cross car beams, knee bolsters, seat frames, intake manifolds, valve covers	Low density, offering good strength-to-weight ratio	- Higher cost of magnesium components - Production of magnesium in sheet and extruded forms
Glass-fiber reinforced polymer composite	Some rear hatches, roofs, door inner structures, door surrounds and brackets for the instrument panel	- Ability to consolidate parts and functions, so less assembly is required - Corrosion resistance - Good damping and NVH control	- Long production cycle time, more expensive at higher volume scale - Cannot be recycled
Carbon-fiber reinforced polymer composite	Some drive shafts, bumpers, roof, beams and internal structures	Highest strength-to-weight ratio, offering significant weight-saving benefit	- As with glass fiber composites - High cost of fibers ($17-22/kg)

Vehicle weight reduction by redesign and secondary weight savings

On a component level, the amount of weight savings resulting from using alternative materials in any vehicle component depends on the application and design intent. For instance, for a body panel designed for strength and resistance to plastic deformation, 1 kg of aluminum can replace 3–4 kg of steel. For a structural component designed for stiffness in order to restrict deflection, 1 kg of aluminum replaces only 2 kg of steel. On a vehicle-level, with aggressive use of lightweight materials, net weight savings of 20–45% can be obtained, as has been demonstrated in a few concept vehicles (see Table 15).

Table 15 Concept lightweight automobiles that embody lightweight materials

Vehicle	Vehicle segment	Curb weight (kg)	Weight savings (%)
Stodolsky, et al. (1995) aluminum-intensive car	Midsize sedan	--	19%
DaimlerChrysler Dodge Intrepid ESX2 concept composite- and aluminum-intensive car	Midsize sedan	1,021 kg	37%
IISI ULSAB-AVC concept high-strength steel intensive car	Midsize sedan	998 kg	38%
Ford P2000 concept aluminum-intensive car (similar to Ford Taurus)	Midsize sedan	912 kg	44%

3.4.2 Vehicle weight reduction by redesign and secondary weight savings

Redesigning or reconfiguring the vehicle is another strategy to achieve weight savings. For example, a marked decline in vehicle weight in the early 1980s was partly achieved by changing some vehicles from a heavier body-on-frame to lighter-weight unibody designs. Although most cars already have a unibody design, the potential exists for smaller sport-utility vehicles to follow suit.

Another way to minimize weight with creative design and packaging is to minimize the exterior dimensions of the vehicle while maintaining the same interior space, or to remove features from the vehicle. Figure 16 plots the interior volume of various midsize sedans offered in model year 2007 with their curb weights, illustrating the potential weight savings using this approach. However, it is acknowledged that the need for safety features, either by regulation or consumer demand, may hinder lightweight vehicle design using this approach.

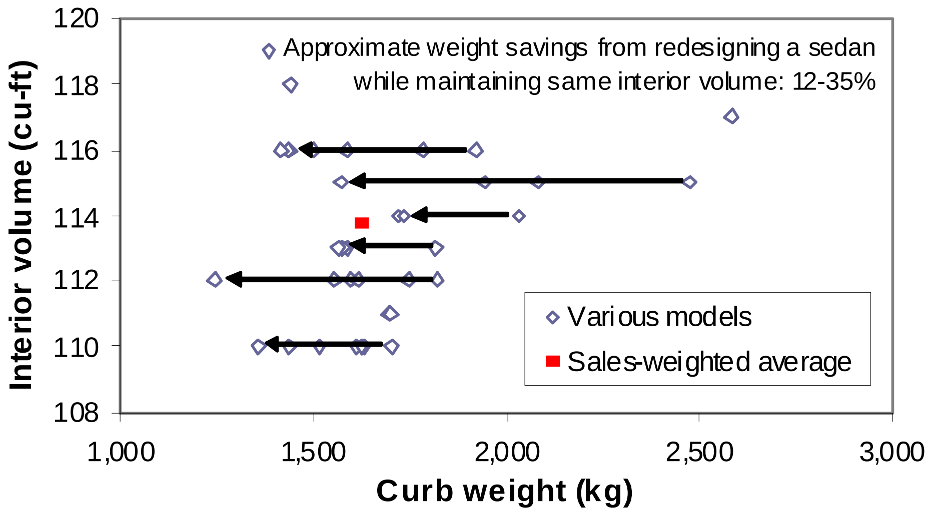


Figure 16 Potential weight savings from redesigning model year 2007/2008 midsize sedans while maintaining same interior volume

Secondary weight savings can also be realized by downsizing subsystems that depend on the total vehicle weight. As the vehicle weight decreases, the performance requirements of the engine, suspension, brake subsystems and others are lowered, and these can be resized accord-accordingly. Recently, researchers at the University of Michigan estimated a 1.25 factor for secondary, compounded weight savings by observing the mass of all subsystems in 35 different vehicle models. [Malen and Reddy 2007] That is, for every 1.00 kg initial mass change, an additional 1.25 kg of mass savings will be realized by resizing subsystems accordingly. It is acknowledged in this report that their approach does not normalize the data for other parameters, such as vehicle size or acceleration performance, which could lead to less optimistic weight savings. For example, simulations of the Toyota Camry reveal that if the car's body weight is reduced by 100 kg using material substitution, the engine weight can be lowered by only 9 kg while delivering the same vehicle acceleration performance.[43]

Reviewing these novel design options, it is clear that the amount of weight savings using this approach is not easily quantified and depends on the final designs of subsystems and the entire vehicle. The amount of secondary weight savings possible by vehicle redesign was moderated; we assumed it to be half the benefit achieved with material substitution. So, for every incremental kilogram of weight reduction from material substitution, one can expect to achieve a further 0.5 kg weight savings with weight-minimizing redesign.

3.4.3 Vehicle weight reduction by size reduction

Vehicle size reduction, the third way to reduce vehicle weight, is distinguished from the two weight-reduction approaches already discussed. Vehicle size generally correlates with weight. This can be seen in Figure 17, which shows vehicle size in terms of a modified footprint—its wheelbase multiplied by overall width—and curb weight of all model year 2005 light-duty vehicle models offered in the United States.

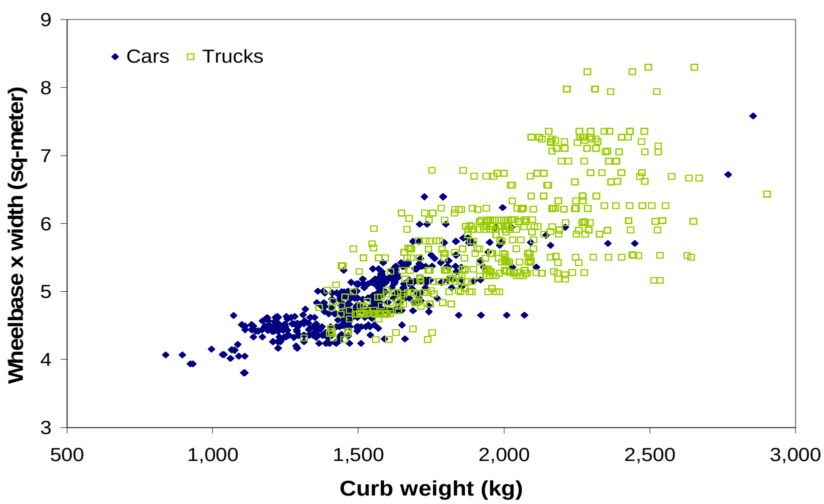


Figure 17 Size (footprint) vs. weight of U.S. vehicles offered in model year 2005

[43] Assuming a constant engine power density of 0.74 kW/kg.

By shifting sales away from larger and heavier vehicle types, reduction in the sales-weighted average new vehicle weight can be obtained. This can be done by 1) reversing the recent sales trend *across* vehicle segments towards larger vehicles, that is, selling more cars instead of light trucks for instance; or 2) by downsizing vehicles *within* each vehicle segment—selling fewer large vehicles in each segment.

Figure 18 shows the 2005 sales distribution of new vehicles by a modified footprint measurement. The distributions are distinguished between the car and light truck segments. The average car (1,630 kg) weighs almost 25% less than the average light truck (2,140 kg).

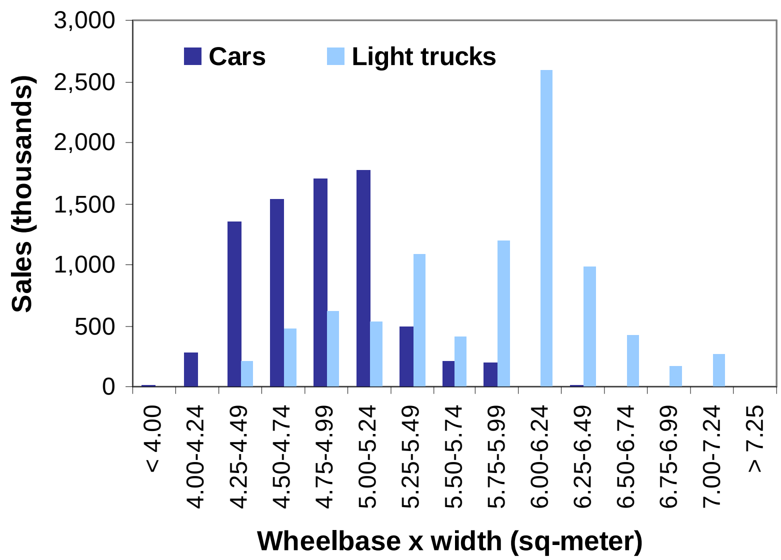


Figure 18 U.S. light vehicle sales distribution in 2005 by size [data from Ward's 2006]

Within the car segment, the average new U.S. car size as measured by interior volume (passenger plus cargo room) has remained relatively unchanged since the 1980s. The average car size decreased in the late 1970s as a response to the oil crisis, but returned close to the pre-crisis levels shortly after and has been growing slightly since (Figure 19).

If large cars were downsized to midsize, and midsize to small (size classes as defined by U.S. EPA), weight savings of 9–12% could be achieved. For other vehicle segments including SUVs, minivans and pickups, weight savings of up to 26% can be seen, as shown in Figure 20.

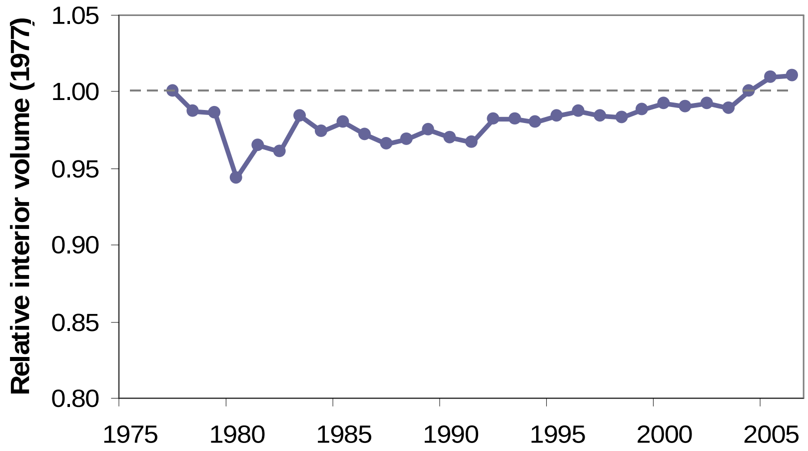


Figure 19 Historical new U.S. car interior volume relative to 1977 values

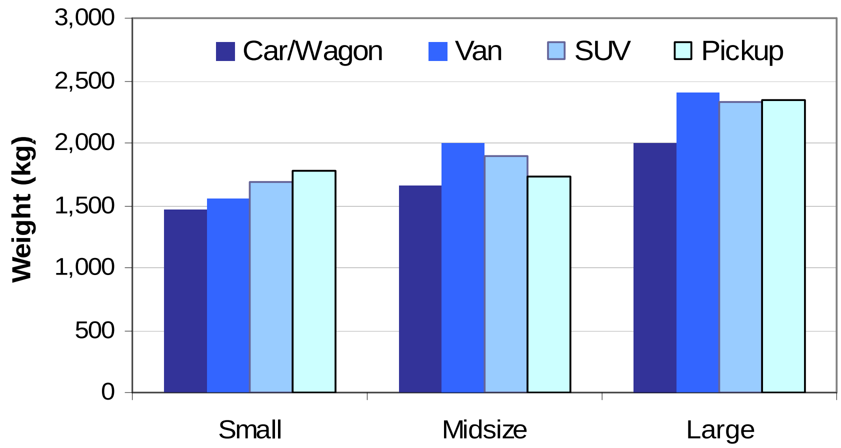


Figure 20 Three-year (2005–2007) sales-weighted average U.S. vehicle weights by EPA size class [EPA 2007]

3.5 Brief discussion on safety

The discussion of vehicle lightweighting is not complete without some mention of safety implications. There is much debate on this topic, and there are studies that indicate how drivers and occupants of smaller and lighter vehicles are at a greater risk in crashes than those in larger and heavier vehicles. The question of how vehicle weight reduction affects overall traffic safety is not as straightforward, however, and is confounded by other driver-, road-, and accident-related factors.

We believe that there will be little compromise in safety standards when reducing the weight and size of the vehicle, for two reasons. First, it is possible to design and build quality small vehicles with similar crashworthiness as larger and heavier ones. Use of new materials, such as aluminum and some composites designs, can offer superior cash energy absorption. By reinforcing the structural stiffness of the vehicle at critical points, including safety features such as side airbags, and introducing crumple zones to absorb energy in case of a collision, automakers are already making smaller cars that protect their occupants better. For example, the MINI Cooper scored 4 out of 5 stars in the U.S. National Highway Traffic Safety Administration frontal and side crash ratings.

Second, aside from the crashworthiness of the vehicle and driver safety, there are other facets of the traffic safety discussion to be considered, including rollover risk, aggressiveness of vehicles to other road users, and vehicle crash compatibility. Considering net or overall traffic safety, some of the larger and heavier SUVs and pickups can actually pose greater safety risks for their drivers and other road users [Ross et al. 2006]. Hence, there is little compromise in safety as vehicle weight and size is reduced, and safety for all might actually improve if the heaviest vehicles could be made lighter.

3.6 Cost of vehicle weight reduction

Cost is an important consideration, because we are interested in detailing the benefits associated with vehicle weight reduction at an acceptable cost of implementation. For weight reduction using lightweight materials, automakers have been reluctant to adopt new materials and manufacturing processes, in part because of the established infrastructure, capital equipment, and knowledge base to promote use of conventional materials, and also because of the cost of substituting these alternative lightweight materials.

Cost estimates of using lightweight automotive materials in the literature vary widely, from $1.20 to $13.70 per kilogram of weight savings. This is not surprising, since much depends on the type of lightweight material proposed, the vehicle component, assumptions made on the processing of the materials, and the production volume.

When comparing the use of lightweight materials in different vehicle components, we reiterate that the weight reduction benefit depends very much on the intended use and design. So the substitution of a lightweight material, say aluminum, for steel brings about a wide possible range of weight reduction for different components. To get a sense of potential applications of lightweight materials in vehicles and their corresponding manufacturing (OEM) costs,[44] results from different case studies available in the literature are summarized in Table 16. Most of the case studies examined lightweight material applications in the body-in-white.

[44] The incremental manufacturing or OEM cost can be converted to retail price by using factors to include the additional overhead. Shaw et al. [2002] used a factor of 2.08, including logistics. Stodolsky et al. [1995] used a factor of 1.55-1.80, including 20% gross margin and 15% dealer discount.

Table 16 Incremental manufacturing cost compared to conventional steel alternative

Lightweight vehicle / component	Incremental OEM cost[45]	Weight reduction	US$ per kg reduction	Volume per yr	Source
General lightweight vehicle	-	-	2.20 to 3.70	-	NRC 2002
High strength steel (HSS)-intensive					
Front end	-$13	11 kg	-1.20	-	Roth 2006
SUV frame	-	(-23%)	0.68	220,000	Altair 2003
Body-in-white	-$32-52	52-67 kg	-1.00 to -0.47	225,000	Shaw 2002
Aluminum-intensive					
Vehicle	$661[46]	346 kg	1.91	200,000	Stodolsky 1995
Unibody	$537	138 kg	3.88	500,000	Han 1994
Polymer composites-intensive					
Body (glass fiber reinforced)	$400	127 kg	3.16	100,000	Kang 1998
Body (glass fiber-thermoset)	$930	68 kg	13.68	250,000	Dieffenbach 1996
Body (carbon fiber reinforced)	-	-	2.20 to 8.82	-	Das 2001
Body (carbon fiber reinforced)	$900	196 kg	4.59	100,000	Kang 1998
Body (carbon fiber-thermoset)	$728	114 kg	6.39	100,000	Mascarin 1995
Vehicle (carbon fiber)	$2,926	444 kg	6.59	200,000	Stodolsky 1995
Body (carbon fiber-thermoplastic)	$1,140	145 kg	7.86	250,000	Dieffenbach 1996

In general, the cost of alternative lightweight automotive material technology per unit weight savings is lower for high-strength steel (HSS), and is followed by aluminum and polymer composites. Automotive composites remain prohibitively expensive given high raw material prices and long production cycle times. HSS and aluminum are likely to remain popular substitutes for steel in passenger vehicles in the near-term.

Given this review, we will assume a mid-range estimate of $3.00–$5.00 per kilogram of weight savings by material substitution. Costs will be on the lower end for early weight reduction, and increase as more aggressive weight reduction is sought. Vehicle redesign and size reduction are simply assumed to be cost-neutral with respect to manufacturing costs. We assume that design costs are already incorporated in the development of new vehicle models and the

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[45] The cost of engine downsizing that could accompany vehicle weight reduction is not included.
[46] For Stodolsky's estimates, the incremental manufacturing cost is the difference in raw material cost only.

manufacturing costs of producing a smaller or larger vehicle do not differ much. As a result, the net cost of weight reduction by all three approaches would be $2.00–$3.50 per kilogram shaved off the average vehicle.

3.7 Summary on vehicle weight reduction

Reduction in vehicle size and weight can significantly reduce fuel consumption. Every 10% of weight reduced from the average new car or light truck can cut fuel consumption by around 7%. The three strategies to reduce weight are (1) lightweight material substitution, (2) vehicle design changes, and (3) vehicle downsizing.

When alternative materials are used to perform lightweighting, aluminum and high-strength steel are more cost effective at large production scales. Plastics and polymer composites, which cost more, will likely take a smaller role. With aggressive material substitution, up to 20% of vehicle weight can be cut. Secondary weight savings can be realized by downsizing subsystems. It is also possible to reduce weight by redesigning or reconfiguring the vehicle. Creative designs can minimize the exterior dimensions of the vehicle while maintaining the same interior space.

Average vehicle weight can also be reduced by downsizing vehicles. That means selling more small vehicles and fewer large ones, both across and within vehicle segments. If a buyer were to choose a small car instead of a midsize, or a midsize instead of a large car, the vehicle's weight could be reduced by 9% to 12%. For SUVs, minivans and pickups, the weight savings can reach 26%.

Based on these assessments of material substitution, vehicle redesign, and downsizing, weight reduction of 20-35% is possible by 2035. We estimate that weight reduction by all three approaches would cost $2 to $3.50 per kilogram of weight saved in the average vehicle.

4.0 Vehicle Fuel Consumption, Performance, and Size Trade-Offs

While engine and vehicle technology have steadily improved over the past 20 years and vehicles have become more efficient at utilizing their fuel's energy, the average fuel consumption of new vehicles sold each year has not changed. The higher efficiencies achieved have been used to offset the impacts of increasing size, weight, power, and other performance attributes of automobiles. This section evaluates the trade-off between the seemingly ever-increasing performance and size of vehicles, and the penalty it imposes on U.S. light-duty vehicle fleet fuel use.

4.1 Vehicle size, weight, power, and fuel economy trends

Since the mid-80s, the average fuel consumption of U.S. light-duty vehicles (LDVs) has remained nearly constant. This stagnation is often mistaken for a lack of advances in vehicle technology. The difference between efficiency and fuel consumption must be understood clearly in this context. Efficiency is a measure of how effectively fuel energy is used to supply the power that drives the vehicle. Fuel consumption is what consumers measure as they drive on the road (and what manufacturers report to the government): how effectively a vehicle uses the energy from fuel to travel a given distance, i.e., the liters of fuel consumed per 100 kilometers of vehicle travel.[47] In addition to holding other attributes constant, and using efficiency improvements to reduce fuel consumption, improved efficiency can also be utilized to offset the negative impact on fuel consumption while increasing vehicle acceleration and power, size, weight, or some combination thereof. An increase in vehicle efficiency can therefore be used to achieve several means: reductions in fuel consumption may be traded-off against increases in other attributes such as acceleration, power, and size.

The overall trend in car and light-truck performance in terms of horsepower, weight, size, and acceleration can be separated into three phases [Heavenrich 2006; Lutsey and Sperling 2005; An and DeCicco 2007]:

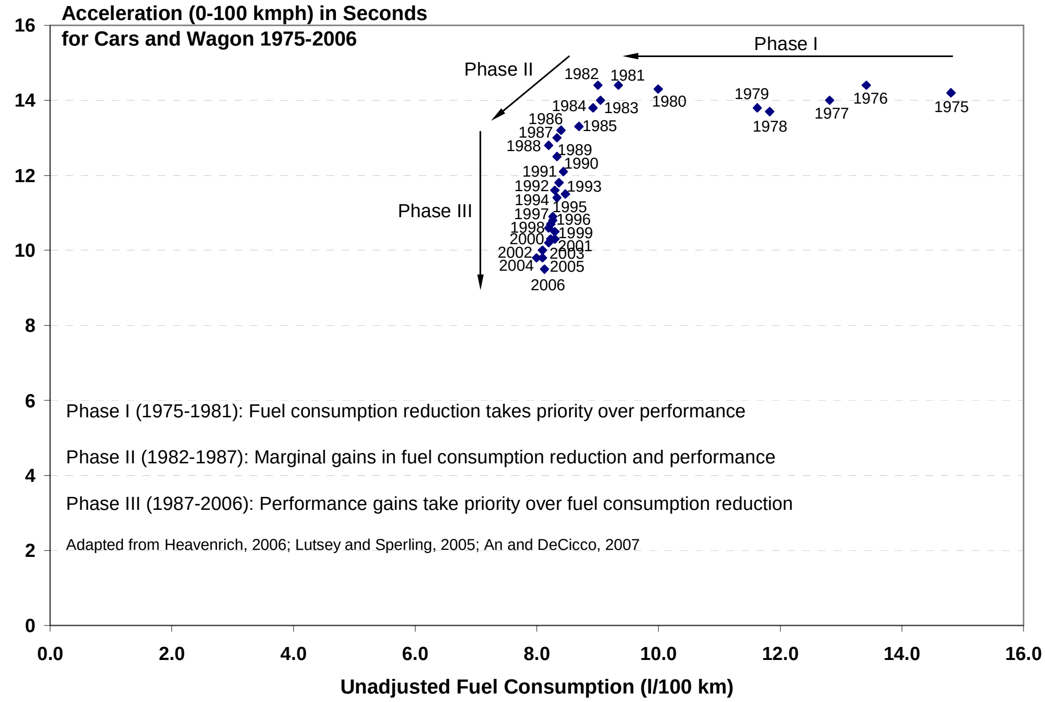
1. The first phase (1977–1981) shows a modest deterioration in vehicle performance (higher 0–100 km per hour time) and substantial reduction in fuel consumption. The fuel con-consumption of new cars and light trucks fell by 27% and 22%, respectively, during this period.

2. The second phase (1982–1987) is characterized by a reversal of the modest performance reductions from Phase I, and a slight reduction in fuel consumption. New cars and light-trucks fuel consumption decreased by 7.5% and 5.4%, respectively.

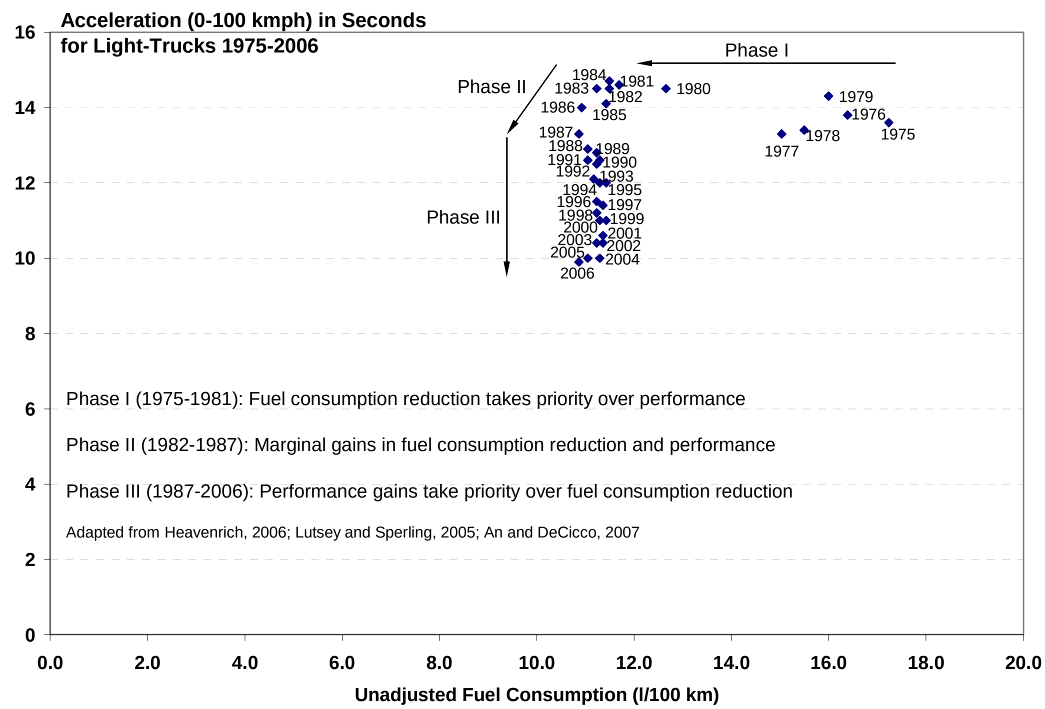
3. The third phase (1988–2005) shows a steady increase in LDV weight, horsepower, and acceleration. There was little further reduction in vehicle fuel consumption during this period.

[47] Fuel economy (expressed in miles per gallon) is the inverse of fuel consumption (expressed in liters per 100 km or gallons per mile). Although fuel economy is often used instead of fuel consumption, fuel consumption is the more basic measure for "fuel consumed" in driving a given distance.

The three phases of change in fuel consumption and vehicle performance, represented by 0–100 kmph acceleration time over the last 30 years, are shown in Figure 21.



(a) Cars



(b) Light-Trucks

Figure 21 Fuel consumption and acceleration of cars and light trucks (1975–2006)

These fuel consumption and performance trends can largely be explained by fuel prices and CAFE standards. High fuel prices induced by the 1970s oil crisis, and the fuel economy regulations of the mid-1970s through the early 1980s led, in Phase I, to efficiency improvements that directly reduced fuel consumption. The ratcheting up of CAFE standards stopped in 1985, just as fuel price began to decline. Taken together, these changes explain the only modest reduction in fuel consumption in Phase II. From the late 1980s until recently, the market for fuel consumption reduction has experienced neither *a pull* through high fuel prices, nor *a push* through more stringent CAFE standards. This has meant that gains in efficiency have been used to increase vehicle performance attributes such as power and weight, while keeping fuel consumption constant. The same period has also seen a shift away from cars towards light-trucks, particularly sport utility vehicles (SUVs) and minivans. The combined result of these trends has been a steady growth in US LDV fuel use since the late 1980s.

4.2 Emphasis on Reducing Fuel Consumption (ERFC)

What happens if the improvements in technology continue to be utilized to improve vehicle performance? Obviously, the fuel consumption trend that is realized in practice will depend on the degree of emphasis placed on reducing fuel consumption.

Kasseris and Heywood [2007] found that if the performance and size of the current Toyota Camry equivalent vehicle is kept constant, then the relative onboard fuel consumption of such a vehicle in 2035 would be 63% of its current value. Note that Kasseris and Heywood assume a 2035 vehicle that is 20% lighter than a current comparable car or light truck. In practice, however, vehicle manufacturers will continue to make improvements in performance, size, and safety features. Thus, not all of the gains from increased efficiency will be realized for the purpose of reducing fuel consumption—instead, a portion of the possible reduction in fuel consumption will be offset as other attributes also improve. For the purpose of understanding the influence of the performance–size–fuel consumption trade-off, we introduce a variable called *Emphasis on Reducing Fuel Consumption*, or ERFC for short.

$$\text{Emphasis on Reducing Fuel Consumption (ERFC)} = \frac{\text{Fuel Consumption (FC) Reduction Realized on Road}}{\text{FC Reduction Possible with Constant Performance and Size}}$$

$$ERFC = \frac{FC_{current} - FC_{realized}}{FC_{current} - FC_{potential}} \qquad (4.1)$$

$$FC_{realized} = FC_{current} - ERFC \times (FC_{current} - FC_{potential})$$

ERFC measures the degree to which improvements in technology are being directed toward reducing onboard fuel consumption. Thus, a 50% emphasis on reducing fuel consumption would mean that the above 2035 vehicle would realize a relative on-road fuel consumption value of $1 - 0.5 \times (1 - 0.625) = 0.8125$, as shown in Figure 22.

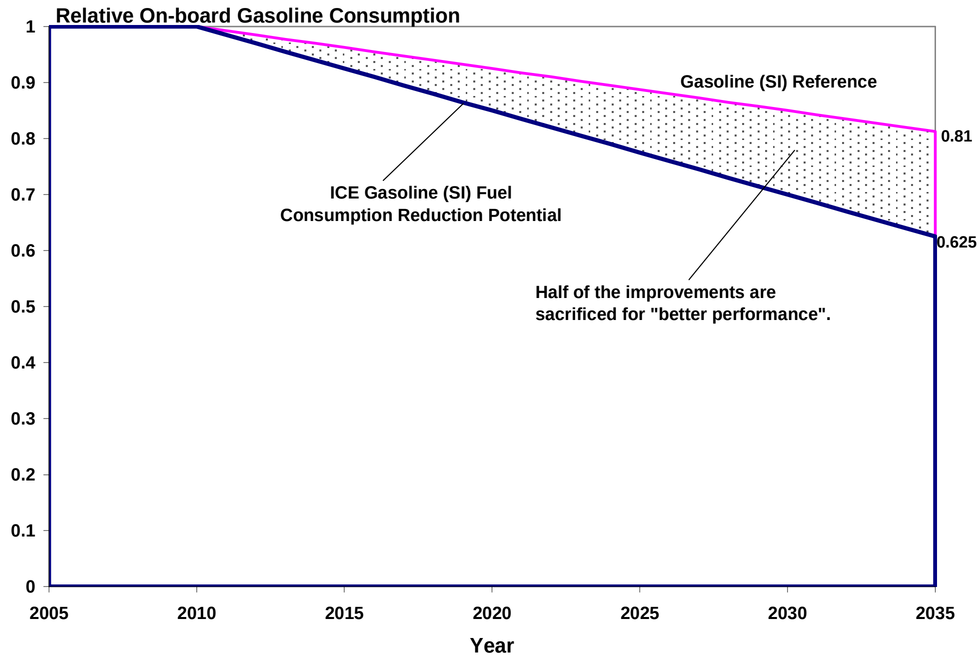


Figure 22 Average U.S. car relative onboard gasoline-equivalent fuel consumption at 50% ERFC

The value of ERFC also impacts the performance and weight of future vehicles. For example, at ERFC value of 25%, only a quarter of the plausible reductions in fuel consumption are realized. The remaining three-quarters of the potential technical improvement is used to increase the vehicle horsepower to weight ratio. Equation 4.2 is used to calculate the effect of increasing acceleration on horsepower [Heavenrich 2006; Santini and Anderson 1993].

$$t = F\ (HP/WT)^{-f} \qquad (4.2)$$

where,

t is an estimate of 0-to-60 mph acceleration time

HP is engine rated horsepower

WT is the vehicle inertia weight, which is calculated as curb weight plus 300 pounds

F is a constant; 0.892 for vehicles with automatic transmissions and 0.967 for vehicles with manual transmission

f is the exponent; 0.805 for vehicles with automatic transmissions and 0.775 for vehicles with manual transmission

While Kasseris and Heywood assume a 20% weight reduction in vehicle weight by 2035 for the 100% ERFC case, when ERFC is below 100%, the corresponding weight reduction is also scaled by ERFC. Thus, the 2035 ICE gasoline vehicle with 50% ERFC is assumed to be 10% lighter than the current ICE gasoline vehicle, and so on. The corresponding improvement in acceleration performance can be calculated by using equation 4.2. The results, shown in Table 17, allow us to gain a better appreciation for the fuel consumption benefits being traded off for higher horsepower and acceleration.

Table 17 Performance-fuel consumption trade-off for the average U.S. car in 2035 at different degrees of emphasis on reducing fuel consumption (ERFC)

(a) Passenger Car

	Current	2035					
		0% ERFC	25% ERFC	50% ERFC	75% ERFC	100% ERFC	120% ERFC
HP/WT (hp/lbs)	0.059	0.087	0.08	0.073	0.066	0.059	0.053
Vehicle Weight (kg)	1620	1620	1539	1458	1377	1295	1295
0-100 kmph (sec)	8.7	6.4	6.8	7.3	8.0	8.7	9.4
Unadjusted L/100 km	8.1	8.1	7.5	6.8	6.1	5.5	5.0

(b) Light-Truck

	Current	2035					
		0% ERFC	25% ERFC	50% ERFC	75% ERFC	100% ERFC	120% ERFC
HP/WT (hp/lbs)	0.049	0.068	0.063	0.058	0.054	0.049	0.044
Vehicle Weight (kg)	2083	2083	2034	1927	1820	1713	1713
0-100 kmph (sec)	10.2	7.8	8.2	8.8	9.4	10.2	10.9
Unadjusted L/100 km	10.0	10.0	9.3	8.6	7.9	7.1	6.6

4.3 European comparison

The fuel consumption versus performance trade-off has played out very differently in Europe, when compared to the U.S. As described in Cheah et al. [2008], and shown in Table 18, the ERFC in the four largest European passenger vehicle markets (Germany, Italy, France, and the UK) has been at or above 50%, except for one instance.

Table 18 Fuel consumption and ERFC in Europe's four largest markets[48]

	Gasoline			Diesel		
	$FC_{realized}$ (L/100km)	$FC_{potential}$ (L/100km)	ERFC (%)	$FC_{realized}$ (L/100km)	$FC_{potential}$ (L/100km)	ERFC (%)
France	6.6	6.2	68	5.5	4.9	64
Germany	7.4	6.7	54	6.5	5.1	22
Italy	6.5	6.3	83	5.7	5.0	61
UK	7.5	7.0	52	5.9	5.1	51

The other important distinctions to consider are that 1) the fuel consumption of today's vehicles is considerably lower in Europe, 2) the mix of vehicles in the future is expected to be

[48] The ERFC was calculated over the period 1995–2006 for France and Germany, and the period 1995–2001 for Italy and the UK. Due to discontinuities in the underlying fuel consumption, performance, and weight data starting in 2002, it was not possible to evaluate the ERFC for Italy and the UK through 2006.

different, and 3) fuel consumption of these vehicles in the future will also be lower and different than was projected in Table 6 for the United States. The following six powertrain technologies were chosen for the European country fleet models: diesel, NA gasoline, turbo gasoline, gasoline hybrid, diesel hybrid, and compressed natural gas (CNG). These technologies were selected because they are either currently sold in large numbers or, in the case of diesel hybrids, because at least a few major manufacturers have announced plans to commercialize their technologies over the next several years [Les Echos 2008; Green Car Congress 2007]. Fuel cell vehicles and plug-in hybrids were not considered because the authors do not expect them to account for a significant fraction of new vehicle sales (e.g., equal to or greater than 5%) in Europe by 2035. This judgment is based on the fact that there are currently no announced plans to commercialize either technology in Europe, cost premiums are projected to be high, and infrastructure challenges pose additional hurdles for adoption.

Table 19 details the current and future average fuel consumption levels of the powertrain technologies chosen for Europe. Current fuel consumption levels were adapted from CONCAWE et al.’s [2007] recent well-to-wheel study. Rather than performing a separate set of Advisor simulations, future fuel consumption levels were estimated by applying the relative improvement projected for the corresponding U.S. powertrains to the fuel consumption of today’s European vehicles.[49]

The current fuel consumption values of European vehicles are roughly 75% of vehicles in the United States. As a result, the magnitude of the projected changes in fuel consumption for different propulsion systems in the future are significantly less than the reductions available from U.S. powertrains.

Table 19 Projected improvement in 2035 vehicle fuel consumption in Europe

Propulsion System	Fuel Consumption* (l/100 km)	Relative to current gasoline ICE	Relative to 2035 gasoline ICE
Current Gasoline	6.57	1	--
Current Diesel (w/ DPF)	5.48	0.83	--
Current Turbo Gasoline	5.9	0.90	--
Current Gasoline Hybrid	5.02	0.76	--
Current Diesel Hybrid	4.51	0.69	--
Current CNG (dedicated)	5.82	0.89	--
2035 Gasoline	4.11	0.63	1
2035 Diesel	3.48	0.53	0.85
2035 Turbo Gasoline	3.66	0.56	0.89
2035 Gasoline Hybrid	2.73	0.42	0.66
2035 Diesel Hybrid	2.45	0.37	0.60
2035 CNG (dedicated)	3.61	0.55	0.88

* Gasoline Equivalent.

[49] Further details on fuel consumption calculations, as well as other aspects of the European analysis, are described in detail by Bodek and Heywood (2008) in *Europe’s Evolving Passenger Vehicle Fleet: Fuel Use and GHG Scenarios Through 2035*.

4.4 Summary

This section has introduced the concept of Emphasis on Reducing Fuel Consumption (ERFC), which defines what percentage of the improved efficiency from powertrain and vehicle technology employed in vehicles is used to reduce vehicle fuel consumption. The impact of steadily increasing vehicle performance on vehicle fuel consumption was evaluated using this index. We found that performance improvements in the U.S. during the past 20 years have been largely responsible for the growth in LDV fuel use during that time. We have also shown that large reduction in future LDV fuel use is possible with mainstream gasoline ICE vehicles alone, if the performance-size-fuel consumption trade-off is favorably resolved. In Europe, the relative vehicle performance increase in recent years has been about half the increase in the United States for both gasoline and diesel vehicles. Thus, the potential for further fuel consumption reductions by moderating improvements in vehicle performance and size is significantly less in Europe than in the United States.

5.0 Light-Duty Vehicle Fleet Model

5.1 Structure of the U.S. fleet model

The U.S. light-duty vehicle (LDV) fleet or "car parc" is composed of approximately 135 million cars and 100 million light-trucks, which include pickups, minivans, and sport utility vehicles (SUVs). New LDV sales in 2006 totaled nearly 16.6 million units, comprising 8.1 million passenger cars and 8.5 million light-trucks, or approximately 7% of the total LDV fleet. To evaluate the impact that emerging propulsion systems and fuels could have on total LDV fleet fuel use and greenhouse gas (GHG) emissions, the dynamics of fleet turnover and usage must be understood. This section explains the logic of the U.S. LDV Fleet Model used for this purpose.

The fleet model is a tool to track LDV stock, travel, fuel use, and greenhouse gas emissions. A simplified overview of the fleet model is shown in Figure 23. A description of previous versions of this model can be found in Heywood et al. [2004], and Bandivadekar and Heywood [2006]. The model is composed of several worksheets in Microsoft Excel that track new vehicle sales, market shares of different propulsions systems and their fuel consumption, vehicle aging and scrappage, vehicle stock, vehicle travel, and fuel mix. Historical data from 1960 onward is used to calibrate the model. In this section we describe the details of the model's individual building blocks.

5.2 Data sources

Three different public sources of data on U.S. LDVs were used:

- The Transportation Energy Data Book (TEDB) compiles data from a variety of trade publications, such as Motor Vehicle Facts and Figures, published by the American Automobile Manufacturers Association, and Ward's Automotive Yearbook. The TEDB data referred to here pertains to Edition 26 of the data book [Davis and Diegel 2007].
- The EPA Light-Duty Automotive Technology and Fuel Economy Trends report is a compilation of the data that are submitted for Corporate Average Fuel Economy (CAFE) standards and gas guzzler tax compliance purposes [Heavenrich 2006].
- The U.S. Department of Transportation report on Summary of Fuel Economy Performance compiled by National Highway Transportation and Safety Administration (NHTSA) for CAFE compliance [NHTSA 2008].

Wherever possible, the fleet model uses data compiled from these three sources. Other sources of data are listed where applicable in the following sections. The results of the model are calibrated against the light-duty vehicle data reported by the Federal Highway Administration [FHWA 2005], as compiled in the TEDB.

