Evaluating the Impact of Advanced Vehicle and Fuel Technologies in U.S. Light-Duty Vehicle Fleet

By

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ABSTRACT

The unrelenting increase in oil use by the U.S. light-duty vehicle (LDV) fleet presents an extremely challenging energy and environmental problem. A variety of propulsion technologies and fuels have the promise to reduce petroleum use and greenhouse gas (GHG) emissions from motor vehicles. Previous work in this domain has compared individual vehicle or fuel alternatives. The aim of this research was to deepen the understanding of the likely scale and timing of the fleet-wide impact of emerging technologies.

A model of the light-duty vehicle fleet showed that fuel consumption of mainstream gasoline internal combustion engine (ICE) technology vehicles will determine the trajectory of fleet fuel use and GHG emissions over the next two decades. Using vehicle simulations and historical data, the trade-off between vehicle performance, size and fuel consumption was quantified. It was shown that up to 26 percent reduction in future LDV fuel use is possible with mainstream gasoline ICE vehicles alone if emphasis of vehicle technology is on reducing fuel consumption rather than improving performance. Addressing this vehicle performance-size-fuel consumption trade-off should be the priority for policymakers.

By considering both supply and demand side constraints on building up vehicle production rates, three plausible scenarios of advanced vehicle market penetration were developed. Due to strong competition from mainstream gasoline vehicles and high initial cost, market penetration rates of diesels and gasoline hybrids in the U.S. are likely to be slow. As a result, diesels and gasoline hybrids have only a modest, though growing potential for reducing fleet fuel use before 2025. In general, the time-scales to impact of new technologies are twenty to twenty-five years.

Integrating vehicle and fuel scenarios showed that measures which reduce greenhouse gas emissions also reduce petroleum consumption, but the converse is not necessarily true. Policy efforts therefore should be focused on measures that improve both energy security and carbon emissions at the same time. While up to 35 percent reduction in fleet GHG emissions from a No Change scenario is possible by 2035, the magnitude of changes required to achieve these reductions are daunting, as all of the current trends run counter to the changes required.

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Chapter 1

Problem Statement

Two Vulnerabilities and Two Opportunities

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

Increasing consumption of petroleum is also responsible for 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 U.S. The emissions of CO_2 from transport have grown by approximately 25 percent during the period from 1990 to 2005. The tailpipe CO_2 emissions from LDVs in year 2005 are estimated to be 1260 million metric tons, or about 22 percent of the total U.S. emissions of CO_2. These emissions are projected to grow at a rate of 1.9 percent per annum [EIA, 2007a]. This unrelenting increase in the consumption of oil in the U.S. light-duty vehicles presents an extremely challenging energy and environment problem. Effective measures will have to be undertaken to reduce fuel consumption to reduce the risks to the economy and the environment.

Advances in vehicle technologies and fuels are expected to contribute greatly towards reducing use of petroleum and CO_2 emissions from transportation. Figure 1 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) which release the chemical energy in the 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 equally common in European light-duty vehicles, and dominate the heavy-duty market globally. While the basic architecture of ICEs has not changed dramatically, engine technology continues to improve steadily. Therefore, it is possible that mainstream ICEs will continue to dominate light-duty vehicle propulsion systems for the next several decades.

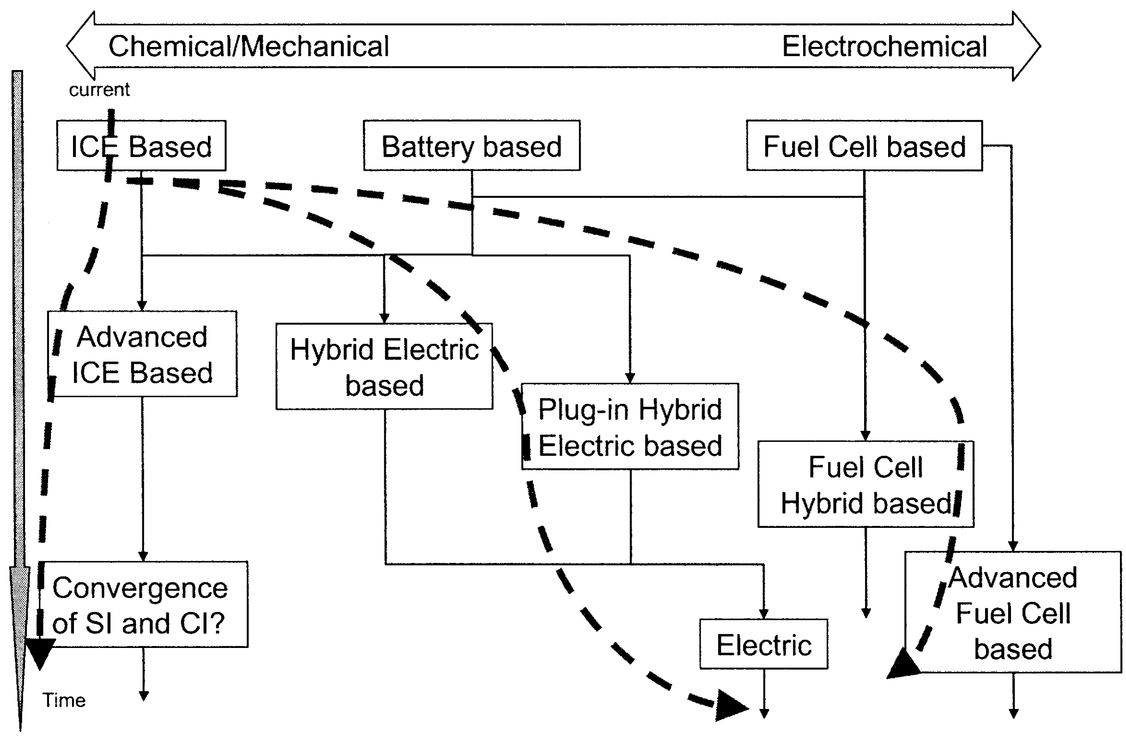


Figure 1 Possible Propulsion System Pathways

Hybrid vehicles (HEVs) are a leading contender among alternative propulsion technologies. HEVs typically combine a high energy 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. The so called plug-in hybrid vehicles (PHEVs) have a larger battery pack on-board that needs to be charged from an external electricity supply, and are capable of driving twenty to sixty kilometers on electricity alone. Successful deployment of PHEVs may pave the path for electric vehicles in the future.

Fuel cell vehicles (FCVs), particularly those running on hydrogen, provide another non-ICE propulsion systems alternative. The initial FCVs are expected to be hybrids with a powerful battery on-board, although fuel cell only vehicles might emerge several decades down the road. Whether ICE-based vehicles continue their dominance, or electric and/or fuel cell vehicles will replace them over time is presently uncertain.

At the same time when the dominance of ICEs as propulsion systems is being challenged, numerous alternatives are evolving to augment or replace petroleum's role as transportation fuel. Figure 2 shows numerous transportation fuel pathways identified in the World Business Council on Sustainable Development's Mobility 2030 report [WBCSD, 2004].

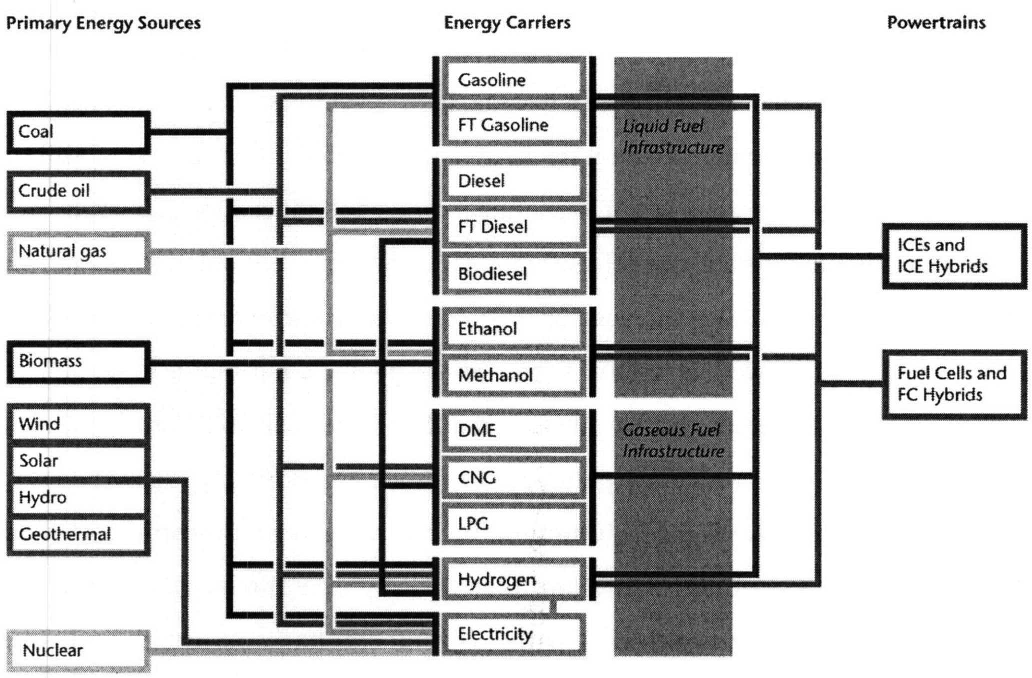


Figure 2 Possible Transportation Fuels Pathways [WBCSD, 2004]

In addition to the conventional sources of crude oil, non-conventional oil sources such as oil sands can be used to produce gasoline and diesel fuels. Gasoline and diesel-like liquid fuels can also be generated from other fossil fuels such as coal or natural gas by using the Fischer-Tropsch (FT) process. Other fossil fuel based transportation fuels include gaseous fuels such as dimethyl ether (DME), compressed natural gas (CNG), or liquefied petroleum gas (LPG). Renewable biomass can be used to produce gasoline or diesel substitutes such as biodiesel and ethanol to be used in ICE powered vehicles. Electricity and hydrogen can be produced from a wide variety of fossil as well as non-fossil primary energy sources.

Objective

As discussed in the previous section, a number of propulsion technologies and fuels alternatives will be competing over the next several decades in the light-duty vehicle market. Well-to-wheel energy and emissions analysis of different vehicle and fuel systems to identify more promising alternative is now a standard practice [An et al., 2001; GM/ANL, 2001; NESCCAF, 2004; Weiss et al, 2000]. The likely scale and timing of the fleet-wide impact of emerging technologies, however, is much less well understood.

For example, gasoline hybrid vehicles have received wide publicity and are touted as a promising solution to solving petroleum and GHG challenges. It is important to note however that even after being in the market for almost a decade, hybrid vehicles are less than half a percentage of total light-duty vehicle fleet on the road, and as such their impact on total fleet fuel use and GHG emissions is very small so far. Gasoline hybrids will indeed make a large contribution to reduction in future fleet fuel use and GHG emissions, but only in the long-term.

This thesis will demonstrate the expected amount of that contribution over the next several decades in absolute as well as relative terms. Similarly, the contribution from other propulsion systems and fuels needs to be evaluated on a fleet wide basis to determine whether technology development efforts as well as policy measures are appropriately focused.

The objective of this thesis is to illuminate the role of advanced propulsion systems and fuels in reducing the use of petroleum and the resulting greenhouse gas (GHG) emissions from the U.S. light-duty vehicles, with a special emphasis on timing and scale of impact.

Thesis Overview

The scale and timing of impact of advanced propulsions systems and fuels on fleet fuel use and GHG emissions is contingent on the fuel consumption of individual vehicle technologies, market penetration of these technologies, and their utilization. An overview of the approach taken in this thesis is shown in Figure 3. Each of the boxes in Figure 3 also indicates the principal chapter that elaborates on the items listed within the box.

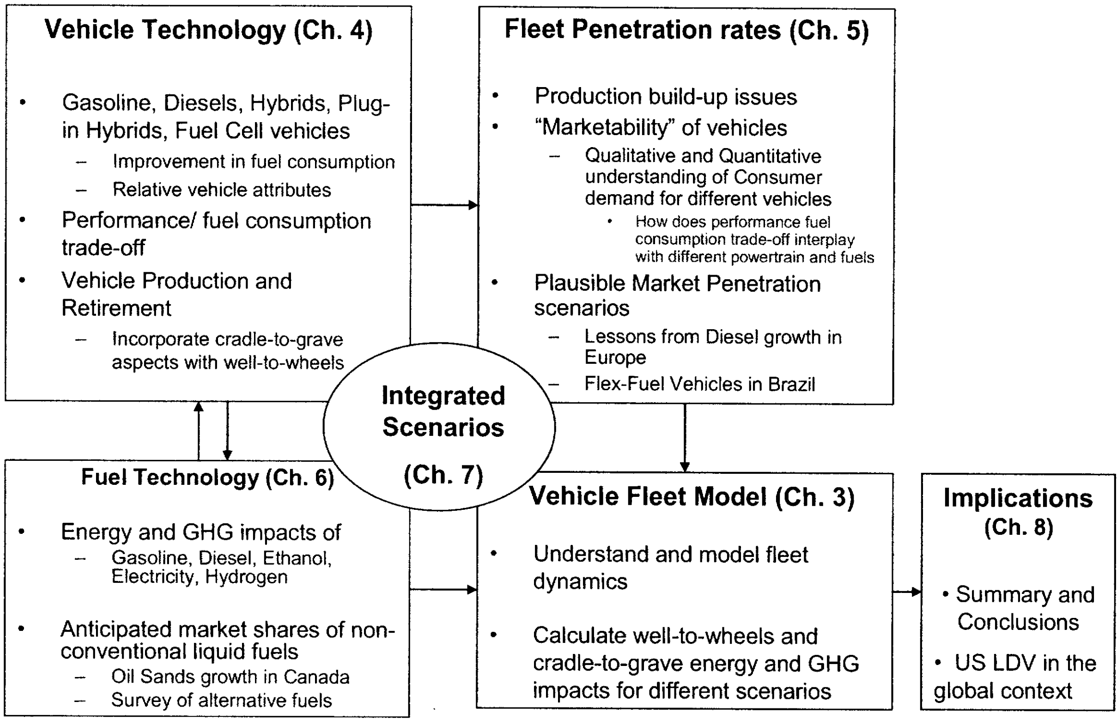


Figure 3 Thesis Overview

Chapter Two introduces the context in which U.S. light-duty vehicle fleet operates. The chapter discusses the factors that drive the growth in demand, the major actors or stakeholders of the system, and the principal policy alternatives to address the fleet fuel use and GHG emissions.

Chapter Three explains the logic of the fleet model used to calculate life-cycle energy use, petroleum consumption and greenhouse gases from light-duty vehicles. The fleet model is then expanded in the next chapters to fully explore the dynamics of light-duty vehicle fleet.

Chapter Four evaluates the trade-off between vehicle performance, size and fuel consumption for different propulsion systems, and introduces the concept of emphasis on reducing fuel consumption (ERFC) for quantifying this trade-off.

Chapter Five details the supply and demand side constraints in building up production of advanced vehicle technologies, and their impact of fleet-wide fuel use. The chapter develops three main scenarios used to illustrate the likely scale and impact of these technologies on LDV fleet fuel use over the next three decades.

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

Chapter Seven provides an integrated perspective on life-cycle greenhouse gas emissions with scenarios that evaluate relative impact of different vehicle and fuel technologies, and to double the fuel economy of new vehicles by 2035.

Chapter Eight summarizes the results of earlier chapters in the context of global light-duty vehicle fleet fuel use and GHG emissions, and provides key conclusions from this work.

Chapter 2

The Context: Factors, Actors and Policies

"We have only two modes – complacency and panic."

– James Schlesinger[1]

The aim of this chapter is to provide a brief context in which U.S. light-duty vehicle (LDV) technology and policy changes operate. The chapter is divided in three sections: The factors that drive the growth in LDV fleet fuel use and greenhouse gas emissions, the stakeholders or actors that shape the policy debate, and the policy alternatives available to affect the LDV fleet fuel use and greenhouse gas emissions.

Factors

GHG emissions from motor vehicles depend on the efficiency of driving (LPK), the amount of driving (VKT), and the greenhouse gas intensity of the fuel (FI) as shown by the following identity:

$$\text{GHG emissions} = \text{LPK} * \text{VKT} * \text{FI} \qquad (2.1)$$

Where,

GHG emissions = Greenhouse Gas Emissions (tons/year)

LPK = Liters per kilometer (l/100km = 235.2/Miles per Gallon (mpg))

VKT = Vehicle kilometers Traveled (VKT in km/year)

FI = GHG Intensity of Fuel (GHG tons/liters of fuel)

Thus, significant reductions in GHG emissions can be achieved if *all three* of the factors can be reduced. However, the three factors may interact with one another. For example, the carbon intensity of diesel as a fuel is slightly higher than gasoline, but diesel powered vehicles are typically 20-25% 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. Since they are more fuel efficient, diesel vehicles are likely to be driven

[1] Quoted in a July 12, 2005 New York Times article by J. Mouawad and M. Wald.

farther than their gasoline counterparts. This "rebound effect" may reduce the GHG emissions benefit from diesel vehicles.

Vehicle Fuel Consumption

New vehicle fuel consumption (as measured in liters of fuel consumed per kilometer traveled) was reduced considerably in 1970's and early 1980's 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 around 10 l/100km for new cars (23.5 mpg) and 13.5 l/100km 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 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 steady at 11.7/100km (20.1 mpg) as shown in Figure 4.

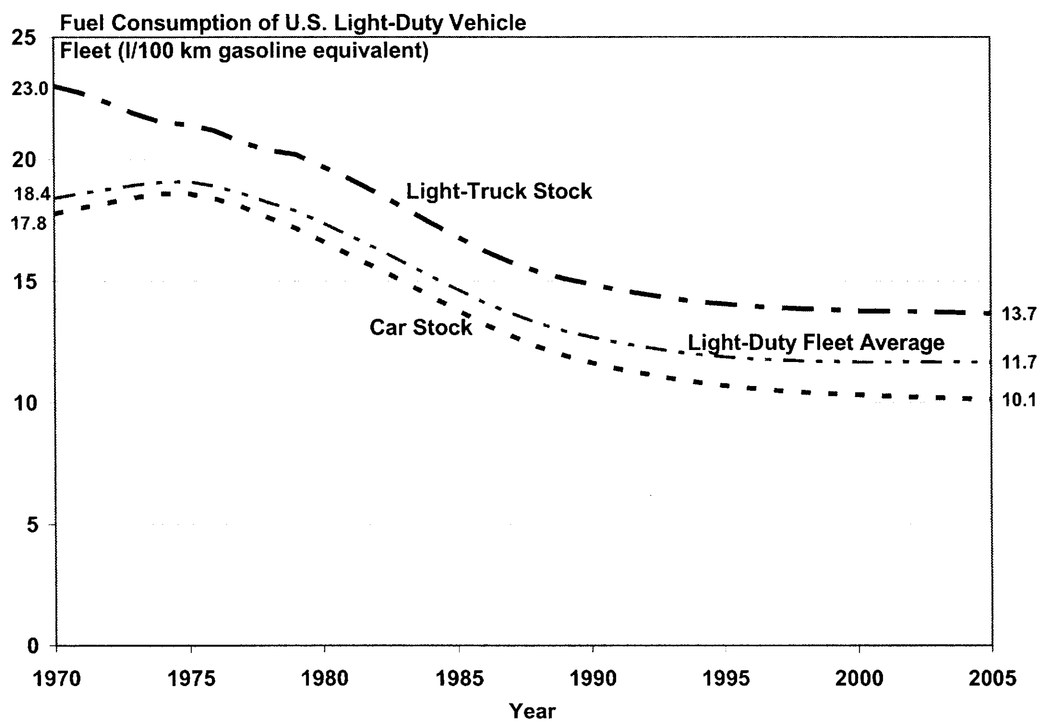


Figure 4 Light-Duty vehicle Fleet Fuel Consumption (1970-2005)

The lack of any significant reduction in vehicle fuel consumption during the last twenty years does not imply stagnation of technology. In fact, engine and vehicle technology has been improving steadily over this entire period. The technology is, however, "fungible" in that it can be used to enable other functions (increased amenities, vehicle power and weight, etc.) rather than to improve fuel consumption performance [Plotkin, 2000]. EPA analysis of vehicle characteristics over the period 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 percent higher fuel economy [Hellman and Heavenrich, 2003]. This trade-off between performance, size and fuel consumption is discussed further in Chapter 4.