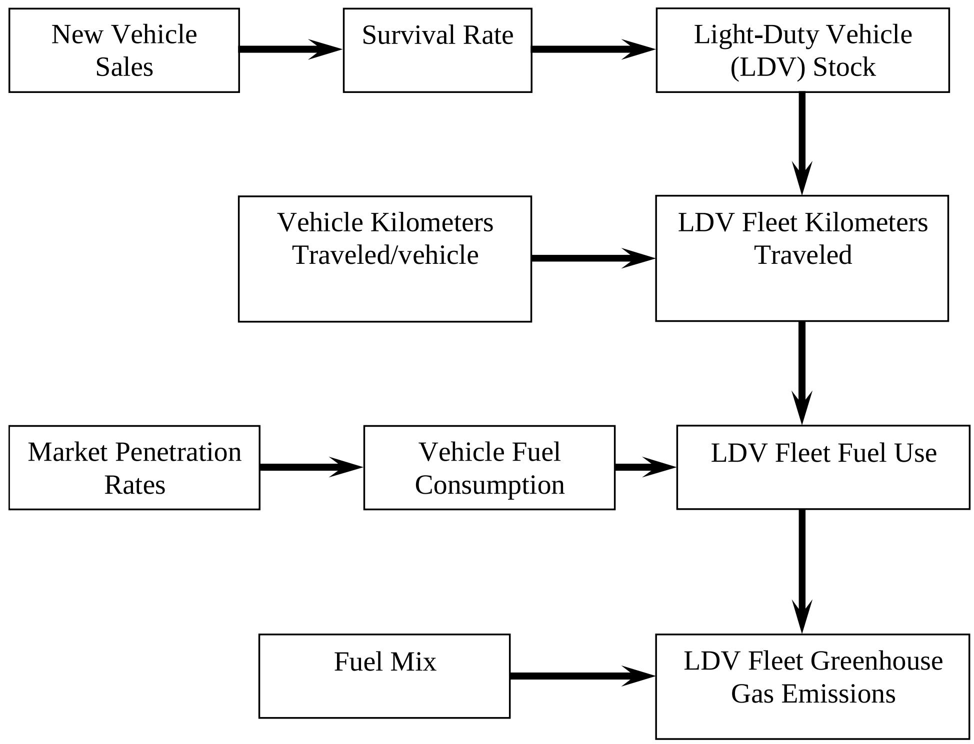


Figure 23 Fleet model overview

5.3 Sales mix

The annual sales of light-duty vehicles in the United States from 1970–2005 are shown in Figure 24. The differences in the data are due to different definitions and classification methods employed by the three data sets. Specifically, the TEDB sales numbers for light trucks include all light trucks weighing 4,550 kg (10,000 pounds) of gross vehicle weight (GVW) or less. The EPA and NHTSA data only include vehicles weighing less than 3,865 kg (8,500 lbs). The light trucks weighing between 8,500 and 10,000 lbs, known as Class 2b trucks, are estimated to account for 6–8% of total light truck sales [Davis and Truett 2002]. As a result, the TEDB sales numbers for light-trucks are substantially higher than the corresponding EPA or NHTSA numbers.

Starting in 2011, NHTSA plans to include in the CAFE program all SUVs and vans weighing less than 10,000 lbs, although light trucks weighing between 8,500–10,000 lbs will remain exempt. The default setting for calculating vehicle sales in the fleet model uses TEDB data, i.e., all light-duty vehicles weighing less than 10,000 lbs.

The share of light trucks in new LDV sales has increased from 15% in 1970 to over 50% in 2005. Much of this increase is due to increased numbers of sport utility vehicles (SUVs) and vans sold at the expense of small cars and wagons. The growth in the light-truck category, however, has slowed in the past few years [Heavenrich 2006]. As such, it is not clear if the market share of light trucks will continue to grow beyond the current new sales market shares. According to the TEDB, the data percentage of light-trucks in the new vehicle sales is currently about 55%, whereas EPA and NHTSA data put the light-trucks market share at 50% of new vehicle sales. The default setting in the fleet model is to maintain the market share of cars and light-trucks at the current level. Any change from the default level is assumed to take place linearly.

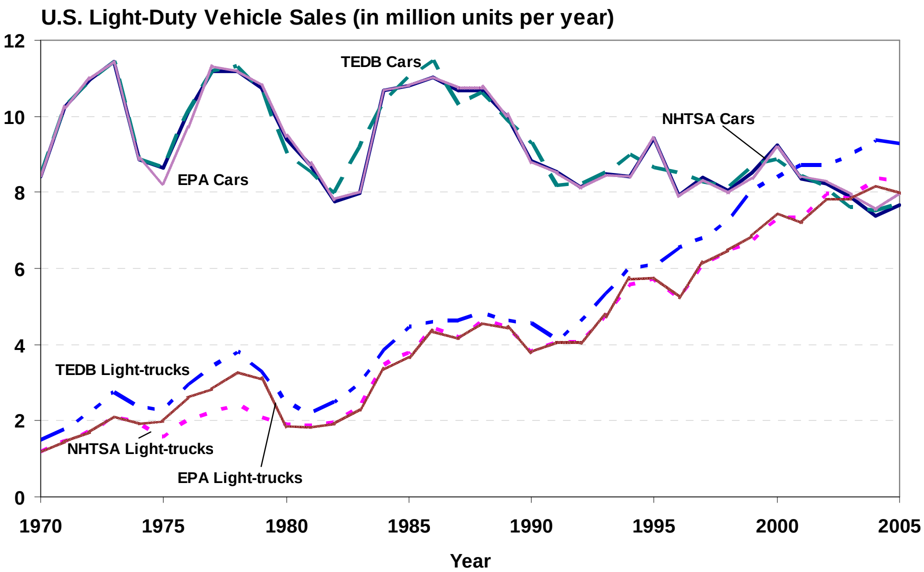


Figure 24 U.S. light-duty vehicle sales [1970–2005]

5.4 Sales growth

There are approximately 800 vehicles per thousand people in the United States. By contrast, there are about 600 vehicles per thousand people in Canada and Western Europe, and fewer than 20 vehicles per thousand people in China. Presently, the number of light-duty vehicles on the road in the United States exceeds the number of licensed drivers [Davis and Diegel 2007]. Given this unprecedented level of vehicle ownership, it is unlikely that growth rate of light-duty vehicle sales will be much faster than the rate of growth in the U.S. population. According to the U.S. Bureau of the Census, the average rate of growth of the population is likely to decrease from 0.9% in the first decade of this century to 0.75% by 2040 [U.S. Census 2004]. Thus, the fleet model assumes an average annual growth rate of new vehicle sales of 0.8% per year.

5.5 Scrappage rate

There is considerable uncertainty about the scrappage rates of motor vehicles. No consistent data on survival of vehicles of different model years is available. In the literature, three different methodologies have been used to estimate vehicle scrappage rates.

Greene and Chen [1981] applied a logistic function to estimate the survival rate of light-duty vehicles. They estimated that the median lifetime of cars and light trucks from 1966–1977 was 9.9 and 14.5 years, respectively. Using a similar approach, Feeney and Cardebring [1988] estimated that the median lifetime of passenger cars increased from about 10 years in 1971 to about 13 years by 1983. Other sources also cite an increase in the median lifetime of vehicles, and indicate that light-trucks last longer than passenger cars. Recent editions of the TEDB, however, report an increase in the expected median lifetime of passenger cars made after 1990 to 16.9 years [Table 20].

Libertiny [1993] applied a Weibull distribution to calculate attrition rates of passenger cars, and found no significant difference between domestic and imported cars. Libertiny also concluded that while vehicle scrappage rates decreased considerably between 1970 and 1980, there was not much difference in scrappage rates in the period between 1980 and 1990.

Table 20 Estimated median lifetime of U.S. light-duty vehicles

	1970 Model Year		**1980 Model Year**		**1990 Model Year**	
	TEBD, Edition 19	TEDB, Edition 24	TEBD, Edition 19	TEDB, Edition 24	TEBD, Edition 19	TEDB, Edition 24
Cars	10.7	11.5	12.1	12.5	13.7	16.9
Light Trucks	16.0	16.2	15.7	15.3	15.2	15.5

TEBD = Transportation Energy Data Book

Greenspan and Cohen [1999] separated the scrappage into engineering scrappage and cyclical scrappage. They defined engineering scrappage as scrappage resulting from vehicle aging and accompanying physical wear and tear. They report that the median lifetime of vehicles, based on engineering scrappage estimation, improved from about 10 years for model years 1960–1963 to approximately 13 years for model years 1977–1979. They estimated the cyclical component of scrappage based on income and price effects, and found that the cyclical scrappage rates vary inversely with the ratio of new car price to repair costs.

NHTSA [2006b] used the data from National Vehicle Population Profile (NVPP) compiled by the R. L. Polk and Co. to linearly regress LN(–LN(1 – Survival Rate)) on vehicle age. NHTSA found support to the argument that attrition rates of passenger cars post-1990 may be lower than those of light trucks.

For the purpose of this model, the survival rate of new vehicles is determined by using a logistic curve as shown in Equation 5.1.

$$1 - \text{Surivival Rate (t)} = \frac{1}{\alpha + e^{-\beta(t - t_o)}} \qquad (5.1)$$

where,

t_0 is the median lifetime of the corresponding model year

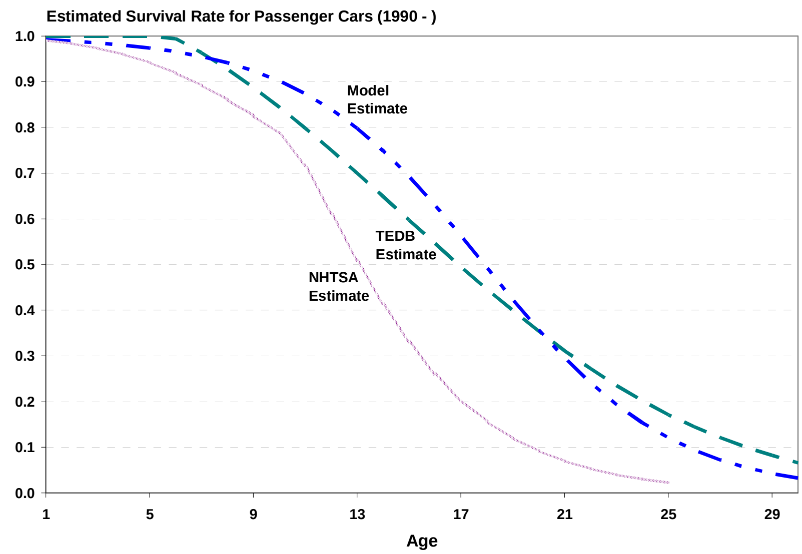
t, the age in a given year

β, a growth parameter translating how fast vehicles are retired around t_0

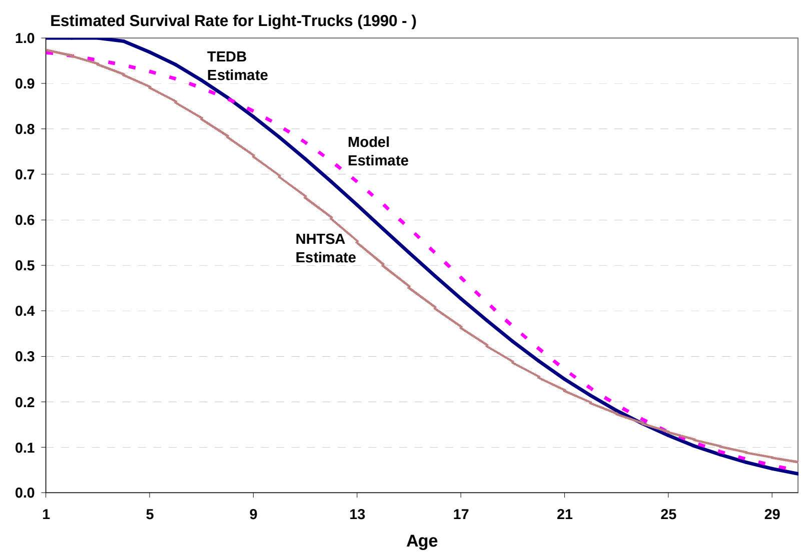
α, model parameter set to 1

The median lifetime is kept constant after the model year 1990 at 16.9 cars, 15.5 for light trucks. The growth parameter β is a fitted to 0.28 for cars and 0.22 for light trucks. For simplification purposes, model parameter α is set to 1, even though Miaou [1995] argues that setting α to 1 is overly restrictive.

Figure 25 shows the estimated survival rates of passenger cars and light-trucks. Note that NHTSA estimates suggest a faster turnover of vehicle fleet. The estimated model survival rates are between the TEDB and NHTSA estimates for vehicles less than 10 years old.



(a) Passenger Cars



(b) Light-Trucks

Figure 25 Estimated survival rates of U.S. light-duty vehicles [model year 1990 onward]

5.6 Average per-vehicle kilometers traveled (VKT)

Increase in total vehicle kilometers traveled takes place as a result of an increase in the number of vehicles on the road and an increase in kilometers traveled per vehicle. Table 21 shows the annualized growth rate in vehicle kilometers traveled (VKT) per vehicle as calculated from the rate of growth in the stock of light-duty vehicles, and total annual vehicle kilometers traveled (VKT) as reported by TEDB.

The long-term growth in VKT per vehicle for light-duty vehicles is thus 0.5-0.6% per year. In the future, the rate of growth in per-vehicle kilometers traveled is assumed to decrease from 0.5% per year between 2005 and 2020, to 0.25% per year in 2021–2030, to 0.1% per year in the years after 2030. This is a simplifying assumption that prevents the distance driven per vehicle from escalating rapidly beyond 30,000 km per year. Note that this represents a decrease in total annual VKT growth rate from 1.3% at present to 0.9% by 2035, since the new vehicles sales are assumed to grow at a rate of 0.8% a year.

Table 21 U.S. light-duty vehicle VKT growth rates (1971–2005) [Davis and Diegel 2007]

	Cars			Light-trucks		
Years	Annual Vehicle Stock Growth (%)	Annual Total VKT Growth (%)	Annual VKT/Vehicle Growth (%)	Annual Vehicle Stock Growth (%)	Annual Total VKT Growth (%)	Annual VKT/Vehicle Growth (%)
1971-1980	3.1	1.6	-1.4	7.0	8.7	1.6
1981-1990	0.9	2.4	1.5	5.9	7.6	1.7
1991-2000	0.5	1.8	1.4	4.5	4.0	-0.5
2001-2005	-0.2	0.9	1.1	3.2	3.0	-0.2
1971-2005	1.1	1.7	0.5	5.6	6.2	0.6

It is assumed that in 2000, new cars are driven 25,760 km (16,000 miles) in their first year, whereas new light trucks are driven 27,370 km (17,000 miles) in their first year of operation.[50] After the first year, the average per-vehicle kilometer travel decreases at an annual rate (denoted r) of 4% for cars and 5% for light-trucks [Greene and Rathi, 1990; NRC 2002]. Thus, the average per-vehicle kilometers of travel (VKT) of a vehicle aged i years is calculated as:

$$VKT_i = VKT_{new} \times e^{-ri} \qquad (5.2)$$

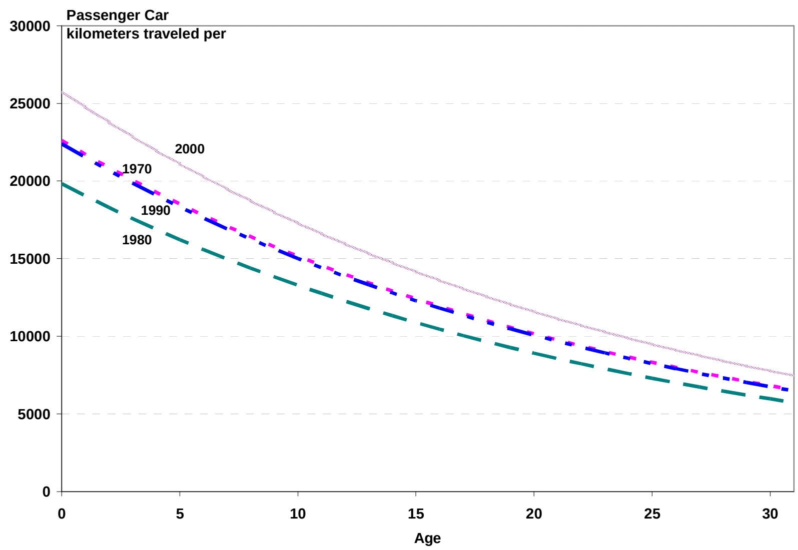
[50] These assumptions are similar to NHSTA and EPA data. NHSTA estimates new car travel at 22,675 km in the first year, and 25,215 for trucks in their first year. EPA uses 24,000 km for the first year of new car travel and 31,375 km for light trucks below 6,000 lbs (2,720 kg), or 34,330 km for trucks between 6,000 and 8,000 lbs (2,720 to 3,630 kg) (NHSTA 2006a; EPA 2007a).

Based on Table 21 and Equation 5.2, the average per-vehicle kilometers traveled by LDVs of different ages can be calculated. Figure 26 shows the distance traveled by the new cars and light-trucks sold in years 1970, 1980, 1990, and 2000.

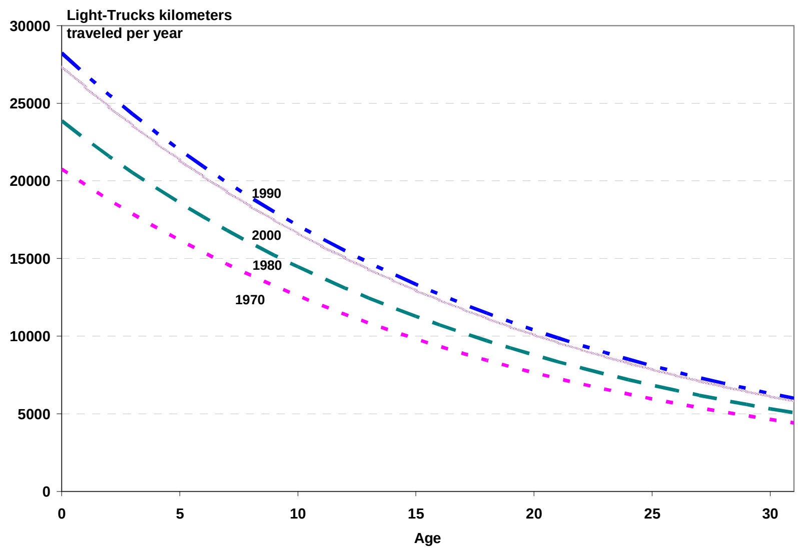
The total VKT for a given calendar year, j, is obtained using Equation 5.3:

$$VKT_j = \sum_i N_{i,j} \times VKT_{i,j} \tag{5.3}$$

Where $N_{i,j}$ is the number of vehicles of age i in calendar year j, and $VKT_{i,j}$ is the average annual vehicle travel for vehicles of age i in year j.



(a) Passenger Cars



(b) Light-Trucks

Figure 26 Per-vehicle kilometer traveled by model year [1970–2000]

5.7 Vehicle fuel consumption

Figure 27 shows the new vehicle fuel consumption trend from 1975–2005, using NHTSA and EPA data. The EPA fuel consumption values are higher than NHTSA reported fuel consumption values primarily because EPA data do not include fuel economy credits from test procedure adjustments for cars, as well as fuel economy credits from alternative/flexible fuel vehicles. The model assumes that the new light trucks meet the CAFE standards for years 2006–2010. The new light truck CAFE standard in 2010 would be approximately 23.5 miles per gallon (10 L/100 km), assuming no major shifts in the sales mix [NHTSA 2006a].

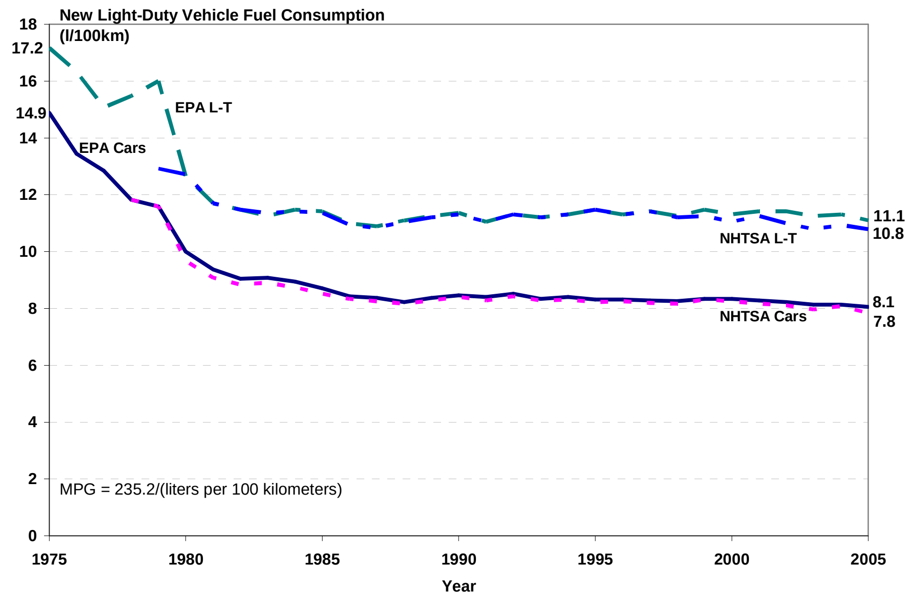


Figure 27 New light-duty vehicle fuel consumption (1975–2005)

The fuel consumption values in Figure 27 are not adjusted for on-road performance. The on-road fuel consumption is higher than the test values because of differences between actual driving conditions and trip patterns, and the test cycles, as well as less than ideal state of maintenance of vehicles and aggressive driving behavior [Hellman and Murrell 1982]. Using actual test runs of a variety of vehicles, Hellman and Murrell [1984] estimated the average miles driven by vehicles per day and the fraction of those miles driven in an urban environment. Using these factors, and actual versus measured fuel economy, they estimated an adjustment factor of 0.9 for city driving and 0.78 for highway driving. When measured fuel economy is degraded by using these factors, the estimate for on-road fuel economy is about 15% lower than test results. In other words, on-road fuel consumption of light-duty vehicles needs to be adjusted upward, by $1/0.85 \approx 1.17$.

Mintz et al. [1993] argue that the adjustment factors are not stable over time, and are in fact increasing. They claim that the 0.85 degradation factor is an underestimation, since it does not adequately consider the impact of increasing share of urban driving as well as urban congestion, and increased vehicle speed on highways. Based on the analysis of 1985 Residential Transportation Energy Consumption Survey (RTECS), they estimated a fuel economy shortfall of 18.7% for cars and 20.7% for light trucks, or increase in fuel consumption by 23% for cars and 26% for light trucks from the test values.

EIA's Annual Energy Outlook incorporates changing city/highway driving ratios, increasing congestion levels, and rising highway speeds to modify the degradation factors, as shown in Table 22.

Starting in model year 2008, EPA has decided to use a five-cycle average that includes an aggressive driving cycle (US06), a cold-start cycle (cold FTP), and an accessories loading cycle (SC03) along with traditional city and highway cycles to come up with fuel economy labels [EPA 2006]. As a result, EPA expects to report vehicle fuel economy values that could be lower by as much as 25% for years 2008–2010 [Heavenrich 2006b; EPA 2007]. According to EPA calculations, the average on-road fuel consumption of new vehicles from 1986–2005 is greater than their test fuel consumption by 21%.

Table 22 Car and light truck degradation factors [EIA 2007c]

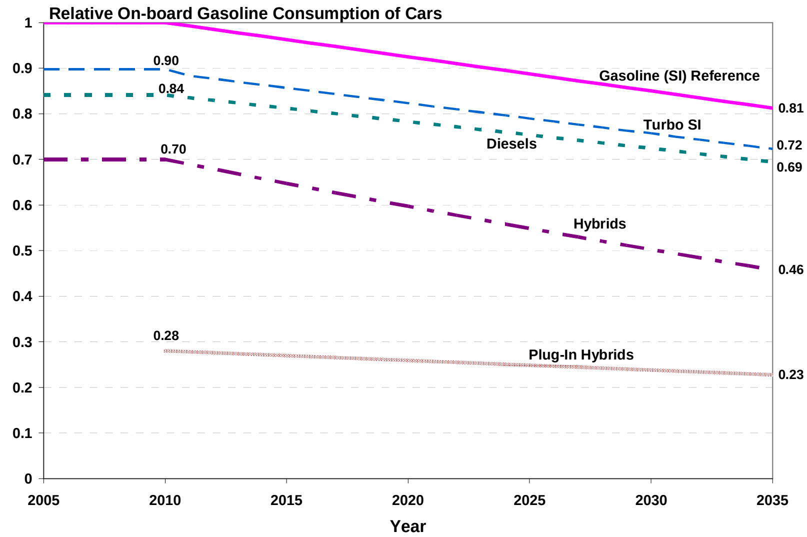
	Cars		Light Truck	
Year	Fuel Economy shortfall (%)	Fuel Consumption Increase (%)	Fuel Economy shortfall (%)	Fuel Consumption Increase (%)
2000	20.8	26.2	20.1	25.1
2005	20.3	25.4	22.7	29.3
2010	20	25	22.5	29
2015	19.8	24.7	22.4	28.5
2020	19.4	24	22.3	28.7
2030	19	23.4	22	28.2

This model uses the same value as the IEA Sustainable Mobility project: an average shortfall of 19% in fuel economy or a 22% increase in fuel consumption [Fulton and Eads 2004]. For simplification purposes, it is also assumed that the fuel consumption of vehicles remains constant over the life of the vehicle.

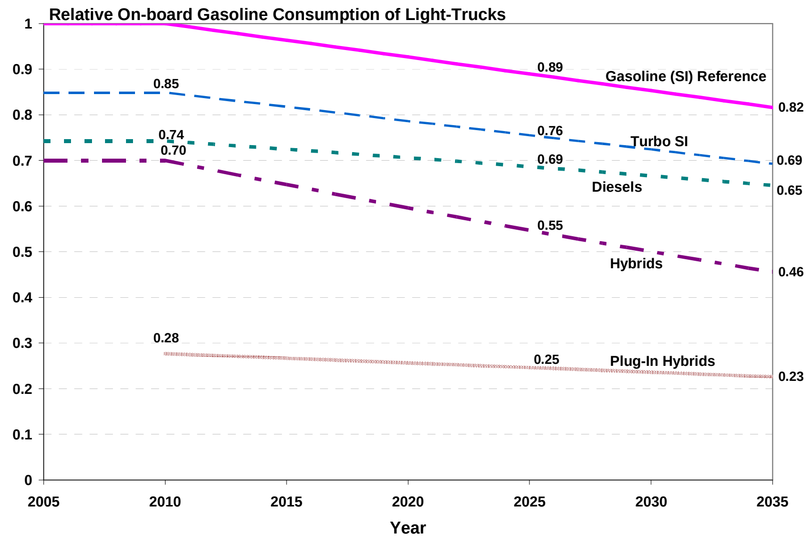
Finally, EPA estimates that the fuel economy of trucks weighing more than 8,500 lbs is, on average, about 14% lower than trucks weighing less than 8,500 lbs [Heavenrich 2006]. Since all Class 2b trucks are included in this model but are assigned the same fuel economy as that of Class 2a trucks, the net result is to underestimate fuel use by the order of 2%.

We assume that future reductions in fuel consumption start in 2010, since the product plans for the next two years have already been finalized. We can estimate the potential fuel use reductions that can materialize if more emphasis is placed on reducing fuel consumption in the future, as opposed to the little or no emphasis being placed on it today. Thus, no emphasis placed on fuel consumption reduction (0% ERFC) becomes our *No Change Scenario*. As can be seen in Figure 54, splitting the fuel efficiency benefit evenly between performance and fuel consumption reduction will level off the light-duty fleet fuel use by 2035 without any alternative propulsion systems. This is termed the *Reference Scenario*, where a modest but sustained pressure from gasoline price, increases in fuel economy standards, and competitive pressures all combine to prompt a shift away from a *No Change Scenario*. Using the information in Table 6 and Equation

4.1c, the relative onboard gasoline equivalent fuel consumption for different propulsion systems in the *Reference Scenario* can be calculated for years 2010–2035, as shown in Figure 28.



(a) Cars



(b) Light-Trucks

Figure 28 Relative onboard gasoline-equivalent fuel consumption at 50% ERFC for different propulsion systems 2005–2035

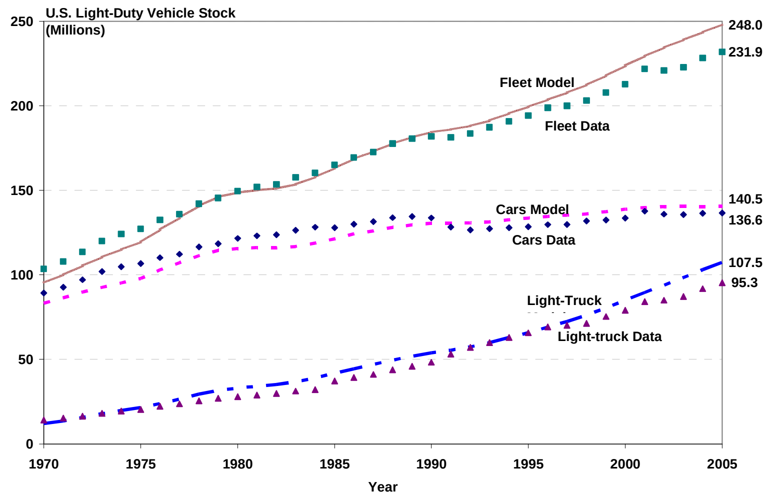
5.8 Fleet fuel use and greenhouse gas emissions

The fuel use of the entire fleet is calculated by summing up the fuel use of vehicles using different technologies of the same age, which in turn is calculated by multiplying the number of vehicles in service of that age and technology type by the number of vehicle kilometers traveled, and then by their respective fuel consumption. Fuel use is calculated separately for each propulsion system type in gasoline equivalent units.

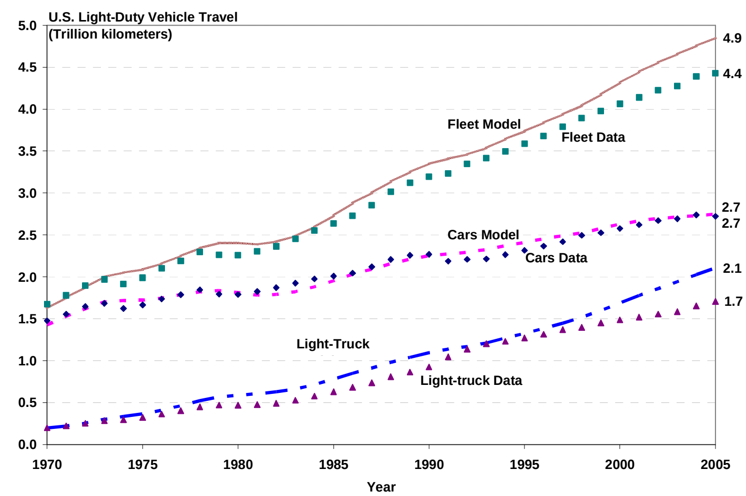
Greenhouse gas emissions are calculated on a well-to-wheel basis by multiplying the fuel use by a corresponding well-to-tank and tank-to-wheel greenhouse gas emissions coefficient, as discussed in Section 6. Energy use and greenhouse gas emissions from the vehicle manufacturing and disposal stage are also incorporated in the model, as discussed in Section 7.

5.9 Model results and comparison with DOE/EIA projections

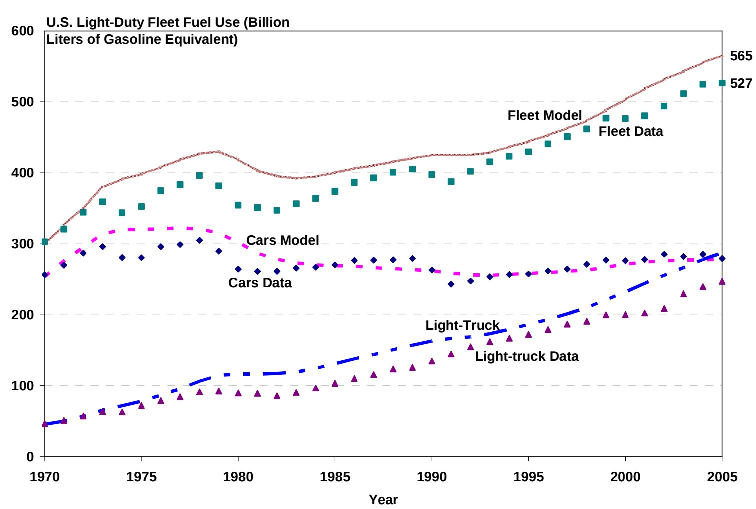
Before comparing future projections of light-duty fleet characteristics, the model results are first evaluated against historical trends. Figure 29 shows the model calculated vehicle stock, vehicle travel, and fleet fuel use compared with highway statistics compiled by the Federal Highway Administration and reported by the Transportation Energy Data Book [TEDB]. The number of vehicles in the U.S. LDV fleet increased from about 108 million vehicles in 1970 to about 240 million vehicles in 2005 [Davis and Diegel, 2007, Table 3.3]. Most of the increase in stock came from the light truck segment. The model consistently overshoots the data, especially for the light trucks; this is because the model includes all light-duty vehicles under a gross vehicle weight of 10,000 lbs., whereas the TEDB data shown in Figure 29 only represents light trucks under 8,500 lbs.



(a)



(b)



(c)

Figure 29 Fleet model results compared with historical data (1970–2005)

Table 23 shows the average error in vehicle stock, VKT, and fleet fuel use for each decade since 1975 relative to the TEDB data. Additionally, the EPA and NHTSA also provide vehicle sales data that differs slightly from the TEDB [EPA 2007; NHTSA 2008]. Using the EPA and NHTSA data to calculate the light-duty vehicle fuel use, the average error between data and model is about 0.7% and 1%, respectively.

Table 23 Percent difference between TEBD data and model calculation

Decade	Stock Difference [%]	VKT Difference [%]	Fuel Use Difference [%]
1975-1985	1.9	-3.4	-11.2
1985-1995	-1.1	-4.4	-5.1
1995-2005	-4.9	-6.3	-4.9

Figure 30 compares the light-duty vehicle fleet fuel use calculated by using the light-vehicle sales numbers from TEDB, EPA and NHTSA. On average, the TEDB fuel use calculation results in 5.8 percent and 6.5 percent higher fuel use than NHTSA and EPA calculations as shown in the Figure 30. The TEDB vehicle sales data is used as the primary source for calibrating and generating results from the MIT model.

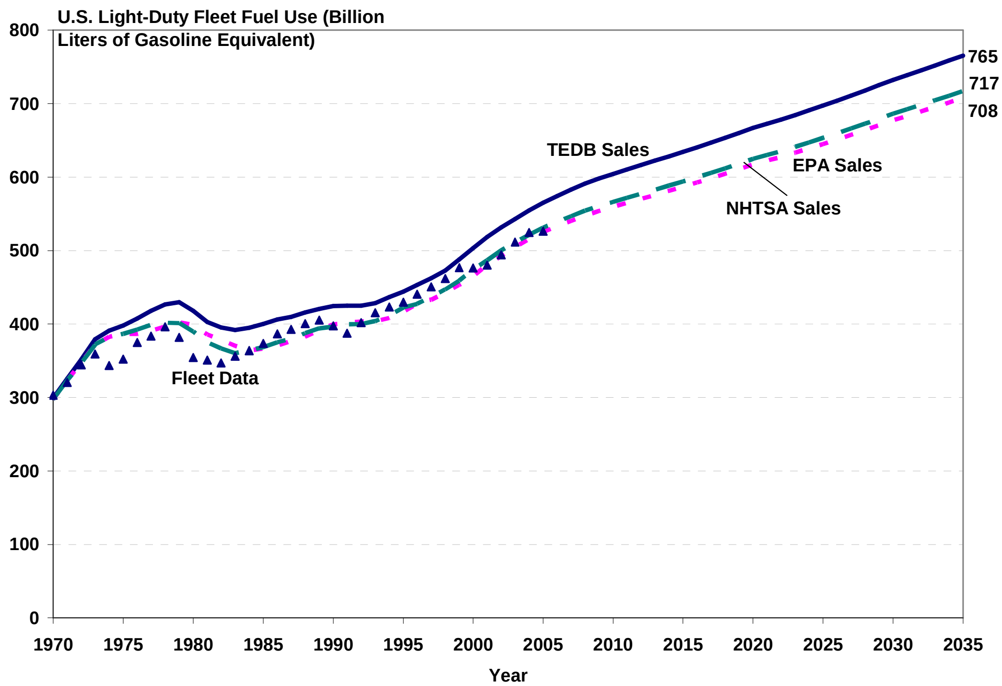
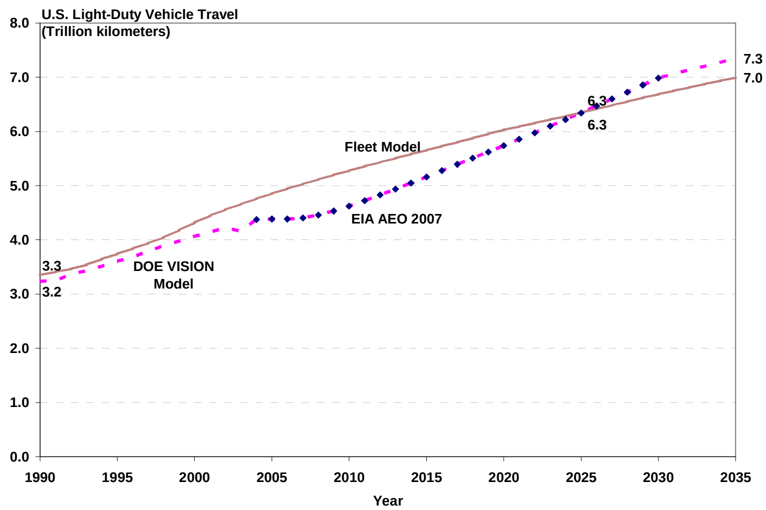


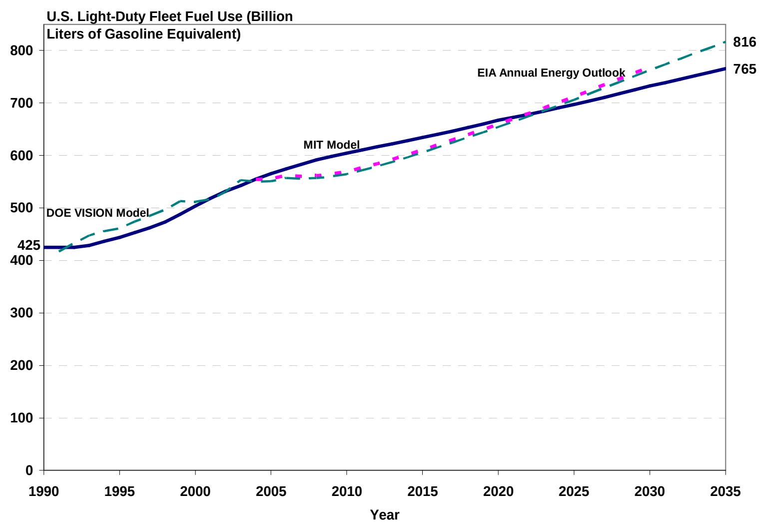
Figure 30 Light-duty vehicle fleet fuel use projections using TEDB, NHTSA, and EPA sales data

Finally, the projections of the fleet model are also compared with the Energy Information Administration's Annual Energy Outlook 2007 [EIA 2007a], and the Argonne National Laboratory's VISION model [Singh at el. 2003] in Figure 31. While the VISION model is updated to include AEO data, the two models differ in their assumptions about vehicle fuel economy under the business as usual scenario [DOE/ANL 2007].

The primary difference in the VKT between DOE/EIA projections and the MIT fleet model is in the assumptions about vehicle kilometers traveled and the rate of growth of travel per vehicle. While the VISION model in 2000 has a similar number of vehicle kilometers traveled per vehicle as the MIT model (~19,300 km/vehicle per year), the long-term VKT growth rate in VISION model is 1.7%, as opposed to 1.2% in the MIT model. In addition, the VISION model assumes a decline in car VKT in the early part of the present decade, so that the total car VKT is at the same level as 2000 in year 2010. The combined result is that the DOE/EIA model estimates of VKT and fuel use are lower than the MIT model until 2025, and higher after 2025. The sensitivity of the model to various parameters is shown in the next section.



(a) Vehicle Kilometers Traveled (VKT)



(b) LDV Fleet Fuel Use

Figure 31 Comparison of Fleet Model Projections with EIA Annual Energy Outlook and DOE VISION Model

5.10 Sensitivity to selected input parameters

The growth in sales of light trucks has been one of the drivers of LDV fuel use growth since the 1980s. Figure 32 evaluates the impact of a further increase or decrease in the light truck sales fraction from today's value of 55%. Whether the light truck sales fraction increases linearly from 55% to 70% or decreases linearly from 55% to 30% by 2035, the total fleet fuel use is affected by less than 2% over the period under consideration. The impact of such changes in fleet composition appears to be limited until 2035, but will be more apparent in the decades to follow. This is due to two reasons. First, the light-truck CAFE standards for years 2005–2010 have narrowed the gap between passenger car and light truck fuel economy. Second, the inertia already present in the LDV fleet means that changes that do not significantly affect vehicle fuel consumption or travel patterns will have limited impact on aggregate fuel use of the fleet.