Vehicle Kilometer Travel

The amount of vehicle kilometers traveled (VKT) has more than doubled in the past thirty years, as shown in Figure 5 [Davis and Diegel, 2007]. This growth has been steady except for the years 1974, 1979, 1980 and 1991.

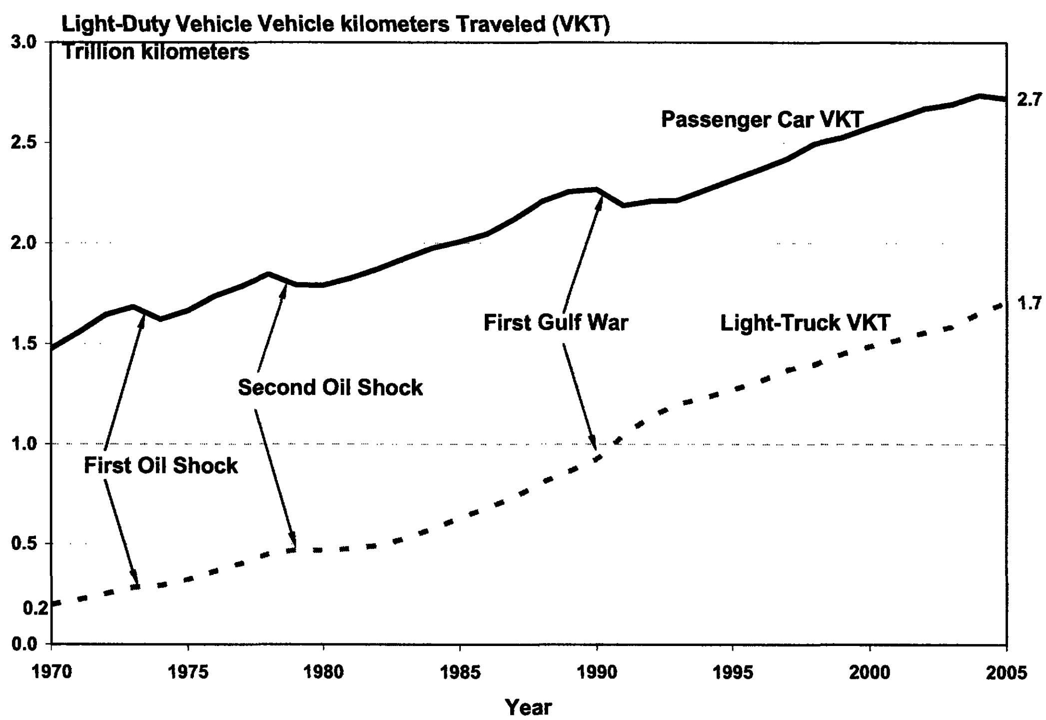


Figure 5 Vehicle Kilometers Traveled (1970-2005) [Davis and Diegel, 2007]

The tremendous growth in VKT can be attributed to the following factors:

Increased number of vehicles: The number of vehicles in the U.S. LDV fleet has 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 percent of the sales in 1970.

Increased driving per vehicle: The average distance traveled per vehicle per year has increased considerably from 1976 to 2005. This increased driving can be attributed to rising level of affluence, continuing urban sprawl, and the low costs of driving, among other factors. When adjusted for inflation, the cost of gasoline per liter has remained essentially constant for the past thirty-five years, except during the oil shocks of 1970s and 2005-2007, as shown in Figure 6.

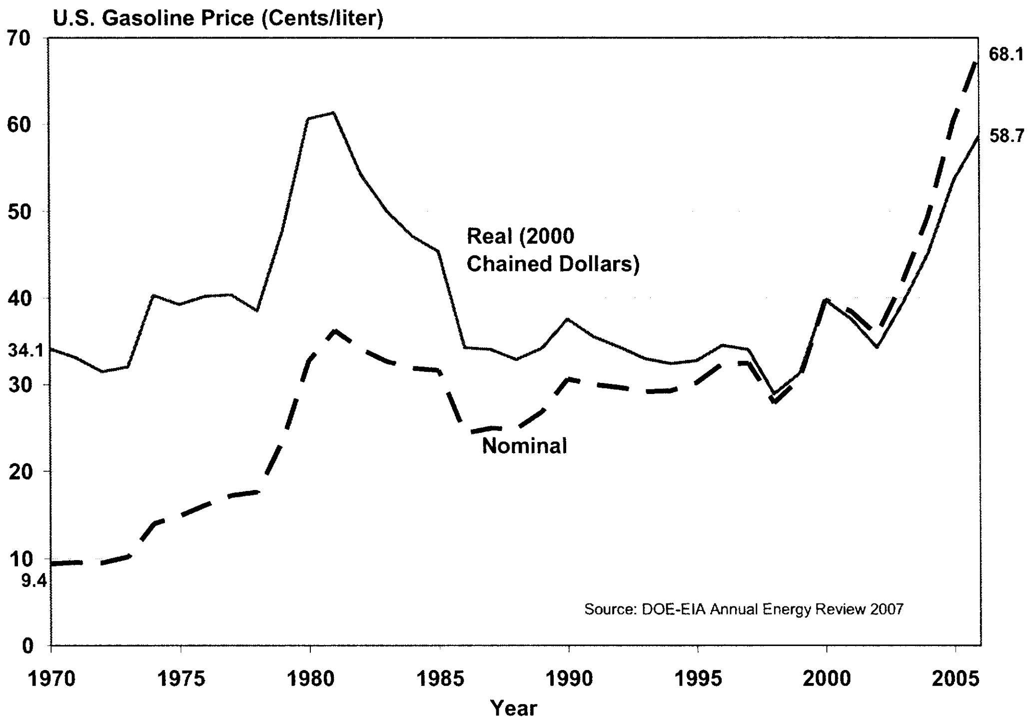
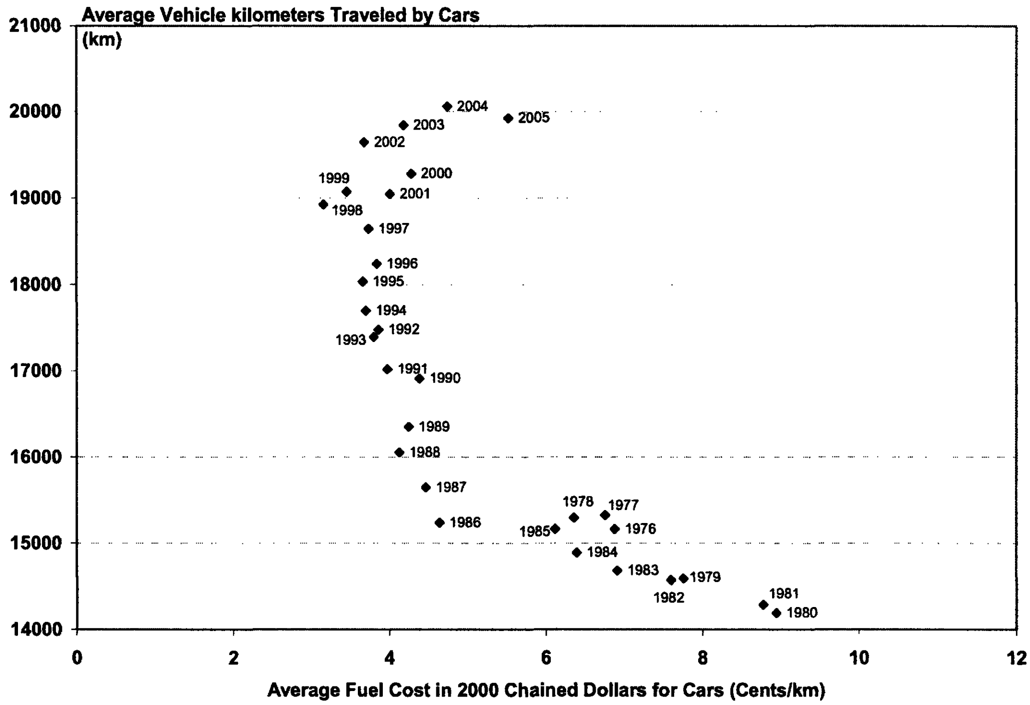
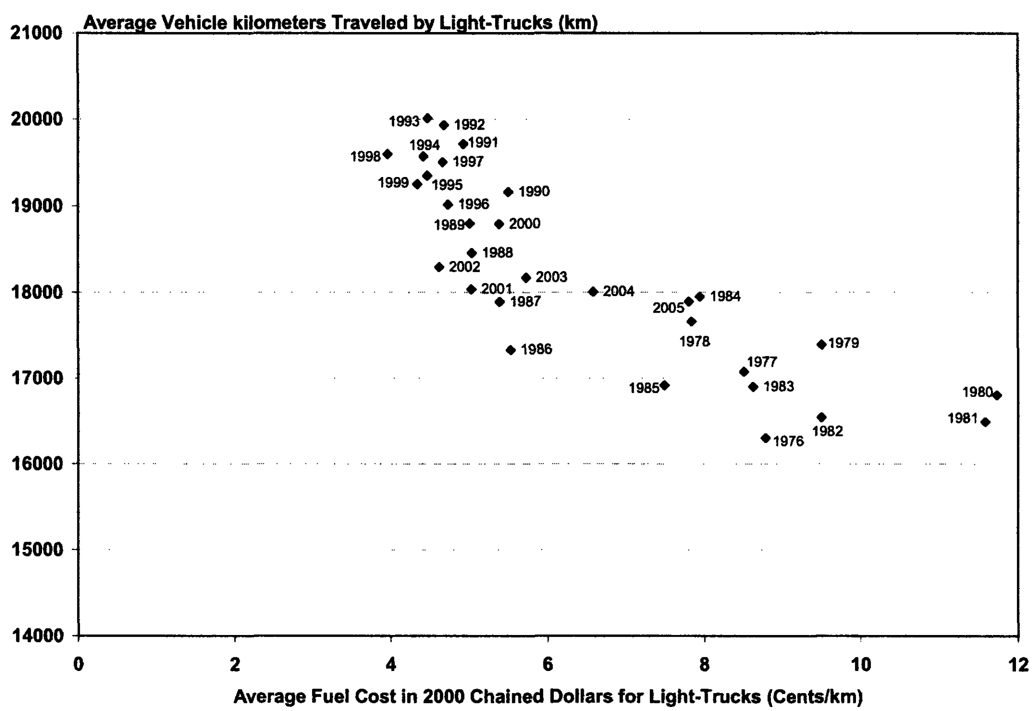


Figure 6 Gasoline Price in Nominal and Real Terms (1970-2006) [EIA, 2007b]

The average fuel consumption of cars and trucks decreased from 1976 to 2001. When combined with flat costs of gasoline per km driven over this period (inflation adjusted), the net effect is a sharp 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 7 shows the increase in average distance traveled while the average costs of driving every kilometer have reduced for both cars and trucks. The rebound effect is estimated to be on the order of 20%, although more recent studies argue that the long-term rebound effect is close to 10% [Greene et al., 1999; Greening et al., 2000; Small and van Dender, 2007]. Figure 7 (a) also shows that while the cost of driving cars in real dollars has not changed very much in the last twenty years, the average driving per car has increased by approximately a third.



(a) Cars



(b) Light-Trucks

Figure 7 Average vehicle kilometer traveled vs. average fuel cost per kilometer [EIA, 2007b]

Greenhouse Gas Intensity of Fuel

Greenhouse gas intensity of fuel used in light-duty vehicle fleet has been essentially constant over time because most LDVs run on gasoline. The increasing amount of ethanol blended in gasoline is altering the greenhouse gas intensity of the fuel. In the future, if the use of diesel and/or electricity powered vehicles as well as different types of biofuels increases the greenhouse gas emissions intensity of the fuel can increase or decrease depending on the fuel production pathway. Chapter 6 and 7 discuss the effect of a changing fuel mix on well-to-wheel energy and greenhouse gas emissions from light-duty vehicles.

Policy Alternatives

Increasing dependence on foreign oil and concerns about greenhouse gas emissions from motor vehicles are the two main reasons for government intervention in the market of fuel consumption. There are several other externalities associated with the use of vehicles, like unpriced highway services, congestion, air pollution, and accidents. Different analyses have estimated that the cost of these externalities is approximately 25-30 cents per liter [Delucchi, 2007; Parry and Small, 2005]. These externalities however, are imperfectly tied to the use of fuels in the light-duty vehicles.

DOE [2000] identifies different barriers to efficiency improvements in the U.S. transportation sector as underpriced fuel and services, imperfect information for consumers to make a rational choice about vehicle fuel economy, fungibility of technology, and risk averseness of the vehicle manufacturers. Different policy options have been proposed to overcome these barriers [OTA, 1994]. The policy measures under consideration can be thought of as a means of providing an economic incentive (E), a regulatory requirement (R), a public investment (I), or some combination of these. They may be further classified as measures that provide incentives for more fuel efficient vehicles, measures that aim to change the cost structure of vehicle operation by increasing or converting some of the fixed or infrequently paid costs to usage costs, or measures aimed at shifting fuel use towards less carbon intensive fuels. Policy options selected for review are summarized in Table 1.

Table 1 Policy Options to Reduce Fuel Consumption of Light Duty Vehicles

Policy Measures	Type of Policy			Anticipated Response/Action
	E	R	I	
CAFE Standards (Existing or attribute based) / Tailpipe Greenhouse Gas Emissions Standards		●		Incorporate fuel efficient technologies, reduce average weight of vehicle fleet, reduce the spread between heavy and light vehicles
Tradable CAFE/Fuel Consumption Credits	●	●		Increase flexibility for manufacturers and reduce cost of compliance with the CAFE standards
Feebates (A system of fees and rebates related to the fuel economy/ fuel consumption of the vehicles)	●	●		Establish fees for less fuel efficient vehicles and rebates for more fuel efficient vehicles to create incentive to produce and purchase more fuel efficient vehicles
Emissions/Carbon Tax (Economy wide)/ Fuel Tax	●			Provide incentive to purchase and use more fuel efficient vehicles by incorporating the externality costs Increase the cost of operating the vehicle and reduce the vehicle miles traveled
Pay-at-the-Pump Schemes	●			Increase the cost of purchase and/or owning high fuel consumption vehicles or transfer it to the cost of motor vehicle use
Subsidies/Tax incentives	●		●	Provide incentive to purchase more fuel efficient vehicles
Government R&D investment			●	Encourage more rapid development of fuel conserving technologies
Retiring old cars	●	●		Provide incentive to purchase newer, more fuel efficient vehicles
An Economic Incentive (E), A Regulatory Requirement (R), A Public Investment (I)				

Several other policy alternatives are available at state or local level, such as increased investment in public transportation and transportation demand management (TDM) tools such as high occupancy vehicle (HOV) lanes, congestion charges, vehicle travel based fees, and telecommuting incentives. These options are not considered here but they can be helpful in reducing energy consumption of light-duty vehicles.

CAFE Standards

The oil crisis in the early 1970's forced Congress to address the issue of fuel economy of new vehicles which had been declining in the early part of the decade. The corporate average fuel economy (CAFE) standards were born out of the Energy Policy and Conservation Act (EPCA) of 1975. The principal objective of the CAFE standards is to increase the fuel economy of U.S. light duty vehicles and consequently reduce the dependence on foreign oil. The legislative history of the act shows no reference to environmental considerations[2] [Chanin, 2003]. The authority to administer the program was delegated by the Secretary of Transportation to the Administrator of National Highway Transportation and Safety Administration (NHTSA). The standard for cars is set separately from that of light-trucks, as shown in Figure 8, and is calculated as the harmonic mean of the fuel consumption of all the vehicles sold in every model year. The penalty of not meeting the standard is set at $5.50 for every 0.1 miles per gallon shortfall per vehicle sold. The CAFE standards have been successful to the extent that the domestic manufacturers have always met the standards without having to pay the fines.

CAFE standards are one of the most – perhaps *the* most – contentious issues in U.S. energy policy. Several attempts have been made in Congress to increase the level of CAFE standards since 1985. None, however, succeeded until late 2007. In fact, in the 90s, Congress barred NHTSA from spending any money at all to study the fuel economy potential for new cars. In 2002, this moratorium was lifted and NHTSA was asked to come up with a modified form of CAFE standard to overcome its limitations. Since then, the standards for light trucks have been revised upwards for years 2005-2011 [NHTSA, 2006a].

In December 2007, the Congress passed Energy Independence and Security Act (EISA) of 2007. EISA will require NHTSA to set attribute based standards for light-trucks and cars separately to achieve an average fuel economy of 35 miles per gallon for the new light-duty vehicles in 2020.

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[2] For a historical perspective of CAFE standards, see John et al. [1979].

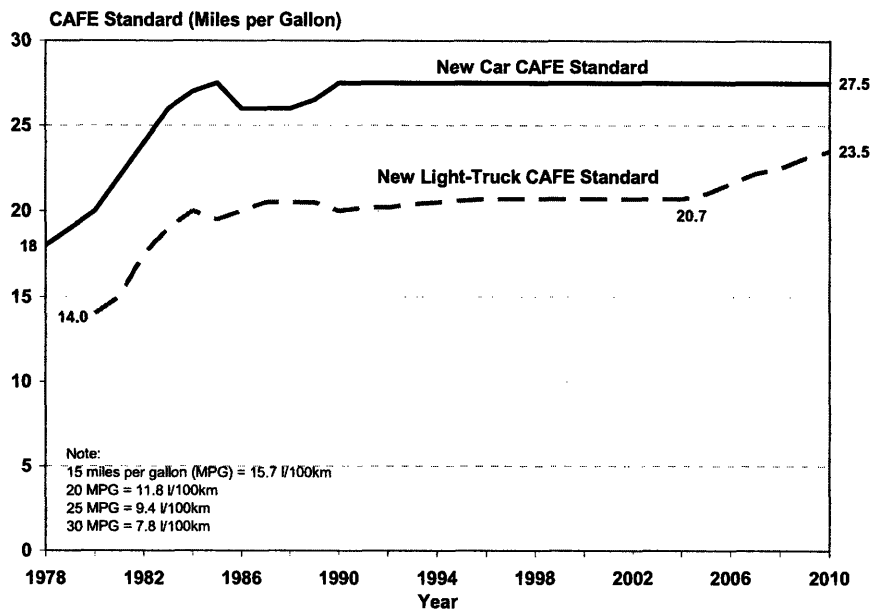


Figure 8 Fuel Economy Standards for Cars and Light Trucks [NHTSA, 2006a]

The difficulty in setting an appropriate level of fuel economy standards arises from the fact that the marginal costs of additional fuel-saving technologies in vehicles must be offset by the marginal benefits to the consumers in terms of fuel savings, assuming that other vehicle performance characteristics stay the same. Note that the vehicle manufacturers must make the decision to incorporate new technology in the vehicles to reduce fuel consumption at an added cost. The consumers are expected to pay up front for these technology improvements and recoup those costs through savings from reduced fuel use over the life of the vehicle.

Greene and Duleep [1993] estimate the present value of fuel savings based on on-road performance as:

$$S_i = \sum_{a=0}^{L} \left\{ \left(\frac{M_a * P_t}{(1+r)^{(a+0.5)}} \right) * \left[\left(\frac{1}{MPG_o} - \frac{1}{MPG_i} \right) * \frac{1}{Adj} \right] \right\} \qquad (2.2)$$

Where:

M_a is the miles driven as a function of vehicle age *a*

P_t is the price of fuel in year *t*

r is the discount rate

MPG_i is the miles per gallon in year *i* (set by CAFE Standards)

MPG_0 is the miles per gallon in year *0*

Adj is the adjustment factor for estimating on road performance

Important objections to CAFE standards include their effect on safety of vehicles, and the hidden costs of technical innovation associated with meeting the standards. At the same time, the standards only apply to new vehicles so that the improvement in fuel economy of the entire fleet lags significantly behind that of the new vehicles. Also, the standards, by the virtue of increasing the fuel economy, decrease the marginal cost of driving. This encourages increased driving as discussed previously. Finally, the cost of introduction of new technologies might make the new vehicles so expensive that certain consumers may hold on to their older cars (more polluting and less fuel efficient) for longer. This is the so called *jalopy effect*.

While current CAFE standards have yielded some useful benefits, they contain several inadequacies as well as some perverse incentives. The current standard provides credits for vehicles capable of running on both gasoline and an alternative fuel (E85 - Ethanol). However, very few of the dual fuel vehicles actually run on ethanol, and rarely realize the intended goal of displacing 85% of the gasoline content of the fuel. The fuel economy of the new vehicle fleet, therefore, appears to be higher than its true value [Rubin and Leiby, 2000]. The National Research Council on fuel economy recommended elimination of dual fuel credits in 2002. The 2007 energy bill has extended the current 1.2 miles per gallon credit for flex-fuel vehicles until 2014. Thereafter, the credit will be phased out gradually by year 2020 [GreenCarCongress, 2007].

Several alternative designs for CAFE standards have been proposed [Hellman et al., 1986; McNutt and Patterson, 1986, OTA, 1991; NRC, 2002; NHTSA, 2003]. For model years 2008-2011, NHTSA revised the structure of light-trucks CAFE standards. The revised light-truck fuel economy standards are established for each increment in vehicle footprint. The vehicle footprint serves as a proxy for vehicle size and is obtained by multiplying a vehicle's wheelbase by its track width. Light-trucks with a smaller footprint are subjected to higher fuel economy target than those with a larger footprint.

Under the current CAFE standards, manufacturers collect fuel economy credits for exceeding CAFE targets. Under a scheme of trading fuel economy credits, manufacturers would be able to buy and sell these credits among each other. Such a scheme could be combined with any other form of the CAFE standards. Manufacturers would purchase the credits, if the cost of meeting CAFE standards were higher than purchasing the credits. This would result in lowered costs for meeting fuel economy targets [Sweeney, 2001]. Two National Research Council studies done on the subject of fuel economy standards have shown a favorable impression towards adopting such an approach. [NRC, 1991; NRC, 2002]. The 2007 energy bill has instituted a provision for trading CAFE credits on a limited basis [GreenCarCongress, 2007]. CAFE standards could also be combined with other measures such as feebates which are discussed below.

Feebates

The concept of a feebate (a combination of "fee" and "rebate") entails charging fees to purchasers of new cars that obtain low fuel economy, and awarding rebates to those who purchase of new cars that obtain high fuel economy. The aim of a feebate program is thus to create a push-pull incentive for the production and purchase of more fuel-efficient vehicles. The judgment as to which vehicles are gas sippers and which are gas guzzlers has to be made relative to a reference level, which could be simply set at the fleet's average fuel consumption level.

The Energy Tax Act of 1978 imposed an excise tax on cars that have very low fuel economy. As structured currently, the tax ranges from $1000 to $7500 on automobiles that get less than 22.5 miles per gallon. Revenues from this tax, known as gas guzzler tax, in year 2005 were in excess of 170 million dollars [Davis and Diegel, 2007]. The gas guzzler tax can be thought of as the basic idea behind a feebate system.

The actual determination of a fee or a rebate can be made based upon a reference feebate rate. For instance, feebate rate could be fuel consumption based ($/gallons per miles) or fuel economy based ($/miles per gallon). From the perspective of fuel savings, the fuel consumption based feebate appears to make more sense. Note that a fee of $55 per MPG is already present as a penalty of not meeting CAFE standards. Feebates could also be designed by taking a class, size or weight based approach, and can be applied separately to cars and light-trucks categories. The attractiveness of a feebate scheme lies in its ability to be a revenue-neutral instrument since the fees from the program could balance the rebates as well as the administrative costs.

The desirable level of feebates is around 5% of the vehicle cost in order to induce a sufficient level of response from the consumers and manufacturers [DeCicco et al., 1992]. The estimated response of the manufacturers is much bigger than that of the consumers [Davis et al., 1995]. As a result, a large rebate may not be necessary. This also means that state-level feebate programs are likely to be less effective than those at the federal level. OECD [1997] compares some of the different feebate options evaluated for U.S. and European markets.

Feebates have been politically more acceptable at the state level; however no feebate program has been implemented in the U.S. so far. The California DRIVE+ proposal was passed in the assembly but was not signed by the governor. The State of Maryland adapted the same proposal as its bill; however it was preempted by the courts on the basis that they violate the federal fuel economy standards. Similar legislative attempts were made in Maine, Massachusetts, and Arizona [Davis et al., 1995]. In 2003, Senator Durbin introduced a Senate bill (S.795) to augment the gas guzzler tax with incentives for purchasing more fuel-efficient vehicles, which would have made it equivalent to a feebate scheme.

Similar to the case of fuel economy standards, manufacturers must be given sufficient lead-time to adjust to the reference level of the feebates. This means that the feebates program has to be dynamic in nature. While feebate rates based upon vehicle size may seem to favor domestic manufacturers, consumers will most easily understand the feebate rates based strictly upon fuel economy numbers. As the goal of feebates aim is to increase penetration of more fuel-efficient technologies into market, some of the fuel savings will most likely be offset due to increased driving.

Fuel/Carbon Tax

A carbon tax aims at internalizing the cost of carbon emissions in the price of fuel. From the perspective of economic efficiency, an economy wide carbon tax would be the most effective method of reducing greenhouse gas emissions. In the case of light-duty vehicles, such a tax may be incorporated as a part of the fuel tax.

Fuel taxes in the U.S. are much lower than in Europe and Japan. In contrast to the U.S. policy of using the revenue from fuel taxes solely for improvement of transportation infrastructure, several European nations use fuel taxes as a source of revenue to meet broader governmental budgetary needs.

The expected effects of fuel taxes are both reduction in vehicle miles of travel (VMT) and increased demand for more fuel-efficient cars. The effect of fuel prices on the driving distances can be calculated as [Hayashi et al. 2001]:

$$D_{t+1} = \left[1 - E_{vmt\_fuelp}\left(1 - \frac{P_{t+1}}{P_t}\right)\right] D_t \tag{2.3}$$

Where:

D_t is the driving distance in year t

P_t is the gasoline price

E_{vmt_fuelp} is the elasticity of vehicle travel with respect to fuel price

The estimates of elasticity of vehicle travel with respect to fuel price vary widely in both the short term from –0.09 to –0.2, and in the long term from -0.2 to –0.5 [Goodwin, 1992; Haughton and Sarkar, 1996; Greene and DeCicco, 2000; Nivola and Crandall, 1995]. Similarly, the estimates of elasticity of fuel economy (MPG) with respect to fuel prices vary from +0.1 to +0.2 in the short term and from +0.2 to +0.5 in the long term [Greene and DeCicco, 2000]. Overall, the elasticity of fuel use with respect to fuel prices is likely to be in the range of -0.1 to -0.4 in the short term, and -0.2 to -1.0 in the long term [Greene, 1998].

Figure 9 shows average lifetime discounted dollar expenditure on fuel at different fuel prices. As average gasoline prices have increased from approximately $1.50 per gallon in 2004 to more than $2.75 per gallon in 2007, there is a significant incentive to improve the fuel economy of high fuel consuming vehicles. However, for vehicles which consume less than 9 l/100km (fuel economy above 26 MPG), substantial increases in fuel economy will be needed to offset the additional lifetime fuel costs. For example, the lifetime discounted fuel costs of a vehicle consuming 9.4 l/100 km (25 MPG) at a fuel cost of $1.50 per gallon are approximately 7300 dollars. The costs increase to 12150 if the fuel price goes up by one dollar. At this higher fuel prices of $2.50 per gallon, the vehicle fuel consumption must be reduced to 5.65 l/100km (41.6 MPG) if the fuel costs are brought back to 7300 dollars. The vehicle manufactures need to decide whether they can reduce the fuel consumption by 40% (or increase the fuel economy by 67%) at a cost of less than (12150-7300=) 4850 dollars. Using higher discount rates than 7%, the prospects for improving fuel economy by increasing fuel prices alone look less bright [Greene, 1998; Kleit, 2002; NRC, 2002].

The two commonly cited advantages of the fuel taxes are that they are less costly than regulations and they affect all the vehicles on the road. The structure to implement fuel taxes is already in place. In a comparison of different policy options to reduce fuel consumption, fuel taxes are generally shown to be economically the most efficient [CBO, 2002].

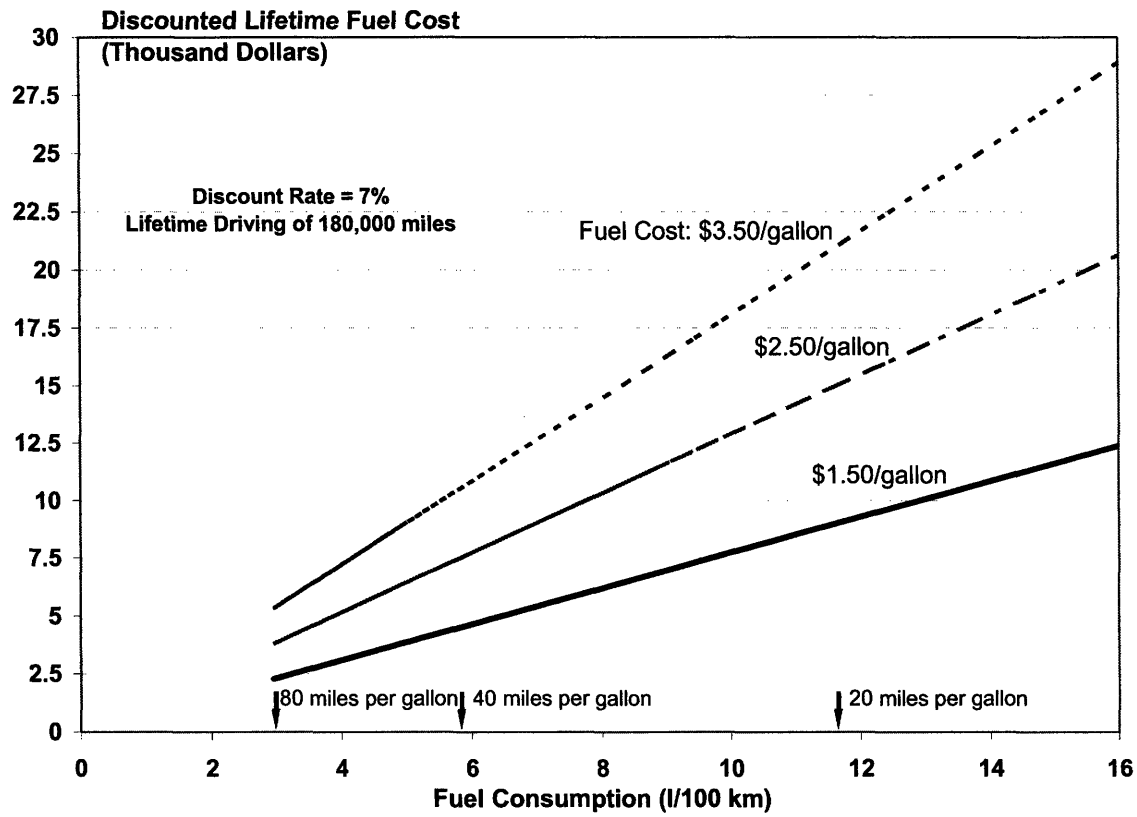


Figure 9 Lifetime discounted fuel cost at different fuel prices and fuel consumption

One common criticism of the fuel taxes is that they are regressive. The impact of fuel taxes on economic efficiency will depend on the distributional effects of the generated revenues. Fuel taxes in the U.S. have been used as a financing mechanism for transportation. Wachs [2003] argues that fuel taxes are in fact the most readily available, effective, efficient and equitable approach to transportation finance. Poterba has claimed that regressive effects of fuel taxes could be partly offset by explicit/earned income tax credits or other social welfare programs such as food stamp programs [Poterba, 1990].

Pay-at-the-Pump (PATP) charges

The Pay-at-the-Pump (PATP) charges, also known as Pay-as-you-Drive (PAYD) charges, aim at transferring a portion of the fixed costs of owning and operating a vehicle to a variable cost. Instead of 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.

Figure 10 shows the costs of owning and operating an automobile in year 2001. The cost of vehicle insurance is roughly equal to the cost of fuel. Since depreciation is not a cash transaction, insurance premiums linked to a PATP program have the greatest potential to impact driving costs followed by registration and license fees.

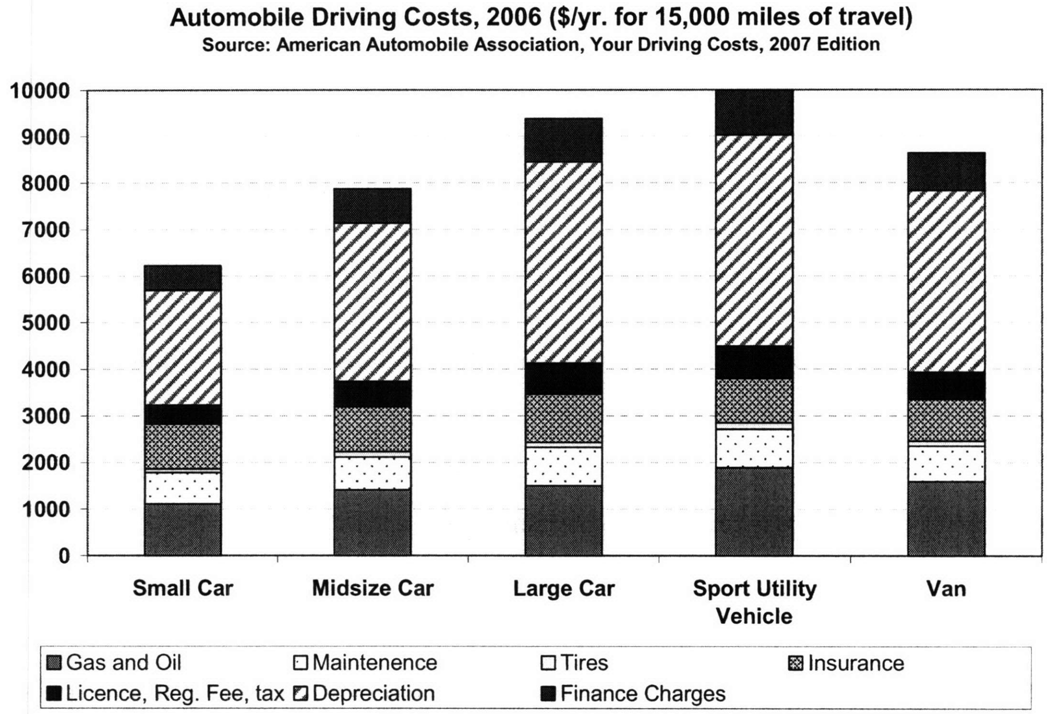


Figure 10 Automobile driving costs, 2006 ($/yr. for 15000 miles of travel)

A major advantage of PATP insurance scheme is that all motorists will have insurance; however uninsured drivers often come from low income households. Many households will pay much more at the pump than they will save by not paying annual registration or insurance fees, and it may be possible to lower average automobile insurance premiums [Wenzel, 1995]. Further, Allen et al. [1994] claim that a no-fault PATP insurance scheme would actually be more equitable and efficient.

A PATP program linked to insurance fees is often controversial because of the issue of insurance reforms. Trial lawyers are opposed to the no-fault PATP programs because they claim that it limits the ability of an individual to sue for non-economic damages [Wenzel, 1995]. Gruenspecht et al. [1994] provide an in-depth analysis of different groups on PATP schemes. Further, insurance and registration fees are state-dependent, so it will be difficult to coordinate a national level PATP scheme. This aspect of the PATP schemes makes it an unattractive policy option at the federal level.

Subsidies/Tax Incentives

Public investment aimed at reducing fuel consumption can come in different ways, such as providing incentives to purchase more fuel efficient vehicles, providing subsidies for alternative fuels and providing financial incentives to manufactures to produce advanced technology vehicles. Broad support exists for such measures. For example, broad-based non-partisan groups such as the Energy Futures Coalition, which had members from industry, labor, environmental NGOs and politicians, endorsed the following measures [Energy Futures Coalition, 2003]:

- Incentives for purchase of fuel-efficient advanced technology vehicles tied to energy and environmental performance metrics.
- Tax credits for investment in existing facilities to produce advanced vehicles or their components, tied to energy and environmental performance metrics.
- Replacing agricultural subsidies with regulatory and financial incentives for the production of bio-based petroleum substitutes.