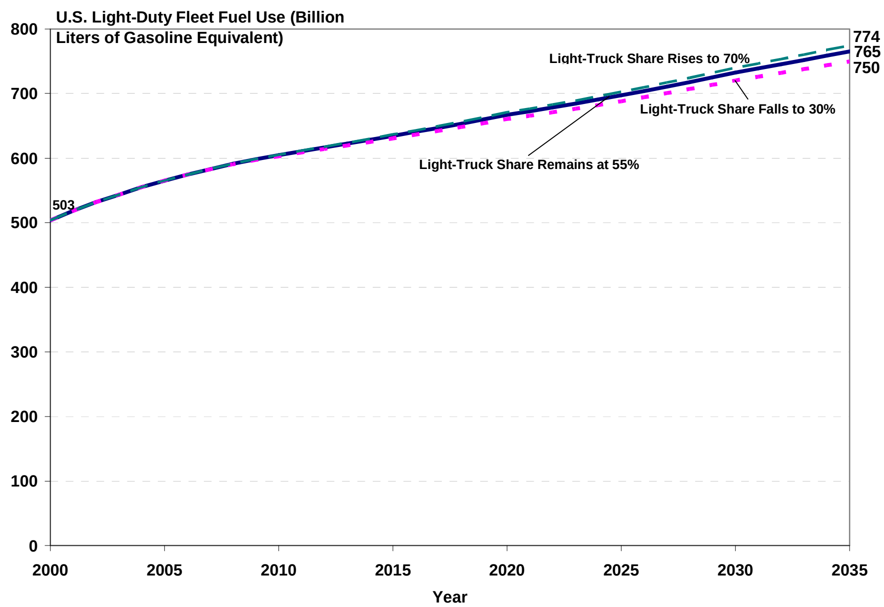


Figure 32 Effect of new light truck sales fraction on fleet fuel use from 2005 to 2035

Figure 33 illustrates the drivers of growth in LDV fleet fuel use, viz. the increase in LDV stock via new vehicle sales growth, and increase in average distance traveled per vehicle. If the sales growth of new vehicles is halved from the present rate of 0.8% per year, the LDV fleet fuel use in 2035 will be some 8.6% lower than indicated by the present growth trajectory. Halving both the rate of growth in travel per vehicle in addition to halving the sales growth will result in about 13.5% savings in fleet fuel use in 2035.

Such a reduction can only be achieved by a mix of mode shifting, trip consolidation, and fiscal and/or regulatory disincentives to own and operate vehicles. Of course, even with no further growth in vehicle sales and travel, i.e., no increase in aggregate vehicle kilometers traveled (VKT), total fleet fuel use will remain at the present level. Thus, even with no growth in demand beyond present level—an unlikely prospect—a dramatic reduction in vehicle fuel consumption will be required if the LDV fuel use is to be brought back to the level of domestic oil production, which is projected to be 325 billion liters (5.6 mbd) in 2030 [EIA 2008].

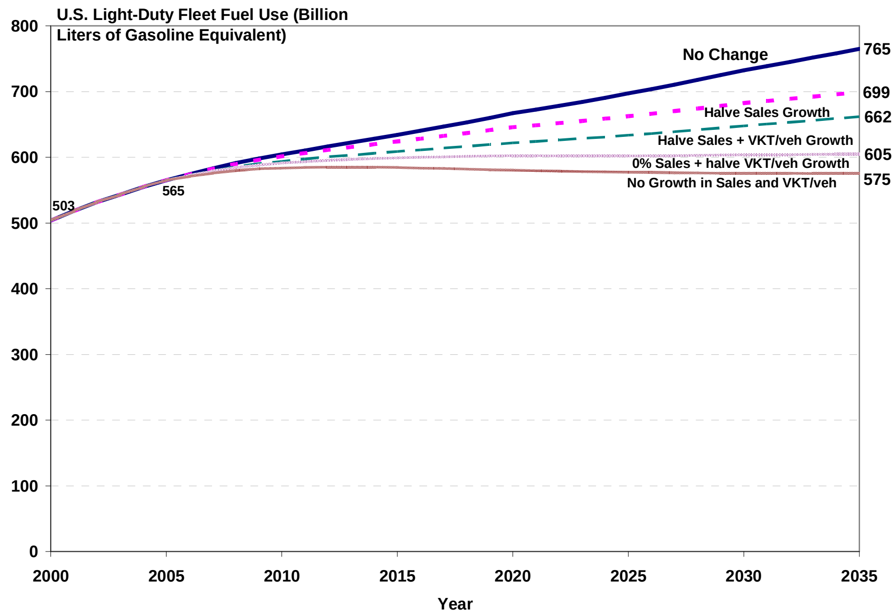


Figure 33 Light-duty vehicle fleet fuel use projections for different sales and VKT/vehicle growth rates (2000–2035)

As noted previously, the median lifetime of LDVs is increasing as the vehicles have become more durable and reliable over time. As a result, there are a greater number of older vehicles on the road today, and they add to the inertia of the vehicle fleet. Reducing vehicle lifetime would slow down the growth in total vehicle stock, since more vehicles would be retired earlier.

The effect of reducing vehicle lifetime is shown in Figure 34. Reducing median vehicle lifetime from 16.5 years to 15.2 years for cars, and from 15.5 years to 14 years for light trucks—a 10% reduction in median vehicle lifetime of vehicles made after model year 2000—results in approximately 6.7% reduction in 2035 fleet fuel use. Similarly, a 20% reduction in vehicle median lifetime (13.5 years for cars, 12.4 years for light trucks) reduces 2035 fleet fuel use by approximately 14%. Note that this calculation does not assume that each vehicle that is scrapped from service is replaced by a new vehicle. Rather, the rate of growth in new vehicle sales is assumed to be constant. In practice, a shorter vehicle lifetime will have the effect of stimulating demand for new motor vehicles, and the actual effect of reducing vehicle lifetime will be much smaller than indicated in Figure 34.

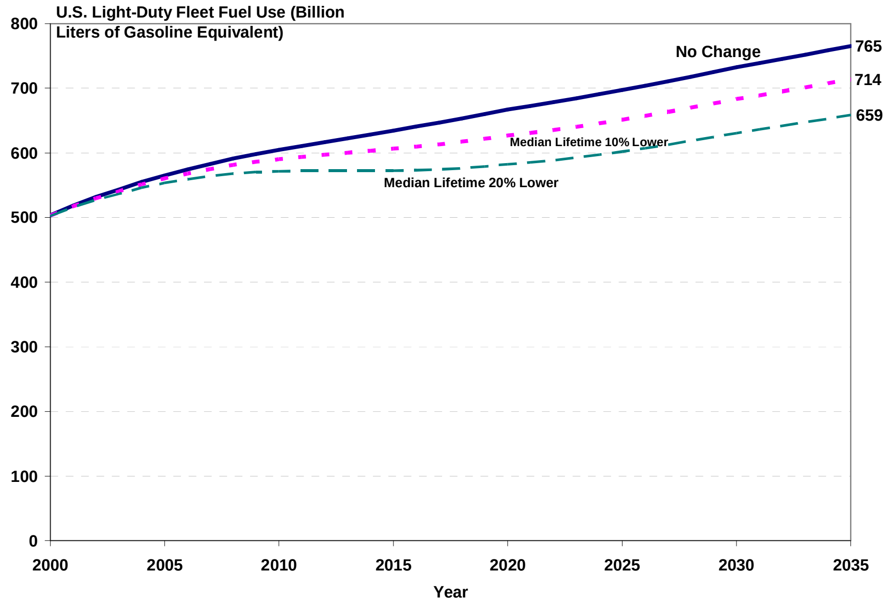


Figure 34 Effect of reducing vehicle lifetime on fleet fuel use

The effect of shortening the median lifetime is similar but not exactly the same as that of chopping off the end of the survival curve of motor vehicles by scrapping older vehicles on the road. For example, if all vehicles of model year 1980 onward were scrapped when they reached age 21, fuel use in 2035 would be about 23 billion liters less (a 3% reduction in 2035 fuel use). Scrapping older vehicles will stimulate the second-hand car market, which in turn will increase the rate of new vehicle sales. While newer vehicles are likely to be more efficient, they are also more likely to be driven farther, as shown in Figure 26. Thus, the fuel savings calculated here provide an ideal lower bound; the actual savings from a vehicle scrappage scheme will be lower. To have a large-scale impact on fleet fuel use, vehicles will need to be scrapped near to their median lifetime, and the costs of doing so are likely to be significant [ECMT 1999].

Finally, the effect of on-road fuel economy adjustment factor on fleet fuel use is shown in Figure 35. The fleet fuel use is quite sensitive to this degradation factor, and a great deal of uncertainty persists about a reliable estimate of on-road versus test fuel economy performance. The fleet model at present uses a uniform 22% adjustment to fuel use for both cars and light-trucks. The latest EPA fuel economy trends report uses an adjustment factor of 17.1% for years 1975–1985, which increases from 1.175 in 1986 to 1.25 in year 2005. Note that variation in the adjustment factor does not affect comparison of the model results unless the adjustment factor is changed between the scenarios.

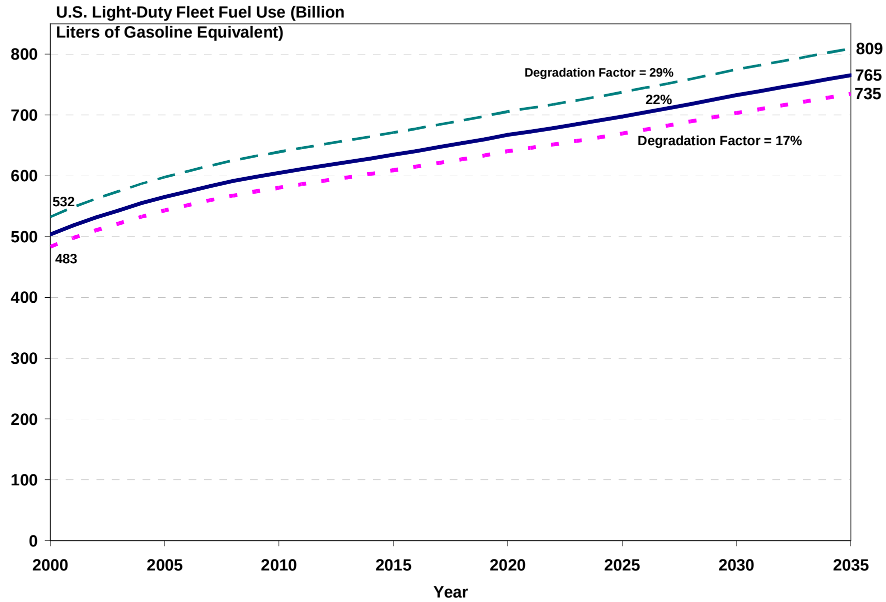


Figure 35 Light-duty fleet fuel use for different on-road fuel economy factors

5.11 European comparison

As described in Bodek and Heywood [2008], a variety of data sources were used to develop and calibrate individual European country light-duty vehicle fleet models. The majority of the data came from country-level statistical offices, such as Deutscher Verkehrs-Verlag in Germany and Observatoire Économique et Statistique des Transports in France. These data sources show that the fraction of diesels in the sales mix has been growing throughout most of Europe for the last 20 years. Although their fraction may continue growing over the next several years, the *No Change Scenario* assumes that the diesel-to-gasoline sales share remains flat at its 2005 in the future. As will be discussed in the following section, a separate scenario was used to model the impact of further dieselization of Europe's vehicle fleet.

The future sales growth rates in France, Germany, Italy, and the UK were modeled differently than in the United States to reflect the fact that, rather than simply tracking the population growth rate, the sales rate will also be influenced by growth in the number of vehicles per 1,000 people. New vehicle sales growth rates were estimated using United Nations [2005] population growth rate estimates and historical motorization (i.e., vehicles per 1,000 people) trends. New sales growth rates, using a five-year interval, were chosen such that the number of vehicles in the entire fleet would be sufficient to sustain the historical motorization trend of each country, given simultaneous changes in its human population. Table 24 details the estimated new sales growth rates necessary for achieving these rates of motorization, as well as the corresponding United Nations population growth-rate projections.

Basing the future VKT behavior of vehicles on historic trends is not as logical an approach for Europe as it is for the United States, where nearly all passenger vehicles are fueled by gasoline. As illustrated in Figure 36, the historic VKT data for gasoline and diesel vehicles in France highlights several important trends. Most significantly, diesel vehicles have consistently been driven further per annum than gasoline vehicles. For example, in 2005 the average diesel vehicle was driven 64% further in France than the average gasoline vehicle. Another relevant trend is that the VKT of both gasoline and diesel vehicles in most European countries has been steadily declining. A number of studies have explored the range of potential factors that are responsible for these trends, such as the preferential use of diesels by high mileage drivers (e.g., taxis), differential tax regimes on gasoline and diesel fuel, and the increasing number of multi-car families in several European countries. Schipper et al. [2002] provide a comprehensive review of the literature in this area.

Despite a multitude of factors, the fundamental dynamic appears to be that diesel VKT—and gasoline VKT, to a lesser extent—decrease as the fraction of diesels in the fleet increases. Although there are always a certain fraction of high-mileage drivers, ordinary drivers who drive less increasingly come to own diesel vehicles. Conversely, as diesels continue to appeal to more and more ordinary drivers, their switching away from gasoline vehicles toward diesel vehicles lowers the average gasoline VKT. Note that the rising ratio of diesel to gasoline fuel demand is already straining diesel fuel refining capacity. These supply constraints may impact future European diesel car growth.

Table 24 United Nations population projections and new sales growth rate estimates

		UN Population and New Vehicle Sales Growth Rate (%)						
		Average	2005-2010	2010-2015	2015-2020	2020-2025	2025-2030	2030-2035
France	Pop.	-0.08	0.0	0.0	-0.1	-0.1	-0.1	-0.2
	Sales	0.33	1.5	1.0	0.5	0.0	-0.5	-0.5
Germany	Pop.	0.17	0.3	0.3	0.2	0.1	0.1	0.0
	Sales	0.83	2.5	1.5	0.5	0.5	0.0	0.0
Italy	Pop.	-0.20	0.0	-0.1	-0.2	-0.3	-0.3	-0.3
	Sales	0.50	1.5	1.0	1.0	0.0	0.0	-0.5
UK	Pop.	0.30	0.3	0.3	0.3	0.4	0.3	0.2
	Sales	1.08	1.5	1.5	1.0	1.0	1.0	0.5

These observations informed the authors' approach for modeling the future VKT behavior of gasoline and diesel vehicles, in addition to the fact that the weighted VKT in both countries has remained roughly flat over the last 30 years. Figure 37 shows the resulting VKT behavior when this methodology is applied to the *No Change Scenario* for France's vehicle sales mix. In this particular instance, diesel vehicles, which comprise nearly 70% of the fleet in 2035, are assumed to only travel approximately 25% farther per annum than gasoline vehicles. When scenarios with alternative powertrains are modeled, it is assumed for simplicity that they exhibit the same VKT behavior as NA gasoline vehicles.

As described in Section 0, the estimated ERFC in Europe is closer to 50%, compared with almost zero in the United States. Therefore, an ERFC of 50% was used when modeling the *No Change Scenario* for these European countries.

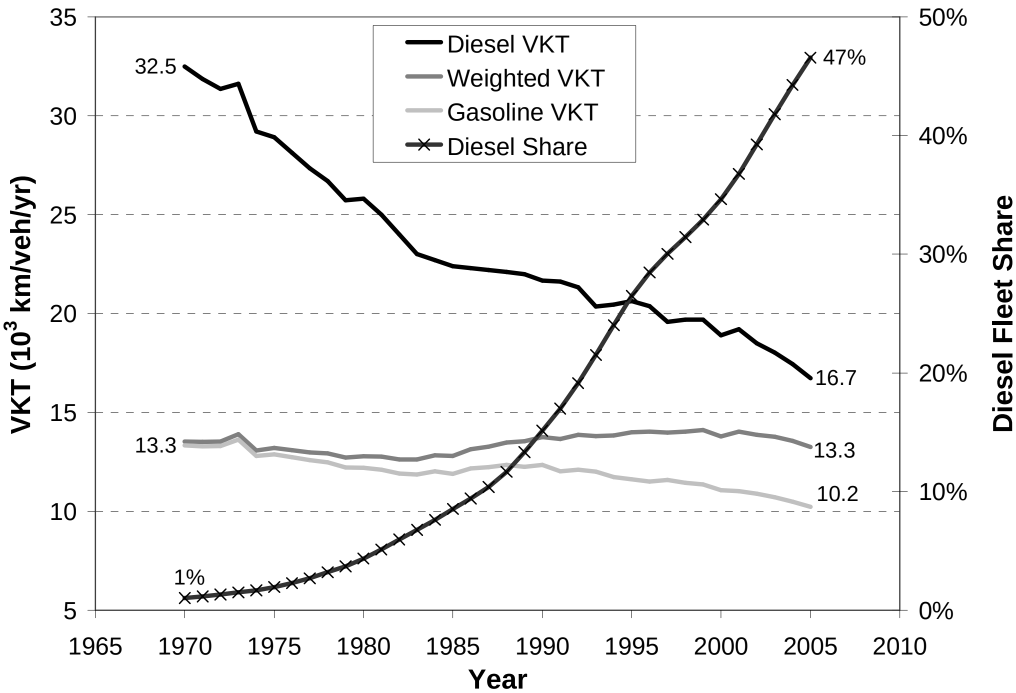


Figure 36 Historic VKT behavior and diesel fleet share in France

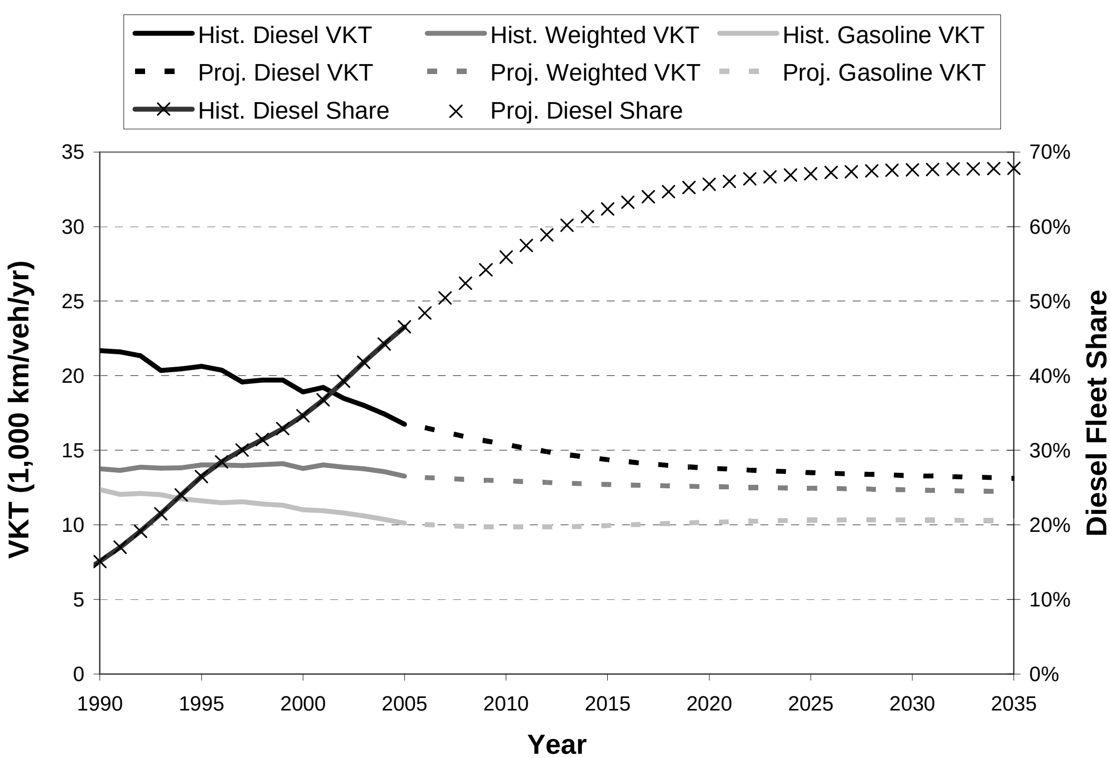


Figure 37 Future gasoline and diesel VKT behavior in the France *No Change Scenario*

5.12 Summary

This section has identified the primary trends underlying different factors for growth in LDV fleet fuel use and introduced the light-duty vehicle fleet model and its structure. The model results for the United States and for four of the larger European countries were compared against historical trends and projections of other models. The sensitivity of the fleet fuel use projection to different model parameters was also evaluated. The next two sections of this report will develop the fleet model further to incorporate the effects of changes in fuels, vehicles technology, and vehicle market penetration rates.

6.0 Fuel Supply Options

6.1 Introduction

More than 97% of the energy used in the U.S. transportation sector comes from petroleum, and transportation accounts for more than two-thirds of U.S. petroleum consumption. The desire to diversify away from petroleum has been at the heart of the search for alternative fuels. More recently, efforts to reduce carbon emissions from transportation fuels have also provided a further boost for this search.

Petroleum use in land-based transportation is split between gasoline and diesel. In the U.S., light-duty vehicles predominantly use gasoline (diesel is some 3%); diesel dominates the heavy-duty vehicle fuel use. In Europe, diesel is a major component of light-duty vehicle fuel use, since the fleet is approaching equal shares of gasoline and diesel vehicles. As in the U.S., diesel also dominates European heavy-duty vehicle fuel use. Since growth in the heavy-duty freight arena is more rapid than in the light-duty fleet, the ratio of diesel fuel demand to gasoline demand is rising. This is straining the petroleum refining system, especially in Europe, with its additional and growing light-duty vehicle diesel fuel requirement (see Section 7.11).

The last few years have seen a rapid increase in the price of oil, and, as a consequence, in gasoline and diesel fuel prices. Significantly more expensive transportation fuels over time will undoubtedly impact fuel demand as well as the light-duty vehicle technology and size sales mix that the market demands. We have not explicitly assessed these impacts. We have also assumed that the petroleum resources are available to meet the various fuel demands we project in our different scenarios (in Section 7), at cost levels that do not significantly reduce demand. Note, however, that our reference assumption regarding growth in kilometers traveled per year per vehicle in the U.S. decreases from the historical trend of 0.5% per year to 0.25% per year in 2020 and 0.1% per year in 2030 (see Section 5.6). We do examine how alternative fuels—non-conventional petroleum and biofuels—would impact petroleum-based fuel consumption.

Non-conventional sources of liquid fuels such as tar sands, heavy oil, natural gas, coal, and oil shale have seen increased interest in the wake of high oil prices. The estimated resource base for these non-conventional resources is very large—of the order of several trillion barrels of oil equivalent [IEA 2005]. The geographic locations of some of the big unconventional resources (tar sands in Alberta, Canada; oil shale in Green River Formation of the western U.S.; and coal in many U.S. states) have the added attraction of being in North America, thus enhancing security of supply. Considerable uncertainty exists, however, regarding the economic and environmental viability of these resources. Non-conventional oil projects are more capital intensive than conventional oil production, and thus are more susceptible to volatility in the global oil market. At the same time, the life-cycle carbon emissions associated with the production and use of non-conventional oil sources can be significantly greater than those associated with conventional oil.

Biomass has the potential to provide a renewable and low greenhouse gas-emitting liquid fuel pathway. There is a rich diversity in the types of biomass resources and conversion technologies available to produce liquid transportation fuels. So far, the worldwide production of liquid fuels from biomass has mainly included ethanol and biodiesel. Ethanol has been produced from annual crops such as corn (maize), wheat, and sugarcane. Biodiesel has been produced from crops such as rapeseed, soybeans, and sunflowers. In the future, there is potential to harvest woody perennials such as poplar, as well as herbaceous perennials such as switchgrass, for ethanol production. Agricultural and forest residues and organic waste matter could also contribute as feedstocks for biofuel production. Energy and environmental impacts of large-scale cultivation of biomass for fuel production are not yet well understood. There is growing consensus, however, that biofuels will be a part of future transportation fuel mix [IEA 2004; WBCSD 2004].

Finally, hydrogen and electricity are the two energy carriers that could become a part of transportation fuel mix if corresponding vehicle technology viz. fuel cell and plug-in hybrid/ electric becomes market competitive. Electricity is familiar and readily available to consumers, but hydrogen will have to overcome the barriers of unfamiliarity and the lack of fueling infrastructure. Both electricity and hydrogen can be produced from a diverse mix of fuel sources. While this has the advantage of fuel diversity, greenhouse gas emissions from the production and distribution of hydrogen and electricity vary widely depending on the source. These fuels, however, will only significantly reduce GHG emissions in the transportation sector if they are produced on a large scale, and from low GHG emission sources.

This section evaluates the impact of a changing fuel mix on U.S. light-duty vehicle (LDV) fleet well-to-wheel greenhouse gas (GHG) emissions. The fuel options under consideration here are non-conventional oil from Canadian tar sands, ethanol from corn and cellulose in the U.S., as well as electricity and hydrogen. Section 6.2 contains brief discussions of each of these fuels and their well-to-tank greenhouse gas emissions. Section 6.3 focuses on evaluating the well-to-wheel greenhouse gas emissions impact of different vehicle and fuel scenarios.

In this section, we do not address the issue—which may come to be critical—of future changes in the fuel infrastructure: fuel production from raw materials and fuel distribution to customers. At one extreme, hydrogen fuel involves the enormous task and cost of an entirely new production and delivery infrastructure. For some oxygenated fuels, portions of the existing infrastructure may be usable. But there will still be major costs for new fuel manufacturing facilities, and for new materials and new capacity to segregate fuel components in the distribution system. As discussed in Section 7.1, in the mid- and longer-term, issues associated with the need for new or modified infrastructures for a particular alternative fuel can be decisive in assessing the commercial feasibility of that fuel.

6.2 Fuel options

6.2.1 Non-conventional oil from tar sands in Canada

Tar sands, also known as oil sands, are essentially a mixture of clay, water, sand, and bitumen. The Canadian Association of Petroleum Producers (CAPP) estimates that recoverable reserves of tar sands are in excess of 175 billion barrels. Unlike the heavy oil found in Venezuela, the oil in tar sands is embedded within the soil when mined and requires processing in order to be extracted. Commercial exploitation of tar sands has been ongoing since the 1960s. Most of the growth in production, however, has occurred since the early 1990s. In 2006, an estimated 1.2 million barrels per day of crude oil was recovered from the oil sands in Canada [CAPP 2006].

Anticipated production volume

Figure 38 shows the growth in production of oil sands versus decline in conventional oil production in Canada. CAPP projects the production of oil sands to increase to 4 million barrels per day by 2020. In a constrained growth scenario, CAPP estimates that the production of oil sands will exceed 3.3 million barrels per day in 2020. The Canadian Energy Research Institute (CERI) estimates that oil sands production could grow to as much as 6 million barrels per day by 2030 [O&GJ 2006].

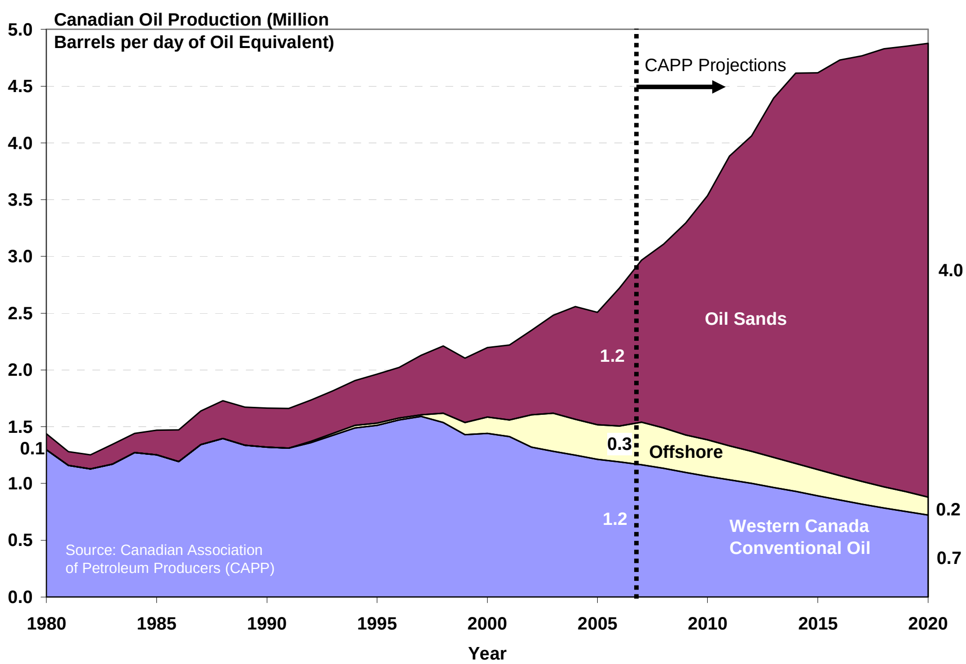


Figure 38 Oil sands versus conventional oil production in Canada [CAPP 2006]

In the reference case of the Energy Information Administration's International Energy Outlook 2007, the Canadian oil sands production grows to 3.6 million barrels per day by 2030, as shown in Figure 39. The EIA estimates a low case of 1.9 million barrels per day and a high case estimate of 4.4 million barrels per day in that year.

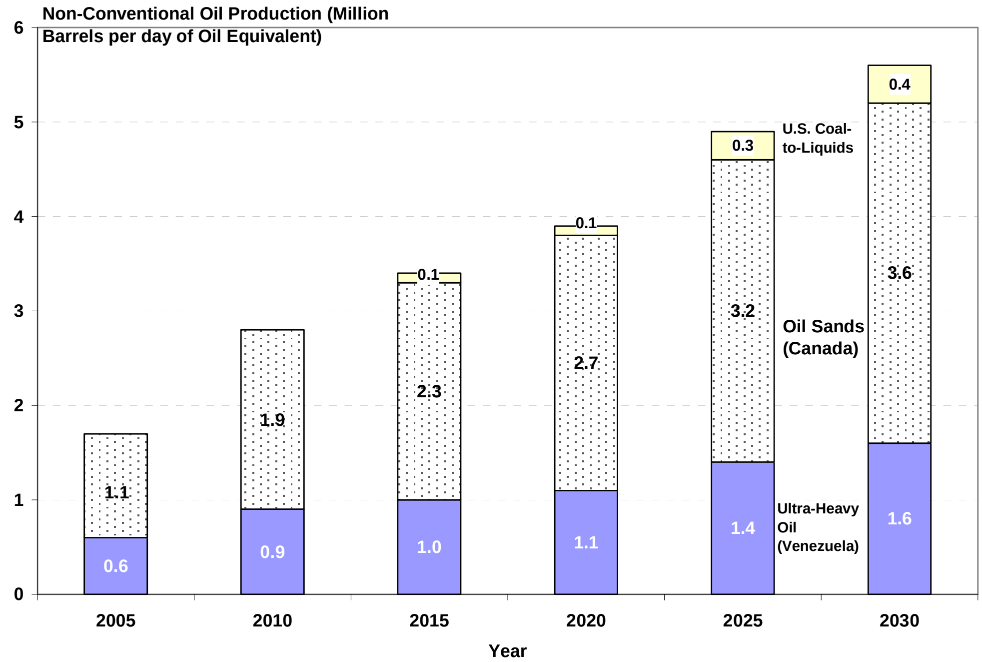


Figure 39 Non-conventional oil production from the U.S., Canada and Venezuela [EIA 2007f]

The National Energy Board (NEB) of Canada estimates that the Canadian oil exports will increase from approximately 1.5 million barrels per day at present to 2.8 million barrels per day by 2015. Most of the exports of Canadian oil are to the United States, and the NEB expects that a majority of future increases in Canadian oil exports will be to the United States. If 80% of these exports comprise synthetic crude oil (SCO) derived from tar sands as shown in Figure 38, then the U.S. imports of tar sands could exceed 2.5 million barrels per day by 2025.

The growth in Canadian oil sands is subject to oil prices (greater than 50 $/bbl), natural gas usage (less than 1 Mcf/bbl at a price of less than 7.50 $/MMbtu), and development of local infrastructure. Recent increases in commodity and labor prices have driven up the costs of constructing oil sands recovery facilities. The estimated capital expenditure required to bring an oil sands project online ranges from $40,000 to $60,000 per barrel of production capacity, compared with $7,000 to $30,000 required for conventional oil production [IEA 2006a; IEA 2006b].

Figure 39 also shows the growth in other non-conventional liquid fuels that are likely to affect the North American market. According to the EIA, the production of ultra-heavy crude from Venezuela could range in 2030 from 0.8 million barrels per day in the low case to 2 million barrels per day in the high case. However, political uncertainty in Venezuela is likely to constrain future growth in production. The production of coal-to-liquids in the United States could range from 0.4 million barrels per day in 2030 under the EIA's reference scenario to 1.6 million barrels per day under its high price scenario. The U.S. Department of Energy's Task Force on Strategic Unconventional Fuels has outlined a goal of recovering more than 5 million barrels per day from non-conventional sources such as coal, shale, and tar sands in the United States [DOE 2007a]. It is important to note the growth in these supplies, as the GHG emission intensity from ultra-heavy crude production in Venezuela is likely to be similar to that of Canadian oil sands, whereas coal-to-liquids production without carbon capture and storage will be even more GHG intensive than oil sands.

Energy consumption and GHG emissions in oil sands processing

Traditionally, most of the tar sands have been recovered by open pit mining operations. An average of four tons of material needs to be removed to separate the two tons of oil sands needed to produce a barrel of SCO. As the bitumen deposits closest to the surface are exploited, and concerns about above-ground impact grow, new production technologies have emphasized in-situ production of bitumen. The most common processes, such as steam-assisted gravity drainage (SAGD), involve steam flooding, which is used to heat the oil to reduce its viscosity so that the bitumen can flow through a pipeline. As a result, energy consumption and GHG emissions from in-situ production of bitumen are approximately 25% higher than those from mining. Newer production techniques such as Vapor Assisted Petroleum Extraction (VAPEX) or in-situ combustion can lower some of these penalties.

Since bitumen is deficient in hydrogen, processing of bitumen to produce SCO requires a source of hydrogen. In the majority of processes, hydrogen is supplied by reforming natural gas on site. Consumption of natural gas and the resulting CO_2 emissions could also become a constraint on further development of oil sands projects.

Figure 40 shows a simplified process overview of production of 1 MJ of gasoline equivalent fuel from in-situ production of tar sands [McCulloch et al., 2005]. Consumption of approximately 0.4 MJ of natural gas during in-situ bitumen production and upgrading are responsible for most of the CO_2 emissions during the process. Emissions during refining of SCO can be similar to refining of conventional crude if the refinery is capable of treating a relatively heavy slate of oil.

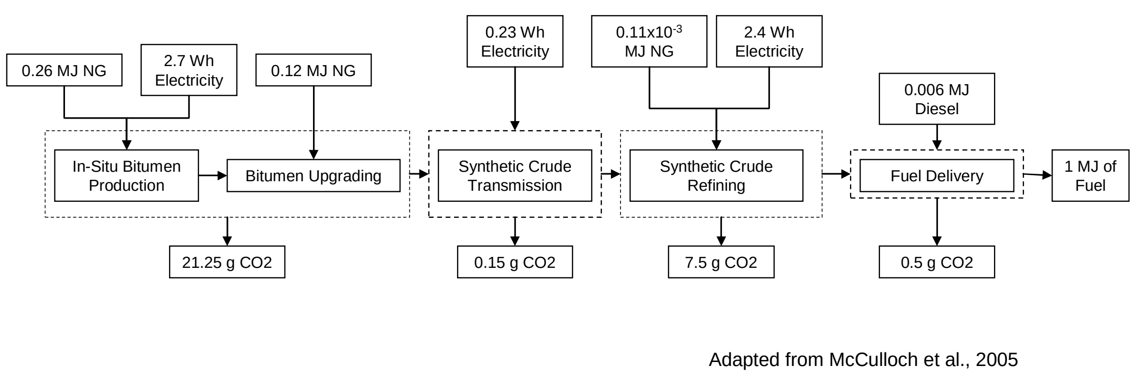


Figure 40 Energy consumption and CO_2 emissions during in-situ production of tar sands

Different estimates of well-to-tank emissions during various stages of production of liquid fuel from tar sands are shown in Table 25. The numbers in part (a) of the table are estimates for current emissions, whereas part (b) of the table represents estimates for future operations. Emissions in the future are estimated to increase for two primary reasons: 1) upgrading of SCO to a higher-grade product with more hydrogen, 2) potential use of coke residue or coal for generating steam. The fleet model uses 38 g CO_2 per MJ of fuel produced from tar sands, which is the higher end of current estimates and lower end of the future estimates.

Table 25 Well-to-tank emissions from production of 1 MJ of fuel from tar sands (all numbers are in g CO_2 per MJ in tank)

YEAR	SOURCE	FUEL CYCLE STAGE			
		In-situ extraction and upgrading	Refining	Transportation and other	Total (well-to-tank)
Current (2005)	OSTRM [2003]	14.5 – 22	11	1	26.5 – 34
	TOTAL [2003]	16.5 – 26.5	4	1	21.5 – 31.5
	Alberta Chamber of Resources [2004]	21 -27	11	1	33 – 39
	Flint [2004]	17	11	1	29
	McCulloch [2005]	21	7.3	2.5	30.8
	Syncrude [2005]	19	11	1	31
	GREET [2007]	--	--	--	32 – 34
Future (2035)	Flint [2004]	20 – 29	11	1	32 – 41
	Alberta Chamber of Resources [2004]	26 – 28	11	1	38 – 40
	GREET [2007]	--	--	--	36 – 46

6.2.2 Biofuels

Current status and options

Biofuel is a general term used to encompass a variety of liquid transportation fuels generated from biomass as the basic feedstock. The most commonly used biomass-based transportation fuels are: biodiesel from rapeseed, ethanol from sugar beets and from wheat in Europe, ethanol from corn in the United States, and ethanol from sugarcane in Brazil.

In 2007, 10.5 billion gallons of ethanol and 2.5 billion gallons of biodiesel were produced globally, representing approximately 2.2% and 1.6% of the global transportation fuels market on a volume and energy basis respectively. In 2007, Europe produced 59% (1.48 billion gallons) of the world's biodiesel fuel from rapeseed. Biodiesel produced from soybeans in the United States and from palm oil fruit in Malaysia represent 20% (0.5 billion gallons) and 2.4% (0.06 billion gallons) respectively of global biodiesel production. Over time, biodiesel and ethanol production have increased due to government blending mandates and tax incentives. Though global biodiesel production has increased over the past five years, it still represents only 20% of the biofuels market. Many hurdles have and will continue to limit the growth of biodiesel; its cost of production and biofuel per hectare yield are some of its main obstacles.

The cost of production for biofuels is highly dependent on the cost of feedstock—i.e., corn, soybeans, and rapeseed. In 2007, the biomass feedstock costs for corn grain ethanol in the United States and rapeseed-based biodiesel in Europe represented on average at least 50% and 85% of total production cost. On an energy equivalent basis without subsidies, the average cost of production in the second quarter of 2008 for biodiesel produced from palm oil fruit, soybeans, and rapeseed was $210, $220, and $250 per barrel. For ethanol produced from sugar, wheat, and corn the cost of production was $90, $170, and $190 per barrel. These high costs make biofuels—and in particular biodiesel—less cost competitive than gasoline or diesel, even as oil prices have increased beyond $100 per barrel in recent months.

Biodiesel has additional hurdles when compared to ethanol, as the biofuel yield per hectare of land on an energy equivalent basis is much lower. Biodiesel produced from soybeans and rapeseed produce approximately 500 and 1400 liters of crude oil equivalent per hectare of land. Ethanol produced from wheat, corn, and sugar produce approximately 1,200, 2,500, and 3,750 liters of crude oil equivalent per hectare of land. While biodiesel produced from palm oil fruit can produce approximately 4,250 liters of crude oil equivalent per hectare, there are additional sustainability issues, such as rainforest depletion, that limit its use and ability to scale up.

While ethanol and biodiesel both have the potential to displace petroleum, this study only considers ethanol due to its current scale of production and the rate at which the ethanol industry is growing. Though biodiesel production may increase over the next several years, the overall scale of biodiesel production in the short to medium term is still limited by its cost of production, poor land use efficiency, and minimal government support. Of the ethanol feedstock options, we discuss ethanol produced from corn and cellulosic materials such as corn stover (an agricultural residue from corn grain production consisting of leaves and stalks of plants left on the field after harvest) and switchgrass (a hardy, indigenous prairie grass in North America currently used as a cover crop on degraded agricultural land). These biofuels are at a stage of development that is not yet matched by other options. Corn-based ethanol production has been encouraged in the United States since the 1970s as a means of displacing petroleum.

The oxygenate requirement of the 1990 Clean Air Act, along with a 51-cent-per-gallon blenders credit, provided a stable market for fuel ethanol. Methyl tertiary butyl ether (MTBE), the other oxygenate blended in gasoline, was phased out during early 2000s due to its impact on groundwater and replaced by ethanol. Though oxygenates are no longer required, further growth in corn ethanol production was guaranteed by the Renewable Fuels Standard (RFS) established by the Energy Policy Act of 2005. The RFS required 7.5 billion gallons of ethanol to be blended in gasoline by 2012 [Yacobucci 2006]. Since then, the RFS has increased to 36 billion gallons by 2022, with 15 billion gallons coming from corn-based ethanol and 21 billion gallons attributed to advanced renewable fuels [EISA 2007].

Anticipated ethanol production volumes

Current production of ethanol in the United States is approximately 0.39 million barrels per day by volume or 0.25 million barrels of oil equivalent [EIA 2007d]. Compared with 5.2 million barrels per day of domestic crude oil production or 10.2 million barrels per day of crude oil imports, this contribution from corn ethanol is small. The new RFS will now ensure that approximately one million barrels per day of corn ethanol by volume (~57 billion liters per year) is produced in the United States. The Renewable Fuels Association estimates that ethanol producers are currently adding new capacity of more than 22 billion liters per year of ethanol production, thus effectively doubling the total ethanol production capacity in the United States to 45 billion liters a year by 2011.