Some such incentives already exist. For example, a tax credit for purchasing highly fuel efficient internal combustion engine-hybrids is already in place, but will likely be phased out by 2007. Ethanol produced from corn receives $0.51 per gallon in tax subsidy. Similar incentives could be established for ethanol produced from cellulosic biomass, which can offer greater energy and greenhouse gas emissions benefits [Lave et al., 2001]. As the volume of ethanol blended in gasoline increases, the absolute value of these subsidies will grow unless the per-gallon incentive is reduced gradually downwards.

Research, Development and Demonstration Initiatives

The Partnership for a New Generation of Vehicles (PNGV) was launched in 1993 as a collaborative venture between the Department of Energy (DOE) and the U.S. Council for Automotive Research (USCAR). The aims of the PNGV were to:

- Develop a production-ready prototype of a mid-sized sedan that has three times the fuel economy of a comparable 1994 vehicle at a comparable cost by year 2004.
- Improve automotive manufacturing operations

- Develop and implement new technologies aimed at reducing emissions and improving recycling performance

The PNGV established a unique industry-government partnership model with investments of over 1 billion dollars per year. While it made tremendous progress on most fronts, by year 2000 it was clear that it could not meet its cost targets of developing an 80 miles per gallon vehicle prototype without sacrificing performance characteristics.

In 2002, DOE and USCAR replaced the PNGV with a new partnership called FreedomCAR, which aims at high-risk research to enable development of vehicles *that will free the nation's personal transportation system from petroleum dependence and from harmful vehicle emissions, without sacrificing freedom of mobility and freedom of vehicle choice* [DOE, 2004].

Public-private partnerships such as PNGV and FreedomCAR can be helpful in developing technologies with the potential for a significant impact on vehicle fuel consumption in the long term. Their short-term impact, however, is quite limited.

Retiring Old Vehicles

As the vehicle quality has improved and average lifetime of vehicles has increased, the number of older vehicles on the road has increased considerably in the last two decades [Wards 2000]. Additionally, the older vehicles tend to be used more for work travel, and vehicles ten years and older generate as much as 22 percent of the total miles traveled [Pisarski, 1995]. The goals of a retirement program for old cars are to replace older, less fuel efficient and less safe vehicles with more fuel efficient and safe vehicles, and in doing so, stimulate the demand for newer vehicles. Old vehicle retirement programs may also provide an additional of reducing criteria air pollution from motor vehicles [OTA 1992].

The amount of fuel savings resulting from replacing older vehicles can be calculated as follows [ECMT, 1999]:

$$FuelSavings = \sum\left(\left[\frac{VMT_{old}}{MPG_{old}} - \frac{VMT_{replaced}}{MPG_{replaced}}\right] * L_{old}\right) \qquad (2.4)$$

Where:

FuelSavings are the savings in fuel use from retiring old vehicles

VMT_{old} and $VMT_{replaced}$ are the vehicle miles traveled by old vehicle and the vehicles that replace them respectively

MPG_{old} and $MPG_{replaced}$ are the Miles per Gallon of the old vehicles and the vehicles that replace them respectively

L_{old} is the life remaining in the old vehicle at the time of retirement

The incentive to retire old cars can be provided directly in the form of a rebate or tied to the purchase of a more fuel efficient vehicles. The latter offers more flexibility and benefits than the former [ECMT, 1999]. The cost of incentive per vehicle is estimated to be around $500 to $1000 per vehicle. It is also possible to tie the benefits of a retirement program to credits in fuel economy standards [OTA, 1992].

Dixon and Garber [2001] estimate that the effects of an early retirement program will tend to level off over a period, as the number of older vehicles in the fleet decreases. If an early retirement program is made mandatory, then it may drive up the sales of new vehicles by increasing the prices of cars in the secondary market. The effect of this on lower income drivers will be negative, since they are more likely to own and operate older and/or second had vehicles.

Individual or Combined Policy Options?

The economic and societal impacts of government intervention in the market for fuel use assume multiple dimensions. The usefulness of individual policy measures cannot be judged on the basis of potential fuel use and greenhouse gas emission reductions alone. Apart from the fuel consumption of vehicles, other key issues under consideration include:

- Vehicle performance: It is expected that broadly popular vehicle performance measures such as acceleration, functional capacity, accessories and amenities will improve or at least remain constant in the pursuit of a more fuel-efficient fleet.
- Safety implications: Effects of vehicle weight reduction on vehicle safety have been debated at great lengths without clear resolution. It is generally accepted that if weight reductions occurred in the heaviest of light duty vehicles, then overall safety should improve.
- Mobility implications: Implementation of certain strategies may change the purchasing, ownership, and usage patters of light duty vehicles. Consumer's essential mobility needs should be satisfied and the regressive effects of policy measures, if any, must be addressed. At the same time, the effect of different policies on other transportation issues such as criteria emissions and congestion must be considered.

- Implementation issues: The effectiveness of a policy measure will also depend upon whether such a policy can be implemented successfully in practice. Generally, policy measures that give different stakeholders more flexibility for action should prove more politically acceptable.

There are, of course, synergies between different policy options. For example, while more fuel efficient vehicles may cause some increase in vehicle travel, this rebound effect could be offset by an appropriate increase in the fuel taxes. Not only that, but additional price at the pump makes it attractive for the automobile manufactures to reduce fuel consumption, thus lowering the risks and costs associated with meeting the CAFE standards. While the feebates and CAFE standards apply only to new vehicles, fuel taxes and alternative fuel use requirements have fleet-wide impact. While introduction of more fuel efficient technology might cost more initially, the rebates given to the more fuel efficient vehicles can reduce the economic burden on consumers. At the same time, the fees on vehicles with low fuel economy will not only discourage the consumers from buying those vehicles, but also provide incentives to the vehicle manufacturers to produce more fuel efficient vehicles. While the cost of renewable alternative fuels may be higher than gasoline currently, regulations requiring increased renewable fuel content along with government purchasing of the alternative fuel vehicles can provide economies of scale and the learning needed to reduce the cost associated with alternative fuels.

Actors

The interactions and behavior of different players affecting the fuel use of light-duty vehicle fleet makes it a highly complex socio-technical system. As with most such complex systems, the general inertia of the system against any change is very large. The main stakeholders of this system include vehicle purchasers and users, the automobile and petroleum industries, and the government at different levels.

Automobile Manufacturers: The automobile manufacturers are a risk-averse group and oppose regulations that will create new uncertainties in the market. While the U.S. light-duty market is the largest in the world, it has also been subjected to heavy competition in the last twenty-five years. Detroit's Big Three – General Motors, Ford, and Chrysler – accounted for two-thirds of the new vehicle sales in 1995. By 2006, their combined market share had dropped to just over 51 percent. While the Big Three have retreated from car market, they continue to dominate the light-truck segment [Wards, 2007].

Over the course of last two decades, Japanese and European manufacturers have significantly increased their production capacity in the United States. As a result, the distinction between domestic and foreign vehicle manufacturers is blurring. At the same time, the Big Three manufactures suffer from the so called *legacy costs*, which are primarily related to healthcare costs of current employees, retirees and their dependents [Wagoner, 2005]. Coupled with declining market share, legacy costs are causing severe financial hardship for Big Three, and making it difficult to invest large sums in risky technologies.

<u>Auto Workers and Unions</u>: The motor vehicle industry employs more than one million U.S. workers. As of 2004, approximately 46 percent of these jobs were in three states – Michigan, Ohio and Indiana [BLS, 2007]. Since 2004, the Big Three have announced several plant closings and layoffs. While new manufacturing capacity is being added, especially in the southern states, the net employment in the manufacturing sector is on a downward path [Wortham, 2007]. Unions are deeply concerned about the possibility that stringent fuel economy standards might further erode manufacturing employment by forcing some vehicle manufactures – notably Ford and GM – to offshore production of smaller cars and light-trucks [Reuther, 2007; Gettelfinger, 2007].

<u>Fuel Suppliers</u>: Fuel suppliers, especially large international oil companies (IOCs), are often in the crosshairs of public opinion because of their size and influence. Alternative fuels, such as liquid fuels made from biomass, are not a part of the core competency of traditional fuel suppliers. On the other hand, IOCs have the capacity to deal with the massive amounts of investments needed in technology and infrastructure to bring alternative fuels to market at scale. Fuel companies tend to point out that improving vehicle fuel economy through vehicle technology improvements has a greater effect on reducing the petroleum use than changing the fuel mix.

<u>Federal Government</u>: Ensuring low prices appears to have beeen the cornerstone of U.S. energy policy for a long time. Perceived political price for systemic changes are high. The Congress appears to be extremely reluctant to consider pricing mechanisms for conservation purposes, and prefer mandates and standards. The regulatory authority to deal with LDV fuel use and GHG

emissions is spread between various federal entities including the Environmental Protection Agency (EPA), Department of Transportation (DOT) and Department of Energy (DOE). Apart from the Alternative Motor Fuels Act of 1988, and the light-truck corporate average fuel economy (CAFE) standards increase for years 2005-2011, there has been little meaningful policy movement at the federal level in the past twenty years. Alternative fuel use targets established under the Energy Policy Act of 1992 have not been realized [McNutt and Rodgers, 2004].

State and Local Governments: State and local governments have shown a greater willingness to tackle environmental issues, led by California and Northeastern states. Traditionally, local air pollution has been more of a concern for states than global climate change, but the political stalemate at the federal level has encouraged the state governments to regulate GHG emissions. Federal legislation prohibits, however, state level fuel economy targets. Vehicle and fuel manufacturers do not like to see standards and mandates that vary state by state. Local authorities have a greater control over land use patterns and transportation demand management (TDM) measures that have proven to be difficult to change.

Vehicle Purchasers and Users: Ultimately, it is the consumers who purchase and use the vehicles and fuels. They may be unwilling to compromise the performance, features, and size of the vehicle in return for increased fuel economy. While increasing price of fuel may be one of the ways to increase demand for increased fuel economy, consumers prefer that automakers bear the responsibility of providing less fuel consuming vehicles. Vehicle users also dislike policy measures that might restrict or reduce the amount of driving.

While this is not meant to be an exhaustive list of stakeholders or their respective positions, it should be clear that there are complex interactions between different stakeholders. Policies aimed at reducing the fuel consumption of U.S. light-duty vehicles must take these stakeholder positions and their interactions into consideration, or the resulting policy will be doomed to failure.

In early 1994, an advisory committee was established at the request of President Clinton, to discuss policy measures to reduce greenhouse gas emissions from light-duty vehicles. The committee consisted of 30 members chosen to represent all the different stakeholder groups. Officially titled as *The Policy Dialogue Advisory Committee to Assist in the Development of*

Measures to Significantly Reduce Greenhouse Gas Emissions from Personal Motor Vehicles, the committee came to be known as *Car Talk.*

Unfortunately, the discussions in *Car Talk* were marred by differences of opinion over increases in CAFE standards and gasoline taxes [Eads, 1996; Bergman, 1996]. The committee met about eleven times in its one year existence but failed to reach an agreement.

When the talks failed, seventeen of the thirty committee members, including some government staff members and environmental NGOs, submitted a "Majority Report to the President". The so called *Majority Report* did not include any of the views of the *minority,* nor did the minority submit its own recommendations. The agenda set by the majority was indeed quite ambitious and included very strict CAFE standards coupled with a variety of transportation demand management measures [Dunn, 1998]. Due to lack of consensus, *Car Talk* sank without having any impact on the policy process.

Clearly, there is no single agreed upon policy measure that would reduce the fuel use of LDVs, and differences over policy measures are likely to persist [McNutt et al., 1998]. A carefully selected combination of policy measures that shares the responsibility among all stakeholders will have more chances of success. A policy package that spreads the costs and benefits among different stakeholders is likely to have a broader political appeal and could be perceived as a more fair approach to fuel use regulation. Such a multidimensional policy approach needs to generate positive commitment from all the stakeholders, without exposing any one set of stakeholder groups to a large risk [Bandivadekar and Heywood, 2006].

Policy options pursued in other countries and at state level

European Policy Measures[3]

There exists no fuel economy regulation in Europe. In July 1998, the association of European car and truck manufacturers (ACEA) made a voluntary commitment to reduce new car CO_2 emissions to achieve a new car fleet average CO_2 target of 140 g/km (~ 40 miles per gallon of gasoline equivalent) by 2008 – a 25% reduction from 1995 or a 33% improvement in fuel economy [ACEA, 2002]. The agreement promised fleet-wide reductions in emissions, although

[3] For a review of policy measures discussed by several different OECD countries, see OECD [2003] and ECMT [2007].

no penalty for missing the targets existed. It was feared that lack of an enforcement mechanism will result in ACEA not meeting its target [WRI/SAM, 2005].

One of the main reasons which brought about the voluntary agreement was the fear of stricter EU regulations. The ACEA agreement has reduced the new car CO_2 emissions to 160 g/km by 2006. As it has become clear that automobile companies will struggle to meet the 140 g/km target by 2008, the European Commission has proposed mandatory targets. The current proposals aim to reduce average new vehicle tailpipe greenhouse gas emission to 130 g/km (~ 42.5 miles per gallon of gasoline equivalent) by 2012, and a stretch goal of 95 g/km of GHG emissions (~ 58 miles per gallon of gasoline equivalent) by 2020. In addition to meeting the 130 g/km of tailpipe CO_2 emissions, the EC directive also requires an additional 10 g/km of emissions reductions through [EC, 2007a].

The current European policy directives have also proposed reducing the greenhouse gas intensity of the transportation fuels by 1% per year starting 2011, such that the GHG intensity of fuel mix in 2020 will be 10% lower than in 2010. At the same time, a separate EU policy objective is to achieve 10 percent biofuels content in transport fuels on an energy basis [EC, 2007b].

Japan and China: Weight based fuel economy

Japan has established weight class based fuel economy targets for year 2015. The standards will require about 24% improvement over the 2004 weight class averages, and will imply a new car fuel economy of approximately 40 miles per gallon by year 2015, assuming no major changes in vehicle sales mix [ICCT, 2007].

Recently, China has also sought to establish weight class based fuel economy standards for cars [Runyan, 2004]. Sixteen weight classes based on European emissions weight categories have been established starting 2006, with the second round of standards phased in starting in October 2008 [ICCT, 2007].

Efforts in the state of California

California Assembly Bill 2076 asked the California Energy Commission (CEC) and the California Air Resources Board to develop and submit to the legislature a strategy to reduce petroleum dependence in California [CEC/CARB, 2003]. The CEC/CARB report recommended that California should adopt a statewide goal of reducing demand for on-road gasoline and diesel to 15 percent below the 2003 demand level by 2020 and maintaining that level for the foreseeable future. The report of the agencies indicates that improving the fuel economy of new vehicles might be the most effective way of reducing California's dependence on foreign oil. California will have to lobby the federal administration for upward revision of CAFE standards.

California AB 1493, the first of its kind in the U.S. directs the CARB to achieve the maximum feasible and cost-effective reduction of greenhouse gases from California's motor vehicles. The bill specifically prohibited new fees or taxes on vehicles, fuel(s) or miles traveled, a ban on the sale of any vehicle category, a required reduction in vehicle weight, a limitation or reduction in the speed limit, or a limitation or reduction in vehicle miles traveled. Since many of the demand side measures are prohibited, all the reductions in greenhouse gas (GHG) emissions will have to come through technological improvements in vehicles.

The final standards adopted by CARB target a 35% reduction in passenger car GHG emissions and 25% reduction in light-trucks GHG emissions. CARB's attempt to regulate tailpipe CO_2 emissions has been challenged in courts as a violation of the Energy Policy and Conservation Act (EPCA) of 1992, which prevents any state from setting its own targets for the fuel economy of vehicles sold in the state. California's effort to receive a waiver from EPA to move forward with the AB 1493 rule received a boost when, in an April 20007 decision, the Supreme Court opined that CO_2 emissions can indeed be classified as *air pollutant* under the the Clean Air Act of 1990[4]. Even if the legal challenges to the CARB standards are resolved, meeting those regulations is difficult because the strict air quality standards in California are likely to inhibit the growth of diesel vehicles in California. In this particular case, a clear tradeoff exists between the short term health impacts of NOx versus the long term climate change impacts of the CO_2 emissions.

A complete absence of measures that can stimulate demand for more fuel efficient vehicles means that California's ambitions to reduce tailpipe GHG emissions may have to be tempered. It is very likely, however, that the California standards will hasten the increase in federal fuel economy standards.

California has also taken a lead over EPA in establishing a framework for Low Carbon Fuels Standard (LCFS). This proposal is similar to the EU effort to reduce greenhouse gas emissions intensity of motor fuels [Farrell and Sperling, 2007a and b].

Summary and Outlook

This chapter has painted a broad brush picture of light-duty vehicle technology and policy landscape. U.S. petroleum consumption and GHG emissions is a complicated technology problem, compounded by the complex interactions between its diverse stakeholders. With this in mind, the following five chapters will focus on different aspects of light-duty vehicle fleet fuel use and greenhouse gas emissions.

[4] The EPA refused to give California this waiver in a controversial decision in December 2007.

Chapter 3

Light-Duty Vehicle 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 pick-ups, 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 percent 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 chapter explains the logic of the U.S. LDV Fleet Model used for this purpose.

Structure of the Fleet Model

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 11. 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 propulsion systems and their fuel consumption, vehicle aging and scrappage, vehicle stock, vehicle travel, and fuel mix. Historical data from 1960 onwards is used to calibrate the model. The following sections describe the details of the model's individual building blocks.

Data Sources

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

- Transportation Energy Data Book (TEDB) compiles data from a variety of trade publications such as Motor Vehicle Facts and Figures published by 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].
- 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].

- 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, 2006a].

Wherever possible, the fleet model uses data compiled from these three sources. Other sources of data are listed 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.

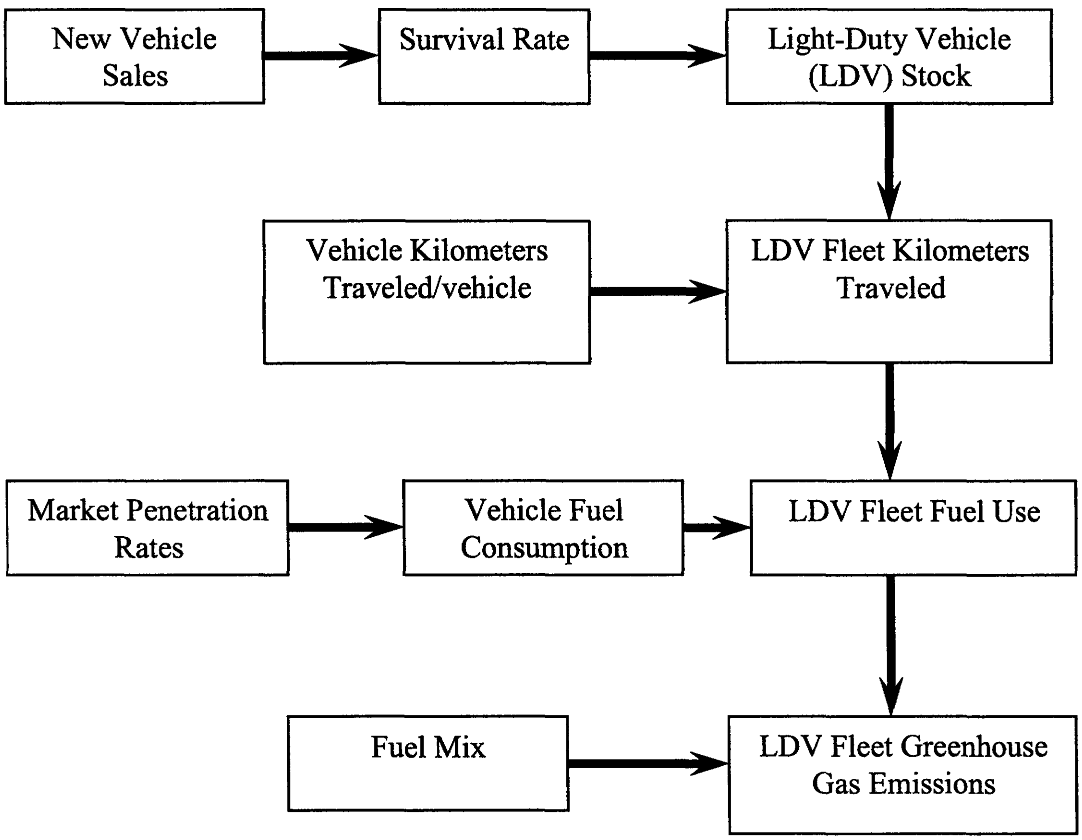


Figure 11 Fleet Model Overview

Sales Mix

The annual sales of light-duty vehicles in the U.S. from 1970-2005 are shown in Figure 12. 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 4550 kg (10,000 pounds) of gross vehicle weight (GVW) or less. The

EPA and NHTSA data only include vehicles weighing less than 3865 kg (8,500 pounds). The light-trucks weighing between 8,500 and 10,000 pounds, known as Class 2b trucks are estimated to account for 6-8 percent 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 year 2011, NHTSA plans to include all SUVs and vans weighing less than 10,000 lbs in the CAFE program, 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.

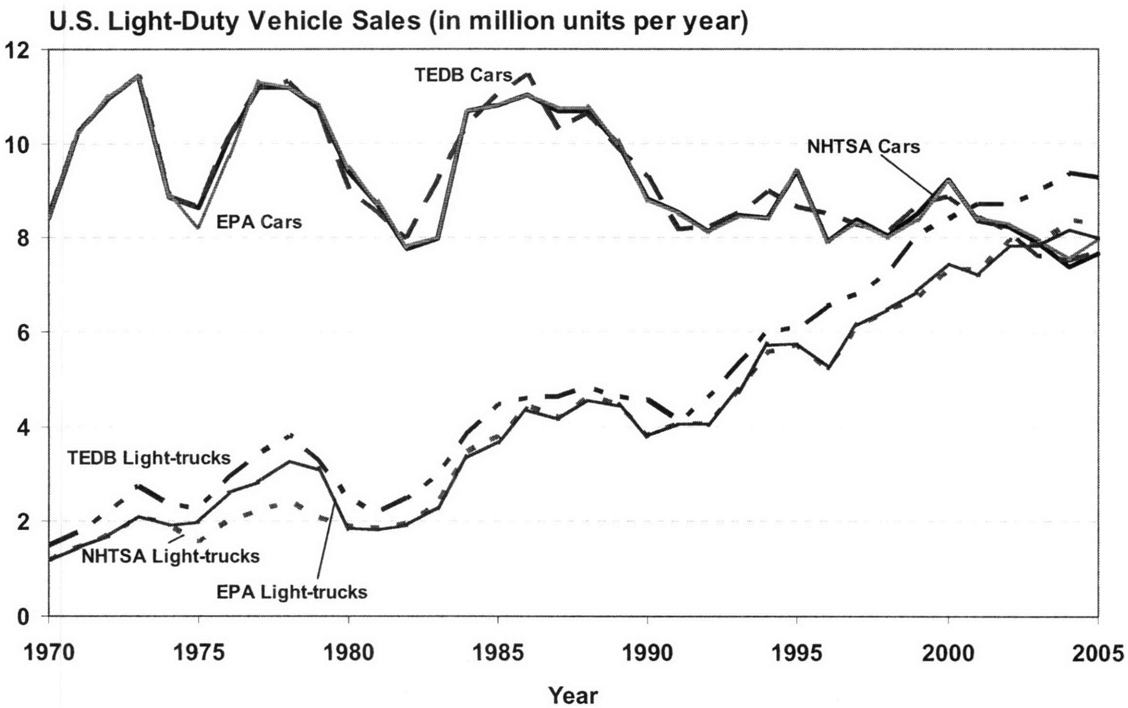


Figure 12 U.S. Light-Duty Vehicle Sales [1970-2005]

The share of light trucks in new LDV sales has increased from 15 percent in 1970 to over 50 percent 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 data the percentage of light-trucks in the new vehicle sales is currently about 55 percent, whereas EPA and NHTSA data puts the light-trucks market share at 50 percent 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.

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 less than 20 vehicles per thousand people in China. Presently, the number of light-duty vehicles on the road in the US 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 US population. According to the US bureau of the census, average rate of growth of population is likely to decrease from 0.9 percent in the first decade of this century to 0.75 percent by 2040 [U.S. Census, 2004]. Thus, the fleet model assumes an average annual growth rate of new vehicle sales of 0.8 percent per year.

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 literature sources also cite an increase in the median lifetime of vehicles, and 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 2].

Table 2 Estimated Median Lifetime of U.S. Light-Duty Vehicles

	1970 Model Year		1980 Model Year		1990 Model Year	
	TEDB (19)	TEDB (24)	TEDB (19)	TEDB (24)	TEDB (19)	TEDB (24)
Cars	10.7	11.5	12.1	12.5	13.7	16.9
Light-Trucks	16	16.2	15.7	15.3	15.2	15.5

TEDB: Transportation Energy Data Book

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, the period between 1980 and 1990 did not see much difference in scrappage rates.

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, and thus dependent on vehicle age. 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 [2006c] 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 3.1.

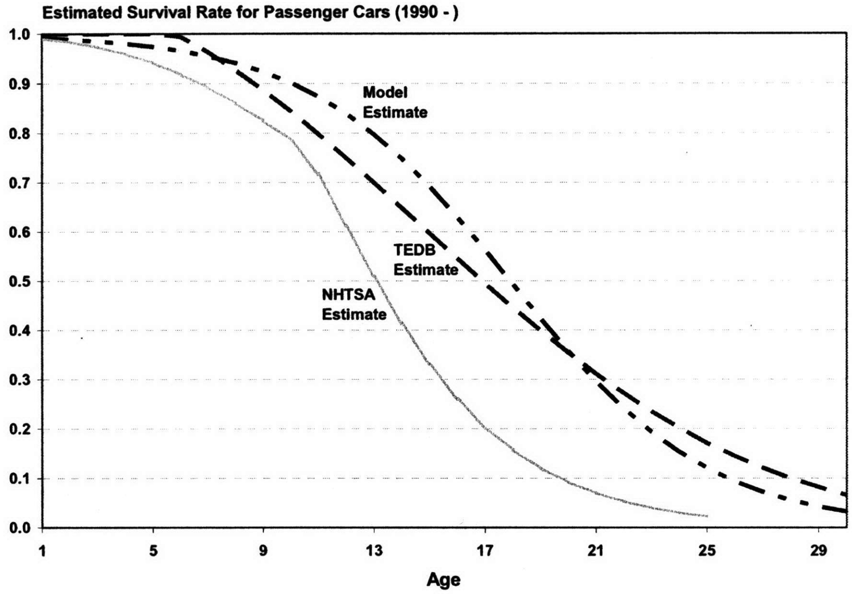
$$1 - \text{Survival Rate (t)} = \frac{1}{\alpha + e^{-\beta(t-t_0)}} \tag{3.1}$$

where,

- t_0 is the median lifetime of the corresponding model year
- t, the age on 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 to1 is overly restrictive.

Figure 13 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.



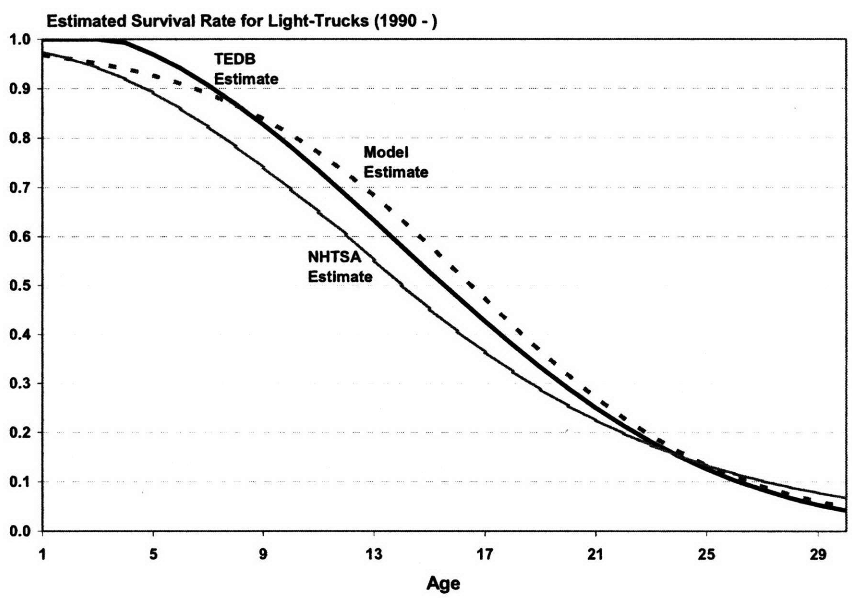


Figure 13 Estimated Survival Rates of U.S. Light-Duty Vehicles [Model Year 1990 onwards]

Average per-Vehicle Kilometers Traveled (VKT)

Increase in total vehicle kilometers traveled takes place through an increase in the number of vehicles on the road, and an increase in kilometers traveled per vehicle. Table 3 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 annual vehicle kilometers traveled (VKT) as reported by TEDB.

Table 3 U.S. Light-Duty Vehicle VKT Growth Rates (1971-2005) [Davis and Diegel, 2007]

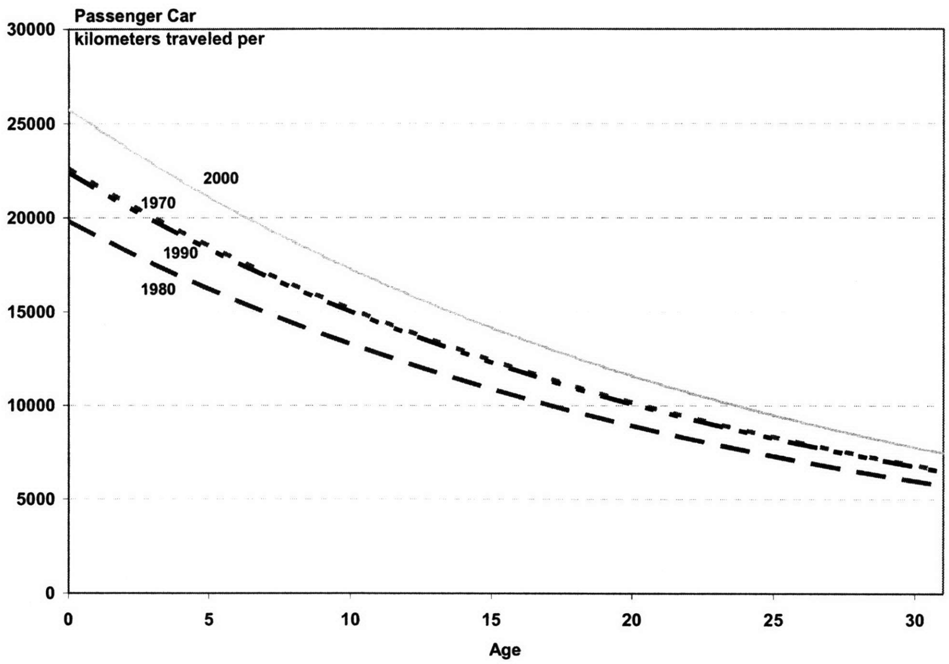
	Cars			Light-trucks		
Years	Annual Vehicle Stock Growth (%)	Annual Total VKT Growth (%)	Annual VKT/Vehicle Growth (%)	Annual Vehicle Stock Growth (%)	Annual Total VKT Growth (%)	Annual VKT/Vehicle Growth (%)
1971-1980	3.1	1.6	-1.4	7.0	8.7	1.6
1981-1990	0.9	2.4	1.5	5.9	7.6	1.7
1991-2000	0.5	1.8	1.4	4.5	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

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

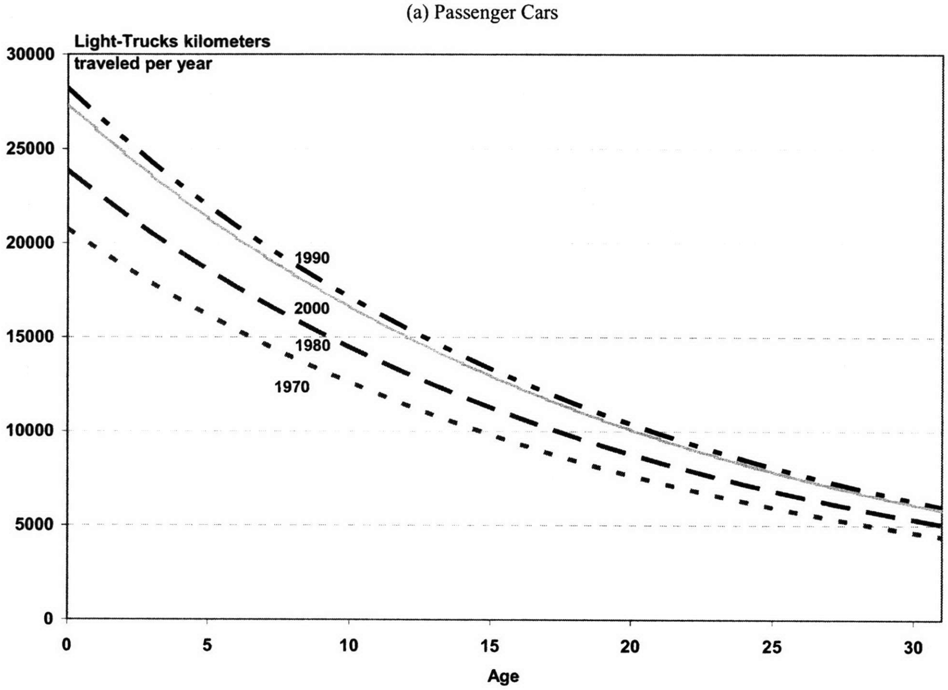
It is assumed that in 2000, new cars are driven 25,760 km (16,000 miles) per year, whereas new light-trucks are driven 27,370 km (17,000 miles) per year in their first year of operation. After the first year, the average per-vehicle kilometer travel decreases at an annual rate of 4 percent for cars and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

$$VKT_i = VKT_{new} * \exp(-\text{usage degradation rate} * i) \quad (3.2)$$

Based on Table 3 and Equation 3.2, the average per-vehicle kilometers traveled by LDVs of different ages can be calculated. Figure 14 shows the distance traveled by the new cars and light-trucks sold in years 1970, 1980, 1990, and 2000.



(a) Passenger Cars



(b) Light-Trucks

Figure 14 Per-Vehicle kilometer Traveled by Model Year [1970-2000]

The total VKT is obtained using Equation 3.3:

$$\text{VKT (year j)} = \sum_{age\ i} (\text{\# of vehicles of age i in year j}) * (\text{Average annual VKT for vehicles of age i in year j}) \qquad (3.3)$$

Vehicle Fuel Consumption

Figure 15 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 does 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].

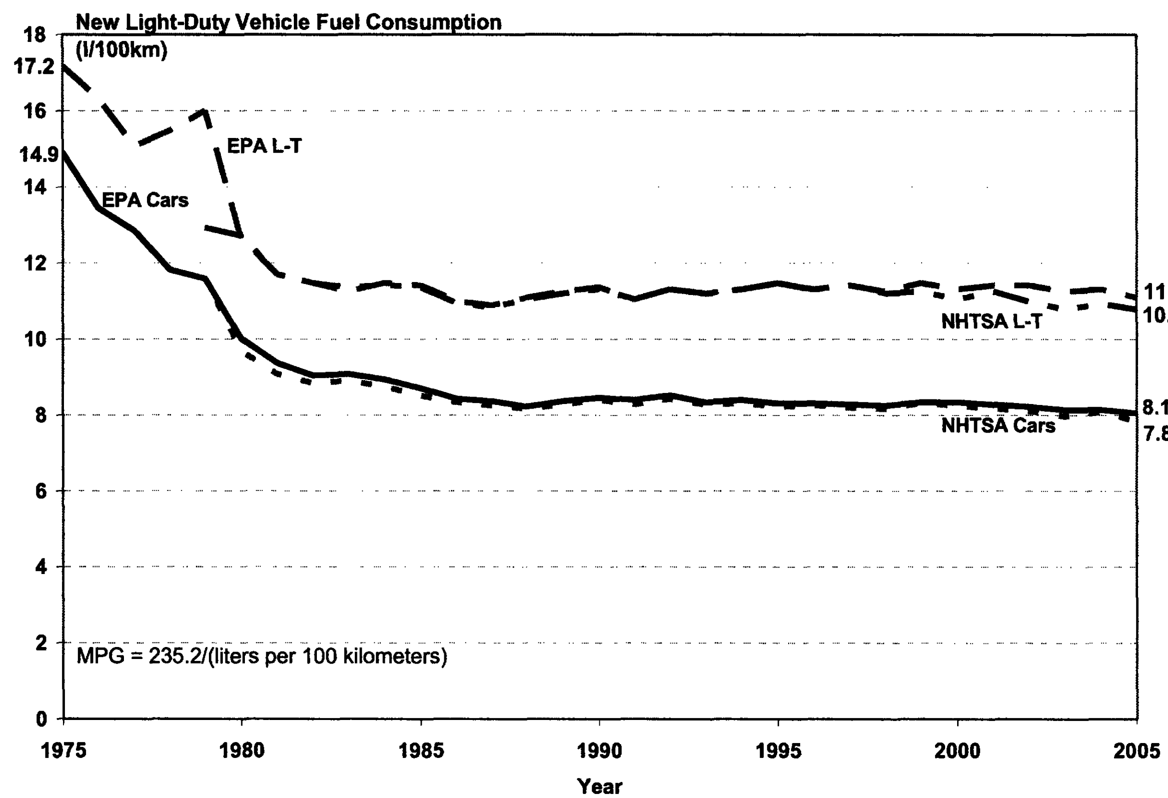


Figure 15 New Light-Duty Vehicle Fuel Consumption (1975-2005)

The fuel consumption values in Figure 15 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 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 percent lower than test results. In other words, on-road fuel consumption of light-duty vehicles needs to be adjusted upwards 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 percent for cars and 20.7 percent for light-trucks, or increase in fuel consumption by 23 percent for cars and 26 percent for light-trucks from the test values.