Currently, ethanol production in the United States is centered in the Corn Belt, with 131 facilities having the capacity to produce 26 billion liters (6.9 billion gallons) of ethanol per year. Over the next two to three years, an additional 23 billion liters (6.5 billion gallons) of capacity is being added from current facilities expanding their capacity and the addition of 73 new facilities. Therefore, by 2009, the corn grain ethanol industry in the United States will be a 50-billion-liter (13-billion-gallon) industry [RFA 2005]. It is expected that corn grain ethanol production will continue to increase over the next decade, especially as the next generation of biofuels are still not economical or scalable in the near-term.

The United States Department of Agriculture (USDA) expects corn ethanol production to reach 50 billion liters by 2015 [Westcott 2007], while the National Corn Growers Association estimates that between 48 and 68 billion liters of ethanol could be produced from corn in 2015–2016 without disrupting agricultural markets [NCGA 2007]. Figure 41 shows the trends in ethanol production in the United States and the anticipated expansion.

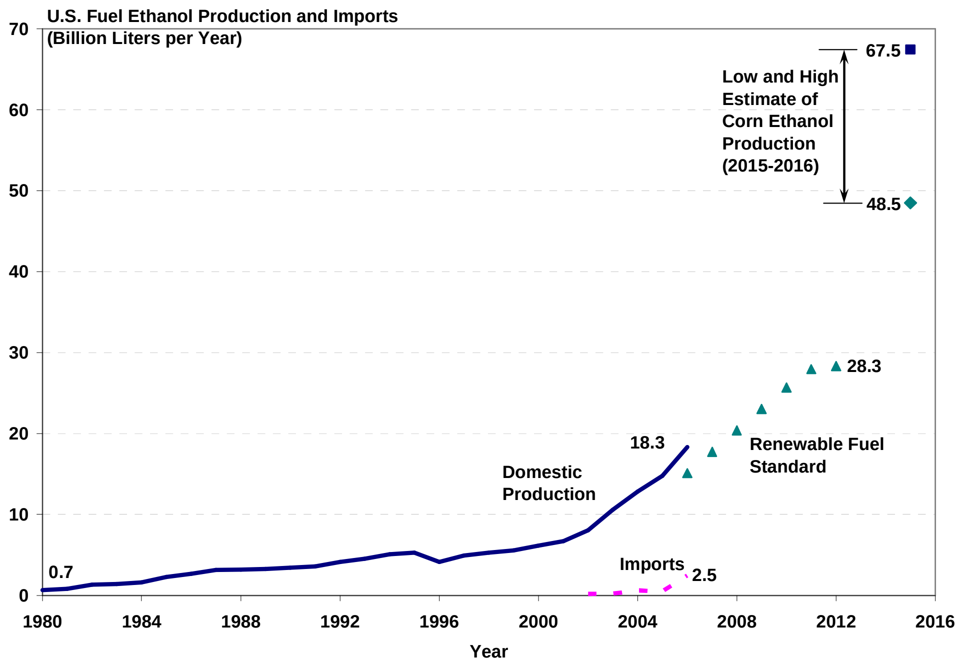


Figure 41 Domestic production and imports of ethanol in the United States [RFA 2007; Yacobucci 2006; NCGA 2007]

The scale of ethanol produced from corn grain as defined by the new RFS will level out at 57 billion liters, by the year 2012 [USDA 2006; EISA 2007]. This is based on the projections by the United States Department of Agriculture and the expected industry-wide efficiency gains [USDA 2006; EISA 2007]. Corn production is expected to continue to increase, though a majority of this increased acreage is not in the expansion of total cropland but in the shifting of other agricultural crops, such as cotton and soybeans to corn production [USDA 2006]. Additionally, corn is expected to be shifted from the export sector to the ethanol industry [USDA 2006]. In the past, U.S. world corn exports represented 60–70% of the U.S. corn market; with an expanding ethanol industry, that share is expected to drop to 50–60% [USDA 2006]. Based on these projections, Section 6.3.2 investigates scenarios where corn ethanol is assumed to contribute 70 billion liters of ethanol by 2035.

In 2006, the Department of Energy identified an agenda for the development of a cellulosic ethanol industry. The first five-year phase would focus on understanding the requirements of sustainable feedstocks for cellulosic ethanol production. The next five-year phase would focus on developing new dedicated energy crops with a high yield and suitability for conversion to ethanol. Finally, the agenda identifies that the next five-year phase would entail integration of bio-refineries tailored to utilize regional energy crops. Whether a bio-ethanol industry will develop from such a systematic research agenda is currently quite uncertain.

No commercial facilities currently process cellulosic material into ethanol, although several pilot plants to convert lignocellulosic material such as corn stover to ethanol have been announced. In February 2007, the Department of Energy provided $375 million for construction of six such pilot plants. The corresponding industry cost share is expected to be $1.2 billion [DOE 2007b]. These pilot plants combined are expected to produce 570 million liters (150 million gallons) by 2010.

The new RFS requires the blending of 80 billion liters (21 billion gallons) of advanced biofuels with 21 billion liters (5.5 billion gallons) blended from cellulosic biomass starting in the year 2012. The Context Network, an Iowa-based consulting service, estimates that production of cellulosic ethanol could grow to 1500 million liters (400 million gallons) by 2015 [Context 2007]. Further growth in cellulosic ethanol will depend on a number of factors, such as the technology conversion success of the first generation pilot plants, capital costs and sizing of commercial scale processing plants, and the prospects of providing feedstocks on a large scale. At present, the capital cost requirements of a cellulosic facility are expected to be five times higher than a comparable corn ethanol facility [Wright and Brown, 2007].

One of the key questions that remains for the feasibility and scalability of cellulosic ethanol is the availability of economical cellulosic feedstocks in sufficient amount to supply a facility year-round. Agricultural residues, such as corn stover and wheat straw, are often cited as initial cellulosic feedstocks, due to their current availability. Corn stover has an additional attractiveness, as it is already located within the Corn Belt near the existing ethanol industry. A challenge with utilizing corn stover for producing cellulosic ethanol, however, is that the amount of stover that can be removed is limited as it provides important environmental benefits to the soil. In addition to agricultural residues, dedicated crops, known as bioenergy crops, are potential cellulosic feedstocks. Such crops include switchgrass, and poplar and willow trees. One of the major challenges of creating a bioenergy crop industry is finding land in dense enough amounts to shift from its current, often agricultural, practice to bioenergy crop production. As a bioenergy crop industry currently does not yet exist, government policies and subsidies may be needed to incentivize farmers into production and to provide a sense of security as the market develops.

To evaluate the potential cellulosic feedstock availability, Groode and Heywood [2008] considered corn stover and switchgrass as two cellulosic feedstocks for ethanol production. Corn stover availability was assessed based on expected future corn production and a 30% corn stover removal rate. Groode and Heywood utilized a model called POLYSYS to assess switchgrass production from agricultural land based on the net returns to the farmer and feedstock farm gate prices. POLYSYS is an agricultural policy simulation model developed by the USDA, Oak Ridge National Laboratory (ORNL), and the University of Tennessee [Walsh et al. 1998; 2003]. POLYSYS includes the eight major crops (corn, grain, sorghum, oats, barley, wheat, soybeans, cotton, and rice), and a livestock sector (beef, pork, lamb and mutton, broilers, turkeys, eggs, and milk). The model was modified to also include hay and pasture land. POLYSYS runs on a ten-year time frame and is based on the *USDA Agricultural Projections to 2016 Baseline* [USDA 2006]. Switchgrass growing characteristics, yields, and costs were added to the model to determine how a bioenergy crop could shift agricultural cropland at various switchgrass farm gate prices.

For a given farm gate price, POLYSYS delivers yearly district-specific data on the amount of land in production for each of the crops, their productivity, and how their market price changes over 10 years. The overall amount of switchgrass produced is then used to determine the amount of ethanol that could be produced at today and future cellulosic ethanol conversion rates.

Based on availability of feedstocks and improvements in processing technology, Groode and Heywood [2008] estimated that 35–50 billion liters of cellulosic ethanol could be produced from corn stover and switchgrass by year 2025. With an increase in ethanol conversion rates, this could further increase to 60 billion liters. Groode concludes that further increases in cellulosic ethanol will come only from increasing the yield of switchgrass per acre of land. If a doubling of switchgrass yield from current levels could be achieved, then more than 60 billion liters of cellulosic ethanol could be produced from switchgrass alone, taking the total amount of cellulosic ethanol available close to 100 billion liters. In a *Low Cellulosic Ethanol Scenario*, the fleet model assumes that 28 billion liters of cellulosic ethanol are available by 2025 and 50 billion liters of cellulosic ethanol are available by 2035. In a *High Cellulosic Ethanol Scenario*, the fleet model assumes that 40 billion liters of cellulosic ethanol are available by 2025 and 70 billion liters of cellulosic ethanol are available by 2035. To achieve this scale of a cellulosic industry in 2035, huge investments, far beyond what is being invested today, would need to be made along with technological advances.

Table 26 Summary of ethanol production from corn grains, corn stover, and switchgrass grown on agricultural and CRP land [Groode and Heywood 2008]

	Corn Grain (billion L)	Corn Stover (billion L)		Switchgrass (agriculture, billion L)	
		238 L / dry ton conversion rate	328 L / dry ton conversion rate	238 L / dry ton conversion rate	328 L / dry ton conversion rate
Today (2006)	18	24	33	9–14	12–20
Future (2025)	57–68	26	36	60–100	85–145

Energy consumption and GHG emissions in corn and cellulosic ethanol production

The debate on greenhouse gas emission reductions realized from different biofuel pathways has not been settled conclusively. The debate persists in part due to the different system boundaries and methodologies used in various studies. There is general agreement, however, that well-to-wheel GHG emissions from production of corn ethanol are close to the values for conventional gasoline, whereas GHG emissions from cellulosic ethanol are substantially lower [Farrell et al., 2006]. If a credit is applied to corn ethanol for the byproducts of corn ethanol production, such as dry distillers' grain with solubles (DDGS), then corn ethanol GHG emissions are lower than conventional gasoline. Applying this credit to corn ethanol's life-cycle emissions may not always be valid as it depends on the degree of saturation of the DDGS market. It is important to understand the feed market and the impact DDGS has at displacing other feed products, such as soybean meal, before a credit is allotted.

Previous corn and cellulosic life-cycle assessments have resulted in differing conclusions over the fossil energy consumption and environmental benefits of bioethanol. The disparity between prior studies is mainly caused by differences in system boundary choices, data choices, and system input value variability. The system boundary defines which fossil fuel inputs in the life-cycle are included or excluded from the analysis. Previous studies have not been able to capture the inherent system variability, as they have used a single value to characterize each input variable. This approach has resulted in a wide range of single-valued results that often lead to varying conclusions. Therefore, to incorporate this type of natural system variability, Groode and Heywood utilize a life-cycle model that incorporates a Monte Carlo simulation approach. This resulted in a range of probable outcomes rather than a single point value as previous published reports have presented [Groode and Heywood 2008].

With this approach, Groode and Heywood quantified the impact of system variability, and support the conclusions of Farrell et al. They also pointed out the role of geographic variability in corn ethanol emissions as shown in Figure 42. Groode and Heywood indicate that future greenhouse gas emissions from corn ethanol could be as much as 20% lower, due to improvements in agricultural yields and conversion efficiency [Groode and Heywood 2008].

Ethanol produced from cellulosic sources, such as corn stover and switchgrass, undergoes different pretreatment and ethanol conversion steps than corn ethanol due to its different molecular structure and mass components. During the conversion process, lignin, a part of the plant not converted to ethanol, can be burned to provide all the thermal energy needed by the ethanol processing facility. In some cases, excess heat can be used to produce electricity that can be used on site or sold to the electric grid. Utilizing lignin eliminates the need for fossil fuel by the processing facility, resulting in decreased GHG emissions. Given the additional reductions in system inputs from the agricultural sector, cellulosic ethanol can reduce GHG emissions by about 90% [Groode and Heywood 2008]. One of the additional benefits of cellulosic ethanol is that feedstocks can be agricultural residues and/or biomass produced on land that in the past has had low agricultural productivity.

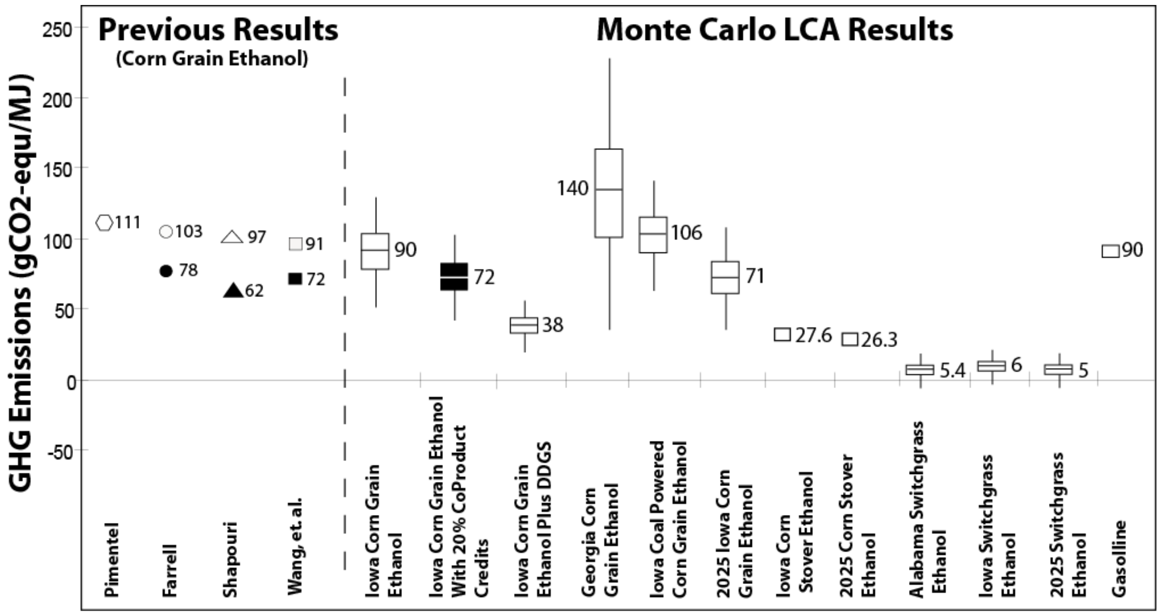


Figure 42 Emissions for various corn and switchgrass ethanol production scenarios [Groode and Heywood 2008]

Prospects for Ethanol

None of the biofuels, except ethanol from sugarcane in Brazil, are cost competitive with conventional gasoline and diesel at a crude oil price of $65 per barrel [IMF 2007]. Figure 43 shows the recent trends in price of ethanol in the United States, with and without the blender's credit, compared with gasoline prices [EIA 2007d].

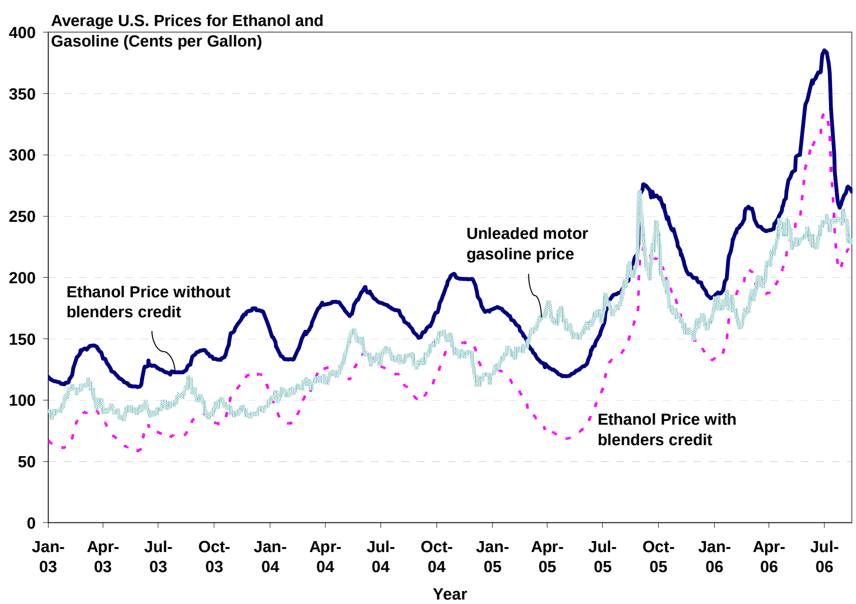


Figure 43 Average U.S. ethanol and gasoline price (2003–2006) [EIA 2007d]

Figure 43 shows that even with 51-cents-per-gallon subsidy, ethanol in the United States has been as expensive as gasoline on a volume basis. When adjusted for its lower energy density, the cost premium for blending ethanol in gasoline has been of the order of 20%. Though corn ethanol has been more expensive than gasoline, it is still produced, as ethanol is mandated by the U.S. government to be blended with gasoline. Cost-competitive alternatives such as sugarcane ethanol from Brazil are currently subject to 54-cents-a-gallon tariff, and will continue to play a marginal role compared to domestic ethanol in the U.S.

Finally, the impact of large-scale biofuel production, particularly from annual crops, on agriculture and environment is not well understood. The 2007 OECD-FAO Agricultural Outlook 2007–2016 has raised concerns that increasing biofuel demand will elevate prices of agricultural commodities "above historical equilibrium" [OECD-FAO 2007]. The report identifies that such inflation in food prices will be particularly of concern for the developing parts of the world. A recent report from National Research Council on water implications of biofuels production in the United States [NRC 2007] concluded that:

> *"…growth of biofuels in the United States has probably already affected water quality because of the large amount of N and P required to produce corn…. Expansion of corn on marginal lands or soils that do not hold nutrients can increase loads of both nutrients and sediments. To avoid deleterious effects, future expansions of biofuels may need to look to perennial crops, like switchgrass, poplars/willows, or prairie polyculture, which will hold the soil and nutrients in place."*

While the impact of biofuels on climate change has been increasingly debated, the last few years have also seen growing expressions of concern about the total costs of biofuels. The societal and environmental costs of biofuels are particularly contentious. These include the impact of increased food prices around the world, as well as the impacts of increased crop water consumption and soil erosion from more energy crop production, and water contamination from increased fertilizer use. The potential for significant GHG emissions from the impact of land use changes, especially when forest lands are converted to croplands, is of growing concern as well. These concerns have been voiced repeatedly in influential media such as the *New York Times*, the *Wall Street Journal*, the *Economist*, and *Science Magazine*. Many of these concerns have focused on corn-based ethanol in the United States, where agricultural policies and political influence have shaped regulatory and statutory mandates to use increasing amounts of ethanol in fuel even though the rationale that established the initial market for ethanol (i.e., that ethanol decreased the tailpipe emissions of criteria pollutants) is no longer valid. Concern about biofuels is not only expressed in the media. Six European countries plus Canada "…have removed or are revising incentives for farmers, biofuel refiners, and distributors…" [Rosenthal 2008]. Our conclusion, however, is that different fuels made from biomass in different ways must be examined separately to assess costs and benefits and that "biofuels" are not socially beneficial simply because they are biofuels. Biofuels are also not a silver bullet for displacing all of U.S. or global petroleum consumption. However, though biofuels are limited in scale by land productivity and biomass availability, they do have the potential to aid in alleviating a portion of petroleum consumption in the nearer term. Their potential to displace petroleum into the future will depend on the improvement in technologies that can covert cellulosic-based biomass to biofuels as well as the social costs of such a system.

As the above discussion indicates, biofuels have the potential to displace a substantial fraction of petroleum while reducing greenhouse gas emissions. There are, however, several economic and environmental challenges to a rapid expansion of biofuels. It appears likely that bioethanol will contribute less than 10–15% of fuel supply by 2035 on energy basis, and will deliver somewhat smaller reduction in greenhouse gas emissions. Other agricultural and biofuel feedstocks as well as conversion technologies may offer greater scalability and economic benefits and should be examined in great detail and scrutiny. Evaluating the environmental impacts of these other options on a life-cycle basis, including when possible impacts of land use change, is needed to determine the appropriate path biofuels production should take to truly have a positive environmental impact.

6.2.3 Electricity

The use of electricity in light-duty vehicles will grow if plug-in hybrids (PHEVs) enter the market in large numbers. While this may help to displace petroleum use, the GHG emissions reductions will depend on the efficiency of vehicles under electric operation, and the GHG intensity of the electricity. The 2007 EIA Annual Energy Outlook reference case projects little change in average U.S. grid mix between now and 2030. As newer, more efficient power plants come online, the average CO_2 emissions from U.S. electricity grid are projected to decrease modestly from 640 g/MWh to 635 g/MWh [Kromer and Heywood 2007]. When losses in transmission (9%) and battery charging (10%) are taken into consideration, the average U.S. emissions rate is approximately 770 gCO_2/MWh or 214 gCO_2/MJ of electricity delivered to the vehicle.

The emissions intensity of electricity will vary regionally, and the initially marginal load imposed by plug-in hybrid vehicles will be taken up by available spare capacity in that region. To demonstrate the plausible range of electricity emissions rate, Kromer and Heywood [2007] estimated the GHG emissions from three different grid mixes as shown in Table 27. Carbon capture and storage was not included as its near term impact was judged to be modest.

Table 27 Fuel cycle energy and GHG emissions for different electricity generation sources [Kromer and Heywood 2007]

Fuel	Energy (MJ/MJ)	GHG Emissions (g CO_2/MJ in "tank")
Coal Only	2.39	318.6
Natural Gas Only	1.84	161.9
Average US Grid Mix	2.30	213.6

In the *Hybrid Strong Scenario*, the market share of plug-in hybrids grows to 15% of new LDVs in 2035. The total electricity demand by plug-in hybrids in 2035 grows to 59 billion kilowatt hours. As the fleet of PHEVs grows, the demand for electricity will increase by approximately 6–10 billion kilowatt hours in the decade after that. The current electricity consumption in the United States is approximately 3,700 billion kilowatt hours, and is projected to increase to over 5,200 billion kilowatt hours by 2035 [EIA 2007a]. Therefore, plug-in hybrids will represent only 1–2% of electricity demand under this scenario, and their energy impact on the electricity grid is likely to be small. Note that the GHG emissions intensity of electricity supply can vary significantly from country to country.

6.2.4 Hydrogen

Like electricity, hydrogen can be produced from a variety of fuel sources. Currently, industrial hydrogen is produced by reforming natural gas. Centralized production of hydrogen will produce less CO_2 emissions compared to distributed production at service stations because it would be more efficient and would lend itself to carbon capture and storage [Kramer et al. 2006]. During the initial phase of hydrogen fuel cell vehicles, however, the demand for hydrogen will be small and the cost effective option will likely be forecourt[51] production. In the much longer term, hydrogen could be produced at distributed locations from renewable electricity, or from coal or biomass with carbon capture and storage. For the time scales under consideration here, distributed steam methane reforming of natural gas will most likely be the source of hydrogen production. Weiss et al. [2000] estimated that 132 g CO_2 will be emitted during production and delivery of one MJ of compressed hydrogen to the tank of vehicle at 350 atmospheres pressure. If hydrogen is stored at twice this pressure, then compression work required will increase the CO_2 emissions intensity of hydrogen to approximately 140 g/MJ.

6.2.5 Summary of fuel options

The life-cycle emissions factors used to calculate future vehicle fleet GHG emissions are shown in Table 28 [GREET 2007; Groode and Heywood 2008; Kromer and Heywood 2007; McCulloch et al. 2005]. All emission factors are calculated on lower heating value (LHV) basis. The tank-to-wheel emissions for electricity and hydrogen are zero, as they do not consume any hydrocarbons during the vehicle use phase. While CO_2 is produced during combustion of ethanol, it is a common simplifying assumption that the CO_2 ingested by the biomass cancels out emissions during combustion. As a result, the CO_2 emissions associated with the use of ethanol during vehicle operation are considered to be zero.

Based on the fuel cycle emissions factors shown in Table 28, and vehicle fuel consumption calculations discussed in Section 2, we can estimate the petroleum consumption and life-cycle GHG emissions of different types of vehicles. Figure 44 shows fuel consumption and well-to-wheel GHG emissions for future cars using different fuels. Note that compared to today's average car, which consumes 8.8 L/100 km of gasoline and emits 250 g CO_2/km, all future vehicles are expected to realize a dramatic reduction on both counts.

[51] Forecourt is the area of the fuel station where fuel pumps are located.

Table 28 Energy use and CO_2 emission factors for different transportation fuels [Kromer and Heywood 2008; GREET 2007; Groode and Heywood 2008; McCulloch et al. 2005]

FUEL	ENERGY (fossil MJ / MJ delivered in tank)	GHG EMISSIONS Fuel Cycle (g CO_2 / MJ delivered to tank)	Vehicle Operation (g CO_2 / MJ delivered from tank to wheels)	Total (g CO_2 / MJ delivered from well to wheels)
Conventional gasoline	0.24	21	71	92
Conventional diesel	0.21	18	76	94
Gasoline from oil sands	0.41	38	71	109
Ethanol from corn	0.68[52]	77[52]	0	77
Ethanol from cellulose	0.09	9	0	9
Electricity (avg. U.S. grid mix)	2.30	214	0	214
Hydrogen from natural gas	0.84	132	0	132

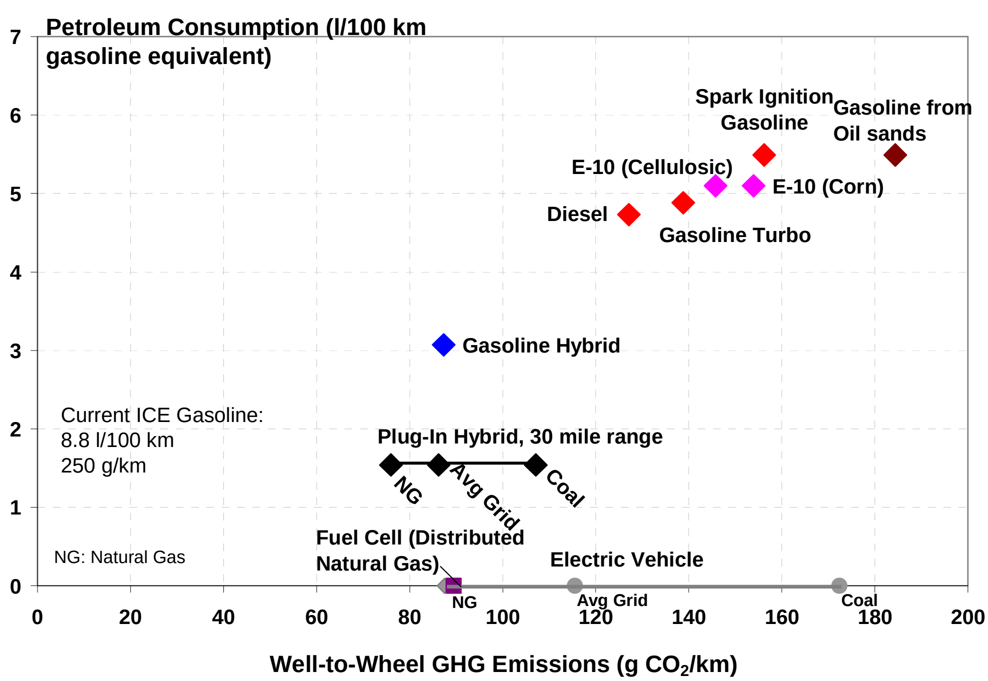


Figure 44 Fuel consumption and well-to-wheel GHG emissions for future (2035) cars

[52] Includes a 20% co-product credit for dried distillers grains with soluble, assuming a market for DDGS exists.

Note that a car running on gasoline derived solely from a non-conventional oil source such as tar sands will have some 18% higher well-to-wheel CO_2 emissions. E-10, which is a blend of 10% ethanol with gasoline by volume, reduces petroleum consumption by approximately 6.5%, since the energy density of ethanol is about two-thirds that of gasoline. When ethanol in E-10 is made from corn, the net reduction in well-to-wheel CO_2 emissions is approximately 1.5%, as opposed to 6.8% when the ethanol in E-10 is made from cellulosic material such as switchgrass.

Gasoline hybrids are significantly separated from the cluster of improved ICE- only vehicles. The plug-in hybrid vehicle achieves a further reduction in petroleum consumption compared with the full gasoline hybrid. The GHG emissions reduction achieved by the PHEV charged by the average U.S. electricity grid mix are comparable to that of a conventional hybrid. Depending upon the emissions intensity of the electricity, the GHG emissions from a 30-mile PHEV can be higher or lower by approximately 20%.

The GHG emissions from a battery electric vehicle (BEV) charged from the average U.S. grid are found to be approximately 30% higher than a conventional gasoline hybrid or plug-in hybrid. The primary reason for comparatively poor CO_2 performance of the BEV is the higher vehicle weight. In the vehicle simulation performed by Kromer and Heywood [2007], the BEV is heavier than a comparable PHEV by some 280 kg, since the energy requirement of the 200 miles range BEV battery is about six times that of a PHEV-30.

Finally, the GHG emissions during production of hydrogen from natural gas without carbon capture are comparable to the GHG emissions from production and combustion of gasoline in a hybrid vehicle.

Figure 44 indicates that while a variety of vehicle alternatives can substantially displace petroleum from light-duty vehicles, their effectiveness in reducing CO_2 emissions varies widely and depends initially on the assumptions that define the fuel cycle. To lower vehicle GHG emissions below 85 g/km, it will require some combination of the following: 1) E-85 derived from cellulosic ethanol or other comparable biofuel, 2) inherently low carbon sources of electricity such as nuclear, wind, and solar, and 3) carbon capture and storage to reduce CO_2 emissions from production of electricity and/or hydrogen from coal and natural gas.

6.3 Impact of changing fuel mix on LDV GHG emissions

This section addresses the effect of changing liquid transportation fuel mix on well-to-wheel greenhouse gas emissions. First, the effect of increasing non-conventional oil on fleet GHG emissions is considered. Second, the combined effect of non-conventional oil and biofuels on fleet GHG emissions is evaluated.

6.3.1 7.5% hybrids needed in 2035 to offset GHG impact from 10% oil sands

The current production of oil sands from Canada is approximately 40% of total Canadian oil production. Assuming that 40% of the 1.5 million barrels per day (MBD) of Canadian exports to the United States were from oil sands, approximately 0.6 MBD of oil from tar sands entered the United States in 2005. Thus, oil sands accounted for approximately 3% of total U.S. petroleum use. If the oil sands exports from Canada to the United States were to increase to more than 2.5 MBD (as explained earlier), oil sands could easily represent approximately 10% of total U.S. petroleum consumption in 2030. As this fraction increases from 3% to 10%, the amount of oil from tar sands in the U.S. LDV fleet use would increase from 0.3 MBD in 2005 to 1.1 MBD in 2035. Figure 45 shows the impact of increasing the fraction of oil sands from 3% to 10% on the reference case well-to-tank emissions. If either a higher amount of oil comes from oil sands or a greater fraction of oil from oil sands is used in LDVs, then the impact on well-to-tank GHG emissions would be worse. Figure 45 also shows the impact on well-to-tank GHG emissions if up to 2 MBD of oil from tar sands enters the U.S. LDV market by 2035.

The increase in fuel cycle greenhouse gas emissions is approximately equal to the loss of one to three MPG in new vehicle fuel economy in 2035. In other words, in order to make up for the additional emissions from fuel cycle, the cars and light-trucks will have to attain higher levels of fuel economy to keep the well-to-wheels emissions from getting worse. This loss is equivalent to the fuel use reduction achieved through a 7.5 % market penetration of hybrid vehicles by 2035 in case of low oil sands share and up to 20% market penetration of hybrid vehicles by 2035 in case of high oil sands share.

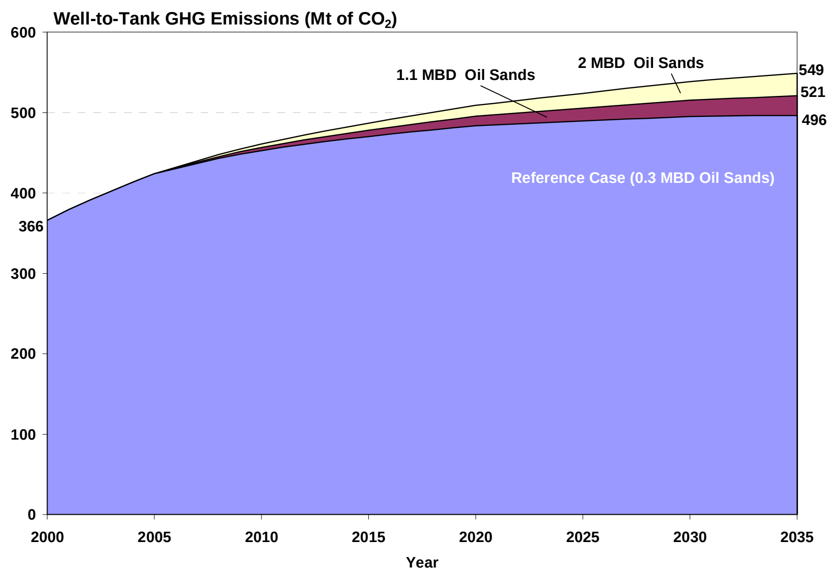


Figure 45 Impact of increasing oil sands on well-to-tank GHG emissions

Note that a greater reliance on Canadian oil sands is desirable from the perspective of security of supply. At present, the growth in coal-to-liquids and shale oil is deemed to be very costly and speculative, and the GHG emissions during their production are much higher than those in production of oil sands [EIA 2007a; Rand 2007]. If the pursuit of energy independence continues to provide incentives for development of these resources, the effect on fleet GHG emissions will be comparable to that of oil sands even at low volumes.

6.3.2 A 2–6% reduction in 2035 well-to-wheel CO_2 emissions is possible by changing fuel mix

If increased use of non-conventional oil increases the fleet GHG emissions, then increased use of biofuels can reduce that impact. Based on the discussion in this section, Table 29 lists the projected low and high volumes of contribution for non-conventional oil, corn ethanol, and cellulosic ethanol.

Table 29 Scenarios of alternative fuel mix by volume

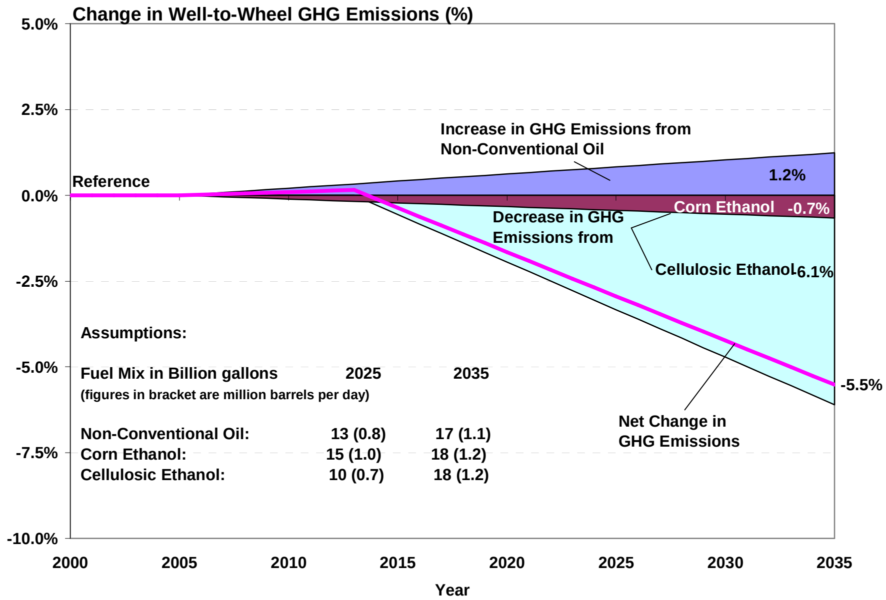
Year	Non-Conventional Oil (MBD[53])		Corn Ethanol (MBD)	Cellulosic Ethanol (MBD)	
	Low	High		Low	High
2010	0.3	0.3	0.45	0	0
2025	0.8	1.4	1.0	0.5	0.7
2035	1.1	2.0	1.2	0.9	1.2

The maximum reduction in GHG emissions will be in the case when the contribution from non-conventional oil such as tar sands is low and the contribution from low carbon biofuel such as cellulosic ethanol is high. Conversely, the lower bound of reduction in GHG emissions will be realized when the contribution from non-conventional oil is high and the contribution from low carbon biofuels is low.

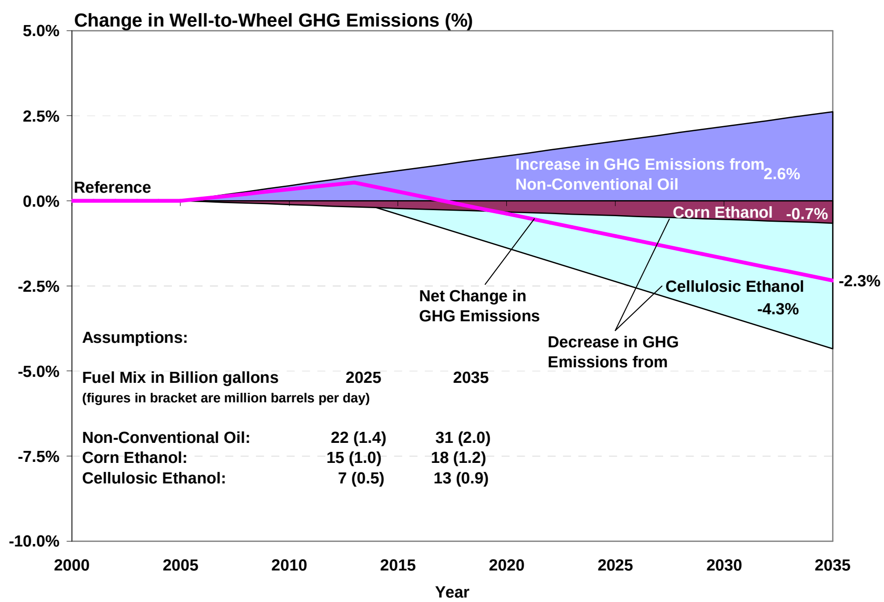
Figure 46 evaluates the percentage change in well-to-wheel (WTW) GHG emissions from these two scenarios. Part (a) of the figure shows a *Low Oil Sands / High Cellulosic Ethanol Scenario*. Here, the share of the fuel mix that comes from oil sands increases well-to-wheel GHG emissions by 1.2% from the *Reference Scenario* in 2035. At the same time, large shares of corn and cellulosic ethanol reduce WTW GHG emissions by 6.8%, leading to a net reduction in 2035 GHG emissions of 5.5% from the *Reference Scenario*. Part (b) of the figure shows a *High Oil Sands / Low Cellulosic Ethanol Scenario* where the net reduction in GHG emissions in 2035 is only 2.3% below the *Reference Scenario*. In part (a), the net emissions due to changing fuel mix are increasing until year 2014 and then decreasing, whereas in part (b), the net emissions due to changing fuel mix are increasing until 2017.

Figure 46 indicates changes in the fuel mix are likely to produce a 2–6% reduction in 2035 WTW GHG emissions compared to the *Reference Scenario*.

[53] MBD: Million Barrels per Day, 1 MBD = 15.34 Billion gallons per year = 58 billion liters per year.



(a) *Low Oil Sands / High Cellulosic Ethanol Scenario*



(b) *High Oil Sands / Low Cellulosic Ethanol Scenario*

Figure 46 Net change in well-to-wheel CO_2 emissions due to fuel mix

This section provided an overview of fuels other than conventional gasoline and diesel that are likely to play an increased role in the U.S. light-duty vehicle fleet. Based on the emissions intensity of the fuel mix, it is possible to calculate the well-to-wheel greenhouse gas emissions for the LDV fleet. A key finding of this section is that a greater number of vehicle and fuel alternatives are available to displace petroleum use than to reduce greenhouse gas emissions. In general, measures that reduce greenhouse gas emissions also reduce petroleum consumption, but the converse is not necessarily true. Policy efforts should therefore be focused on measures that improve energy security and carbon emissions at the same time.

7.0 Fleet Scenarios

The last decade has seen the market introduction of gasoline-electric hybrid vehicles (HEVs), a renewed interest in diesels in the U.S. market, and increasing exploration of more exotic propulsion systems, such as Plug-In Hybrid Vehicles (PHEV) and Hydrogen Fuel Cell Vehicles (FCVs). The extent to which these technologies can challenge conventional gasoline vehicles in the marketplace will determine the long-term trajectory of light-duty vehicle fuel use. This section explores the challenges that must be overcome in order to achieve a greater market penetration of these alternatives. Future scenarios of market penetration are developed to illustrate the impact of these technologies on fleet-wide fuel use and greenhouse gas (GHG) emissions over the next 30 years.

7.1 Barriers to new propulsion systems and alternatively fueled vehicles

New propulsion systems and alternatively fueled vehicles face many hurdles on their way to market acceptance [Sutherland 1991; Jaffe and Stavins 1994; Stoneman 2002; Romm 2004; McNutt and Rodgers 2004]. The major barriers include:

High first cost for vehicle. Initial purchase price plays a large role in consumers' choice when selecting a new vehicle, since it typically represents the largest component of the life-cycle cost of owning and operating the vehicle. Purchasing a PHEV, FCV, or battery electric vehicle (BEV) could entail a cost premium as large as 35–70%, thereby greatly reducing the number of consumers willing to consider purchasing these vehicles.

Fuel storage/limited range. Liquid petroleum fuels, by the virtue of their energy density, have enabled consumers to expect a driving range of 500–600 kilometers without having to refuel. Gaseous fuels such as natural gas or hydrogen are only able to provide this type of driving range if compressed to very high pressures and stored in larger fuel tanks. Similarly, batteries for PHEVs or BEVs add substantial mass to the vehicle and occupy valuable cargo space in order to provide similar range. The actual risk or the perception of risk of running out of fuel limits the attractiveness of these vehicles in the minds of consumers. A modified ICE gasoline vehicle fueled with E-85 is not range limited to the same extent, although its range is only about 70% that of a comparable gasoline vehicle with a fuel tank of the same size.

Safety. Thermal runaways in batteries are the main concerns from a safety point of view in the PHEV and BEV. Development of more stable cathode materials and electrolytes will likely resolve that concern in the future. With respect to the fuel cell vehicles (FCVs), the safety concern has to do with the fueling and storage of hydrogen. Unlike gasoline vapor, gaseous hydrogen is prone to auto-ignite with even a small static electricity discharge. Hydrogen is also liable to explode in confined spaces such as enclosed garages and tunnels. As a result, preventing leaks of hydrogen from fueling stations and onboard storage tanks will be of paramount importance. Unless new scientific breakthroughs are realized, the storage of hydrogen onboard is likely to be in high-pressure (700 bar, or 10,000 psi) tanks. Safe handling and storage of hydrogen under such conditions will require not just development of codes and standards, but also consumer awareness and education [NRC 2004].

Reliability and Durability. Lack of familiarity with new vehicle technologies may lead to doubts about their reliability in consumers' minds. The initial experience with Hybrid Electric Vehicles (HEV) has proven that electric propulsion systems can be reliably integrated with the conventional engine-transmission systems. The durability of batteries in the case of PHEVs and BEVs remains to be proven, however. Kromer and Heywood [2007] have identified that the durability challenge for batteries consists of "meeting the combined rigors of repeated charge/discharge cycles, and extended shelf life" under on-road operating conditions. With respect to the hydrogen fuel cell vehicles (FCVs), experiments such as the California Fuel Cell Partnership are generating valuable hands on experience of operating FCVs. Degradation of platinum catalyst over time and failure of membrane materials are the major durability challenges for FCVs. Kromer and Heywood [2007] estimate that the focus of FCV development will shift from weight, size, and cost reductions to addressing durability concerns by the early 2010s. So the challenge is for the new technologies to match the high reliability and durability of conventional internal combustion engine vehicles.

Fueling cost compared to gasoline. A gasoline price of $3 per gallon at the pump is equivalent to about $25 per GJ. Electricity for PHEVs and BEVs will be cheaper on an energy basis if it costs less than nine cents per kWh. If hydrogen is generated from centralized natural gas or coal plants, then it could be produced at $3 dollars per kilogram or $25 per GJ, provided distribution and dispensing costs could be roughly halved from current estimates [Kramer et al. 2006]. Ethanol from corn currently receives a subsidy of 51 cents a gallon or $6.30 per GJ. The cost of producing ethanol from cellulosic material such as switchgrass is currently estimated to be around $2.25–2.75 per gallon, depending on the feedstock cost and on ethanol conversion efficiency [NREL 2006a].

Lack of refueling infrastructure. There are currently about 175,000 refueling stations serving gasoline across the United States. A large number of these refueling stations are also capable of serving diesel fuel. According to the Alternative Fuels Data Center maintained by the U.S. Department of Energy, there were 1,154 refueling stations for E-85, 444 stations for electricity, and 31 stations serving hydrogen as of June 2007. The prospect of getting stranded due to lack of fuel availability, coupled with the limited range of several alternatively fueled vehicles, severely limits the market penetration of such vehicles. Vehicle manufacturers are therefore reluctant to produce alternatively-fueled vehicles. On the other hand, the capital cost of building a hydrogen refueling station based on a centralized hydrogen production model is estimated to be between $0.7–1.5 million [Padro and Putsche, 1999]. Thus, large-scale investment in fuel infrastructure may not be worthwhile unless a number of alternatively fueled vehicles are already on the road. This is popularly known as the Chicken-and-Egg dilemma.

Difficulty breaking into an established market. There are about two billion internal combustion engines in operation around the world in mobile and stationary applications. With over a hundred years of engineering and development behind them, ICE-based vehicles are tough competition for any alternative powertrain. An enormous amount of engineering effort and learning has gone into integrating vehicle systems with ICE engines. Thus, any new technology faces the challenge of offering the same functionality as the mainstream ICE gasoline vehicle, but at a lower cost or offering additional functionality at a comparable cost. The new technologies have yet to realize learning and economies of scale, making their task of breaking into the light-duty vehicle market even more difficult.

Learning and economies of scale not realized. During the early stage of market introduction, the capital and other fixed costs are a high part of vehicle cost. As the number of vehicles produced increases, the fixed costs can be spread over a larger number of vehicles, bringing down the cost per vehicle. With respect to newer vehicle technologies such as batteries or fuel cells, manufacturing costs come down as a result of learning-by-doing. Such learning benefits are realized only when a substantial quantities of these units are produced.

Lack of awareness. Consumers may not have a new technology on their list of purchase options because they are unaware or unfamiliar with the new technology. For example, in a survey conducted by the National Renewable Energy Laboratory in 2004, more than half of the people surveyed could not name a hybrid vehicle [Kubic 2006]. As more vehicle models become available and familiarity of consumers with new technology increases, there is a greater chance that they will consider it at the point of next purchase.

Discount factors and attitudes to risk. Sutherland [1991] notes that consumer discount rate for investing in more energy efficient technology is around 20%. Greene [1996] has argued that when depreciation in vehicle value (resale price) is taken into consideration, a discount rate of 20% for vehicle purchase is not unrealistic. At such a high discount rate, consideration for the initial cost of purchase might overwhelm the lifetime savings realized from a more fuel-efficient vehicle.

Uncertain demand for fuel economy. Consumers may also have questions about potential for fuel savings realized for adopting a costlier technology. From a vehicle manufacturers' perspective, undertaking a major vehicle redesign when consumers' preference for increased fuel economy is unclear is a risky endeavor.

7.2 Role of supply-side constraints

Even if the demand for an emerging vehicle or propulsion system is strong, the supply of such systems could be limited. This could primarily be attributed to the constraints in engineering and capital resources, as well as supply chain considerations. Some of these constraints are discussed below:

Development lead times and availability across product platforms. The automobile is a highly complex product, and consumer expectations from a mass-produced vehicle are quite demanding. Development and engineering of a "new" propulsion system must take into consideration the product architecture, and integration of new sub-systems with the old sub-systems into account. As a result, even proven sub-systems or components may take on the order of 15 years to become available across all market segments. Figure 47 shows the deployment of different engine and transmission technologies in the U.S. LDV market from 1948–2006 [Ward's 2003; Heavenrich 2006]. Notice that even very cost-effective technologies such as Variable Valve Timing (VVT) have taken 10–15 years to penetrate to half of new vehicles, whereas automatic transmissions, having reached half of the market by 1950, required 20 more years to be available in 90% of the vehicles.

Based on a broad survey of technological change in automobile industry, Nakicenovic [1986] observed that it took 10–30 years after introduction of a new technology before it was deployed on half of the new vehicles. With respect to emerging technologies such as hybrids, the integration of technology in vehicles is more complex than the components or sub-systems shown in Figure 47. It is also possible that additional time may be needed for adequate development of certain components so that they meet traditional safety and reliability constraints. For example, Toyota announced in June 2007 that the introduction of Lithium-Ion batteries in the 2008 version of Prius would be delayed by at least one year due to concerns about fire hazards [Shirouzu 2007]. The development and system integration costs of new technologies can be managed if the technology is introduced during the normal product development cycle. With respect to hybrid vehicles, Toyota's executive engineer, David Hermance, said in early 2005:

> *"We won't turn a switch and tomorrow we'll have hybrids in everything," says Hermance. "There will still be a rollout of which models make sense and then some time to develop." But it can be steady, and it is being whittled down from multiple years to about 18 months. The goal is to include hybrid development in the regular vehicle-development cycle." [Priddle 2005]*

Applying this logic to penetration of emerging propulsion systems across all market segments will yield at least a 15–20 year timeframe before they could garner a third of the market share, even if there were no demand-side constraints.

Capital investment required. Automobile manufacturing is both a capital- and labor-intensive business, and the established industry players are, in general, risk averse. It normally takes two to three years for an OEM to build a completely new production facility. Retooling an existing facility to produce different components takes 12–18 months. Based on expert interviews, Hammet et al. [2004] estimated the cost of tooling and equipment of converting existing factories to produce hybrids and diesels [Table 30]. Note that this does not include the costs of development and engineering of these vehicles.

Table 30 Estimated tooling and equipment investment to convert brownfield sites to produce hybrids and diesels (in 2004 dollars)

		Capital Costs in Millions of Dollars (2004)	
		Hybrids	Diesels
Plant capacity per year	100,000	190	145
	200,000	330	240

Thus, to convert 10% of the US domestic production capacity (~1.3 million vehicles per year) to produce hybrids and diesels each will take a capital investment of approximately $2.2 billion and $1.6 billion, respectively. For comparison purposes, the U.S. Census Bureau estimates that the annual capital expenditure of motor vehicle manufacturing sector is about $20 billion [U.S. Census 2007].

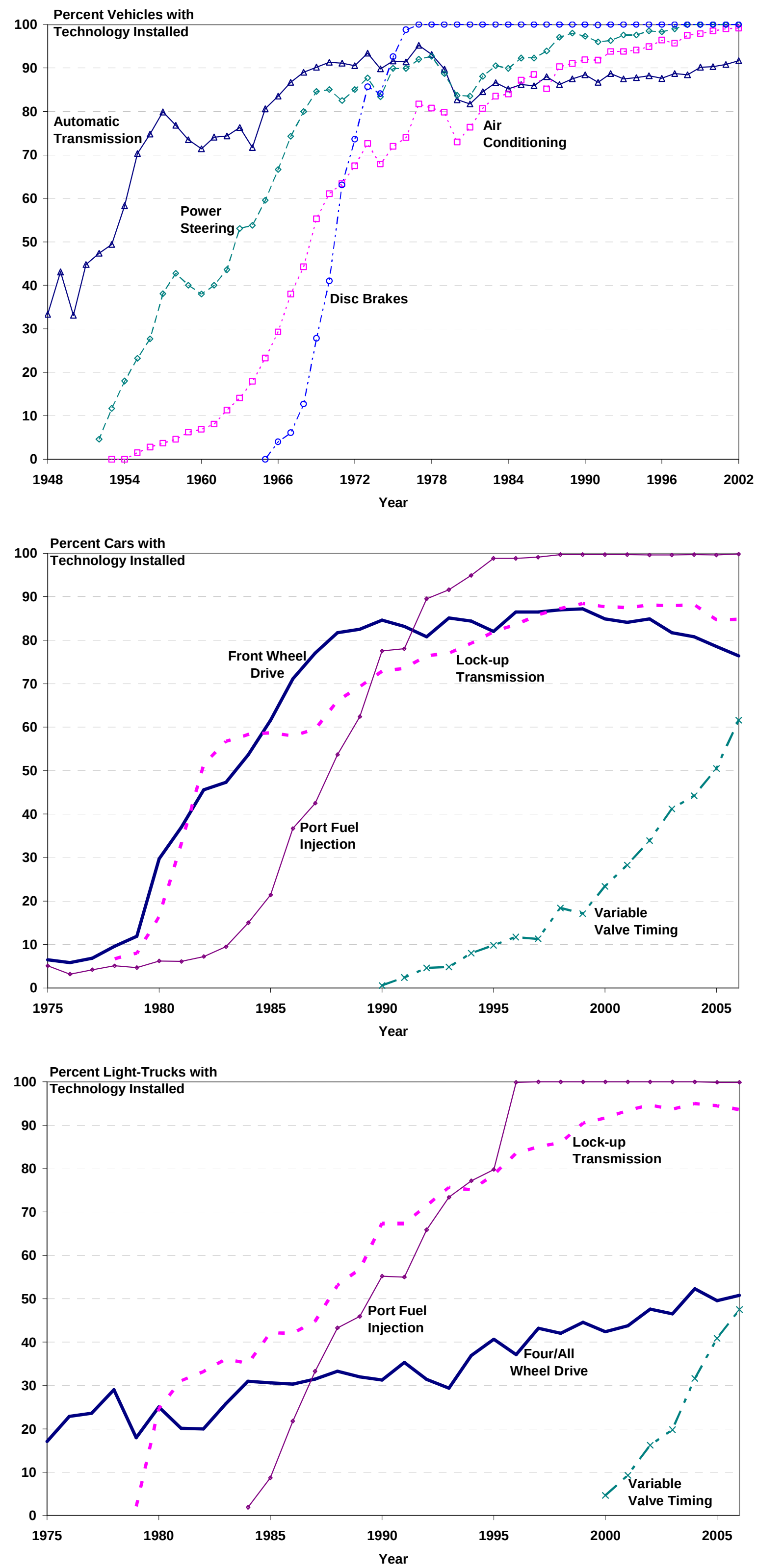


Figure 47 Technology deployment in new vehicles, 1948–2006 [Ward's 2003; Heavenrich 2006]

Supply of critical systems/components. As the demand for alternative propulsion systems grows, it will be critical to develop a supply chain that is capable of expanding accordingly. Presently, two Japanese companies (Panasonic EV Energy and Sanyo) dominate the global hybrid vehicle battery market [Anderman 2007]. As the global demand for batteries for hybrid vehicles grew, both Panasonic and Sanyo found it difficult to keep up with demand. In 2004, this led to waiting lists of 4–10 weeks for prospective hybrid customers. As more OEMs have announced hybrid vehicle plans, production capacity for batteries is starting to build up, mainly through joint ventures between battery and automotive companies. In spite of this capacity build-up, batteries are likely to remain supply-constrained hybrid system components. A similar argument can be made for diesel sub-systems such as fuel-injections systems, although the industry is much better positioned to supply diesel components from Europe.

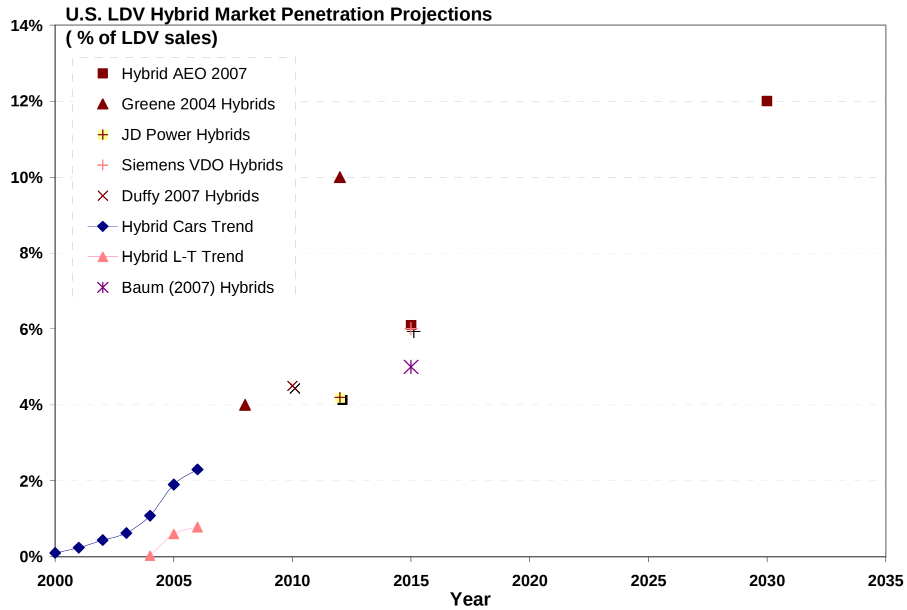
Capacity utilization. Since the capital costs of setting up automotive manufacturing facilities are quite high, OEMs attempt to utilize the manufacturing facilities to the fullest extent possible to spread the capital costs over a larger number of vehicles. They must match the demand for different motor vehicles with the flexibility in the production and assembly lines to vary the capacity over time [Lindgren et al. 1974; German 2007]. Newer vehicle systems and models, which are typically produced in low volume, have to be appropriately phased in while keeping the overall capacity utilization high.

As these supply side constraints suggest, the time scales by which new technologies can have an impact on fleet fuel use are rather long. Schafer et al. [2006] split this timeline in roughly three stages, as shown in Table 31.

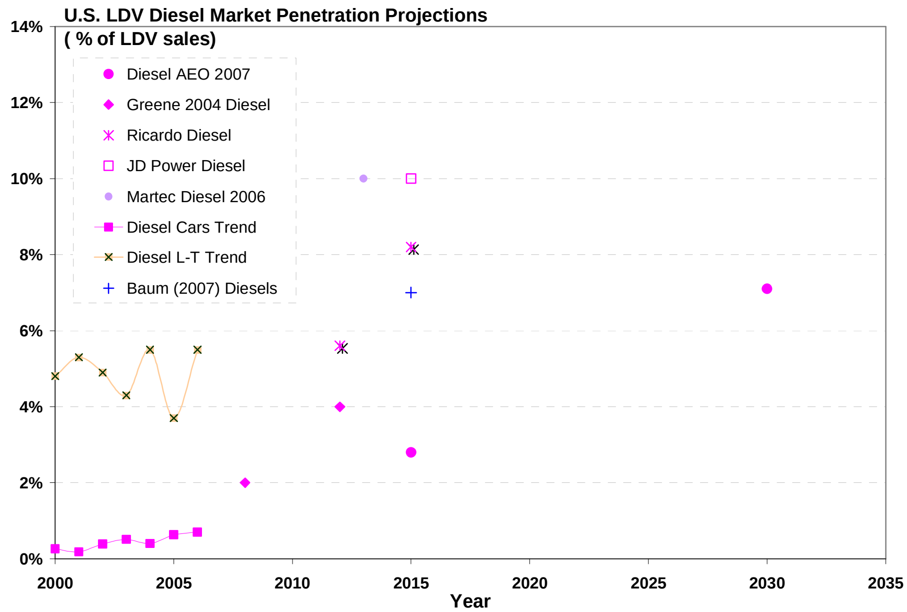
Table 31 Estimated time scales for technology impact [adapted from Schafer et al. 2006]

Implementation Stage	Vehicle Technology				
	Gasoline Direct Injection Turbocharged	High Speed Diesel with Particulate Trap, NOx Catalyst	Gasoline Engine/ Battery-Motor Hybrid	Gasoline Engine/ Battery-Motor Plug-In Hybrid	Fuel Cell Hybrid with onboard Hydrogen Storage
Market competitive vehicle	~ 2-3 years	~ 3 years	~ 3 years	~ 8-10 years	~ 12-15 years
Penetration across new vehicle production	~ 10 years	~ 15 years	~ 15 years	~ 15 years	~ 20-25 years
Major fleet penetration	~ 10 years	~ 10 -15 years	~ 10 -15 years	~ 15 years	~ 20 years
Total time required	**~ 20 years**	**~ 25 years**	**25 -30 years**	**~ 30-35 years**	**~ 50 years**

In the first stage, a market-competitive technology needs to be developed. Schafer et al. do not define the phrase "market-competitive technology." It is assumed here that for a technology to be market competitive, it must be available across a range of vehicle categories at a low enough cost premium to enable the technology to become mainstream rather than a niche. The time scales shown in Table 31 represent our current assessment of time required for different propulsion systems to be broadly available mainstream alternatives in the U.S. market. Of these, only turbocharged gasoline, diesels, and gasoline hybrids are available in model year 2008. While no concrete product plans have been announced for a plug-in hybrid vehicle, several major OEMs including General Motors and Toyota have publicly expressed interest in developing a commercial product within the next decade. The case for a market competitive fuel cell vehicle is more speculative. A survey of announcements from major automakers suggests that a commercial mass-market fuel cell vehicle is at least 10 years away [Adamson and Crawley 2006].



(a) Hybrid Market Share Projection



(b) Diesel Market Share Projection

Figure 48 Various forecasts of U.S. light-duty vehicle diesel and hybrid market penetration

In the second stage of technology implementation shown in Table 31, penetration across the new vehicle market represents the required time scale for the vehicle technology to attain a market share of the order of a fourth to a third of the total vehicle sales. Broadly, the time scale reflects the expectations about large-scale viability of these propulsion systems based on engineering and cost constraints, and are similar to the time scales required by major vehicle technologies to achieve a large market share. Figure 48 shows various forecasts of diesel and hybrid market share in the U.S. light-duty vehicle market. Note that the only long-term forecast available is from the Department of Energy's 2007 Annual Energy Outlook (AEO). AEO also provides the most conservatives estimates of diesel and hybrid market penetration. The most optimistic projections in the near term are of about 10% market share of diesel and hybrid each, by 2012–2015.

The third stage of technology implementation represents the build-up in actual use of these vehicles. A meaningful reduction in fleet fuel use is not realized until a large number of more fuel-efficient vehicles are being driven. This will happen over a time scale comparable to the median lifetime of vehicles, which is around 15 years.

Thus, the three phases summarized in Table 31 provide a rough estimate of the time before significant impact for new vehicle technologies. There is some overlap between each of the three phases, and the net time to impact is thus somewhat smaller than the sum of each stage.

7.3 Scenarios of market penetration rates

The barriers and constraints outlined in sections 7.1 and 7.2 provide the rationale for our choice of a 25-year time scale for large-scale deployment of improved mainstream engine, transmission, weight reduction technologies, and significant numbers of advanced propulsion system technologies, such as low-emissions diesels and gasoline hybrids, and plug-in hybrids. In this section, four scenarios are presented that encompass a range of assumptions about market penetration rates of different technologies. Prospects for each of the vehicle technologies, namely turbocharged gasoline engines, diesels, gasoline hybrids, and gasoline plug-in hybrids, are described briefly before the combined market penetration scenarios are discussed.

Direct-injection turbocharged gasoline powered vehicles offer an attractive alternative for reducing fuel use at a low cost. As indicated in Table 6 and Table 8, a future turbocharged gasoline vehicle is expected to offer some 11% reduction in vehicle fuel consumption relative to the future gasoline vehicle at a cost of less than $1,000. Presently, the market share of turbocharged gasoline vehicles in Europe is about 14%, as compared to less than 0.5% in the United States. The market share of turbocharged gasoline vehicles in Europe is expected to top 22% by 2010. While turbocharged gasoline vehicles have been slow to take off in the United States, market shares similar to those projected for Europe early in the next decade can be expected in the U.S. market over the next 15–20 years [Beecham 2005; Shahed 2007].

Several diesel models were introduced in the United States following the oil shocks of 1973 and 1979, and the sales of diesel vehicles in the U.S. LDV market increased from less than 0.1% in 1973 to about 4.6% in 1980. This sharp increase in diesel car sales helped the U.S. manufacturers meet the sharply increasing CAFE requirements from 1977–1980. Increasing dieselization came to be seen as an important strategy towards meeting higher CAFE standards, and General Motors envisioned a scenario in which a quarter of new vehicle sales in 2000 would be comprised of diesel vehicles [NRC 1982]. The diesel vehicles produced during the late 1970s emitted 10–30 times as much particulate matter as the gasoline vehicles available at that time. Concern over increased criteria pollutants from growing number of diesel vehicles prompted the initiation of a National Academies study on “Impacts of Diesel Powered Vehicles” in 1979.

The popularity of diesel vehicles in the light-duty market proved short-lived, primarily because of poor vehicle performance. The sales of diesel passenger cars peaked at a little over 6% in 1981, and by 1990, diesel cars had all but disappeared from new vehicle sales mix, as shown in Figure 49. While diesel sales in light-trucks were also adversely affected, they continued to enjoy 3–6% market share in the overall light-truck sales due to the popularity of diesel in the Class 2-b segment (gross vehicle weight of 8,500–10,000 lbs) for towing applications.

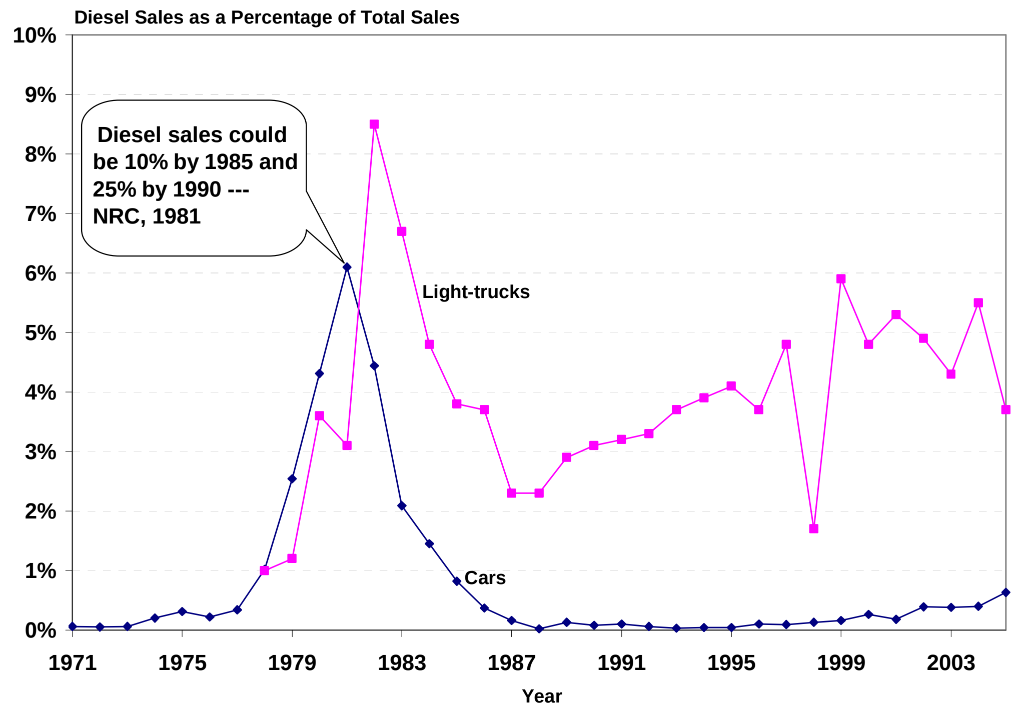


Figure 49 Market share of diesel vehicles in the U.S. (1971–2005) [Davis and Diegel 2007; NRC 1982]

As discussed in the previous section, diesels have penetrated the European car markets substantially, especially since arrival of common rail injection systems in the early 1990s. They have not yet made any progress in the U.S. market, however, due their inability to meet the strict criteria air pollutants standards in California and other states that adopted California standards. In the past, emissions standards for NOx and hydrocarbon emissions have been less stringent in Europe than in the United States. While the Euro V and VI standards for gasoline engines approach the U.S. Tier II Bin 5 standards, the NOx and HC emissions standards for diesel engines will be less stringent than the U.S. Tier II bin 5 standards. As a result, diesel vehicles have been able to operate in the European markets without the need for an expensive NOx after-treatment system such as a lean NOx trap or a selective catalytic reduction unit.

Even though diesel engines' emissions performance today is dramatically improved from the diesels built in the 1970s and 1980s, the new clean diesel still needs to overcome the *perception* of diesel as a smoky, noisy engine. Reduced emissions from clean diesels have come at a fuel economy penalty of 3–5%, and an added cost of several hundred dollars. This added cost of the diesel after-treatment system, coupled with the narrowing of the gap between turbocharged gasoline and diesel efficiency, is the reason for expecting only modest growth of diesels in the LDV market in the United States.

Since their introduction in 1999, gasoline hybrid electric vehicles (HEVs) have steadily gained in popularity in the U.S. market, and in 2006 accounted for about 2% of new car and 1% of new light-truck sales. During this period, awareness about hybrid technology has grown rapidly. While hybrid vehicles still sell at a large premium relative to their conventional gasoline counterparts, the second generation of hybrid vehicles can match the performance expectations of average consumers.

According to Kasseris and Heywood [2007], the expected reduction in relative fuel consumption of future hybrid vehicles is larger than comparable diesel or turbocharged gasoline vehicles. In other words, the hybrid technology has the potential to reduce fuel consumption at a greater rate than other propulsion systems while lowering the cost premium relative to a comparable gasoline vehicle. If these benefits are realized in practice, then hybrid vehicles are likely to become the propulsion system of choice over comparable diesel vehicles.

The availability of commercial hybrid vehicles and advances in battery technology have given rise to the hope of plug-in hybrid electric vehicles (PHEVs). No major OEM has made a commitment to build a PHEV as a commercial product before 2010, however. Toyota Motor Corporation announced in July 2007 that it has plans to test several PHEVs on road in Japan, the United States, and Europe [Toyota 2007]. General Motors intends to put its Chevrolet Volt Plug-In Hybrid Concept vehicle in limited production around 2010 [GM 2007]. Ford Motor Company has announced a partnership with Southern California Edison Company to test 20 PHEVs in California [Woodall 2007]. While these may be encouraging signs for PHEV advocates, it should be noted that a market-ready PHEV is unlikely to emerge before model year 2012, and a mass-market competitive vehicle is unlikely before the 2015–2017 timeframe [Kromer and Heywood 2007; DOE 2007c].

Based on the discussion so far, three scenarios for market penetration of different propulsion systems in the U.S. LDV market were examined. These scenarios are meant to illustrate plausible evolutions of technology in the U.S. LDV market and illustrate the impact of new vehicle technologies on fleet fuel use and greenhouse gas emissions. At the same time, they are not intended to be predictions. As shown in Figure 50, the three scenarios explore three possible directions in which the U.S. light-duty vehicle market can evolve.

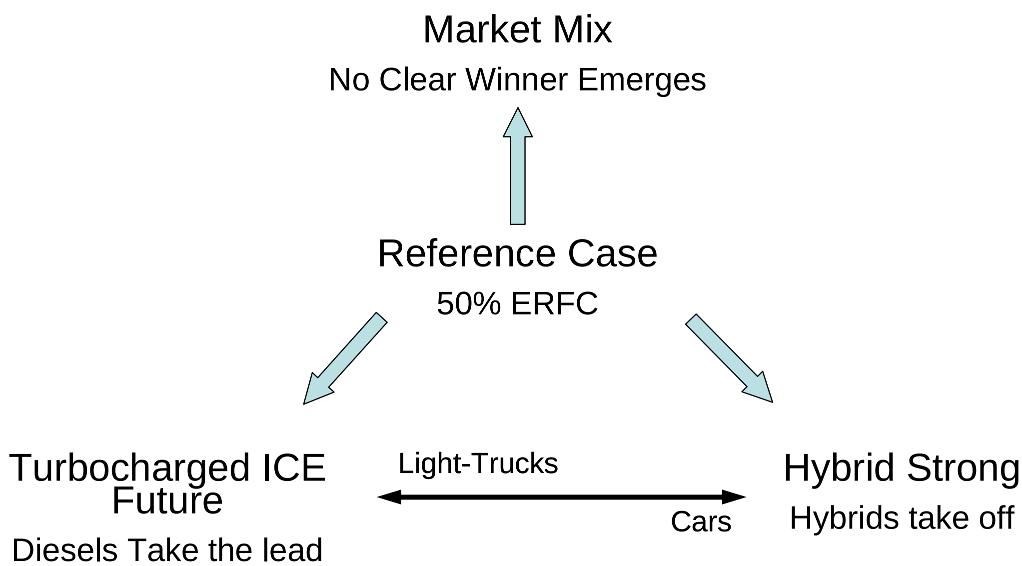


Figure 50 Scenarios for market penetration rates of advanced propulsion systems

The *Market Mix Scenario* represents a diverse pathway into the future, as no particular propulsion system dominates the LDV market over the next three decades.

The *Turbocharged ICE Future* Scenario represents a continuing dominance of internal combustion engines, but with an increasing emphasis on turbocharged gasoline engines as well as advanced (turbocharged) diesels.

The *Hybrid Strong* Scenario represents the situation where gasoline hybrids and plug-in hybrids emerge as the dominant powertrain combinations.

Following the approach of the *Reference Scenario* described in Section 5.7, the three scenarios above assume that increases in fuel efficiency are utilized evenly between reducing fuel consumption and increasing vehicle performance (50% Emphasis on Reducing Fuel Consumption, or ERFC; see section 4.2 for details). The fleet model can model both a linear and S-shaped growth in market shares up to 2045. The shape of the S-curve is determined by the time taken to reach half of their eventual market share in 2045. This time is estimated from Table 31 as 15–17 years for turbocharged gasoline, diesels, and hybrids, 20 years for plug-in hybrid vehicles, and around 30 years for hydrogen fuel cell vehicles. Note that while the scenarios for market penetration extend up to 2045, the fleet model only calculates the fleet fuel use up to 2035, using the vehicle penetration rates up to that point.

7.3.1 Market Mix–No Clear Winner Scenario

One plausible scenario is that no clear winner emerges, and the LDV market in the United States will have a mix of different propulsion technologies. In such a scenario, the high costs of gasoline hybrids and diesels limit their market share to moderate proportions. Plug-in hybrids (PHEVs) establish a niche for themselves primarily in city-driving urban markets, and their growth follows hybrid vehicles but with a time lag corresponding to the difference between introduction of PHEVs and HEVs in the U.S. market. In this *Market Mix Scenario*, diesels, HEVs, and PHEVs together are assumed to account for a little over a third of the new vehicle market by 2035, with a combined market share approaching half of new vehicle sales by mid-century. The remainder of the market is split between turbocharged gasoline and conventional gasoline vehicles, with turbocharged gasoline vehicles becoming a majority of new gasoline vehicles sales around 2040, as shown in Figure 51.

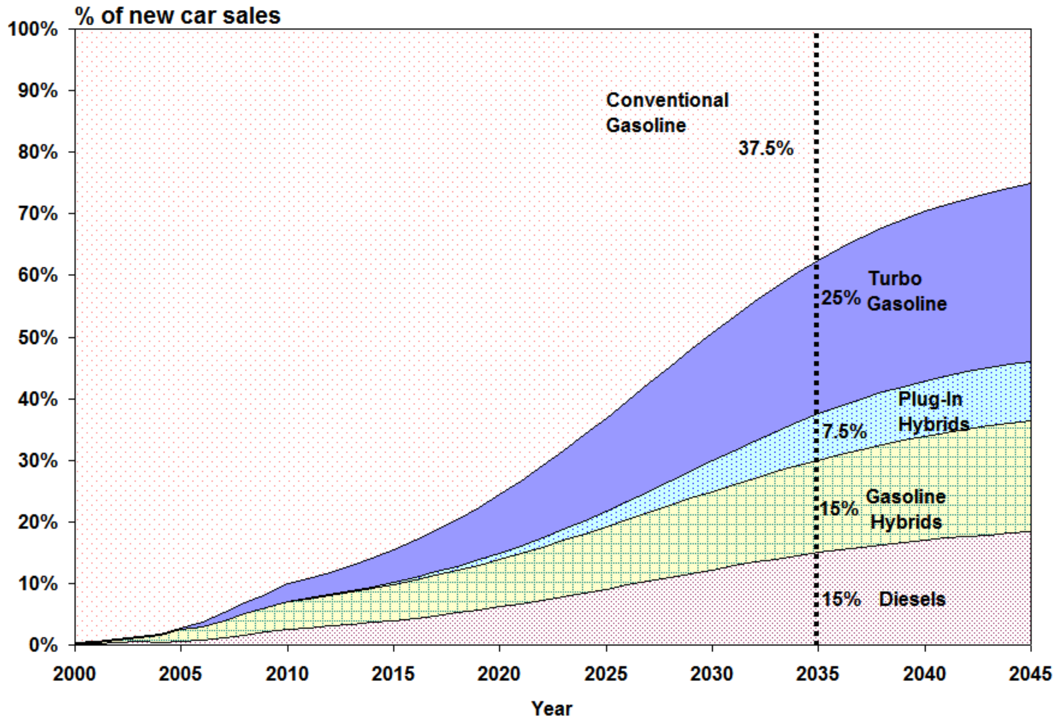


Figure 51 *Market Mix–No Clear Winner Scenario*

7.3.2 Turbocharged ICE Future Scenario

In the *Turbocharged ICE Future Scenario*, both turbocharged gasoline and diesel vehicles gain prominence. In this scenario, future gains from battery technology on safety, calendar life and costs are limited, and as a result the relatively high costs of hybrid vehicles prevent them from expanding beyond the market mix scenario. Similar issues plague any meaningful adoption of plug-in hybrid technology. Preferential taxation of diesel, and successful implementation of PM and NOx after-treatment might bring about an interest in diesels at the level similar to the European market. Diesel vehicles under this scenario could garner approximately 40% of the market share by 2035, and their market share could approach 50% by mid-century (Figure 52). This represents a 40-year compounded annual growth rate of 12% for diesel cars and 6% for diesel light trucks. Turbocharged gasoline vehicles follow a similar growth pattern and overtake conventional gasoline vehicles sales by 2030, eventually replacing all conventional gasoline vehicles by 2040. Notice that, by 2025, under this scenario more than 50% of new vehicles sold in the U.S. have alternative propulsion systems.

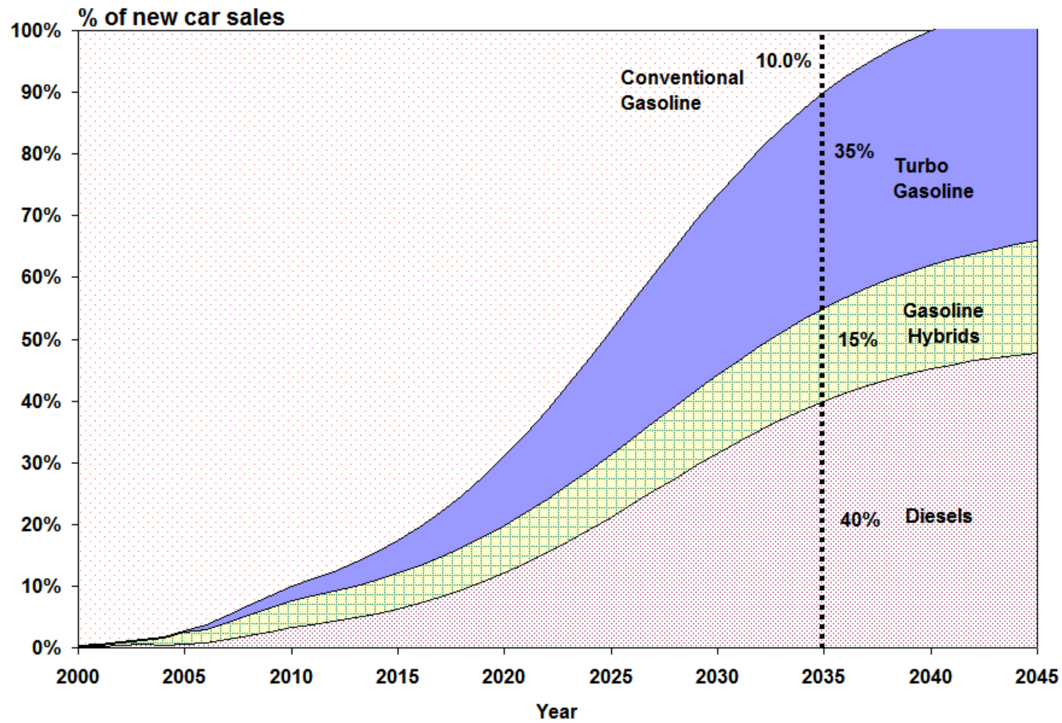


Figure 52 *Turbocharged ICE Future Scenario*

7.3.3 Hybrid Strong Scenario

In a *Hybrid Strong Scenario*, hybrid vehicles emerge from their current niche level and become the mainstream vehicle of choice. Improved battery-motor-engine integration and reductions in lithium-ion battery costs increase the acceptance of the hybrid technology. Hybrid vehicles account for a quarter of new vehicle sales by 2025 and half of new vehicle sales by 2050. This represents a 40-year compounded annual growth rate of 8% for hybrid cars and 11% for hybrid light trucks. Aided by sustained pressure to reduce petroleum consumption and further reductions in battery costs, the growth of plug-in hybrids in the LDV market accelerates after 2020. The PHEV market share approaches 15% by 2035 and 20% by mid-century. As the fuel economy gap between turbocharged gasoline and diesel narrows, the relative cost-to-benefit of choosing diesel over turbo-gasoline increases. As a result, diesel vehicles remain on the fringe, and the market of conventional ICE vehicles is taken up by the turbocharged gasoline vehicles. By 2040, less than 10% of the new vehicle sales in the U.S. LDV market are conventional ICE gasoline vehicles, as shown in Figure 53.