EIA's Annual Energy Outlook incorporates changing city/highway driving ratio, increasing congestion levels, and rising highway speeds to modify the degradation factors as shown in Table 4.

Table 4 Car and Light-Truck Degradation Factors [EIA, 2007b]

	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

Starting 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 percent 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 percent.

The IEA Sustainable Mobility project uses an average shortfall of 19 percent in fuel economy or a 22 percent increase in fuel consumption, and the same value is used in this model [IEA/SMP, 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 fuel economy of light-trucks weighing more than 8,500 lbs is about 14 percent lower than trucks weighing less than 8,500 lbs on average [Heavenrich, 2006]. Since all class 2b trucks are included in this model, but assigned the same fuel economy as that of class 2a trucks, the net result is to underestimate the fuel use by of the order of 2 percent.

Fleet Fuel Use and Greenhouse Gas Emissions

The fuel use of the entire fleet is calculated by summing up the fuel use of vehicles of the same age, which in turn is calculated by multiplying the number of vehicles in service of that age, by the number of vehicle kilometers traveled, by their respective fuel consumption. Fuel use is calculated separately for each propulsion system type in gasoline equivalent units. Greenhouse gas emissions on a well-to-wheel basis are calculated by multiplying the fuel use by a corresponding well-to-tank and tank-to-wheel greenhouse gas emissions coefficient as discussed in Chapter 6. Energy use and greenhouse gas emissions from the vehicle manufacturing and disposal stage are also incorporated in the model as discussed in chapter 7.

Model Results and Comparison with DOE/EIA projections

Figure 16 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 has increased from about 108 million vehicles in 1970 to about 240 million vehicles in 2005 [TEDB Table 3.3]. Most of the growth in stock has come from the light-truck segment. The model consistently overshoots the data, especially for the light-trucks since the model includes all light-duty vehicles under gross vehicle weight of 10,000 lbs., whereas the TEDB data shown in Figure 16 only represents light-trucks under 8,500 lbs.

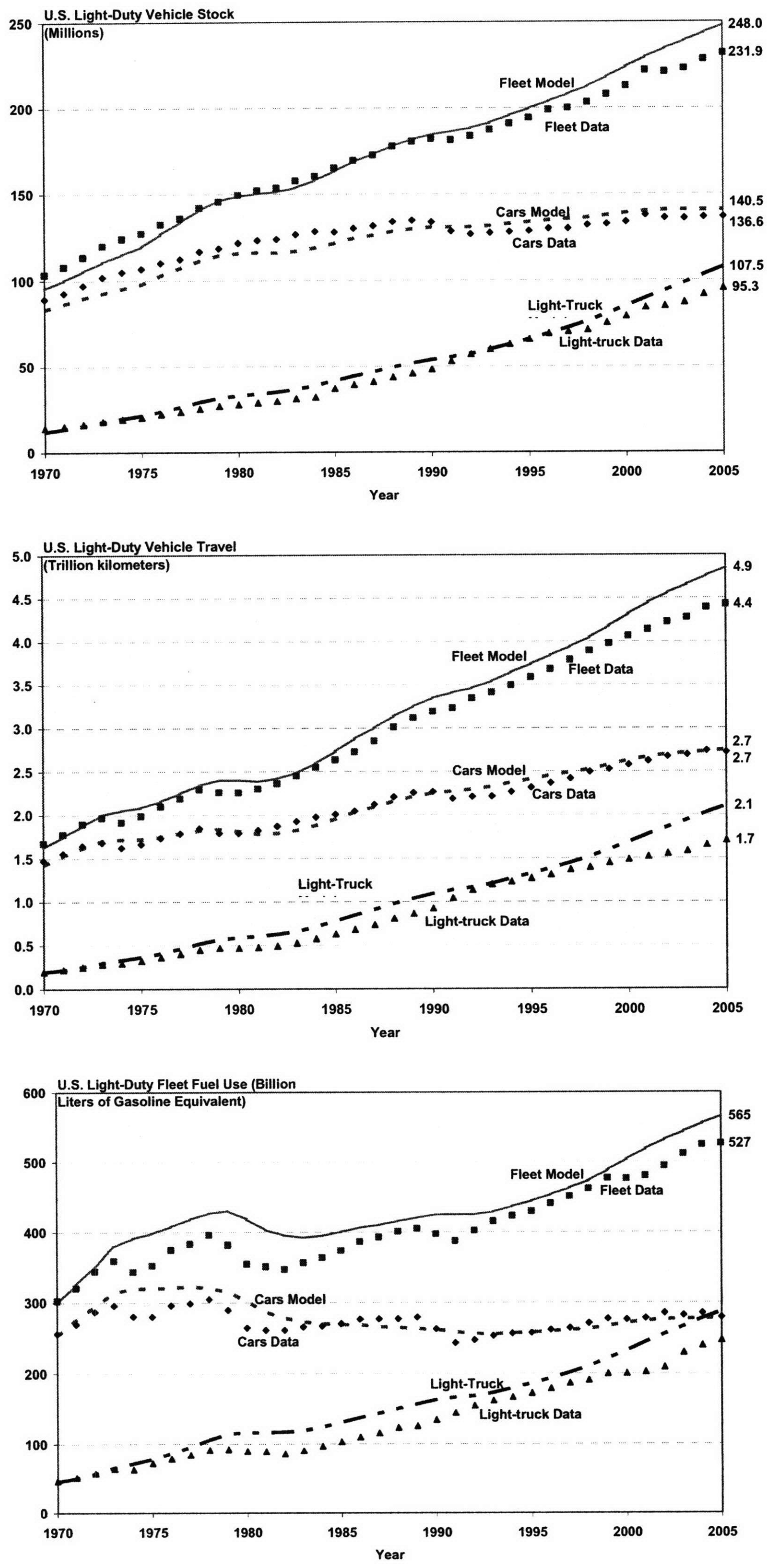


Figure 16 Fleet Model Results compared with Historical Data [1970-2005]

Table 5 Percent Difference between FHWA data and Model Calculation

Decade	Stock Error	VKT Error	Fuel Use Error
1975-1985	1.9 percent	-3.4 percent	-11.2 percent
1985-1995	-1.1 percent	-4.4 percent	-5.1 percent
1995-2005	-4.9 percent	-6.3 percent	-4.9 percent

Table 5 shows the average error in vehicle stock, VKT, and fleet fuel use for each decade since 1975. If vehicle sales data from EPA and NHTSA are used to calculate the light-duty vehicle fuel use, the average error between data and model calculated fuel use is about 0.7 percent and 1 percent respectively. Figure 17 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 17.

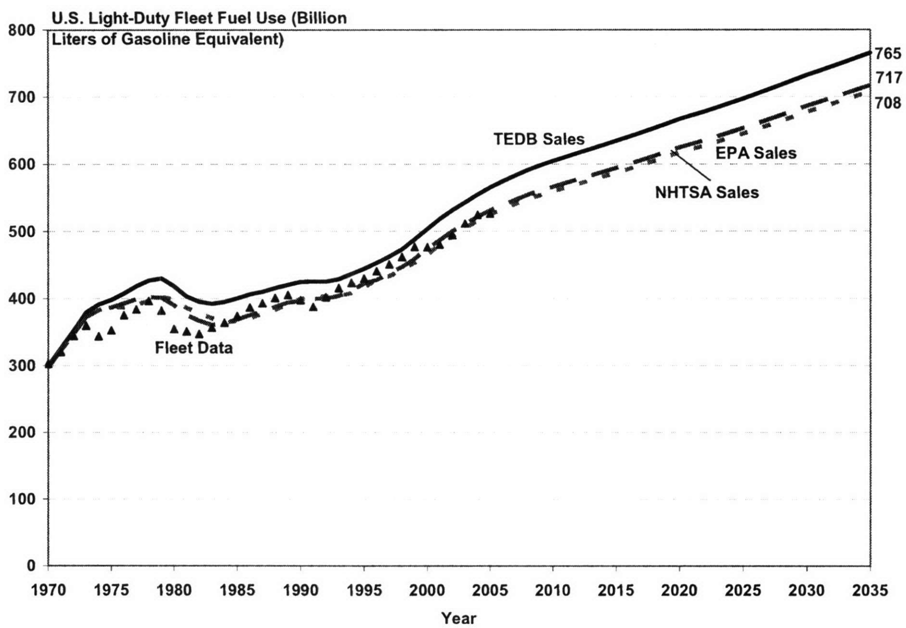


Figure 17 Light-Duty Vehicle Fleet Fuel Use Projections using TEDB. NHTSA and EPA Sales Data

The projections of the fleet model are also compared with the Energy Information Administration's Annual Energy Outlook 2007 [EIA/AEO, 2007a], and the Argonne national Laboratory's VISION model [Singh at el., 2003] in Figure 18. 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].

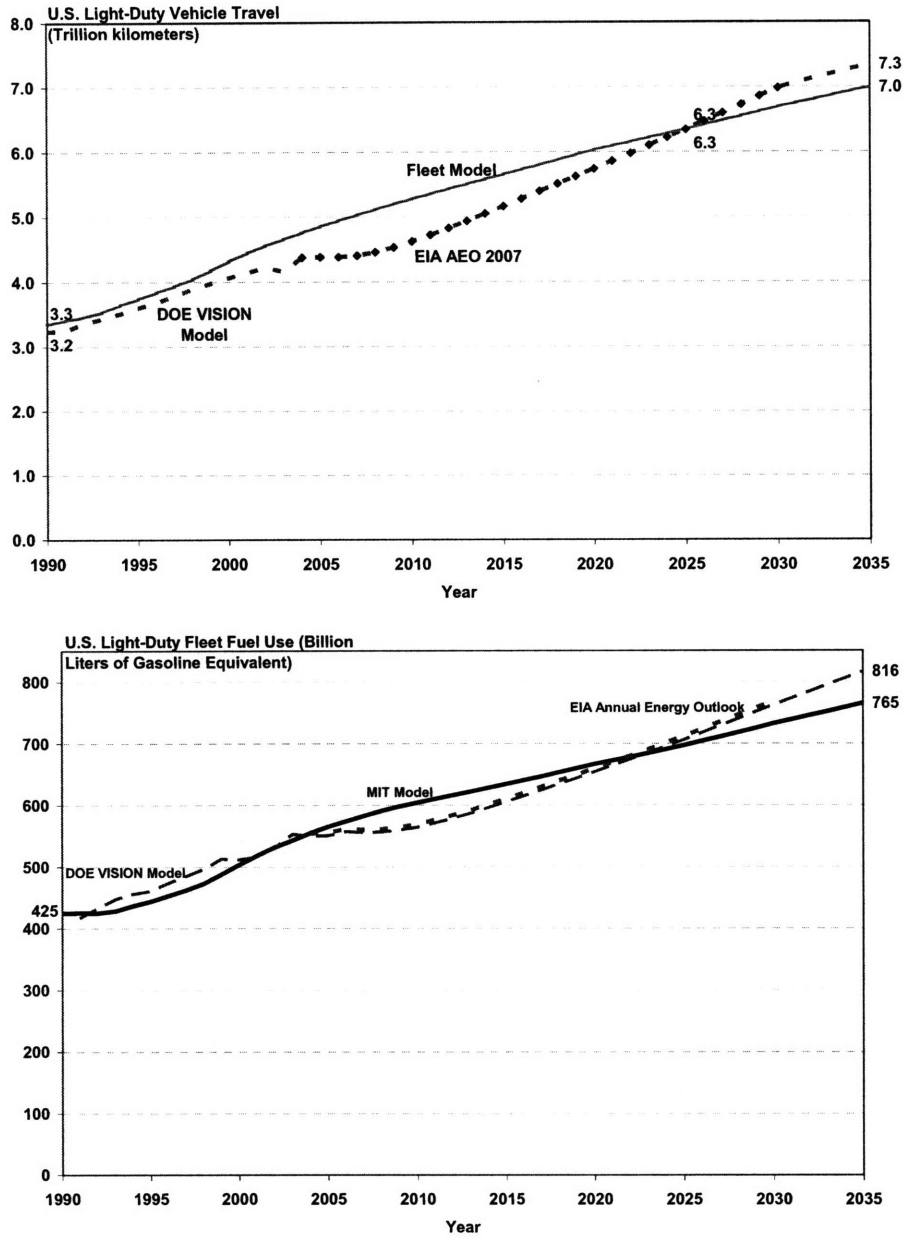


Figure 18 Comparison of Fleet Model Projections with EIA Annual Energy Outlook and DOE VISION Model

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 (~19300 km/vehicle per year), the long term VKT growth rate in VISION model is 1.7 percent as opposed to 1.2 percent 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 model to various parameters is shown in the next section.

Sensitivity to Selected Input Parameters

The growth in sales of light-trucks has been one of the drivers of LDV fuel use growth since 1980s. Figure 19 evaluates the impact of further increase or decrease in light-truck sales fraction from today's value of 55 percent. Whether the light-truck sales fraction increases linearly from 55 percent to 70 percent or decreases linearly from 55 percent to 30 percent by 2035, the total fleet fuel use is affected by less than 2 percent over the time period under consideration. The impact of such changes in fleet composition appears to be limited until 2035, but will be much 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 affect vehicle fuel consumption or travel pattern are likely to have limited impact on aggregate fuel use of the fleet.

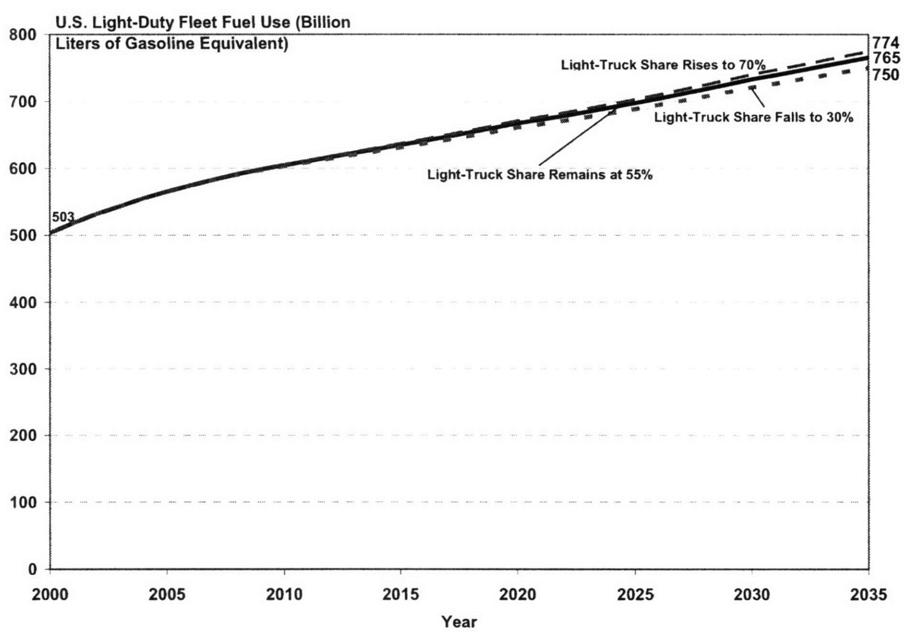


Figure 19 Effect of New Light-Truck Sales Fraction on Fleet Fuel Use

Figure 20 illustrates the drivers of growth in LDV fleet fuel use, viz. 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 percent per year, the LDV fleet fuel use in 2035 will be some 8.6 percent 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 percent savings in fleet fuel use in 2035. Such a reduction can only be achieved by a mix of mode shifting, trip consolidation, as well as 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) the 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.

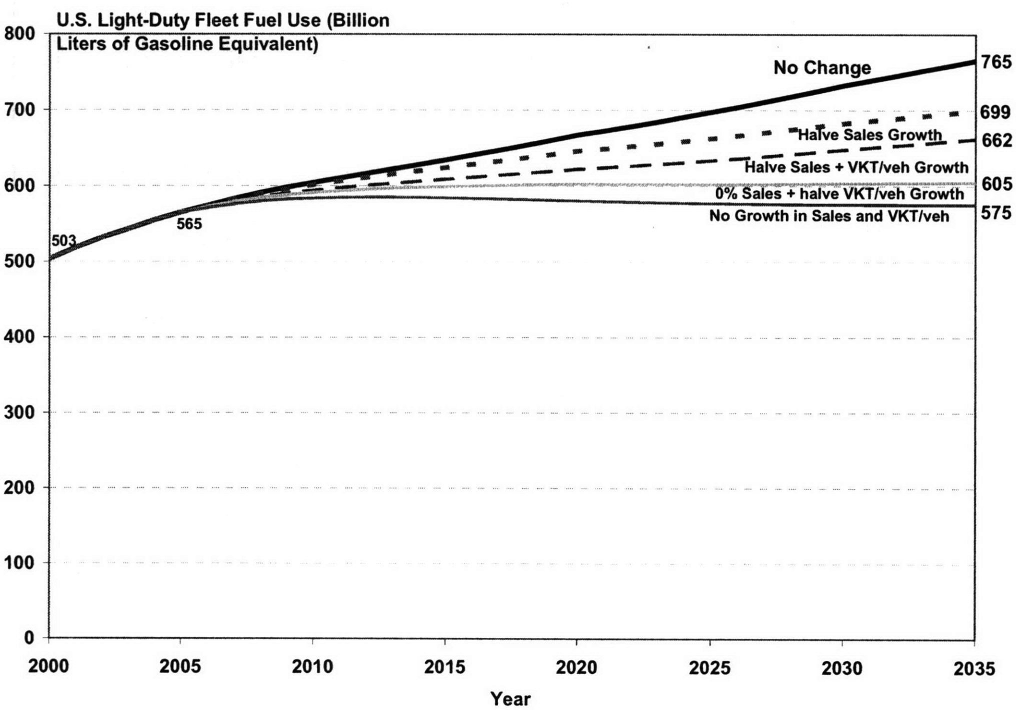


Figure 20 Light-Duty Vehicle Fleet Fuel Use Projections for different Sales and VKT/Vehicle Growth Rates [2000-2035]

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 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 in life. The effect of reducing vehicle lifetime is shown in Figure 21. 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 percent reduction in median vehicle lifetime of vehicles made after model year 2000 – results in approximately 6.7 percent reduction in 2035 fleet fuel use. Similarly, a 20 percent reduction in vehicle median lifetime (13.5 years for cars, 12.4 years for light-trucks) reduces 2035 fleet fuel use by approximately 14 percent. 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, 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 21.

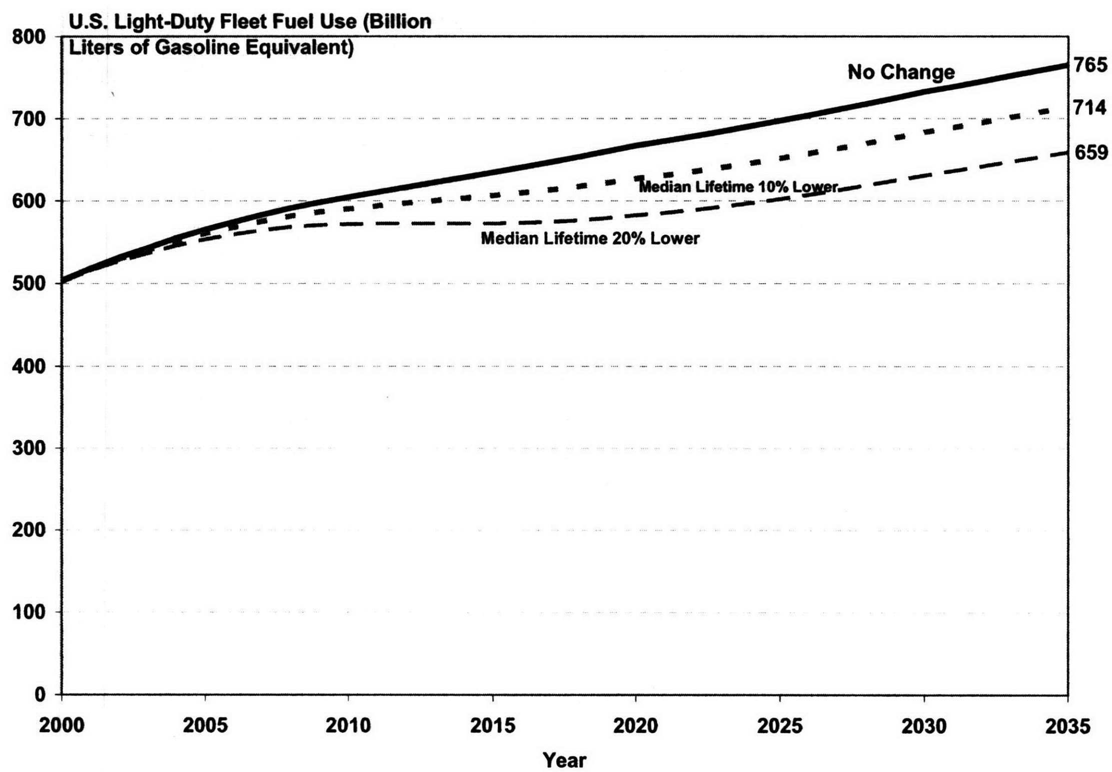


Figure 21 Effect of Reducing Vehicle Lifetime on Fleet Fuel Use

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 road. For example, if all vehicles of model year 1980 onwards were scrapped when they reached age 21, the net savings in 2035 fleet fuel saving would be about 23 billion liters of fuel. Again, scrapping older vehicles will stimulate the second hand car market, which in turn will grow the rate of new vehicle sales. While the newer vehicles are likely to be more efficient, they are also much more likely to be driven farther as shown in Figure 14. Thus, the resulting fuel savings from a vehicle scrappage scheme will be much lower than calculated here. 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 22. 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 percent adjustment to fuel use for both cars and light-trucks. The latest EPA fuel economy trends report uses an adjustment factor of 17.1 percent for years 1975-1985, which increases from 1.175 in 1986 to 1.25 in year 2005. Further extension of the model could include different fuel economy adjustment factors for cars and light trucks that vary over time. Note that variation in the adjustment factor does not affect the model results qualitatively unless the adjustment factor is changed between the scenarios.

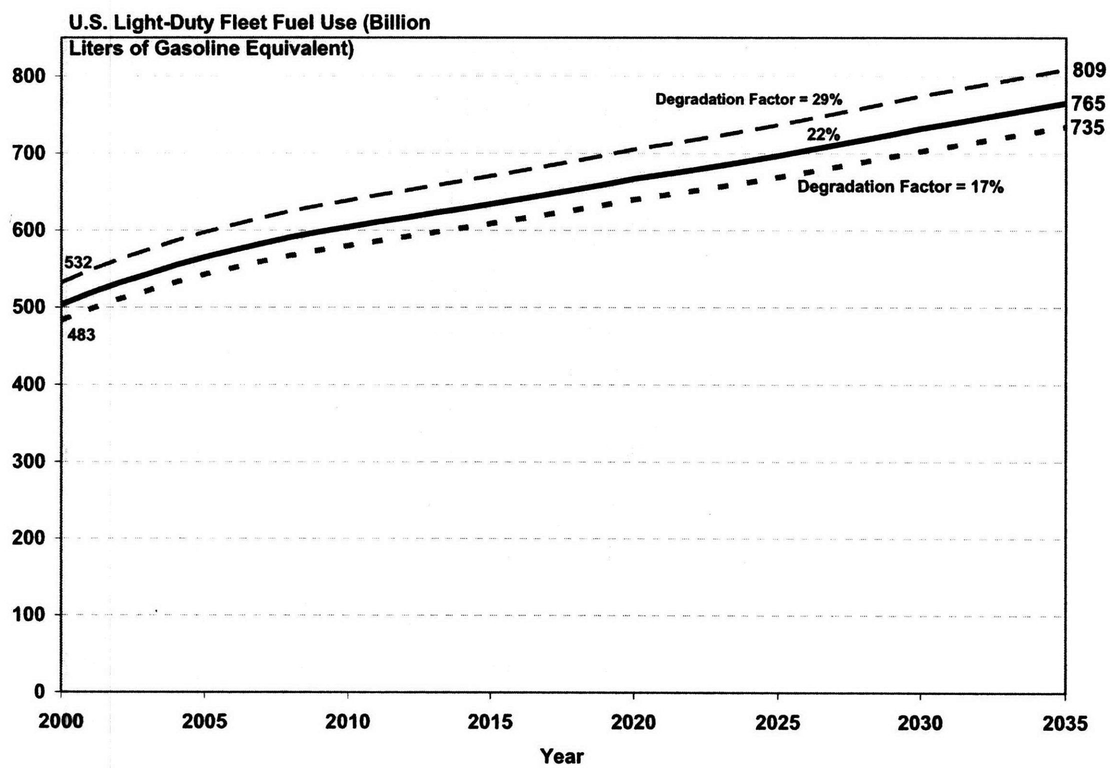


Figure 22 Light-Duty Fleet Fuel Use for Different On-Road Fuel Economy Factors

Summary and Outlook

This chapter identified the primary trends underlying different factors for growth in LDV fleet fuel use and introduced the U.S. light-duty vehicle fleet model and its structure. The model results 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 three chapters will build the fleet model further to incorporate the effects of changes in vehicles technology, vehicle market penetration rates, and fuels.

Chapter 4

Impact of Vehicle Technology Changes

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

Vehicle Size, Weight, Power and Fuel Economy Trends

The stagnant fuel consumption of light-duty vehicles (LDVs) since mid-1980s is often misinterpreted as lack of advances in vehicle technology. The difference between fuel efficiency and fuel consumption must be understood clearly in this context. Fuel efficiency is a measure of how effectively a vehicle uses the energy from fuel, whereas fuel consumption is what consumers measure as they drive on the road, and what manufacturers report to the government, i.e., the liters of fuel consumed per 100 kilometers of vehicle travel. The fuel efficiency of vehicles has improved steadily over the last twenty years. Improved fuel efficiency can be utilized to reduce fuel consumption of vehicle or to improve vehicle performance attributes such as acceleration and power, or some combination fuel consumption and performance.

Figure 23 shows the relative change in car and light-truck performance in terms of horsepower, weight, size, and acceleration [Heavenrich, 2006]. The overall trend can be separated into three phases [Lutsey and Sperling, 2005; An and Decicco, 2007]:

1. The first phase from 1977 to 1981 shows a modest deterioration in vehicle performance. The fuel consumption of new cars and light-trucks light-duty vehicles reduced by 27 percent and 22 percent respectively during this period.
2. The second phase from 1982 to 1987 shows that any modest performance reductions from phase I were largely reversed, while the fuel consumption of new cars and light-trucks light-duty vehicles reduced by 7.5 percent and 5.4 percent, respectively.

3. The third phase from 1988 to 2005 shows a steady increase in LDV weight, horsepower and acceleration. There has been little further reduction in vehicle fuel consumption over this time period.

The three phases of change in fuel consumption and 0-100 kmph acceleration performance over the last thirty years are shown in Figure 24.

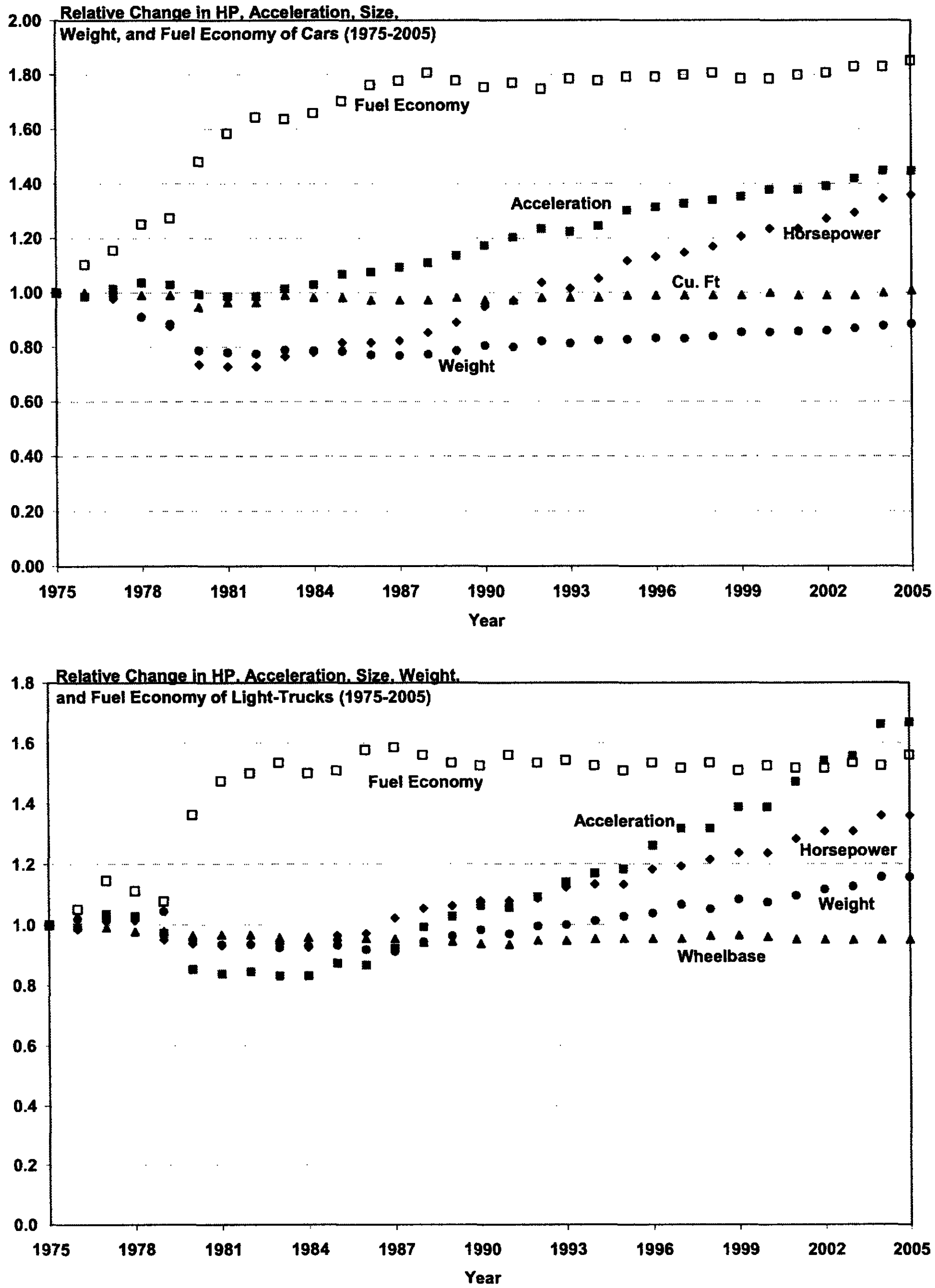
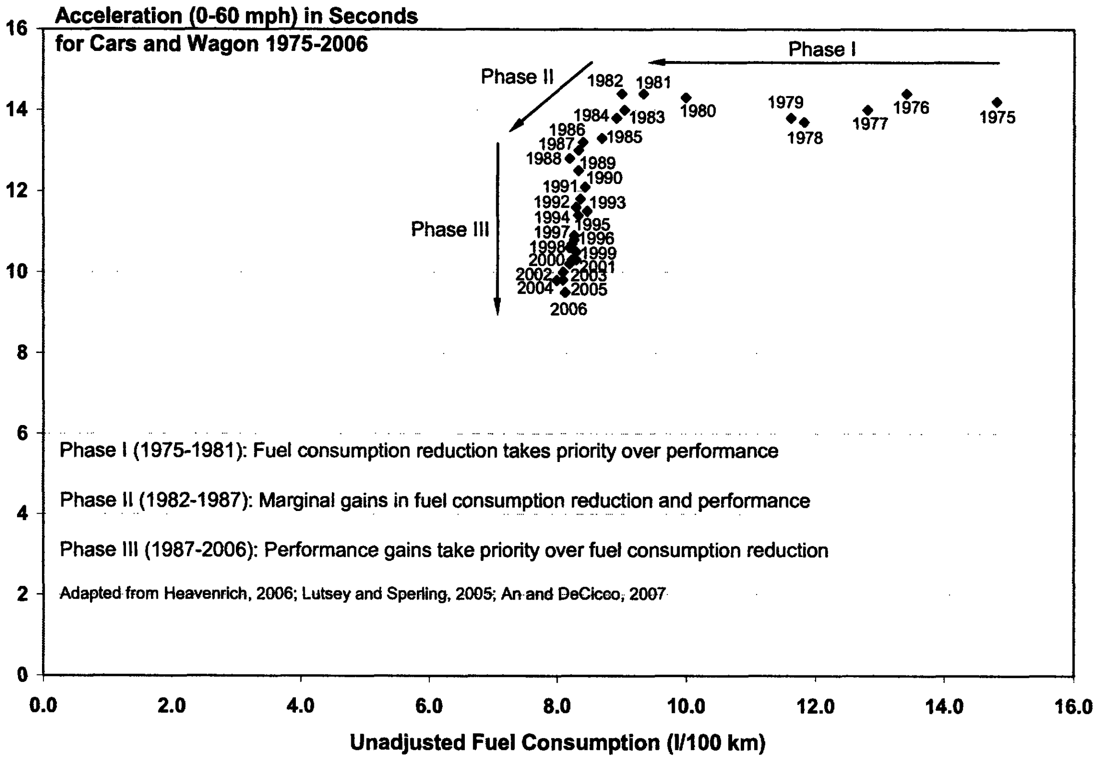


Figure 23 Relative Change in horsepower, acceleration, size, weight, and fuel economy of cars and light-trucks (1975-2005) [Heavenrich, 2006]



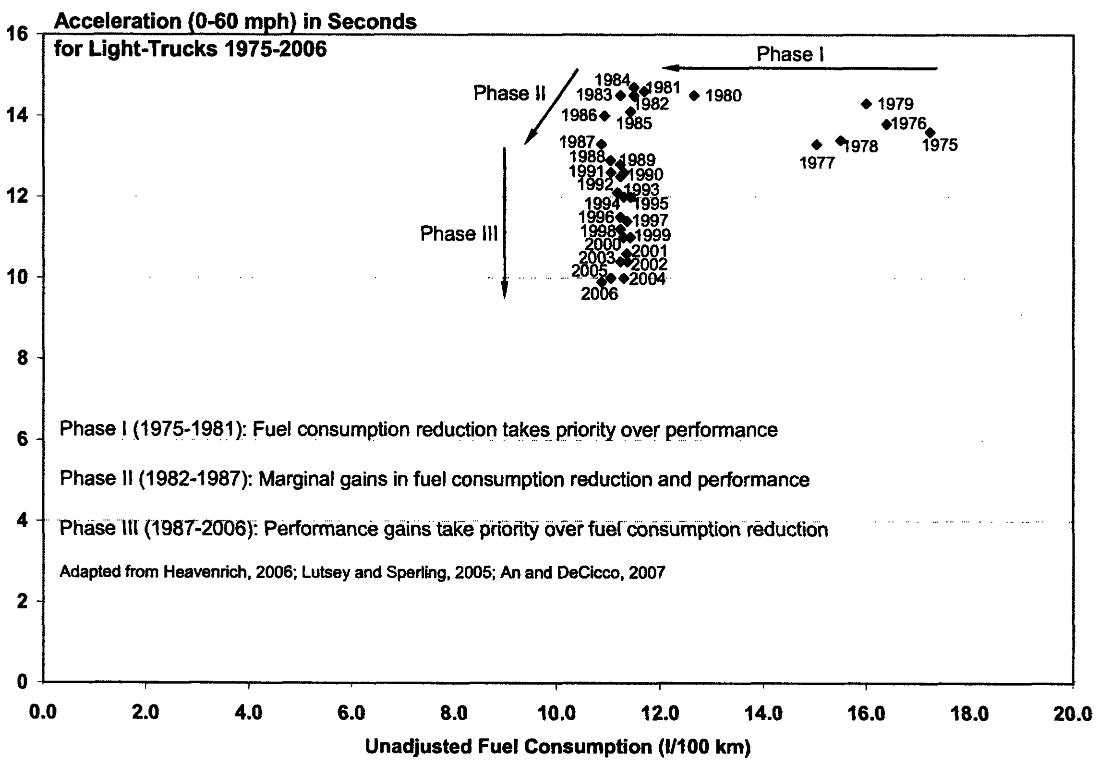


Figure 24 Fuel Consumption and acceleration of Cars and Light-Trucks (1975-2006)

In short, the high fuel prices induced by the 70's oil crisis and subsequent fuel economy regulations led to the utilization of efficiency improvements for the purpose of reducing fuel consumption during phase I. The ratcheting up of CAFE standards stopped in 1985, and that coupled with the decline in oil prices saw only a modest reduction in fuel consumption in Phase II. Since late 1980s until mid-2000s, 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 the gains in efficiency over the past 20 years have been used to improve other vehicle attributes such as power, weight, and additional safety features, while keeping the vehicle fuel consumption constant. The same period also saw 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.

Trade-off between Performance, Size and Fuel Consumption

An and DeCicco [2007] defined a *Performance-Size-Fuel economy Index* (PSFI) to better characterize the trade-offs between vehicle fuel consumption and performance attributes. The PSFI index is defined as follows:

$$PSFI = P \cdot S \cdot F = \begin{cases} HP/LB \cdot FT^3 \cdot MPG \ldots\ldots\ldots\ldots\ldots\ldots Cars \\ HP/LB \cdot WB \cdot MPG \ldots\ldots\ldots\ldots\ldots\ldots Light-Trucks \end{cases} \tag{4.1}$$

where:

Performance index P is defined as the ratio of horsepower to vehicle inertia weight (HP/LB)

Size index S is defined as the interior volume of cars (FT^3) and wheelbase of light-trucks (WB)

Fuel economy index F is defined as the unadjusted composite 55/45 combined miles per gallon value (MPG)

Figure 25 shows the PSFI trend for cars and light-trucks from 1975-2006[5]. As noted by An and DeCicco, the PSFI shows a remarkable long-term linear trend.