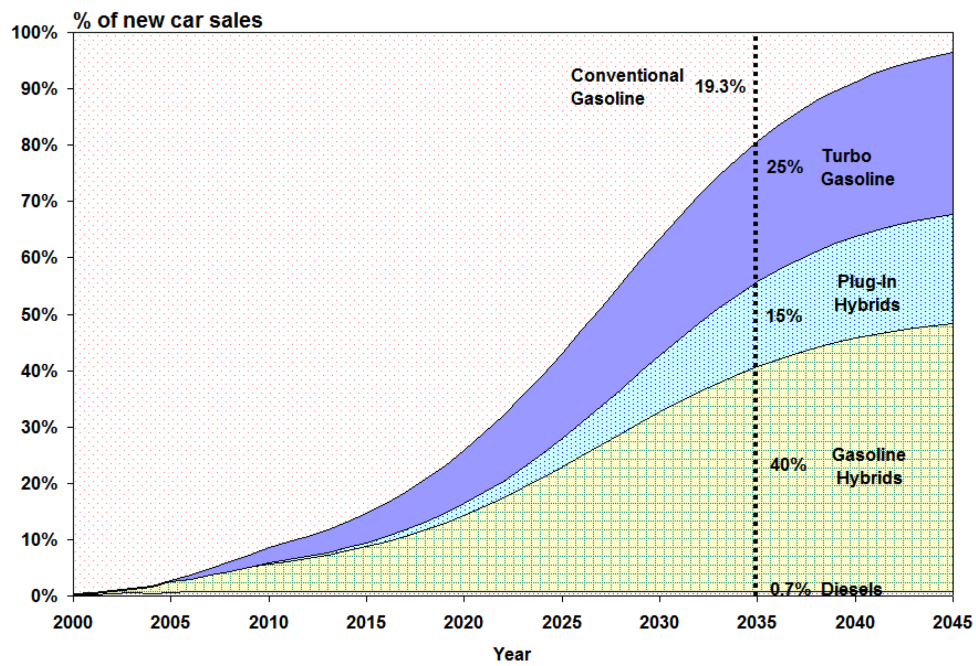


Figure 53 *Hybrid Strong Scenario*

7.4 Scenario Results

Let us start by examining what could be achieved under the *Reference Scenario*, in which efficiency improvements in gasoline engines, transmissions, and some weight reduction achieve reductions in average new vehicle fuel consumption without any penetration of advanced powertrains into the fleet. As discussed in section 5.7, this scenario is assumed to correspond with a 50% Emphasis on Reducing Fuel Consumption, or ERFC (see also section 4.2). When the fuel efficiency benefits are used fully to reduce fuel consumption (i.e. 100% ERFC), the LDV fleet fuel use can be reduced by as much as 26% from the *No Change Scenario* in 2035. Table 32 lists the light-duty vehicle fleet fuel use in 2035 for different values of ERFC. Each 25% increment in ERFC represents approximately 50 billion liters of fuel saved in 2035.

Table 32 U.S. light-duty vehicle fleet fuel use in 2035 for different degree of Emphasis on Reducing Fuel Consumption (ERFC)

	Degree of Emphasis on Reducing Fuel Consumption (ERFC)					
	0%	25%	50% (*Reference Scenario*)	75%	100%	120%
2035 LDV Fleet Fuel Use (in billion liters)	765	715	664	614	563	522
Percentage Reduction from No Change (%)	0	6.5	13.2	19.7	26.4	31.8

Figure 54 shows the impact on fleet fuel use under the *Reference Scenario* (50% ERFC) relative to the *No Change Scenario* and full emphasis on reducing fuel consumption (100% ERFC) from 2010 to 2035.

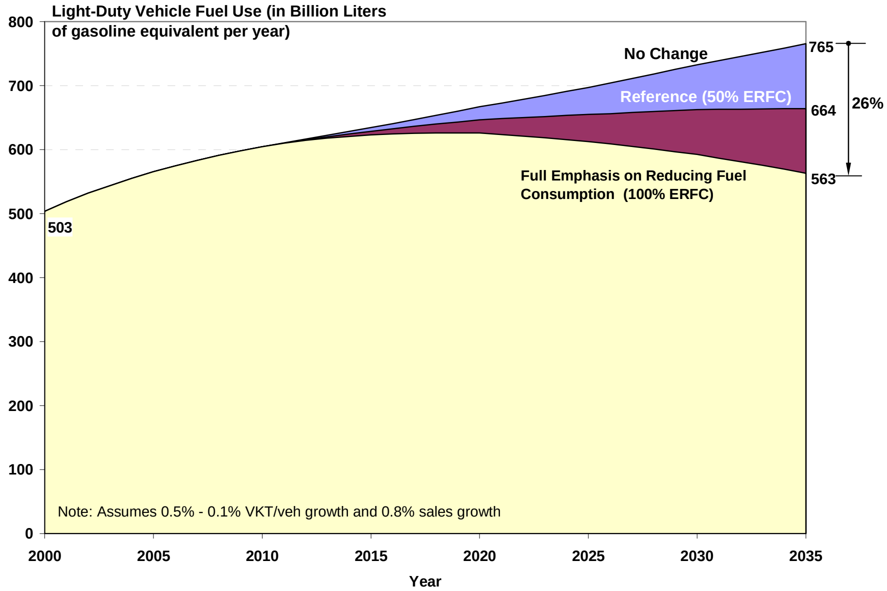


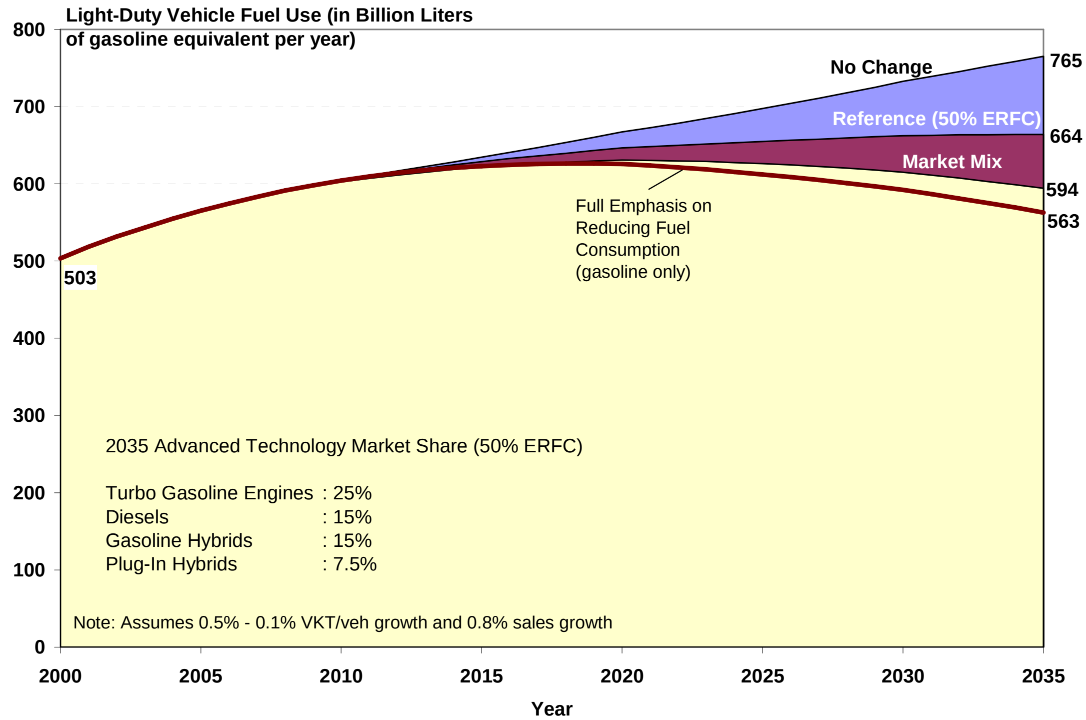
Figure 54 U.S. LDV fleet fuel use with full emphasis on reducing fuel consumption

Figure 55 (a) shows the estimated fuel use savings from the *Market Mix Scenario*. The increasing market share of advanced propulsion systems under this scenario contributes to a 10.5% reduction in 2035 LDV fuel use from the *Reference Scenario*. Notice that the LDV fleet fuel use with 100% ERFC and no increase in advanced propulsion systems' market share achieves a greater reduction in 2035 fleet fuel use than the *Market Mix Scenario* with 50% ERFC.

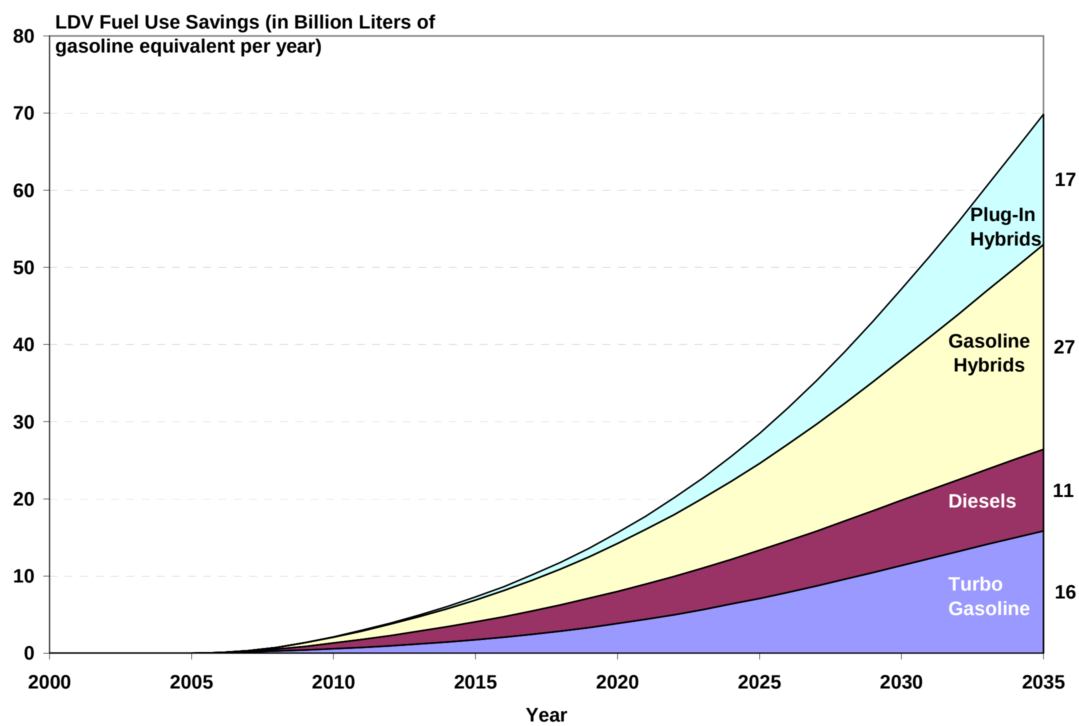
This demonstrates the importance of a strong emphasis on reducing fuel consumption through engine and transmission improvements with some weight reduction, rather than offsetting these gains by emphasizing other attributes such as size and performance.

Figure 55 (b) shows the contribution of different propulsion systems in reducing LDV fuel use. The cumulative fuel savings over this 25-year period is approximately 703 billion liters. The biggest contribution to fleet fuel use reduction comes from gasoline hybrids. Even though the market share of PHEVs remains small, the fuel savings per year from PHEVs grow rapidly to overtake fuel savings from diesel vehicles by 2030. The cumulative fuel savings from PHEVs (122 billion liters) are comparable to the diesel (140 billion liters) or turbocharged gasoline (169 billion liters).

This indicates that the potential of electric propulsion systems to influence fleet fuel use is strong. The GHG emission reductions realized from PHEV are not as high for the reasons discussed in Section 6.



(a) LDV Fuel Use



(b) Contribution of different propulsion systems in fuel savings

Figure 55 LDV fuel use under the *Market Mix Scenario*

LDV fleet fuel use under the *Turbocharged ICE Future Scenario* is shown in Figure 56. Fleet fuel use in 2035 in this scenario is approximately 12% lower than the *Reference Scenario*. When compared with the *Market Mix Scenario*, the 2035 fleet fuel use is lower by only 9 billion liters under the *Turbocharged ICE Future*, but the cumulative fuel savings are approximately 100 billion liters more than in *Market Mix Scenario*. It is interesting to note that the peak in LDV fleet fuel use in a *Turbocharged ICE Future Scenario* is at 629 billion liters in 2020 when compared to 631 billion liters in 2020 in a *Market Mix Scenario*. In other words, the fuel savings from the two scenarios diverge significantly only after 2025.

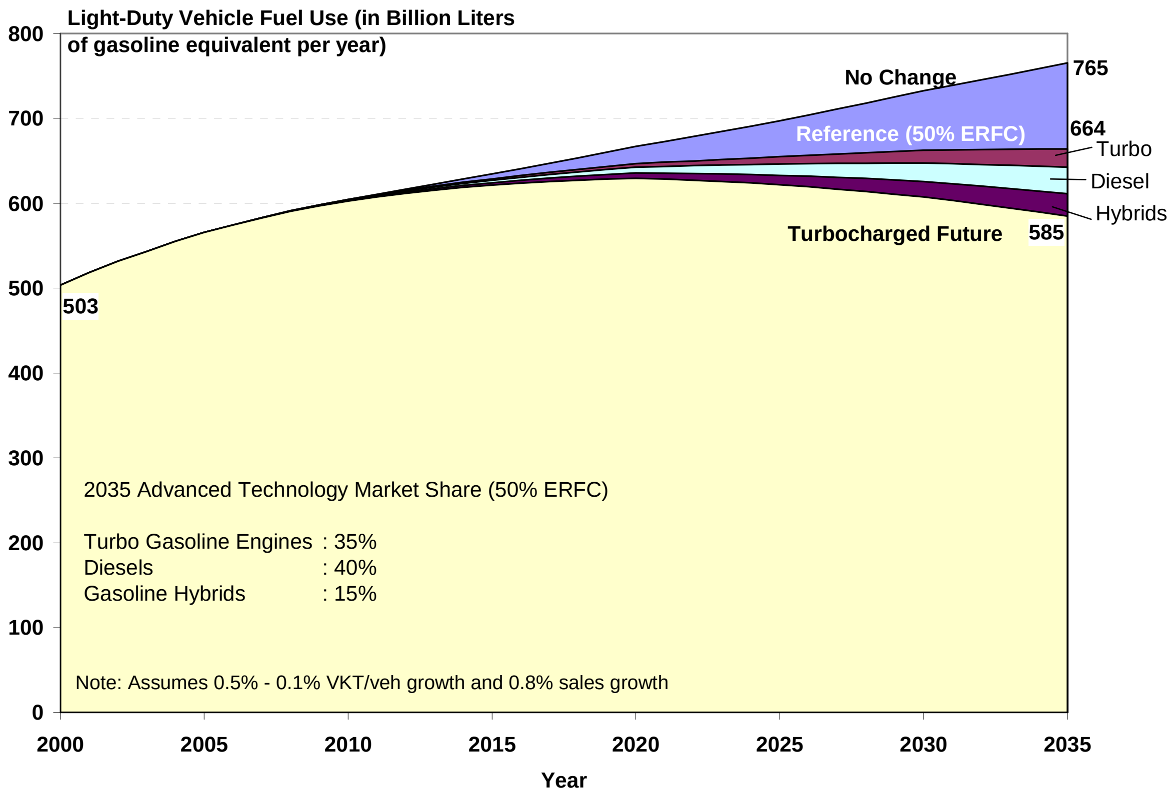


Figure 56 LDV fuel use under the *Turbocharged ICE Future Scenario*

As the market share of diesel-fueled vehicles grows, the amount of diesel fuel as a fraction of total LDV fuel increases dramatically. In 2005, diesel fuel accounted for approximately 2% of the LDV fleet fuel use on an energy basis. Under the *Turbocharged ICE Future Scenario*, the diesel share of LDV fuel grows to 26% on an energy basis by 2035. This represents 137 billion liters (~36 billion gallons) of diesel fuel use per year, or approximately 2.4 Million Barrels per Day (MDB) (Figure 57). The current U.S. demand for distillate fuel is approximately 4.3 MBD, of which only 0.18 MBD is used for LDV applications [EIA 2007e]. Therefore, in the *Turbocharged ICE Future Scenario*, this large change in the quantity of diesel fuel demanded for LDV applications would require U.S. refineries to adjust their product mix over time, although in the short term the impact of dieselization on LDV fleet fuel demand is relatively modest.

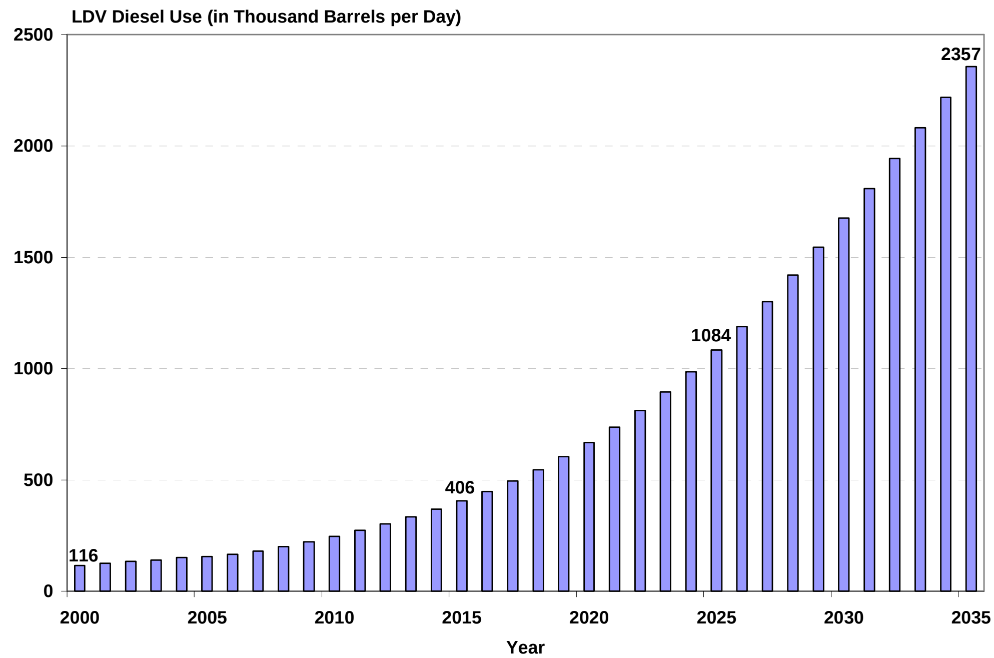


Figure 57 U.S. LDV diesel demand under the *Turbocharged ICE Future Scenario*

When compared with the previous two scenarios, the *Hybrid Strong Scenario* achieves the greatest reduction in fuel use (Figure 58). Not only is the 2035 fuel use in this scenario lower by 18% from the *Reference Scenario*, this is the only scenario among the three which has lower 2035 fuel use than the case with 100% ERFC and no increase in advanced propulsion systems' market share. Thus, aggressive hybrid vehicle market penetration may allow a greater improvement in vehicle performance when compared with other scenarios while achieving the same level of fuel use reductions. The total cumulative fleet fuel savings in the *Hybrid Strong Scenario* are more than 1040 billion liters, 60% of which come from gasoline hybrid vehicles.

The Hybrid Strong Scenario also demonstrates the potential of plug-in hybrid vehicles to reduce fuel use in a relatively short period of time. Even though the market share of PHEVs in this scenario is only 5% by 2025, compared with 15% for turbocharged gasoline vehicles, PHEVs achieve a greater reduction in fuel use annually by 2025. The cumulative fuel savings from PHEVs during the period 2010–2035 exceed the fuel savings from turbocharged gasoline vehicles by more than 40%.

Finally, similar to the earlier two scenarios, the LDV fleet fuel use under this scenario peaks in year 2020 at 629 billion liters. Thus, even with 50% ERFC and a substantial penetration of advanced vehicles, growth in the LDV fleet fuel use over the next decade will inevitably occur.

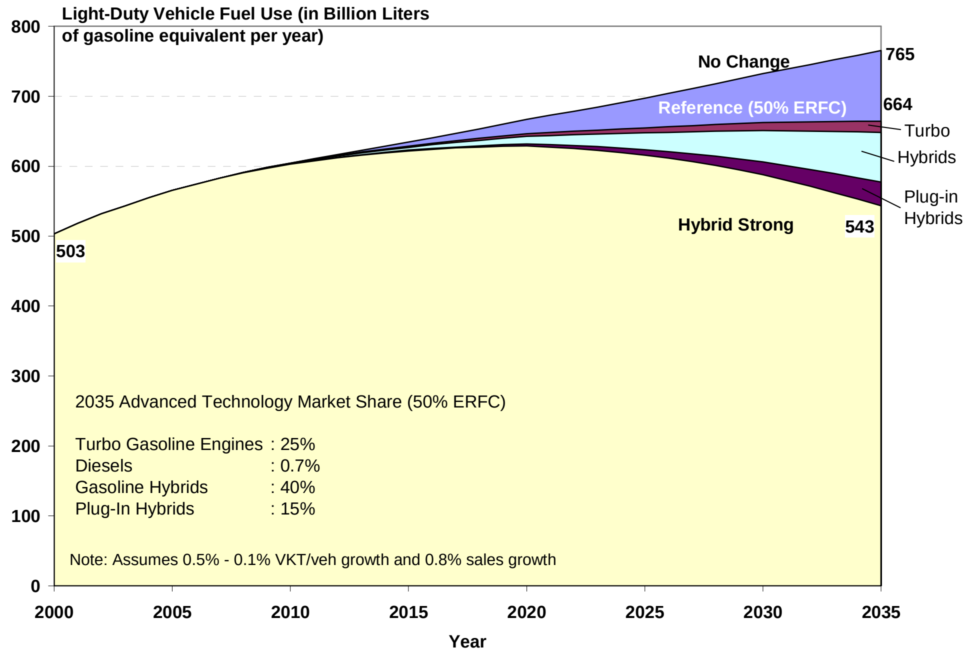


Figure 58 LDV fuel use under the *Hybrid Strong Scenario*

Results from different fleet scenarios are summarized in Table 33. These scenarios show a 18–44% reduction in 2035 average new vehicle fuel consumption from a *No Change Scenario*. In the very near term (~2015), though, all scenarios show similar values of new vehicle fuel consumption.

Table 33 Summary of LDV fleet fuel use scenarios

	ERFC*	Average new vehicle fuel consumption (L/100km)			Average fleet fuel consumption (L/100km)			LDV fleet fuel use (Billion liters/year)		
		2015	**2025**	**2035**	**2015**	**2025**	**2035**	**2015**	**2025**	**2035**
No Change	0%	11.0	11.0	11.0	11.2	11.0	11.0	634	697	765
Reference	50%	10.6	9.8	9.0	11.1	10.3	9.5	629	655	664
Gasoline only	100%	10.2	8.6	6.9	11.0	9.7	8.0	623	612	563
Market Mix	50%	10.3	9.0	7.5	11.0	9.9	8.5	621	626	594
Turbocharged ICE Future	50%	10.3	8.9	7.4	11.0	9.8	8.4	621	622	585
Hybrid Strong	50%	10.3	8.5	6.2	11.0	9.7	7.8	622	616	543

* ERFC: Emphasis on Reducing Fuel Consumption

The average fleet fuel consumption reduces at a slower rate than the new vehicle fuel consumption, with the scenarios showing a range of 14–30% reduction in fleet fuel consumption from *No Change* in 2035. This is reflected by the fleet fuel use across scenarios in 2015. None of the scenarios achieve more than 2% reduction in LDV fleet fuel use by 2015 when compared to the *No Change Scenario*. As newer, less-fuel-consuming vehicles become a larger fraction of fleet, and are used on road in increasing numbers, the fuel use in the scenarios begins to diverge from the *No Change Scenario*. The scenarios show up to a 12% reduction in fleet fuel use by 2025 and a 30% reduction fleet fuel use by 2035.

7.4.1 Total life-cycle energy and greenhouse gas emissions

The total life-cycle energy and greenhouse gas emissions of the LDV fleet are obtained by adding together the well-to-tank, tank-to-wheel, and vehicle manufacturing and end-of-life disposal energy and GHG emissions.[54] Figure 59 shows the U.S. LDV fleet life-cycle GHG emissions under *No Change* and the *Reference Scenario.*

In 2000, the shares of vehicle cycle, well-to-tank, and tank-to-wheel components of total fleet GHG emissions were 9%, 22%, and 69%, respectively. The tank-to-wheel GHG emissions in 2000 from light-duty vehicles are estimated to be 1,129 million metric tons, which compares well with the EPA estimate of 1,105 million metric tons [EPA 2007]. Under *No Change*, the LDV fleet GHG emissions increase from 1,647 million metric tons in 2000 to 2,514 million metric tons, whereas in the *Reference Scenario* the fleet GHG emissions plateau at around 2,213 million metric tons in 2035.

LDV fleet GHG emissions under *Turbocharged ICE Future* and *Hybrid Strong Scenarios* are shown in Figure 60. In both scenarios, the fleet GHG emissions peak at 2066 million metric tons in years 2020–2021 and decline thereafter. In spite of declining emissions, the fleet GHG emissions in 2035 are some 21% higher in a *Turbocharged ICE Future* and 15% higher in a *Hybrid Strong Scenario* when compared with emissions in year 2000. As the total fleet emissions decrease, the share of vehicle cycle emissions increases, particularly in the *Hybrid Strong Scenario.*

The impact of a changing fuel mix on fleet GHG emissions is shown with the help of the *Market Mix Scenario* in Figure 61. While the fuel use in the *Market Mix Scenario* peaks in 2020, the GHG emissions do not peak until 2024. The 2035 GHG emissions under the *Market Mix Scenario* (2,027 million metric tons) are approximately 9.5% below emissions under the *Reference Scenario*, and 20% below the *No Change Scenario*. When the fuel mix is changed according to the *High Oil Sands / Low Ethanol Scenario* described in Section 6, the LDV fleet GHG emissions in 2035 reduce by an additional 2.3%, to 1,981 million metric tons [Figure 61 (b)]. On the other hand, a *Low Oil Sands / High Ethanol Scenario* reduces the GHG emissions by 5.5%, to 1,918 million metric tons [Figure 61 (c)].

In either case, maximum annual emissions occur in year 2020, but peak GHG emissions in the *High Oil Sands / Low Ethanol Scenario* are 2,060 million metric tons compared with 2,033 million metric tons in the *Low Oil Sands / High Ethanol Scenario*. Compared with a 22.4% share of well-to-tank emissions in the *Reference Scenario*, the share of well-to-tank emissions in the *Fuel Mix Scenario* is between 27 and 28% of total life cycle GHG emissions in 2035.

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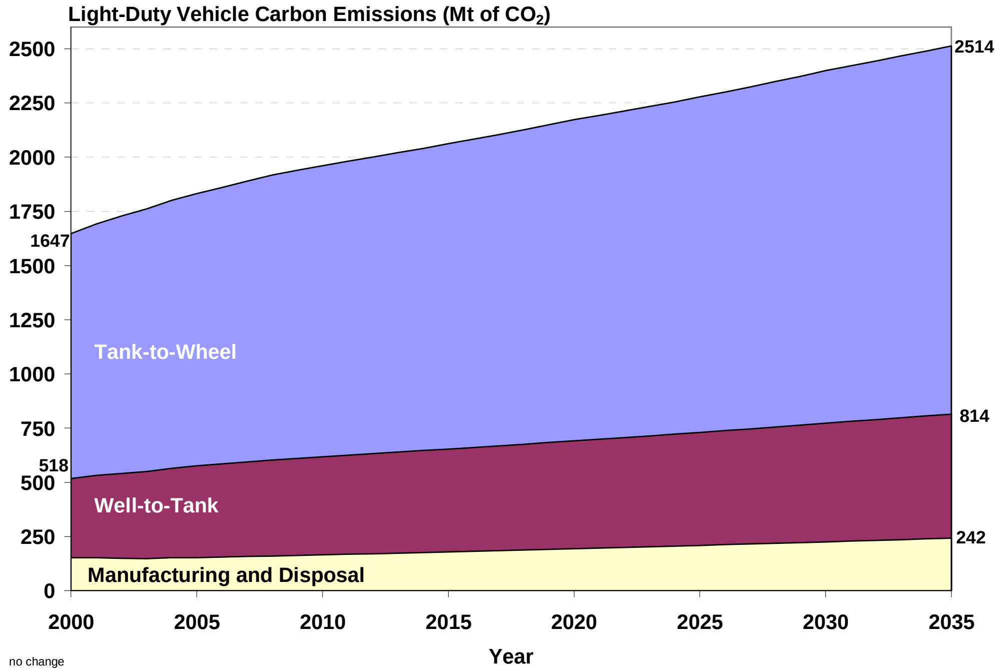
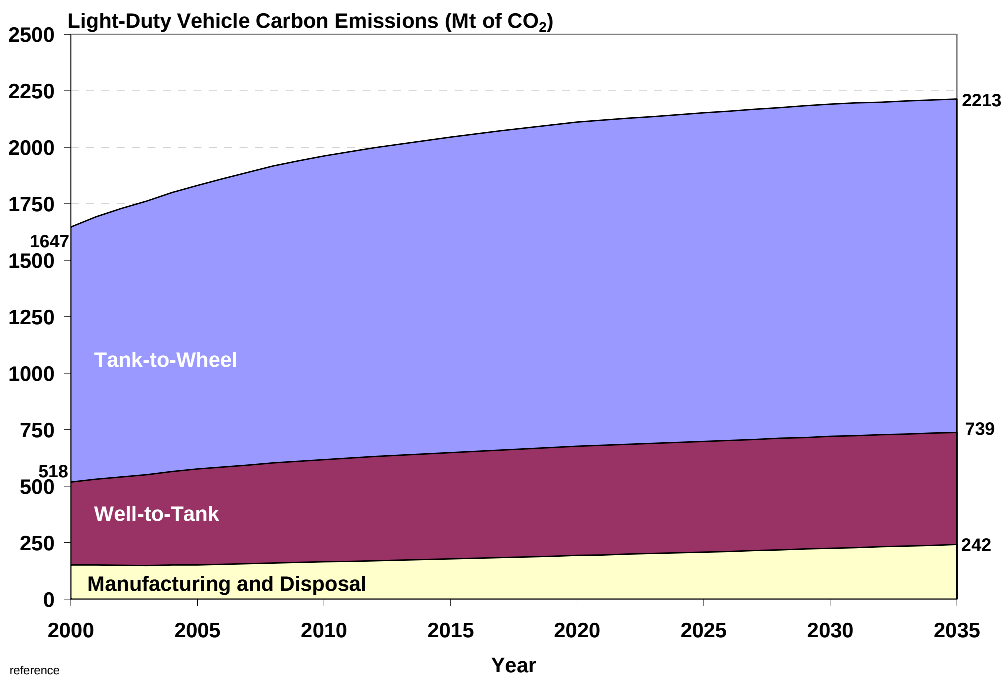
[54] The life-cycle greenhouse gas emissions impacts described in this section attribute all greenhouse gas emissions to the U.S. light-duty vehicle fleet. Not all of these emissions are counted as U.S. emissions in an inventory of greenhouse gas emissions. For example, the GHG emissions during extraction of imported oil, refining of imported gasoline, or manufacturing of imported cars would not be counted as U.S. emissions.

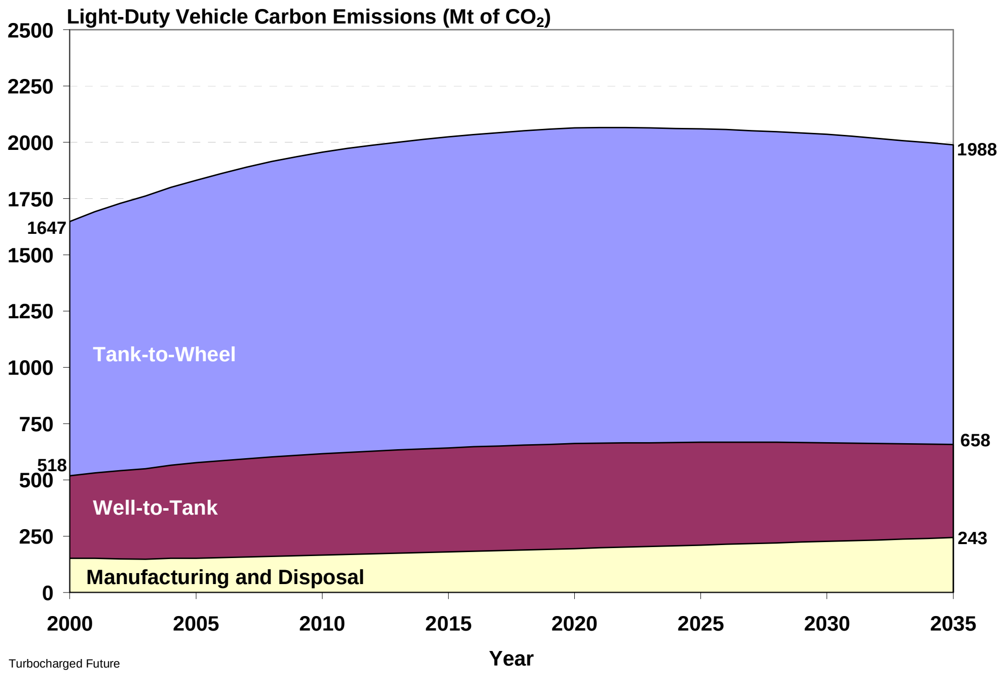


(a) *No Change*

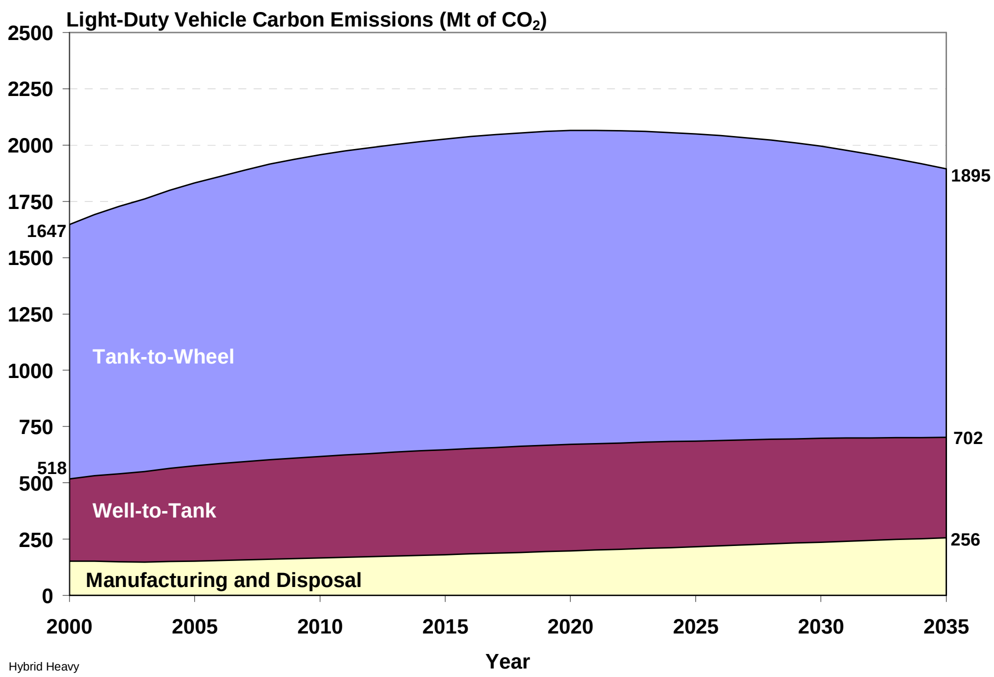


(b) *Reference Scenario*

Figure 59 LDV fleet GHG emissions under the *No Change* and *Reference Scenarios*

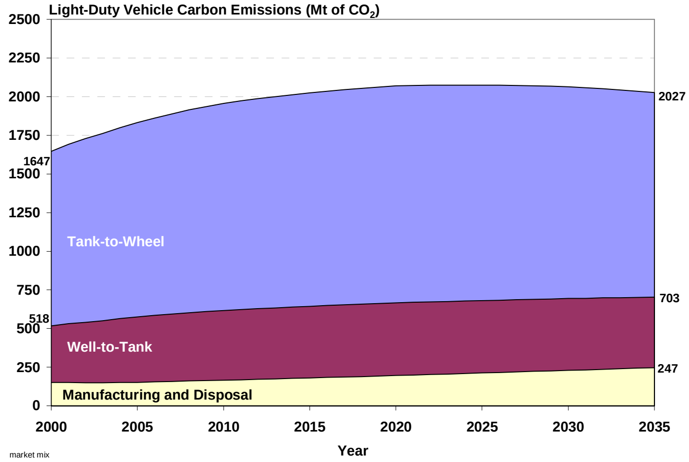


(a) Turbocharged ICE Future Scenario

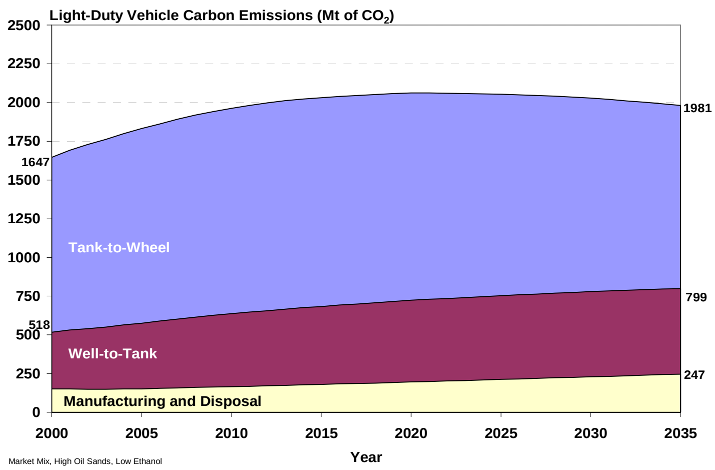


(b) Hybrid Strong Scenario

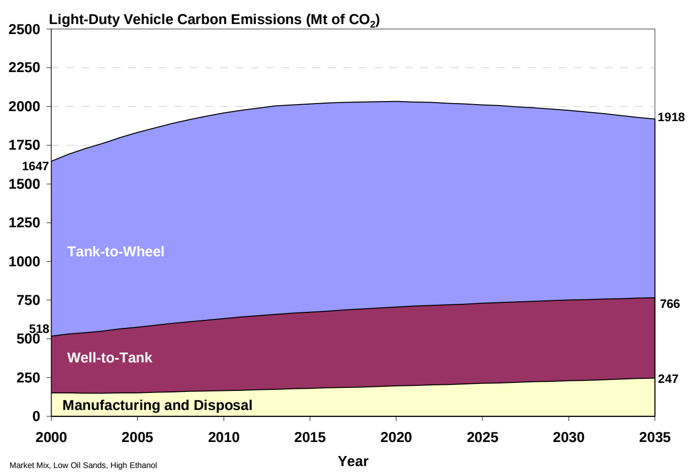
Figure 60 LDV Fleet GHG emissions under the *Turbocharged ICE Future* and *Hybrid Strong* Scenarios



(a) Market Mix Scenario



(b) Market Mix Scenario with High Oil Sands and Low Cellulosic Ethanol



(c) Market Mix Scenario with Low Oil Sands and High Cellulosic Ethanol

Figure 61 LDV Fleet GHG emissions under *Market Mix Scenario* with changing mix of non-conventional oil and ethanol

7.5 Additional scenarios

In addition to the three main scenarios discussed above, three variations on these scenarios are explained briefly below.

7.5.1 Increased market penetration of hybrids in passenger cars and diesels in light trucks

Diesel vehicles offer an added advantage over hybrid vehicles in terms of a sustained towing capability as well as other heavier-duty vehicle attributes. Therefore, there is a reason to believe that diesel and hybrid vehicles will penetrate at different rates in passenger car and light-truck markets. This scenario is evaluated by combining the market penetration rates from the Turbocharged ICE Future and Hybrid Strong scenarios. The market penetration rates from the Hybrid Strong scenario are applied to the cars only and from the turbocharged ICE Future are applied to the light-trucks only.

Figure 62 shows the results of this combined scenario. As would be expected, the resulting 2035 fuel use and cumulative fuel savings is between the Turbocharged ICE Future and Hybrid Strong scenarios. Average new vehicle fuel consumption in 2035 under this scenario is 6.8 L/100 km, while the fleet fuel consumption is 8.1 L/100 km. It should be noted that the results of this scenario match very closely with the 100% ERFC scenario with no change in the sales mix.

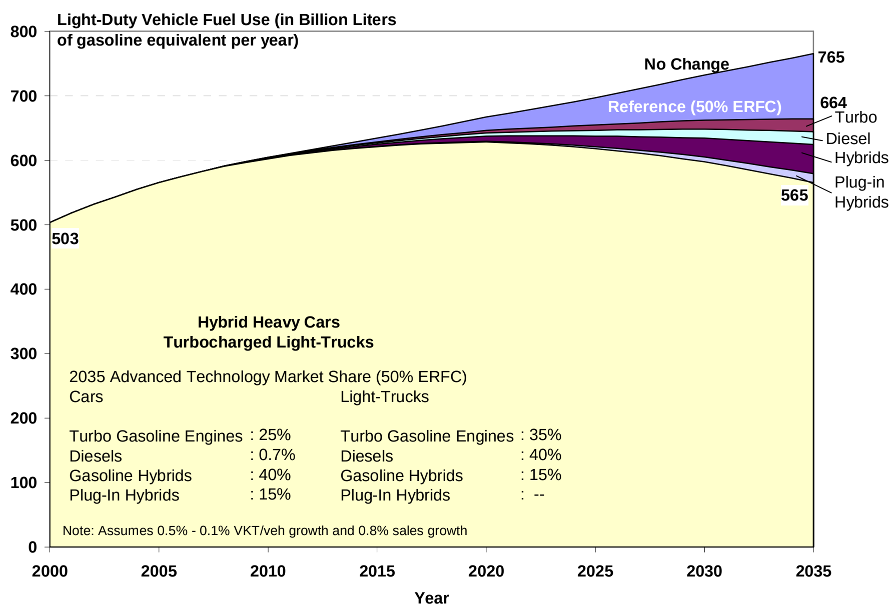


Figure 62 LDV fleet fuel use under the combined *Hybrid Strong Scenario* in cars and the *Turbocharged Light-Trucks Scenario* in light trucks

7.5.2 Increasing the emphasis on reducing fuel consumption in the Hybrid Strong Scenario

The *Hybrid Strong Scenario*, which resulted in the most fuel savings of all of the scenarios, assumes a 50% emphasis on reducing fuel consumption. With our growing concerns about climate change and petroleum security, a greater emphasis may be placed on reducing fuel consumption. Figure 63 shows the impact on LDV fleet fuel use when ERFC is increased from 50% to 75% and 100%.

LDV fleet fuel use in 2016 under this scenario is 616 billion liters, which is only 3% lower than the fuel use in year 2016 in a *No Change Scenario*. This, however, represents the peak in LDV fleet fuel consumption in the *Hybrid Strong Scenario*, with 100% ERFC. Figure 63 shows that by increasing the emphasis on reducing fuel consumption from 50% to 100%, the 2035 fleet fuel use could be reduced by a further 10% from the *No Change Scenario*. This represents a cumulative fuel savings of 850 billion liters over the fuel savings in the *Hybrid Strong Scenario*, with 50% ERFC.

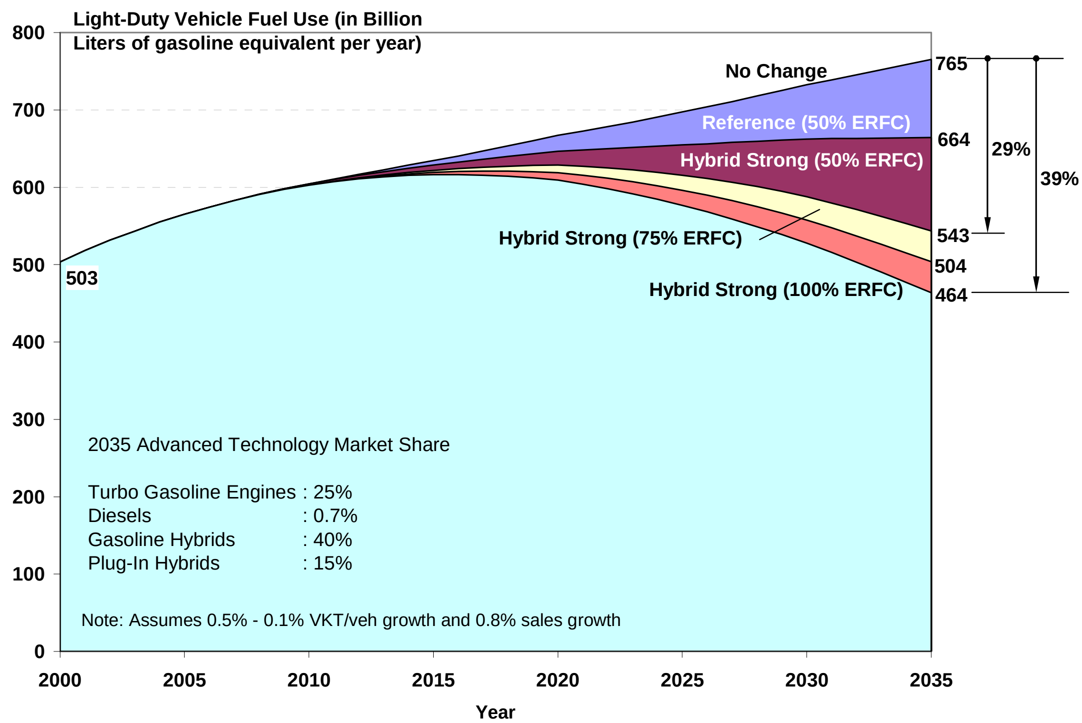


Figure 63 Increasing the emphasis on reducing fuel consumption in the *Hybrid Strong Scenario*

7.5.3 Introduction of hydrogen fuel cell vehicles

So far, the scenarios for market penetration of advanced vehicles have not included hydrogen fuel cell vehicles (FCVs). If technical and cost issues with FCVs are resolved, then we could expect the introduction of commercial FCVs by 2020. In the initial years, the number of fuel cell vehicles will be small enough that fueling infrastructure will not be such a major issue, but as FCV technology improves and costs come down, fuel cell vehicles can be expected to enter the market in increasing numbers. In this illustrative scenario, the market penetration rate of hydrogen fuel cell vehicles is similar to that of plug-in hybrid vehicles, except for a 10-year time lag in the introduction of FCVs.

Since FCVs do not consume any petroleum during vehicle operation, they can have a relatively quick impact on fleet fuel use. Figure 64 shows that increasing the market share of FCVs to 5% would reduce the 2035 fleet fuel use by 3.5% below the *Market Mix Scenario*. If the FCVs take hold in the market, they will have an even larger impact on reducing the petroleum use of LDVs after 2035. Over the next two-and-a-half decades, however, their impact is unlikely to be much larger than indicated here.

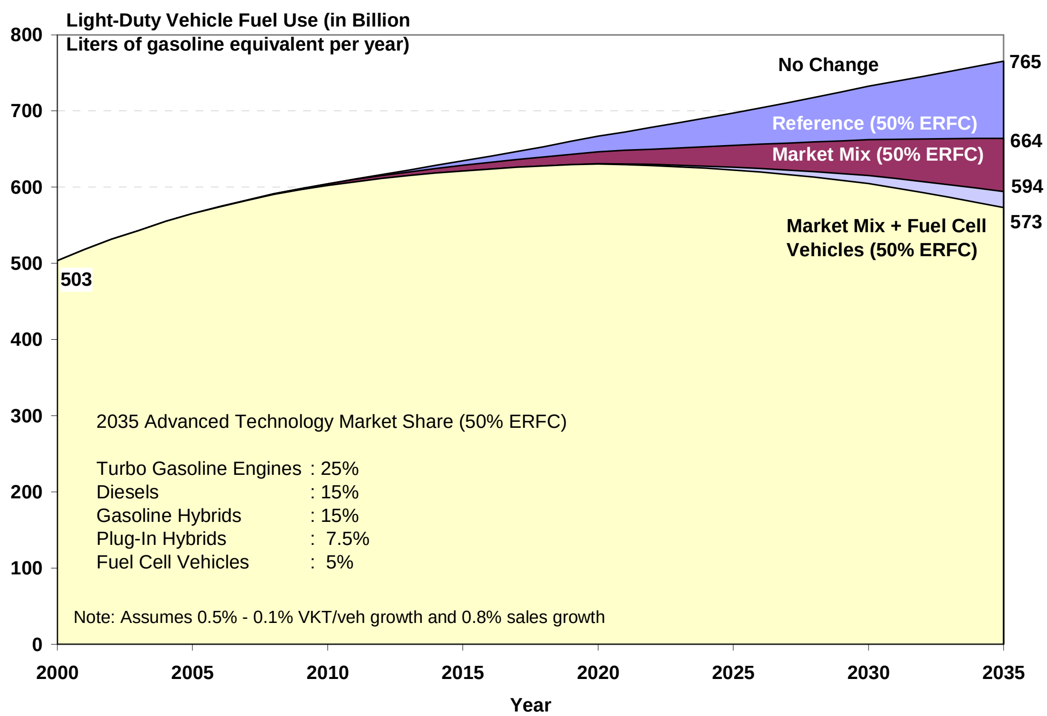
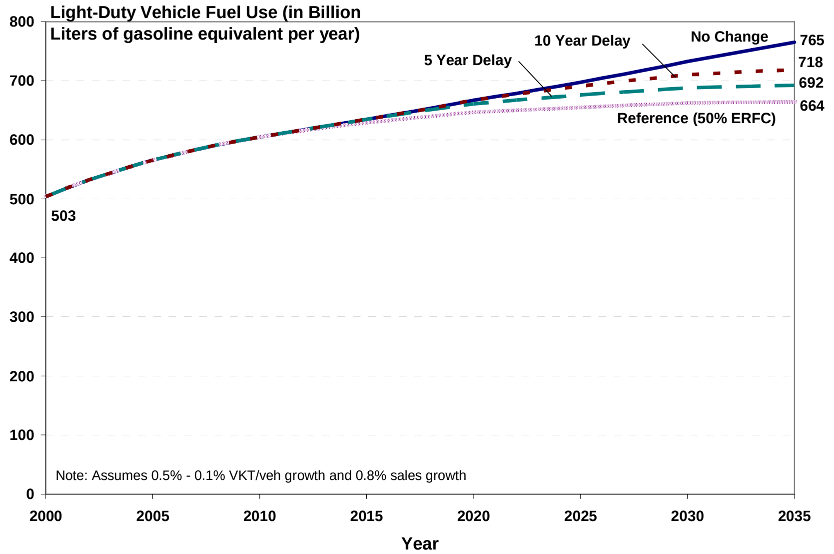


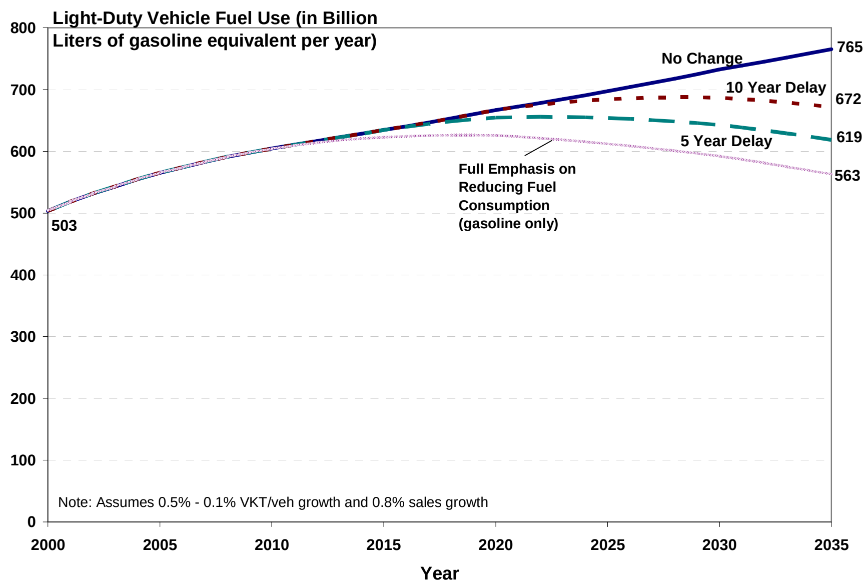
Figure 64 Impact of Hydrogen Fuel Cell Vehicles on LDV fleet fuel use

7.6 Impact of delays

A scenario of delayed action demonstrates the consequences of postponing action by 5 or 10 years on overall fuel consumption and greenhouse gas emissions. The purpose of these scenarios is to investigate the level of additional effort required to reduce vehicle fuel consumption in the future, as opposed to taking action immediately. Figure 65 shows the impact on LDV fleet fuel use if the fuel economy improvements, which begin in year 2010 in the *Reference Scenario* or *100% ERFC Scenarios*, are delayed by 5 or 10 years.



(a) Delay with 50% ERFC



(b) Delay with 100% ERFC

Figure 65 Effect of delayed action on light-duty vehicle fuel use (2000–2035)

It is clear from this scenario that delayed action results not only in shifting the problem out in time, but also increases the magnitude of the problem we are addressing. It is also clear that even small changes made sooner could result in larger benefits than more aggressive actions taken later. Even if inherently low CO_2-emitting or non-petroleum-based fuels were to become feasible in the future, the magnitude of the problem would be much more manageable if some action were to be taken now, as opposed to waiting for a cure-all.

7.7 Reducing fuel use and GHG emissions by 5% below the Reference Scenario

The next two sub-sections compare the market penetration rates of different vehicle technologies, with varying emphases on reducing fuel consumption, to achieve a predetermined target. In this first sub-section, the target is based on fleet fuel use and GHG emissions, whereas in the second sub-section, the target relates to the fuel consumption of new vehicles sold. The policy debate over energy security and climate change tends to focus on developing measures to promote the adoption of specific propulsion systems or fuels such as tax credits or mandates. This debate can be better informed by evaluating the relative effort required to achieve a 5% petroleum and GHG reduction in 2025 below the *Reference Scenario*, using various propulsion systems, fuel alternatives, as well as demand-side measures, as shown in Table 34.

Table 34 Alternatives considered to independently reduce fuel consumption or GHG emissions by an additional 5% below the Reference Scenario (by 2025)

Propulsion system alternatives	• Turbocharged gasoline • Diesels • Gasoline hybrids • Plug-In hybrids
Emphasis on Reducing Fuel Consumption (ERFC)	Dedicating more emphasis on reducing fuel consumption than performance as compared with 50% in the *Reference Scenario*
Vehicle weight and size reduction alternatives[55]	• Reduction in vehicle weight through material substitution • Shift within vehicle class (e.g., from large cars to small cars) • Shifts between vehicle classes (from light-trucks to cars)
Fuel alternatives	• Ethanol from corn • Ethanol from switchgrass
Demand side alternatives	Reducing the rate of growth in vehicle kilometers travel from the current rate of 0.5% per year to 0% in 2025

To compare the relative fleet-wide impact of different propulsion systems, the market shares of each of the technologies listed in Table 34 are increased linearly starting in year 2010, and the fraction of new vehicle sales in 2025 that will have to come from these technologies to achieve the desired 5% reduction in fuel use and GHG emissions is estimated (Table 35). The market shares required to achieve a 5% reduction in GHG emissions are more aggressive than

[55] The impact of weight and size reduction on vehicle fuel consumption and GHG emissions was evaluated by Lynette Cheah. Based on vehicle simulation work by Cheah, every 100 kg weight reduction, the adjusted fuel consumption can decrease by 0.3 L/100km for cars, and 0.4 L/100km for light trucks. In other words, for every 10% weight reduction, the vehicle's fuel consumption reduces by 6 to 7%. More details are available in Cheah et al., 2007.

those required to achieve the same reduction in fuel use for each individual propulsion system. This is a result of the higher material cycle GHG emissions that are embodied within future new vehicle fleets, for example: from greater use of lightweight materials such as aluminum, and from a greater fraction of alternative propulsion technologies. In the case of plug-in hybrids, however, the share required to meet the GHG target is increased even further by GHG emissions produced from the electricity consumed by these vehicles, assuming an average U.S. grid mix.

Table 35 Percentage of new vehicle sales that new propulsion technologies must independently achieve to reduce fuel use and GHG emissions by 5% relative to the *Reference Scenario* (50% emphasis on reducing fuel consumption) in 2025

PROPULSION SYSTEM	MARKET SHARE REQUIRED FOR A 5% REDUCTION IN 2025	
Turbocharged gasoline		
Fuel use	69%	44%
GHG emissions	77%	54%
Diesel		
Fuel use	48%	31%
GHG emissions	57%	39%
Hybrids		
Fuel use	27%	18%
GHG emissions	32%	22%
Plug-in hybrids		
Fuel use	15%	9%
GHG emissions	24%	16%

↓ Increasing cost and engineering effort required ↓

half (50%) emphasis placed on reducing fuel consumption

two-thirds (65%) emphasis placed on reducing fuel consumption

Note: 90% emphasis on reducing fuel consumption achieves the targeted 5% reduction with gasoline ICE vehicles alone.

From Table 35, we conclude that the market penetration of emerging vehicle technologies will need to be sizeable in order to realize a noticeable benefit by 2025. Note that in none of the scenarios discussed in Section 7.3 do any of the propulsions systems achieve the required market shares shown in Table 35, except for hybrids under the *Hybrid Strong Scenario* with 65% ERFC. This is primarily due to slow rates of change in fleet composition, and only a portion of technology potential being used to reduce fuel consumption. A noteworthy reduction in fuel use will not materialize by 2025, unless a substantial number of new, less-fuel-consuming vehicles have already penetrated into the fleet, and have been in use for several years.

Instead of relying solely on increasing the market share of advanced propulsion systems, directing more of the efficiency improvements towards reducing on-road fuel consumption rather than increasing performance and size can provide greater leverage. Increasing the emphasis on reducing fuel consumption (ERFC) from 50% in the *Reference Scenario* to 88% and 93% would achieve the 5% reduction in fuel use and GHG emissions goal, respectively, with ICE gasoline vehicles alone. If some two-thirds of the emphasis were to be placed on reducing fuel consumption across all the vehicle technologies including mainstream ICE gasoline vehicles, then the market penetration rates of advanced propulsion technologies could be reduced by one-third compared to the *Reference Scenario* ERFC to achieve the same objective (Table 35). This striking drop in the market share required by advanced propulsion systems is enabled by the combined improvement of advanced and conventional new vehicles when ERFC is increased from the *Reference Scenario* value of 50%.

Among the fuel alternatives, cellulosic ethanol appears to be an attractive way to reduce both petroleum use and GHG emissions in the LDV fleet. In the *Reference Scenario*, it is assumed that ethanol from corn contributes 3% of the LDV fleet fuel use, which translates into 25 billion and 31 billion liters [530 and 660 petajoules] of ethanol in 2005 and 2025, respectively. Displacing an additional 5% petroleum beyond the *Reference Scenario* requires twice the amount of ethanol mandated by the Energy Policy Act of 2005 [Groode and Heywood 2007]. The use of corn-based ethanol needs to be much higher, however, to achieve a 5% reduction in life-cycle GHG emissions across the LDV fleet, even after assuming a 20% co-product credit (Table 36). Thus, if GHG emissions reduction is desired through fuel alternatives, then rapid development of cellulosic ethanol technology is critical.

Table 36 Amount of additional ethanol blended in gasoline as a percentage of total gasoline use to achieve a 5% reduction in fuel use and GHG emissions

Fuel	Ethanol Required (billion liters)	Ethanol Share of Fuel Supply Required (by Volume) for a 5 percent Reduction in 2025
Corn Ethanol		
Fuel use	50	7.5%
GHG emissions	335	43.2%
Cellulosic Ethanol		
Fuel use	47	6.9%
GHG emissions	62	9.1%

Achieving a 5% reduction by altering vehicle weight and size is also challenging (Table 37). In the *Reference Scenario*, recall that the weight of new cars and light trucks is already assumed to decline by 6% from 2010–2025, while vehicle size is kept constant. To realize a 5% reduction in LDV fleet fuel use through further vehicle weight reduction, the sales-weighted average new vehicle weight must decrease by an additional 13%, from 1,860 kg in 2005 to 1,540 kg in 2025. The 5% reduction in fleet life-cycle GHG emissions requires around the same 19% reduction in new vehicle weight from today's value. To realize weight reduction by downsizing without any material substitution, large vehicles—currently accounting for a third of new vehicle sales—would have to disappear from the market to offset 5% of fleet fuel use by 2025, while compact or small vehicles must grow from their current 23% market share to 84% of new vehicles sold in 2025. We can also consider shifting sales away from light trucks to cars to reduce the average vehicle weight. However, to realize the targeted fuel savings in this manner, light trucks will need to either all but disappear from the market, or they will need to achieve the same average fuel consumption as cars in 2025.

To achieve a 5% reduction in fleet GHG emissions by downsizing vehicles without material substitution, small vehicles must account for 90% of the market in 2025. Similarly, if light trucks were completely phased out from the new vehicle market in 2025, this will realize only a 5% reduction in GHG emissions from the LDV fleet. Thus, significant downsizing changes are necessary to achieve the targeted impact within the next 20 years.

Table 37 Weight/size reductions required to achieve a 5% reduction in fuel use and GHG emissions

WEIGHT AND SIZE REDUCTION	CURRENT VALUE IN 2005	VALUE REQ'D. FOR A 5% REDUCTION BY 2025
Material substitution		
Fuel use	1,860 kg average vehicle weight	1,551 kg average vehicle weight
GHG emissions		1,541 kg average vehicle weight
Shifting within classes to smaller vehicles		
Fuel use	23% market share of small vehicles	84% market share of small vehicles
GHG emissions		90% market share of small vehicles
Shifting from light trucks to cars		
Fuel use	44% market share of cars	> 100% market share of cars (max. 4.2% reduction in fuel use)
GHG emissions		100% market share of cars

Finally, reducing the rate of growth of per vehicle travel from 0.5% to zero between 2010 and 2025—plausible, albeit challenging—would reduce the total fuel use and GHG emissions by 6% from the *Reference Scenario* in 2025.

7.7.1 Policy implications

The key to reducing light-duty vehicle fuel use and GHG emissions is not what specific propulsion or fuel technology to deploy, but how to deploy these technologies. For example, when only half of the gains anticipated from future technology are used to reduce fuel consumption directly, the market penetration rates of advanced vehicles required to achieve even a 5% reduction in fuel use appear infeasible. With two-thirds of the anticipated gains applied to reduce fuel consumption, the required market penetrations rates of advanced technology vehicles appear much more plausible. Irrespective of the propulsion system or fuel used, it will be critical to utilize the anticipated advances in vehicle technology for the specific purpose of reducing fuel use rather than for improving significantly on current performance, or allowing vehicle size (and therefore weight) to increase.

Due to the life-cycle impacts of alternative propulsion systems and biofuels, reducing GHG emissions is a more daunting challenge than reducing fuel use. Particularly, in the case of plug-in hybrids and ethanol produced from corn, the effort required to achieve a 5% reduction in GHG emissions is greater than with other propulsion system and fuel alternatives. While alternate fuel options, such as ethanol or electricity, are available to displace the use of conventional petroleum, simultaneously reducing petroleum and GHG emissions from these sources requires that they are derived from low-emissions fuel production pathways.

7.8 Doubling the fuel economy of new vehicles by 2035

In a widely cited paper, Pacala and Socolow [2004] described a climate stabilization wedge as a strategy that can reduce a cumulative total of 25 Gt of carbon of reduced emissions over 50 years. One strategy described by Pacala and Socolow is to raise the fuel economy of all two billion passenger vehicles globally from approximately 30 miles per gallon at present to 60 miles per gallon in 50 years.

Starting with President Bush's 2007 State of the Union address, a series of legislative proposals have been introduced in the congress which intend to increase the fuel economy of new vehicles at a rate of 2–4% per year [Yacobucci and Bamberger 2007]. Increases on the order of 3% per year would effectively require new vehicles in 2035 to consume half as much fuel per unit distance traveled as in 2006. The transportation efficiency of the technology subgroup of the National Petroleum Council Committee on Global Oil and Gas estimated that *"…technologies exist or are expected to be developed, that have the potential to reduce fuel consumption of new light-duty vehicles by 50 percent relative to 2005 vehicles…(at) constant vehicle performance and …higher vehicle cost"* by 2030. [NPC 2007] Most recently, in December 2007, the U.S. Congress enacted a new CAFE requirement of 35 miles per gallon for light-duty vehicles by 2020. This corresponds to an annual fuel economy increase of about 4% over a 10-year period.

Here, a scenario that requires doubling the fuel economy or halving the fuel consumption of new vehicles by 2035 is evaluated. In this scenario, the adjusted average fuel consumption of new vehicles sold in year 2035 would be 5.7 L/100km, or half of today's 11.4 L/100km. Such a reduction in vehicle fuel consumption can be achieved by increasing the emphasis on reducing fuel consumption, increasing the market share of advanced vehicle technologies, as well as reducing vehicle size and weight. Only the first two strategies are considered here. Furthermore, only the propulsion systems available in the market today are taken into consideration. An evaluation of doubling the fuel economy of new vehicles using all three alternatives can be found in Cheah et al. [2007].

Table 38 (a) shows the market share of advanced propulsion systems that would double the fuel economy of new vehicles by 2035 when used with evolving mainstream gasoline internal combustion engines. Of the propulsion systems available in the market today, a 2035 hybrid vehicle is the only future technology that is projected to have less than half the fuel consumption of today's gasoline ICE vehicles (see Table 6). As a result, even 100% market share of turbocharged gasoline vehicles or diesels will not achieve a factor-of-two reduction in new vehicle fuel consumption. If only 25% emphasis is placed on reducing fuel consumption, then nearly all vehicles sold in year 2035 will have to be hybrids in order to realize a factor-of-two reduction in fuel consumption. On the other hand, with 100% ERFC, the market share of hybrids needs to be less than half to achieve the same target.

Table 38 Market share of advanced propulsion systems to double the fuel economy of new vehicles by 2035

	Market share in 2035 required to double Fuel Economy of new vehicles sold		
Emphasis on Reducing Fuel Consumption (ERFC)	Gasoline turbocharged	Diesel	Hybrids
25%	> 100% Not possible	> 100% Not possible	98%
50%			84%
75%			66%
100%			42%

(a) Using Single Advanced Propulsion System only

Market share in 2035 required to double FE of new vehicles sold at 50% ERFC (Combined options)			
Gasoline ICE	Gasoline turbocharged	Diesel	Hybrids
16%	0%	0%	84%
0%	22%	0%	78%
0%	0%	25%	75%

(b) Using Two Advanced Propulsion Systems

When two of the advanced propulsion systems are combined, the market shares needed in 2035 to double the fuel economy at 50% ERFC is shown in Table 38 (b). In any of the three cases shown above, the market share of advanced propulsion systems in 2035 needs to be substantial.

Another way to look at the aggressiveness of the target of reducing fuel consumption by half is to calculate the ERFC required in each of the advanced vehicle market penetration rates scenarios described previously. As shown in Table 39, both *Market Mix* and *Turbocharged ICE Future Scenarios* of market penetration will require new vehicles in 2035 to give back some performance compared with their 2005 counterparts if a doubling of fuel economy is to be achieved. By contrast, only two-thirds of the emphasis on reducing fuel consumption in a *Hybrid Strong Scenario* is necessary in 2035 new vehicles to reduce fuel consumption by half. This difference in ERFC is due to two reasons. First, the hybrid vehicles consume much less fuel than turbocharged gasoline or diesels. Second, the *Hybrid Strong Scenario* assumes a 15% market penetration of plug-in hybrids (PHEVs) by 2035. Since PHEVs consume relatively small amount of petroleum, their gasoline equivalent fuel economy is quite high, and a small number of PHEVs can reduce the average new vehicle fuel consumption substantially.

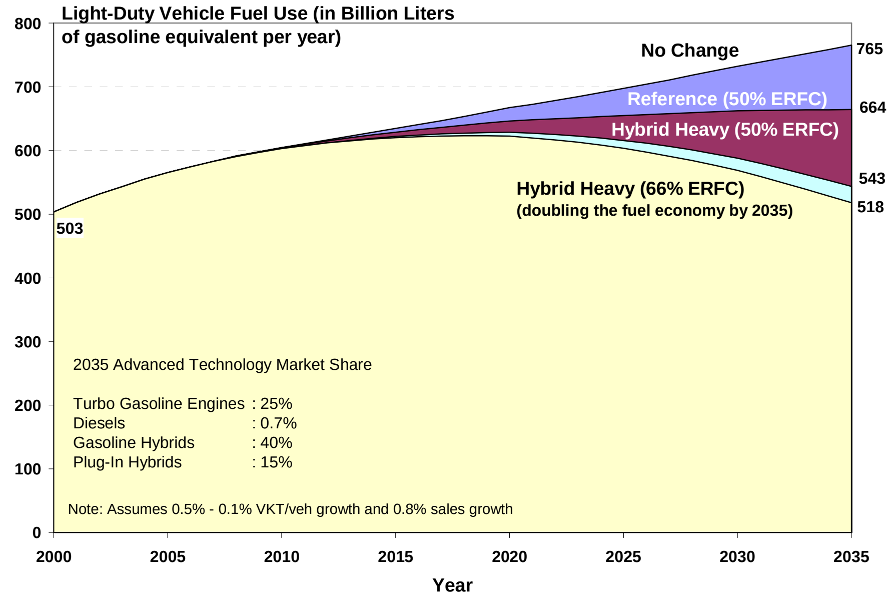
Table 39 Emphasis on Reducing Fuel Consumption (ERFC) required to double the fuel economy of new vehicles in 2035 for different scenarios

Scenario	ERFC
Market Mix	102%
Turbocharged Future	101%
Hybrid Strong	66%

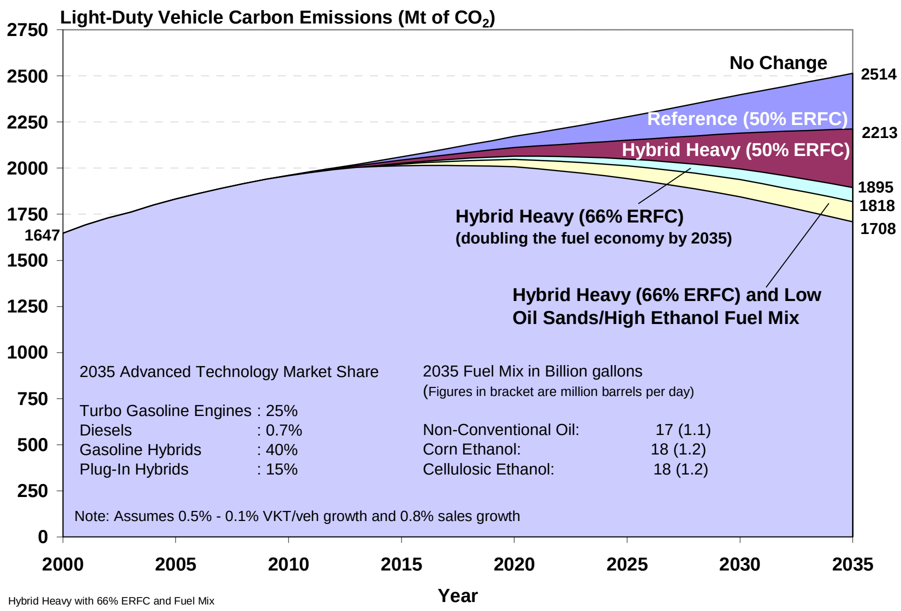
If a doubling of new vehicle fuel economy is achieved by increasing ERFC to 66% in the *Hybrid Strong Scenario*, the resulting light-duty vehicle fleet fuel use and CO_2 emissions are shown in Figure 66. The fuel use shown in Figure 66 (a) under this scenario maxes out at 623 billion liters in year 2018, and returns to its 2001 value by year 2035. The corresponding GHG emissions shown in Figure 66 (b) max out at 2047 million metric tons in 2020, and reduce by 28% in 2035 compared with the *No Change Scenario*.

Vehicle weight (and size) reduction provides an additional option for achieving the target. With a 20% reduction in average new vehicle weight, doubling the 2035 new vehicle fuel economy can be achieved with 75% ERFC and a market penetration consisting of 15% turbocharged gasoline, 15% diesel, and 54% gasoline hybrid vehicles [Cheah et al., 2007].

Adding the *Low Oil Sands / High Ethanol* fuel mix to the *Hybrid Strong* scenario can reduce the 2035 GHG emissions by a further 6%, to 1,708 million metric tons of CO_2. The cumulative GHG savings of more than 7,800 million metric tons of CO_2 compared with *No Change* and 4,900 million metric tons of CO_2 compared with the *Reference Scenario.*



(a) Fuel Use



(b) GHG Emissions: Low Oil Sands and High Ethanol Fuel Mix

Figure 66 LDV fleet fuel use and GHG emissions achieved by doubling fuel economy

Cheah et al. [2007] evaluated the potential for halving the fuel consumption of new vehicles by 2035 using a combination of ERFC, advanced vehicle technology, and vehicle weight and size reductions. They estimated that doubling the fuel economy would result in an extra cost of approximately 20% of baseline vehicle manufacturing costs. While these costs could be recouped during the vehicle operation through fuel savings, the changes necessary to achieve this run counter to the current trends in the U.S. light-duty vehicle market.

Automakers may be hesitant to make such large-scale changes in the product mix unless consumers are willing to forego their continuing pursuit of ever-higher performance, larger vehicle size and other amenities. …[A factor-of-two reduction]…. will challenge the auto industry to make the capital investments necessary to realize alternative technologies at a substantial scale, and requires the government to address the market failures that promote size, weight, and acceleration at the expense of higher vehicle fuel consumption and its associated impacts related to energy security and global warming. [Cheah et al. 2007]

In short, reducing the fuel consumption of new vehicles in 2035 by half and realizing a corresponding 30–35% reduction fleet fuel use and GHG emissions is technically feasible, but achieving this in practice will require aligning the preferences of consumers and manufacturers through strong fiscal and regulatory incentives.

7.9 Effect of reducing travel demand

While the goal of this report was to demonstrate the timing and impact of changing vehicle technologies and fuels, the job of these technologies can be made easier in a relative sense if the rate of growth in travel demand can be lowered by other means. This is illustrated in Figure 67.

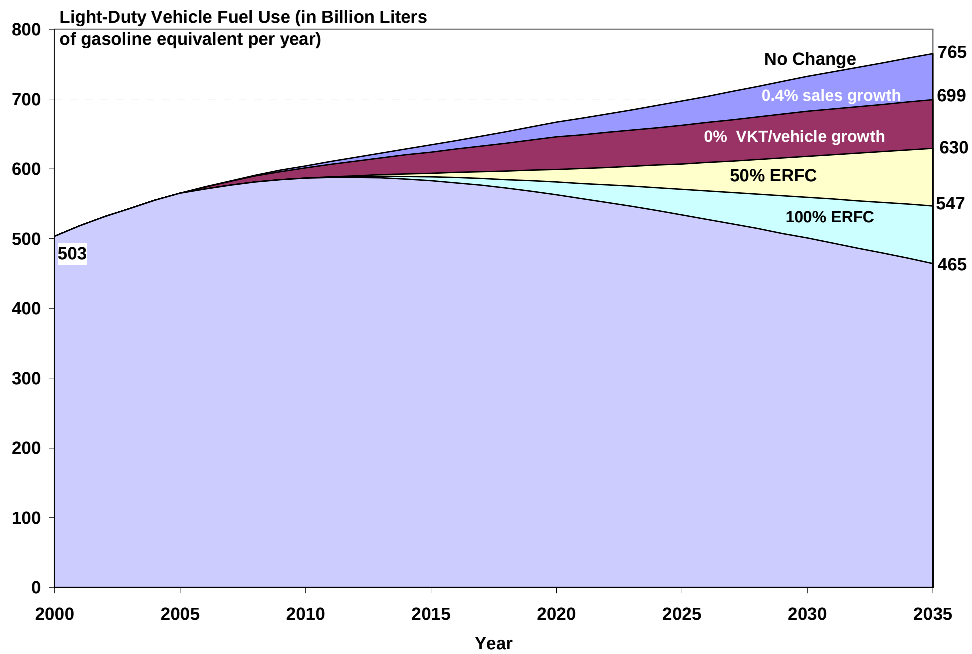


Figure 67 Effect of reducing rates of growth on LDV fleet fuel use

As discussed briefly in Section 5, halving the vehicle sales growth rate from 0.8% per year will reduce the 2035 LDV fuel use by approximately 8.6%. In addition, if the growth in per vehicle kilometer travel could be halted, i.e., per vehicle travel were held at today's value, a further 10% reduction in 2035 fuel use could be realized even with no emphasis placed on reducing fuel consumption in vehicles. If the ERFC is increased to 100%, an additional 26% reduction in 2035 fuel use can be realized, therefore bringing the total reduction of more than 39% from the *No Change Scenario*.

Note that no advanced propulsion systems are assumed in this scenario. Even the *Hybrid Strong Scenario*, with 100% ERFC (as described in Section 5) achieves the same amount of reduction in 2035 fuel use (See Figure 63). It is also important to note that the changes in rate of growth in vehicle travel affect all vehicles on the road, and hence reductions in fuel use and GHG emissions are realized sooner. When compared with the *Hybrid Strong Scenario* (100% ERFC), this scenario achieves an additional cumulative fuel use reduction of 835 billion liters (five billion barrels of oil) and 3,200 million metric tons of CO_2 emissions over the 30-year period from 2005 to 2035.

7.10 U.S. LDV greenhouse gas emissions in the global context

While the U.S. light-duty vehicles are the largest contributor to global light-duty vehicle greenhouse gas emissions, the growth in light-duty vehicles elsewhere in the world will also be a big contributor to the growth in global LDV greenhouse gas emissions. This growth in the global LDV CO_2 emissions is illustrated in Figure 68, which was generated with the WBCSD Sustainable Mobility Project (SMP) global fleet model [Fulton and Eads 2004].

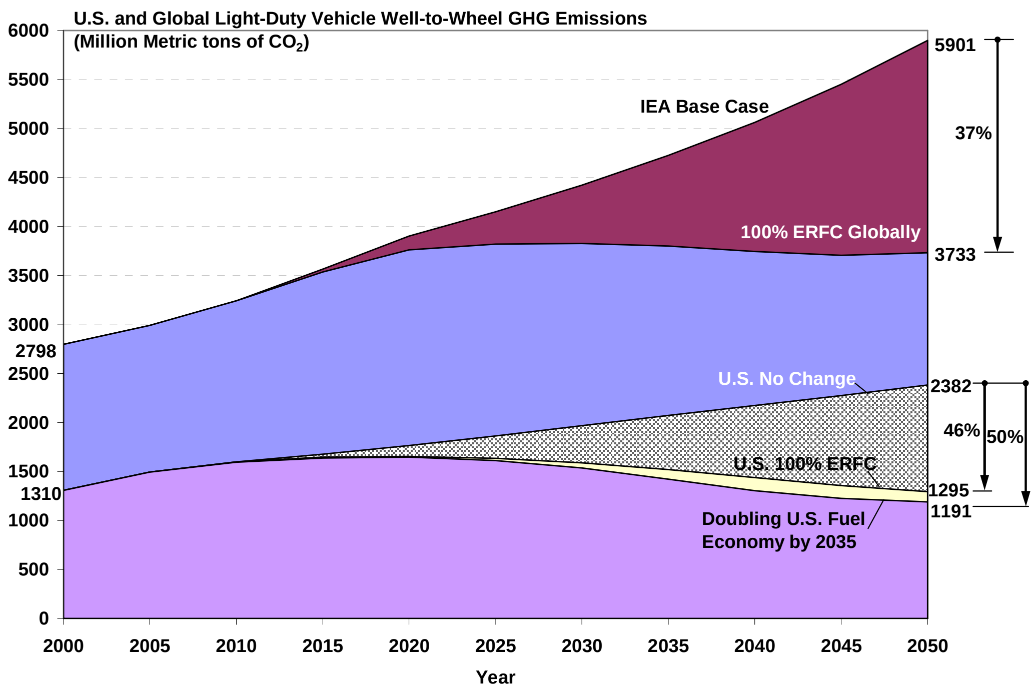


Figure 68 U.S. and global LDV well-to-wheel GHG emissions (2000–2050)

The SMP global fleet model estimates that the global LDV fleet CO_2 emissions will more than double between 2000 and 2050 if no measures are taken to reduce vehicle fuel consumption. A large part of the growth results from expansion of LDV fleets in developing Asia and Latin America, as well as steady growth in travel in North America.

If it is assumed that the fuel consumption of new LDVs worldwide can be reduced at the same rate as the 100% ERFC in U.S. LDVs, then the global LDV fleet GHG emissions will plateau around 3,750 million metric tons in around 2025. Unlike the U.S. LDV fleet, where the actual fuel use and GHG emissions can decline, the growth in the stock of vehicles worldwide means that the emissions from the LDV fleet can be stabilized at best during this period, without additional help from advanced propulsion systems and alternative fuels.

Figure 68 highlights the urgency of reducing LDV emissions in the United States, if global LDV GHG emissions are to decline sharply in the coming decades. Development and commercialization of new vehicle technologies and fuels in the U.S. market might enable the developing parts of the world to adopt these technologies more quickly. Hence, the United States will have to pursue ambitious targets, such as doubling the fuel economy of new vehicles by 2035. As indicated above, deeper cuts in U.S. emissions would provide significant benefits on the global LDV GHG emissions front.

7.11 European scenarios

Three scenarios were considered for each European country examined in this report: 1) *No Change*, 2) *Diesels Dominate*, and 3) *Alternative Technologies Emerge*. These scenarios were differentiated by vehicle sales mix, ERFC, and biofuels content. In the *No Change Scenario*, the existing vehicle sales mix, ERFC, and fraction of biofuels was held constant at 2005 levels.[56] In the *Diesels Dominate Scenario* and the *Alternative Technologies Emerge Scenario*, the ERFC was raised from the historic average 50% to 75%, and the fraction of biofuels in the fuel mix was increased over time to a 10% energy share by 2035.[57] The two scenarios differed in that *Diesels Dominate* assumes that the sales fraction of diesel vehicles grows to 75% by 2035, whereas the *Alternative Technologies Emerge Scenario* assumes that a mix of alternative powertrains (e.g., gasoline turbo, hybrids, and CNG) achieve a 55% sales share by 2035. The exact sales mix scenario for each country is detailed in Table 40 and described in further detail below.

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[56] The fraction of biofuels in the European fuel mix is approximately 2% by volume (Emerging Markets Online 2006).

[57] The biofuels assumption is modeled after the European Commission Directive targeting 10% biofuels by 2020. The scenario used here differs from the Directive in that it extends the deadline for compliance to 2035 to reflect the fact that a 10% biofuel energy share is an ambitious target that is unlikely to be achieved until sometime after 2020. It is assumed for simplicity that in 2035 ethanol and biodiesel will each comprise 10% by energy of gasoline and diesel, respectively. Corresponding well-to-tank and tank-to-wheel energy and GHG values were taken from CONCAWE et al.'s (2007) well-to-wheel assessment.

Table 40 European scenarios' sales mix assumptions

		2005	2035		
		Today	No Change	Diesels Dominate	Alternative Technologies Emerge
France	Diesel	69	69	75	35
	NA Gasoline	28	28	22	10
	Gasoline Turbo	3	3	3	30
	Gasoline Hybrid	0	0	0	15
	Diesel Hybrid	0	0	0	5
	CNG	0	0	0	5
Germany	Diesel	43	43	75	30
	NA Gasoline	51	51	19	15
	Gasoline Turbo	6	6	6	30
	Gasoline Hybrid	0	0	0	15
	Diesel Hybrid	0	0	0	5
	CNG	0	0	0	5
Italy	Diesel	59	59	75	35
	NA Gasoline	37	37	21	10
	Gasoline Turbo	4	4	4	30
	Gasoline Hybrid	0	0	0	15
	Diesel Hybrid	0	0	0	5
	CNG	0	0	0	5
UK	Diesel	38	38	75	25
	NA Gasoline	56	56	19	20
	Gasoline Turbo	6	6	6	30
	Gasoline Hybrid	0	0	0	15
	Diesel Hybrid	0	0	0	5
	CNG	0	0	0	5

7.11.1 Vehicle sales mix: Diesels Dominate vs. Alternative Technologies Emerge

The *Diesels Dominate Scenario* simulates the potential for diesels to continue to capture a larger and larger share of new sales. It caps the total sales share in 2035 at 75% in each of the four markets. Under this scenario, the market share of turbo gasoline vehicles maintains its 2005 share, which is approximately 10% of total gasoline vehicle sales, and the growing diesel share causes a decline in the share of NA gasoline vehicles [Beecham 2005].

The *Alternative Technologies Emerge Scenario* assumes that the sales share of turbo gasoline, gasoline hybrid, diesel hybrid, and CNG vehicles grows significantly between 2005 and 2035. The assumptions that underlie this scenario are as follows:

1. Due to several factors (e.g., loss of tax revenue, unsustainable gasoline/diesel refinery split, etc.), the sales fraction of diesel vehicles does not increase above its current level.

2. It is assumed that the trend of turbo gasoline vehicles comprising a larger and larger fraction of total gasoline vehicle sales will continue. Similar to the rapid diffusion and high rate of market penetration observed for other subsystem technologies, such as port fuel injection and front wheel drive, this scenario projects that gasoline turbo vehicles achieve a significant fraction of total gasoline vehicle sales by 2035.

3. Gasoline hybrids are assumed to account for 15% of all new vehicles sold in 2035. While seemingly arbitrary, this target could be achieved if gasoline hybrids were able to reach 3% market share (similar to the current U.S. hybrid sales share) by 2015 and then maintain an 8% compound annual growth rate until 2035, which is the same rate that diesel sales have maintained in western Europe since 1990 [ACEA 2008].

4. In 2035 there will be approximately one-third as many diesel hybrids sold as gasoline hybrids, due to the former's incremental fuel consumption benefit, but significantly greater cost (e.g., engine block, aftertreatment, etc.).

5. The growth in the sales share of CNG vehicles by 2035 will be modest (i.e., 5%). A significantly greater market share is limited by several factors, including the inconvenience associated with refueling, continued demand growth for natural gas by other sectors, and infrastructure limitations. For example, CONCAWE et al. [2007] estimated that if CNG were to comprise more than 5% of the 2020 road fuels market, additions to the existing gas distribution network would be required.

6. Finally, it was assumed that, as the market share of these alternative technologies grows, gasoline hybrid, diesel hybrid and CNG sales will take equally from existing NA gasoline and diesel market share. Also, since turbocharging primarily involves changing subcomponents, gasoline turbo vehicle sales are assumed to take exclusively from existing NA gasoline market share. Just as it is not possible to know how these various alternative powertrains will fare in the marketplace with respect to one another, it is similarly uncertain whether they will be replacing diesel or NA gasoline technology. The decision to have the alternative technologies take equally from each incumbent was made to avoid deriving a more complicated, yet no more likely, retirement scheme. The only caveat to this rule is that the market share of NA gasoline vehicles was never allowed to fall below 10%, to account for the fact that, as the lowest-cost powertrain option, there will always be some level of demand for conventional NA gasoline vehicles.

7.11.2 Scenario results

In conjunction with the European fleet models, the above scenarios were used to evaluate the feasibility of proposed new vehicle GHG emission targets, the evolution of the diesel-to-gasoline fuel use ratio, and the relative ability for changes in the sales mix, ERFC, and biofuels share to reduce fleet-wide fuel use and GHG emissions over the next 30 years. A full description of the results of MIT's European fleet modeling work is provided in the literature [Bodek and Heywood 2008]. Rather than discuss what was found for each of the four countries, the following discussion summarizes the most relevant findings. In some cases, the results from a country with a high existing sales share of diesel vehicles (France, at approximately 75%) is contrasted with a country with a lower diesel sales share (the UK, at approximately 40%) in order to further deepen the analysis.

Feasibility of vehicle CO_2/km target deadlines

The feasibility of achieving the proposed 2012 binding CO_2/km GHG emission targets (130 g/km and 120 g/km), as well as the hypothetical 2020 engineering target (95 g/km), was evaluated [European Commission 2007]. For example, Figure 69 shows the historic trend in specific GHG emissions from the average new vehicle in France between 1995 and 2006, the linear trajectories required to meet the three targets, and the future specific GHG emissions for the *Alternative Technologies Emerge Scenario* produced by the model. It suggests that, under this particular scenario, the year in which all three targets are met may be delayed by approximately a decade. For instance, when the added benefit of biofuels is included, the model suggests that the 2012 target of 120 g CO_2/km may not be met until as late as 2020. When summarized for all four countries, this analysis suggests that under a *No Change Scenario* there could be significant delays (10–20 years, if not longer) before proposed 2012 and 2020 CO_2/km targets are met. Even under the *Diesels Dominate* and *Alternative Technologies Emerge Scenarios* there may still be delays, ranging from approximately 5–15 years, depending upon the country.

Petroleum fuel use and GHG emissions:

Under the *No Change Scenario*, total petroleum fuel use and GHG emissions remain relatively constant in France and Germany between 2005 and 2035 (emissions decrease by approximately -5%), decline significantly in Italy (by approximately -20%), and grow measurably in the UK (by approximately +15%). The *Diesels Dominate* and *Alternative Technologies Emerge Scenarios* produce similar reductions to each other in total fuel use and GHG emissions. The approximate relative reduction in total fuel use and GHG emissions in each country by 2035for *Alternative Technologies Emerge* and *Diesels Dominate* was, respectively: Italy (35% and 30%), Germany (30% and 25%), France (20% and 15%) and the UK (10% and 5%). This ranking is consistent with the ranking of countries by average new sales growth rate, detailed in Table 40.

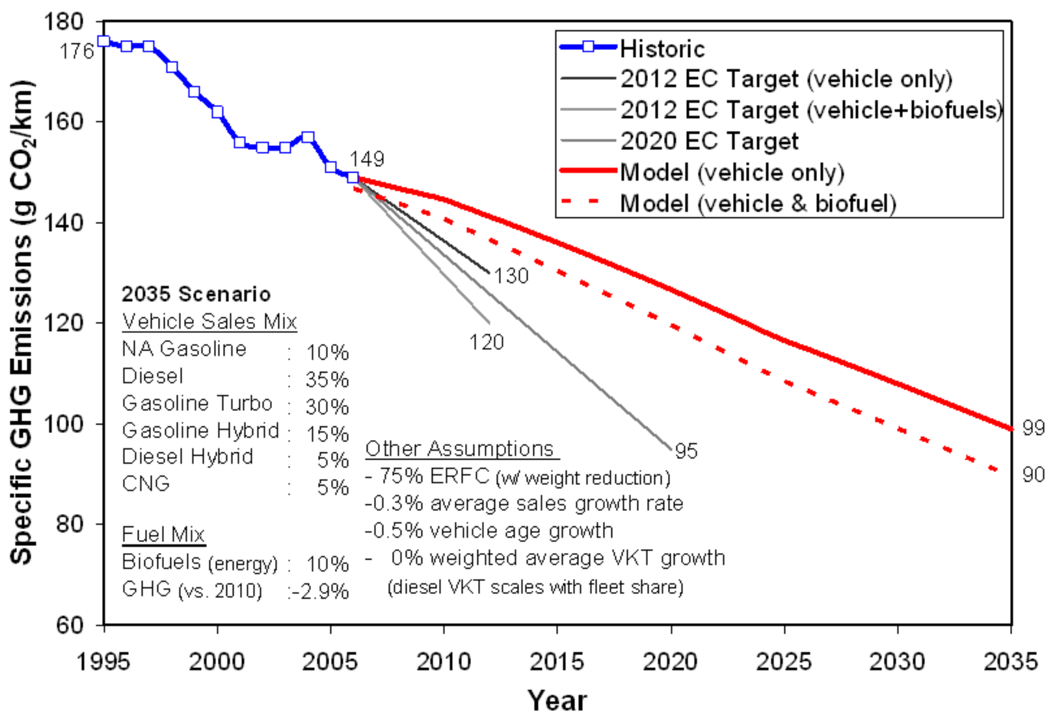
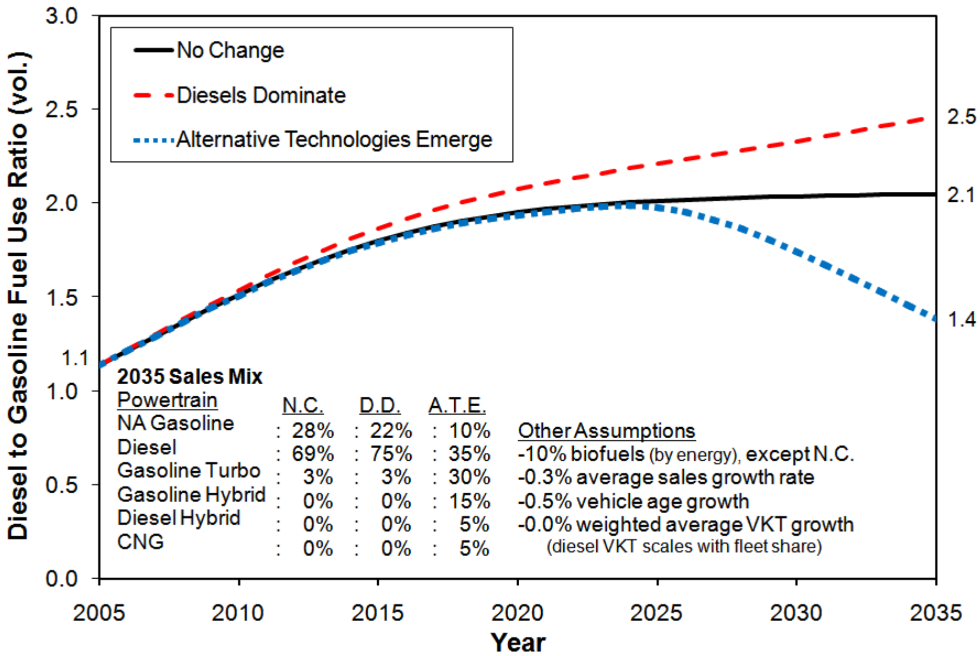


Figure 69 Specific GHG emissions of the average new vehicles in France

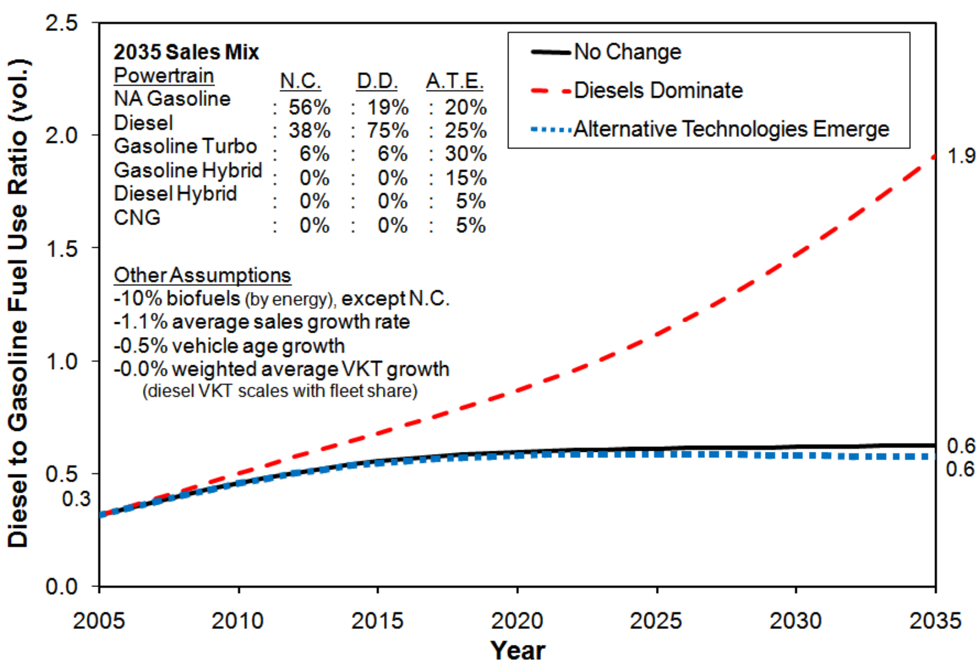
Petroleum fuel use ratio

A useful method for analyzing petroleum gasoline and diesel fuel use is to consider the ratio in which they are consumed. This is a particularly relevant metric for European fuel refiners, who are concerned about the growing imbalance between diesel and gasoline fuel demand. The diesel-to-gasoline fuel use ratio was found to continue to increase for at least the next 10 years, regardless of the future scenario or country, reflecting the time it takes to establish the diesel fraction of the total vehicle fleet.

Interesting distinctions emerged for those countries with a high existing diesel sales share and those with a lower share. Figure 70 (a) and (b) illustrate the potential trajectories (each corresponding to one of the three scenarios) that the fuel use ratio in France and the UK, respectively, could follow. It shows that under the *Diesels Dominate Scenario*, the rate of growth in the fuel use ratio increases at a declining rate in France and at an increasing rate in the UK. This reflects the fact that, while the diesel to gasoline fuel use ratio is already greater than one in France, it has the potential to increase from less than one to significantly greater than one in the UK under continued dieselization. Under the *Alternative Technologies Emerge Scenario*, the fuel use ratio curves for France peaks in approximately 2035 before beginning to decline, whereas in the UK, a leveling off in the fuel use ratio occurs after approximately 10 years, similar to the *No Change Scenario*. This suggests that, especially for countries with a high existing diesel sales share, the *Alternative Technologies Emerge Scenario* could help restore the fuel demand imbalance. The resulting decline in fuel use ratio, however, could be problematic to petroleum refiners' abilities to properly stage capacity additions.



(a) France



(b) United Kingdom

Figure 70 Diesel-to-gasoline fuel use ratio in the France and the UK

Reduction potential from a new sales mix, greater ERFC, and increased biofuels use

While it is not possible to analyze the relative impact of sales mix, ERFC and biofuels individually (since all three are connected to each other), it is instructive to examine their relative contribution to reducing the fuel use and GHG emissions of the future vehicle fleet. Figure 71 (a) and (b) depict the WTW GHG reduction potential of the *Diesels Dominate* and *Alternative Technologies Emerge* scenarios, respectively, in France. Similar graphs for the UK are shown in Figure 72 (a) and (b). The wedges in these graphs should be interpreted as the additional reduction in GHG emissions obtained by incorporating an added measure.

Similar to the U.S. analysis, simply increasing the ERFC is shown to have a significant impact on 2035 fuel use and GHG emissions. The relative impact, however, is not as great as in the United States. The reduction attributable to transitioning from 50–75% ERFC across all European countries was approximately 10%, whereas the reduction in the United States from going between zero and 50% ERFC was approximately 13%.

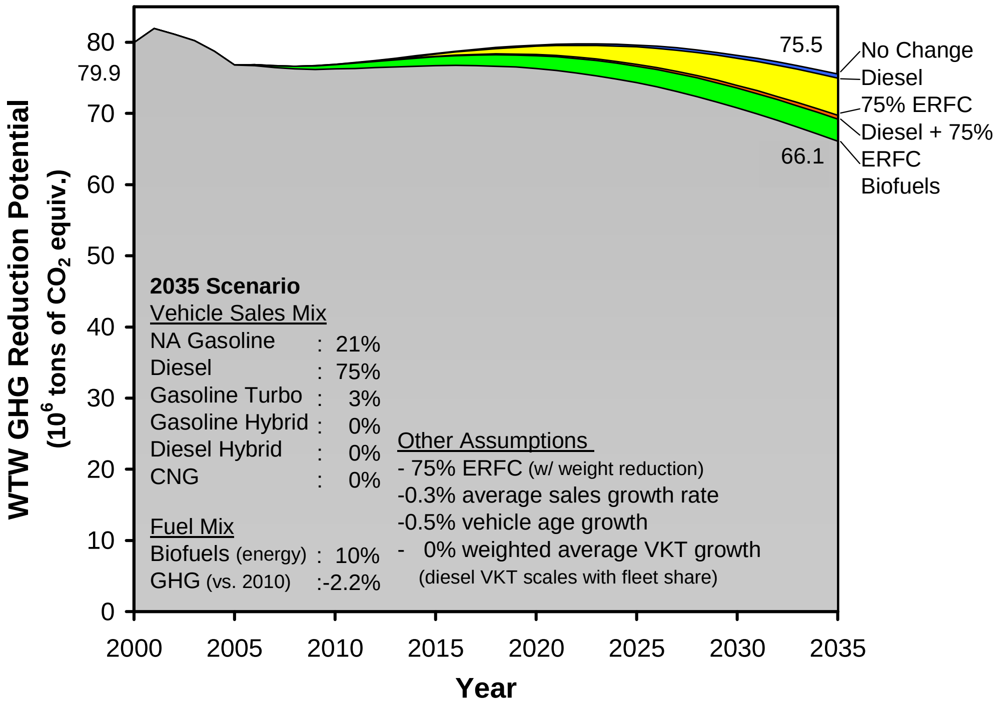
As illustrated by Figure 71 (a), the *Diesels Dominate Scenario* is shown to have very little impact on total fuel use and GHG emissions in France. This is not surprising, given the fact that the sales share of diesels is already close to 75%. By comparison, as shown in Figure 72 (a), the same scenario in the UK achieves approximately half of the reduction that is achievable by increasing the ERFC to 75%.

Similar to the results obtained from the U.S. fleet modeling study, the impact of introducing alternative technologies is relatively small and takes several decades to manifest. Both the fuel use and GHG reduction in 2035 attributable to the *Alternative Technologies Emerge Scenario* ranged between approximately 2.5 and 5%. The following factors help explain why the impact from this scenario is smaller than observed by the corresponding U.S. scenario:

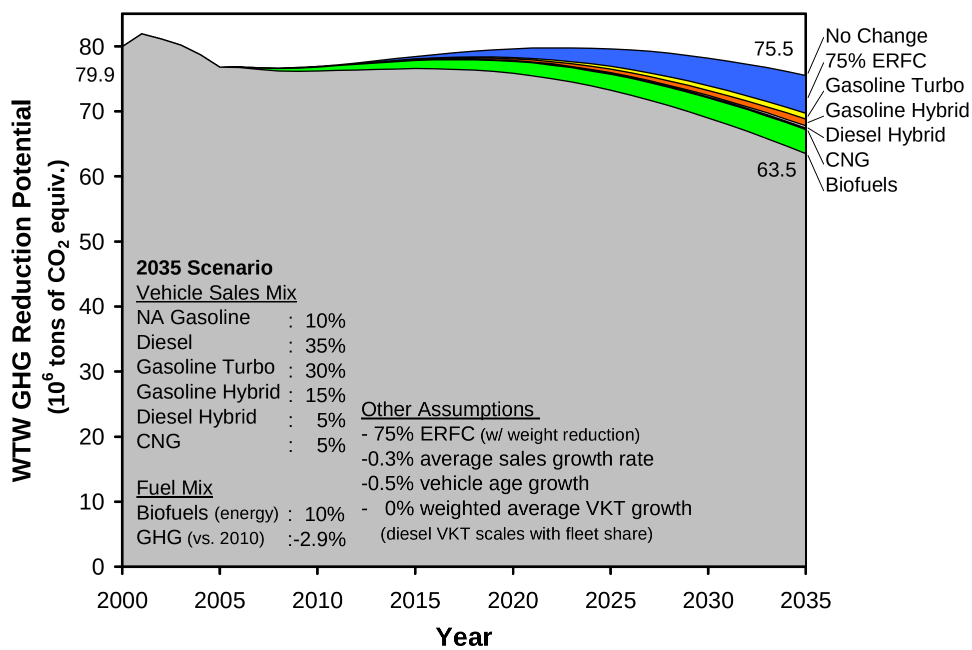
When an alternative propulsion system is introduced into a European fleet it takes the place of what would otherwise have been a NA gasoline or diesel vehicle. In the latter case, the relative fuel consumption improvement on a vehicle basis is not as large as occurs when that vehicle takes the place of strictly a NA gasoline vehicle, as in the United States. The advantage from introducing alternative powertrains becomes smaller with higher levels of ERFC. For example, the fuel consumption of 2035 NA gasoline and gasoline hybrid vehicles in France, assuming 50% ERFC, is estimated at 5.34 and 3.55 L/100km, an absolute difference of 1.79 L/100km. When the ERFC is increased to 75%, the absolute difference becomes 1.58 L/100km (i.e., 4.72 minus 3.14 L/100km).

In countries with low or negative new sales growth rates, the youngest vehicles account for a smaller and smaller fraction of the entire fleet. Thus, if those vehicles use alternative propulsion systems with lower average fuel consumption their impact will be smaller than it would otherwise have been if the size of the fleet were growing. For example, compare the size of the wedges in the fuel use reduction graph for France (Figure 71), where new sales growth rates are expected to decline by approximately 1% over the next 30 years, with the UK (Figure 72), where new sales growth rates are expected to increase by 1%.

Lastly, the impact of increasing the fraction of biofuels in the fuel mix was found to have a similar impact on reducing fuel use as adjusting ERFC, at approximately 10%. The contribution from biofuels to reducing GHG emissions was however significantly lower, at 4– 5.5%. This is, of course, because replacing one liter of gasoline with wheat ethanol only reduces GHG emissions by 30%, and replacing one liter of diesel with biodiesel only reduces emissions by 45%.

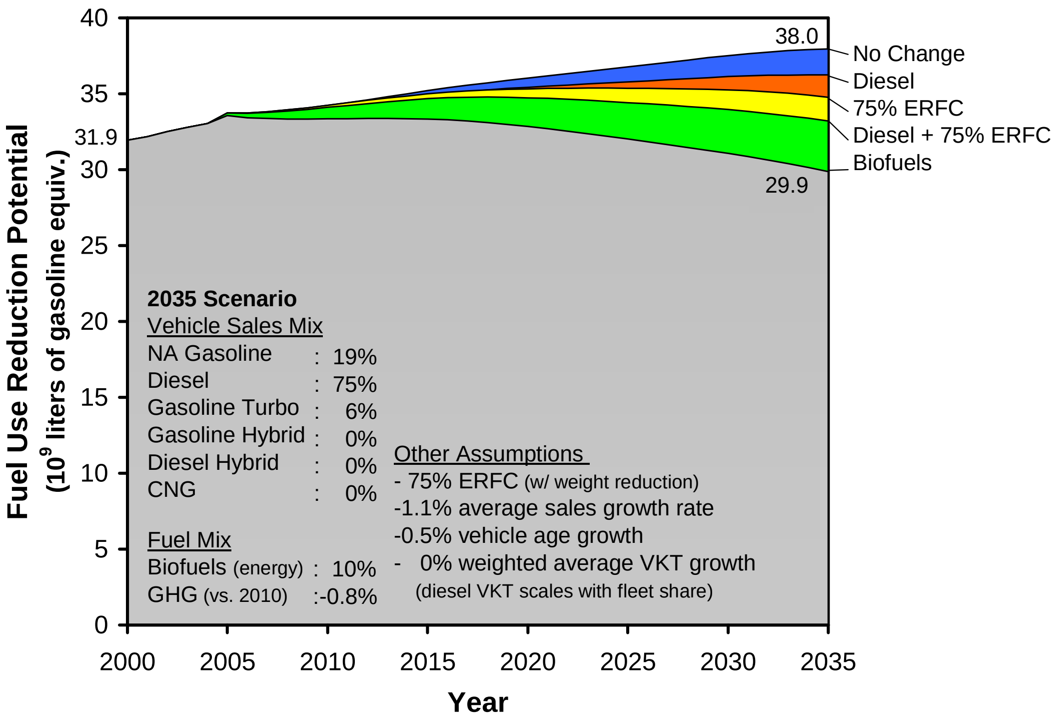


(a) Diesels Dominate Scenario in the France

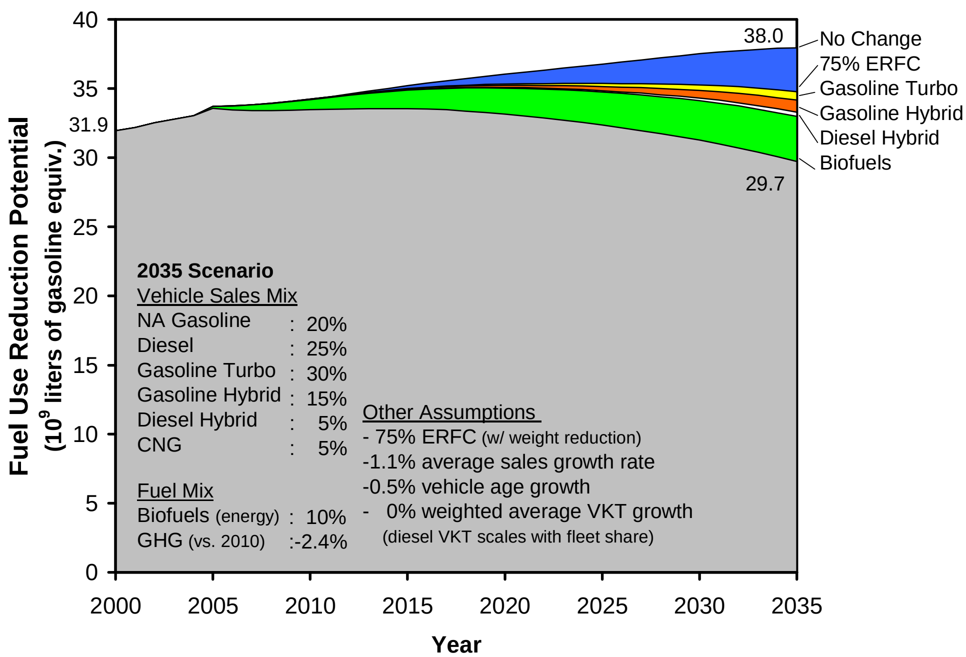


(b) Alternative Technologies Emerge Scenario in the France

Figure 71 GHG reduction potential in France



(a) *Diesels Dominate Scenario* in the UK



(b) Alternative Technologies Emerge Scenario in the UK

Figure 72 GHG reduction potential in the UK

7.12 Conclusions

This discussion on market penetration rates of new propulsions systems and of the various scenarios we have examined of LDV fleet fuel use and GHG emissions reveals the following:

1. Reducing LDV fleet fuel use substantially below the *No Change* continuing growth projection through changes in vehicle technology will take decades. Much of the near-term growth in LDV fleet fuel use is a consequence of changes that have already occurred, or that are already in progress.

2. Uncertainties in consumer demand make undertaking major vehicle redesigns a risky endeavor for vehicle manufacturers. This, when coupled with the high initial cost and strong competition from steadily improving mainstream gasoline vehicles, means that market penetration rates of low-emissions diesels and gasoline hybrids in the United States are likely to be slow. As a result, diesels and gasoline hybrids are likely to show only a modest, though growing, potential for reducing fleet fuel use before 2025.

3. Due to slow rates of fleet turnover, the fleet fuel use is much less sensitive to changes in the new vehicle market than is generally believed. 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.

4. The long delay between the introduction of advanced vehicle technologies and their impact on fleet fuel use should not be taken in a negative light, however. The difference between near- and long-term impacts needs to be properly understood. In the longer term (30-50 years), the impact of advanced technology vehicles will indeed be far larger than the near-term (less than 25 years) impact. Advanced vehicle technology introduction needs to start as early as possible, however, to realize deep reductions in long-term fuel use and minimize delays in deployment.

5. For similar levels of market penetration, gasoline hybrid vehicles are more promising vis-à-vis diesels in terms of reducing fleet fuel use. The *Market Mix Scenario*, with a small number of plug-in hybrids, produces results that are similar to that of the *Turbocharged ICE Future*, with a large market penetration of diesel vehicles. The *Hybrid Strong Scenario* outperforms these other two scenarios, but only by 7–9% (in 2035).

6. Shifting the emphasis on reducing fuel consumption from 50–100% in mainstream ICE gasoline vehicles alone can produce fuel use reductions equivalent to about 80% market penetration of advanced vehicle technologies. The emphasis that consumers and auto manufacturers place on directly reducing fuel consumption is a critical factor in making real progress.

7. Whether Europe continues along its current dieselization trajectory or whether significant numbers of turbo gasoline and gasoline hybrid propulsion system vehicles enter the fleet will have important repercussions on the future ratio of diesel-to-gasoline fuel demand. Regardless of the scenario, that ratio can be expected to continue to increase for at least

the next 10 years. Given the fact that the reference ERFC is already at approximately 50% in Europe's largest markets, the benefit from further increasing the ERFC is diminished when compared to the United States.

7.13 Summary

This section has discussed a variety of issues concerning the likely scale and impact of advanced propulsion system deployment. By taking both supply and demand side constraints on building up vehicle production rates, three plausible market penetration scenarios were developed (*Market Mix, Turbocharged ICE Future*, and *Hybrid Strong*).

These scenarios indicate that substantial potential exists to reduce light-duty fleet fuel use over the next two to three decades in the United States. The LDV fleet fuel use in 2035 could be up to 40% lower than in the *No Change Scenario* if advanced propulsion technologies such as hybrids, turbo gasoline, or diesel engines can capture more than half of the new vehicle market by 2035, if significant weight reduction is achieved, and if all the advances in technology are used to emphasize reduction in fuel consumption. The scenario results also show that life-cycle GHG emission reductions will likely lag reductions in petroleum use, although cuts of up to 35% in fleet GHG emissions from a *No Change Scenario* are possible by 2035. The magnitude of the vehicle design and sales mix changes required to achieve these reductions are no less daunting than those required in the post-oil crisis period of the late 1970s.

8.0 Summary and Conclusions

8.1 The need for coordinated policies

This report envisions a transportation future in which light-duty vehicles attain substantial reductions in their rate of fuel consumption and greenhouse gas intensity by 2035. Even so, the potential for propulsion system technologies, weight reduction, and the supply of alternative fuels to limit emissions and save energy will not be realized without significant changes to business as usual. Achieving these goals will depend upon the following: 1) the ways in which industry implements new technologies, 2) the willingness of consumers to modify their personal mobility choices, and 3) the ability of decision-makers to implement appropriate and robust policy drivers.

Just as there is no "silver bullet" in the technology options available, it is unlikely that one dominant strategy or policy can satisfy the necessary political and economic constraints while achieving dramatic reductions in energy use and greenhouse gas emissions. As discussed in the introductory section to this report, a coordinated set of various measures could form a policy approach that would better account for the following factors:

1. Fiscal as well as regulatory approaches have a role to play. Alongside the push for new technologies and fuel options through mandatory requirements, fiscal policies can harness market forces to pull efficiency gains in vehicles toward reducing fuel consumption.

2. A broad base of stakeholders influences energy use and greenhouse gas emissions in light-duty vehicle transportation. Using incentives to align the interests of transportation consumers with the goals of a policy intervention would improve the effectiveness of regulations placed on smaller groups of industrial actors.

3. There are numerous opportunities to reduce energy use and emissions along the entire vehicle life-cycle. Policy drivers that influence the choices of manufacturers and consumers can be applied at the time of vehicle design, production, purchase, operation, and retirement. Without addressing these different life-cycle stages, a measure may unintentionally alter the behavior of stakeholders in ways that reduce the effectiveness of policy interventions.

8.2 Summary of available opportunities

As this report has described, a substantial research effort on the options for reducing petroleum consumption and greenhouse gas (GHG) emissions from transportation has been carried out at MIT for the past several years. While our focus has been primarily on the situation in the United States, comparative studies in major European countries have also been completed. Our focus has been on light-duty vehicles and their fuels, and on how engine and vehicle technology improvements and alternative fuels streams are likely to change future evolving fleet energy consumption patterns and GHG emissions.

Here we summarize the major conclusions that have emerged from our more recent studies. These studies have examined the potential for improved propulsion system and vehicle technologies, the introduction of alternative fuel streams to augment mainstream petroleum-based fuels, plausible time scales and rates at which improved technology production volumes could increase, how changes in the weighting of the vehicle attributes—performance, size, and on-the-road fuel consumption—affect the impact the technology improvements would have, and especially the evolving impacts of these vehicle technology, fuel, vehicle purchase, and use patterns, have on the fuel consumption and GHG emissions of the future U.S. in-use vehicle fleet. Our findings thus cover a wide range of topics. In addition, they allow us to provide a comprehensive summary, a set of conclusions, and broad recommendations as to how we can move forward.

1. **The challenge.** Petroleum use and greenhouse gas emissions are increasing steadily in the United States, the rest of the developed world, and especially in the developing world, due to seemingly inexorable growth in demand for land, air, passenger and freight transportation. Our first challenge is to offset this growth.

2. **Significant reductions are achievable through technology.** At constant vehicle performance and size, a 30–50% reduction in new light-duty vehicle fuel consumption is feasible over the next 20–30 years. Such a reduction in fuel consumption can be achieved by a combination of the following:

    a. Improved gasoline and diesel engines and transmissions, as well as gasoline hybrids in the nearer term

    b. Vehicle weight and drag reductions

    c. Plug-in electric hybrids and hydrogen fuel cells in the longer term

    The lower end of this range is achievable through improvements in mainstream engines and transmissions, which could be deployed in high volumes in the nearer term. It would take longer for more complex or advanced technologies such as hybrids to achieve significant overall reductions in fuel consumption and GHG emissions, due to their higher cost and slower deployment build-up. Radically different technologies such as plug-in hybrids and hydrogen and fuel cells—if developed to the point where they are market-feasible—would at best take more than 30 years to have a significant impact.

    The nearer-term changes, when combined in vehicles in appropriate combinations, will result in vehicle cost increases between $1,500–$4,500, if they are produced in significant volumes. The additional costs of plug-in hybrids and fuel cell vehicles are uncertain, but are anticipated to be significantly higher.

3. **Policy has a major role to play.** Policies developed to reduce vehicle fuel consumption will need to take into account the trade-offs between vehicle performance, size (and thus weight), and fuel consumption. Vehicle purchasers and users have shown a clear preference for increasing vehicle performance and size providing market "pull" for these attributes. The automobile companies compete among each other by offering ever-increasing performance and vehicle size, providing the "push." In the United States, the

emphasis on enhanced performance has been so strong that (with some size increases) 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 potential fuel consumption improvements have been achieved.

4. **Reducing vehicle weight and size has important benefits.** Vehicle weight and size reduction could contribute significantly to reduced petroleum consumption and greenhouse gas emissions. Direct weight reductions through substitution of lighter materials and basic vehicle design changes (which, for example, maximize the interior volume for a given vehicle length and width) enable secondary weight reductions as vehicle components are appropriately downsized. Much of this is straightforward engineering, and some of this weight reduction is relatively low cost. 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 a 20% reduction in sales-weighted average vehicle weight could be achieved over about 25 years. This would cost about $800 per vehicle. The maximum potential for weight reduction at plausible cost is about 35%; this would cost significantly more. These estimates allow for the additional weight required by future safety requirements and convenience features. Vehicle weight reductions of 20–35% on their own result in some 12–20% reduction in vehicle fuel consumption.

5. **Emphasizing reduced fuel consumption over other attributes is critical.** Due to slow rates of fleet turnover, the fuel consumption of mainstream technology vehicles (improved internal combustion engines, transmissions, some weight reduction) will determine the near-term fleet fuel use and GHG emissions profiles. Directing the efficiency improvements thus achieved toward reducing in-use fuel consumption of these high-sales-volume vehicle technologies is therefore critical.

6. **Mainstream technologies will dominate near-term impact.** Due to 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 be slower than is widely believed. As a result, diesels and gasoline hybrids have only a modest, though growing potential for reducing U.S. fleet fuel use before 2025. In Europe, the potential for impact through improved mainstream engines and weight reduction is significantly less, due to the fact that roughly half the fleet is already diesel, and vehicle size and weight are some two-thirds of average U.S. vehicle values.

7. **Strategies and opportunities for longer-term impact must be explored as early as possible.** In the longer-term, the impact of advanced technology vehicles will be far larger than their near-term impact. However, the time scales to impact of new technologies are long, since they include the build-up to substantial production volumes and significant penetration into the in-use vehicle fleet. Thus, advanced vehicle technology development and introduction when market ready needs to start as early as possible if the long-term reductions in fuel use and GHG emissions that successful deployment would bring are to be realized.

8. **The future benefits of alternative liquid transportation fuels are uncertain.** 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. petroleum use. This could expand to about 10% of total U.S. consumption in 2030, which would increase well-to-tank GHG emissions by about 5%. Both corn-grain based ethanol and cellulosic ethanol from, say, switchgrass, displace gasoline by two-thirds, volume for volume. The GHG emissions impacts are substantially different, with corn grain ethanol proving only modest GHG benefits and cellulosic biomass-based ethanol potentially providing substantial GHG benefits. Recent discussions of the GHG penalties associated with land use changes to produce the biomass material suggest that the presumed GHG benefits may not be realized. While ambitious targets for ethanol production and use have been set in many parts of the world (e.g., displacing 20% of gasoline by 2020 in the United States), it is unclear whether the targets for cellulosic ethanol (comparable volumes to corn ethanol by 2035) can be met, and what the GHG emissions benefits are going to be. Ethanol has not been cost competitive with past gasoline prices without significant subsidies. With the price of petroleum rising, that situation may be changing.

9. **GHG emission reduction poses additional challenges.** A greater number of vehicle and fuel alternatives are available to displace petroleum use than to reduce greenhouse gas emissions:

    a. Plug-in hybrids, at present a costly and heavy option, might over the longer term play an important role in reducing petroleum use. However, due to the likely GHG emissions from the electricity production required, the GHG emissions reduction that plug-ins would achieve 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, increasing the biomass-to-liquids supply in the near term might help reduce well-to-wheels GHG emissions, but increased use of non-conventional oil is likely to negate this impact. Ethanol's contribution is likely to be constrained by land availability and yields.

It is thus important that policy efforts be focused on measures that both improve energy security and reduce GHG emissions at the same time.

8.3 What we should do

From the results of this study, it is clear that fuel consumption and GHG emissions of our light-duty vehicle fleet can be reduced significantly in the United States. 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.

Worldwide demand for transportation services is growing inexorably, and 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 1) develop and market more efficient vehicles and more environmentally benign fuels, 2) find more sustainable ways to satisfy demands for transportation services, and 3) 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. Implementation 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.

1. 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), some in the mid-term (15–30 years), and some in the long term (more than 30 years). The preparatory work for both mid- and long-term programs—including extensive research and development—must begin now if we are to ensure that they will be ready to be implemented as currently planned.

2. 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 increases in vehicle power and size. The latter poses a serious problem of marketability to customers since the long-term market trend has been toward increasingly powerful, larger, and heavier vehicles. Changing that trend may well require both manufacturer and government incentives.

3. A second important opportunity to realize is vehicle weight and size reduction, along with reducing vehicle drag and tire rolling resistance. Weight reduction can be accomplished via the use of lighter materials and vehicle redesign. Vehicle size reduction can be attained by producing and popularizing smaller vehicles to replace larger ones. While some aspects of vehicle functionality may be diminished, the basic mobility attractions of personal transportation can be maintained.

4. Alternative fuels (fuels derived from raw materials other than petroleum) do reduce petroleum consumption, but in the U.S. and Europe they are more likely to increase GHG emissions, in the near term at least, than decrease them. 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. But biofuels production is largely set by agricultural policy as well as energy or environmental policy, and the overall environmental and economic benefits of some biofuels, notably corn-ethanol in the United States, are being increasingly questioned, as are 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.

5. Government policies will be needed to further the overall objectives of our road transportation system as well as reduce its energy and environmental impacts. These policies should be structured to achieve the following:

    a. Both push development and deployment of appropriate technologies and generate market pull for those technologies with policies that reinforce each other through synergies. Incentives should be for outcomes, not particular technologies such as current incentives for hybrids, which put other vehicles with low fuel use and emissions at a competitive disadvantage. Such policies will need to be coordinated to achieve the desired progress.

    b. Be transparent and appear fair to all stakeholders, especially those suffering the highest costs of the necessary transitions. Transportation-related taxes, fees, and credits should have clear objectives and be revenue-neutral to the extent feasible, and be distributed equitably among stakeholders and user groups.

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

Overall, this report makes clear that we have many options available for reducing petroleum consumption and greenhouse gas emissions from private motor vehicles in countries like the United States. By realizing these options, current consumption and emission 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 market place 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 keep in mind that what matters is effecting changes that will have substantial impact on these issues. We will need much better technology, more appropriate types of vehicles, greener fuel streams, and changes in our behavior that emphasize conservation. We 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.

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