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[5] Car interior volume for 1975-1976 is assumed to be the same that or 1977 car. Wheelbase for 1975 truck is assumed to be the same as that of 1976 truck.

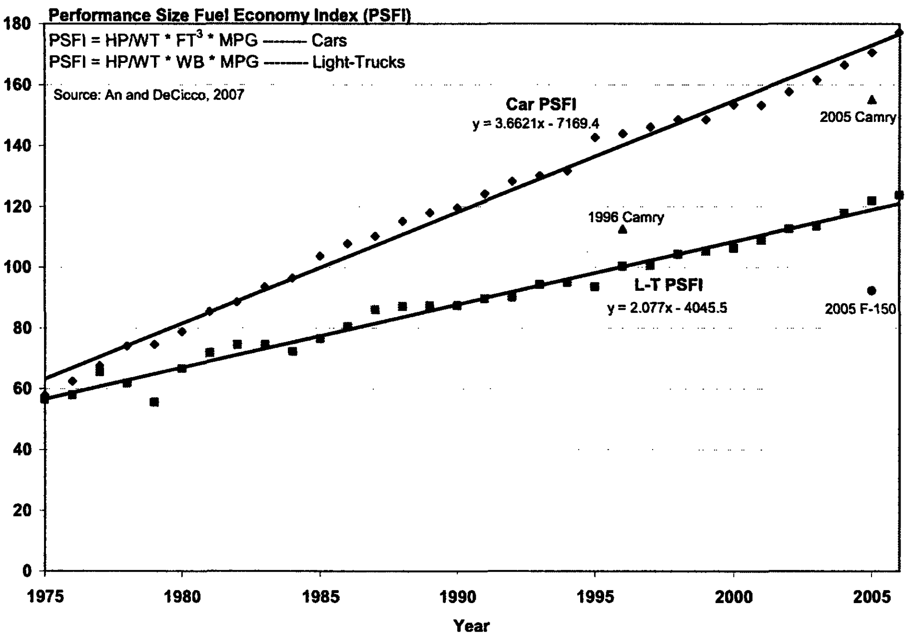


Figure 25 Performance-Size-Fuel Economy Index (PSFI) for cars and light-trucks (1975-2006)

PSFI trend can be used to evaluate the trade-off between performance, size and fuel consumption, as long as the following caveats are kept in mind. First, the trend is derived from a sales weighted average of ICE gasoline vehicles, and its applicability to other propulsion systems needs to be evaluated further, especially for vehicles with hybrid/electric powertrains. Second, wheelbase is an imperfect measure of size characteristics of light-trucks. The current NHTSA rulemaking on light-truck fuel economy uses vehicle footprint[6] as a proxy for vehicle size [NHTSA, 2006a]. It is not clear however if footprint would be a better proxy for size than wheelbase for PSFI calculations. It could be possible to separate the minivan and SUVs from pick-up trucks since interior volume can be clearly defined for the former two. Unfortunately, there is no consistent data set available for interior volume of these vehicles. Third, by using the ratio of horsepower to weight as a proxy for performance, the index fails to distinguish between vehicles with different engine and vehicle weights, but the same horsepower to weight ratio. As a result, the PSFI is not able to factor in the impact of reducing vehicle weight on increase in fuel economy appropriately. Fourth, the slope of PSFI trends for cars and light-trucks are significantly different. An and DeCicco hypothesize that the reason is likely to be the inability to represent size accurately. Recent technology assessment work indicates that similar levels of technology improvement can be expected from both cars and light-trucks in the next twenty five years [Kasseris and Heywood, 2007]. Hence, use of PSFI trends to extrapolate in to the future will have to account for expected gains in technical efficiency for both cars and light-trucks separately, with careful attention to the size definition.

We can use the PSFI relationship to estimate the potential reduction in fuel consumption during the Phase III of Figure 24, if acceleration and weight of the new light-duty vehicles had been maintained at 1987 levels. Figure 4 shows the contribution of increased acceleration and weight of vehicles to the growth in sales-weighted horsepower of cars and light-trucks respectively over the last thirty years. When the acceleration performance is held constant, the hp would have grown only to the point of keeping the horsepower to weight ratio constant i.e.

$$\frac{HP_{2006}}{WT_{2006}} = \frac{HP_{1987}}{WT_{1987}} \tag{4.2}$$

where,

HP is engine rated horsepower

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

Thus, the horsepower of a new car would have had to be increased from 111 in 1987 to 130 in 2006 to maintain the same acceleration as shown in Figure 26.

Equation 3 is used to calculate the effect of increasing acceleration on horsepower [Heavenrich, 2006; Santini and Anderson, 1993].

$$t = F\,(HP/WT)^{-f} \tag{4.3}$$

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

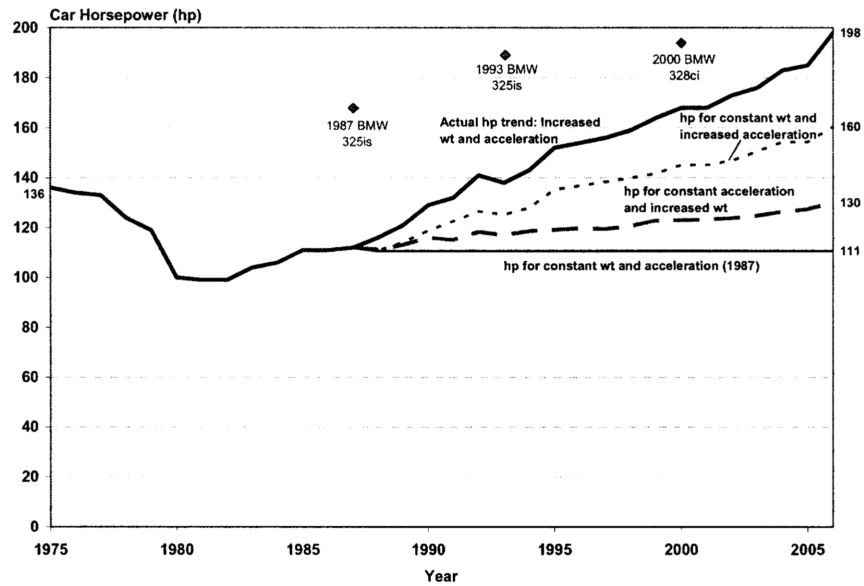
F is a constant; 0.892 for vehicles with automatic transmissions and 0.967 for vehicles with manual transmission

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

---

[6] NHTSA defines footprint as the product of the average track width (the distance between the centerlines of the tires) and wheelbase (the distance between the centers of the axles).

Thus, if the weight of new cars had remained at the same level, but the 0-60 mph time had decreased from 13.0 seconds to 9.5 seconds, then the horsepower of the cars would have had to increase from 111 in 1987 to 160 in 2006 as shown in Figure 26. Similar results are obtained for the light-trucks.



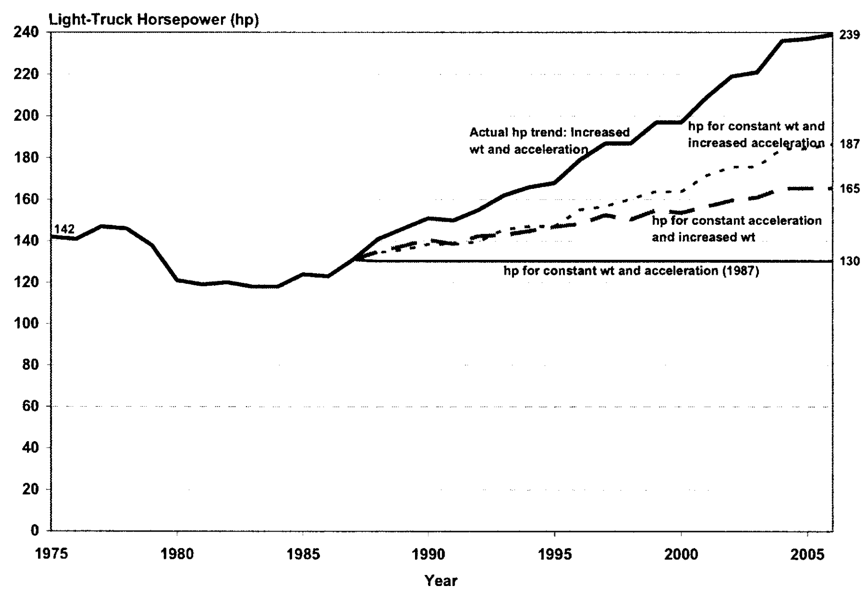


Figure 26 Horsepower for Cars and Light-Trucks (1975-2006)

Similarly, equations 1, 2 and 3 can be used to estimate what the fuel consumption of new cars and light-trucks would have been if acceleration and weight of the vehicles had been kept at 1987 levels. Note that size of the vehicles is allowed to increase in these calculations as per historical trends. The PSFI calculations indicate that the effect of increased vehicle performance as measured by acceleration has had a much more dramatic impact on vehicle fuel consumption than the increase in vehicle weight as shown in Figure 27. The unadjusted fuel consumption of new cars and light-trucks in 2006 would have been 5.4 and 7.5 liters per 100 kilometers respectively, if the technology improvements had been directed towards reducing fuel consumption instead of improving performance. The corresponding adjusted fuel consumption values are 6.4 and 8.8 liters per 100 kilometers for cars and light-trucks respectively. This would have marked a 50% increase in fuel economy of new cars and a 45% increase in fuel economy of new light-trucks when compared to the realized fuel economy of new vehicles in 2006.

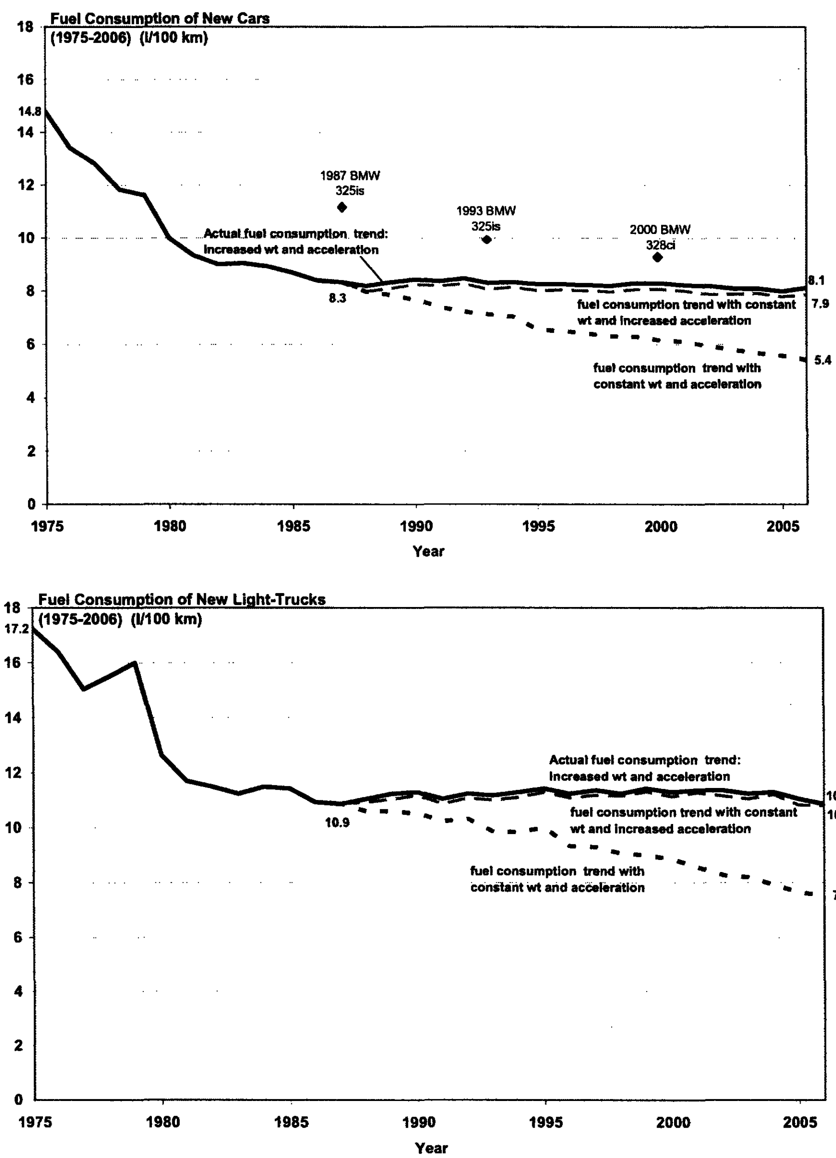


Figure 27 Plausible Reduction in Fuel Consumption of New Cars and Light-Trucks (1987-2006)

As noted previously, the PSFI calculation may not be estimating the impact of vehicle weight increase/reduction on fuel economy. To understand this effect, an ADVISOR model of a 2005 Toyota Camry developed by Kasseris and Heywood [2007] was used to simulate what the current 2.5 liter Camry might achieve in terms of fuel economy, if it's weight and acceleration performance were scaled back by the ratio of 1987 and 2005 sales weighted averages. The vehicle simulation[7] results are summarized in Table 6 below.

Table 6 Comparing the Performance-Fuel Consumption Trade-off for 2005 Toyota Camry

	Current	ADVISOR Simulation		
		Adjusting for Weight Only	Adjusting for Weight and Performance	
HP/WT (hp/lbs)	0.051	0.051	0.038	0.048
Vehicle Weight (kg)	1571	1365	1365	1365
0-100 kmph (sec)	9.4	9.4	12.5	10.3
Adjusted l/100 km	8.8	7.9	7	7.6

The ADVISOR simulations indicate that when adjusted for weight only the fuel consumption of today's Camry equivalent car would be 0.89 times the actual 2005 Camry. If the same ratio is applied to average vehicle, the unadjusted fuel consumption of a 2005 average car would be 7.4 l/100km. The PSFI calculates this to be 7.8 l/100km. When adjusted for weight and performance, the fuel consumption of today's Camry equivalent car would be 0.79 times the actual 2005 Camry. If the same ratio is applied to average vehicle, the unadjusted fuel consumption of a 2005 average car would be 6.5 l/100km. The PSFI calculates this to be 5.6 l/100km. These ADVISOR simulations indicate that 1) PSFI does indeed underestimate the impact of vehicle weight reduction and 2) PSFI may be overestimating the impact of performance on vehicle fuel consumption.

Had the fuel consumption reductions shown in Figure 27 been realized in the vehicle fleet, the total fuel use of light-duty vehicles in 2006 would have been 442 billion liters as compared to the actual fuel use of 579 billion liters, a 24% reduction as shown in Figure 28. In addition if the market share of light-trucks had remained constant at 31% from 1987 onwards, then the 2006 fuel use would be 426 billion liters. The important point here is that the increase in the size and performance of cars and light-trucks has had a much larger impact on LDV fuel use

[7] I am grateful to Lynette Cheah, and Matt Kromer for their help in running all vehicle simulations mentioned in this chapter.

than the shift in the market share from cars to light-trucks. Of course, we have experienced both the shift from cars to light-trucks AND the increase in size and performance of vehicles, and the net effect is about 30% more fuel use in 2006 than what would have occurred with holding performance constant.

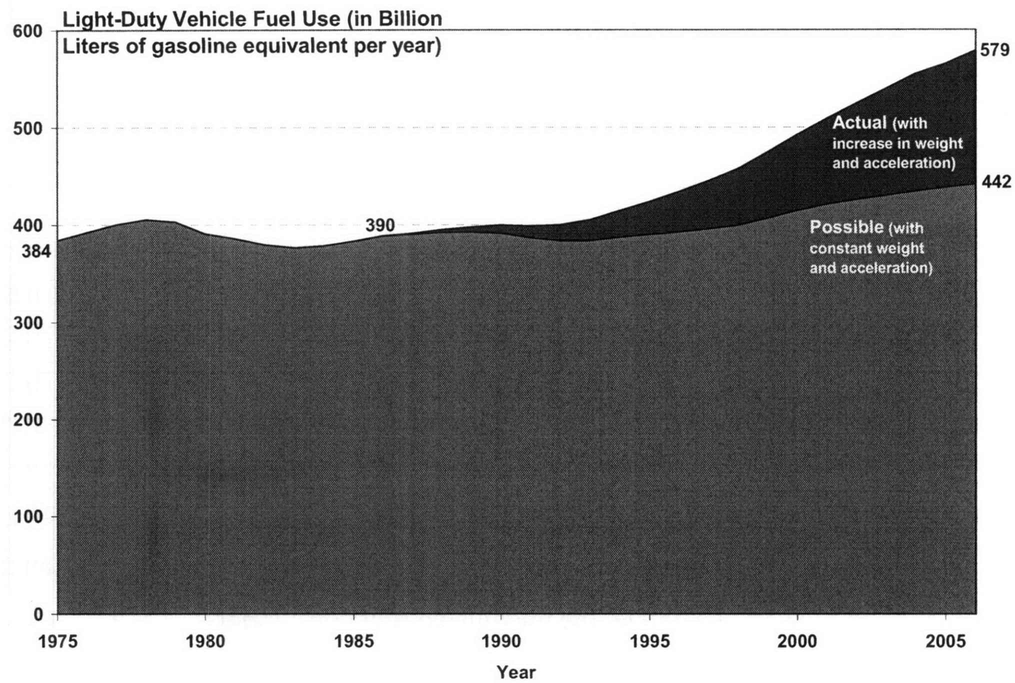


Figure 28 Light-Duty Vehicle Fleet Fuel Use with Constant Weight and Acceleration Performance from 1987-2006

Emphasis on Reducing Fuel Consumption (ERFC)

What happens if the improvements in technology continue to get utilized to improve vehicle performance? We can extrapolate the PSFI trend into the future and evaluate the trade-off between future vehicle acceleration and fuel consumption. 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 on-board fuel consumption of such a vehicle in 2035 could reduce to 5/8th of its current fuel consumption. 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 emphasize improvements in performance, size, and safety features. Thus not all of the gains from increased fuel efficiency will be realized for the purpose of reducing fuel consumption. For the purpose of understanding the influence of performance-size-fuel consumption trade-off, we introduce a variable called *Emphasis on Reducing Fuel Consumption* or ERFC for short.

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

or

$$ERFC = \frac{FC_{current} - FC_{realized}}{FC_{current} - FC_{potential}}$$

or

$$FC_{realized} = FC_{current} - ERFC * (FC_{current} - FC_{potential}) \quad \text{--- (4.4)}$$

ERFC measures the degree to which improvements in technology are being realized for reducing on-board fuel consumption. Thus, a 50% emphasis on reducing fuel consumption would mean that a 2035 vehicle would realize a relative on-road fuel consumption value of 1-0.5*(1-0.625) = 0.8125 as shown in Figure 29.

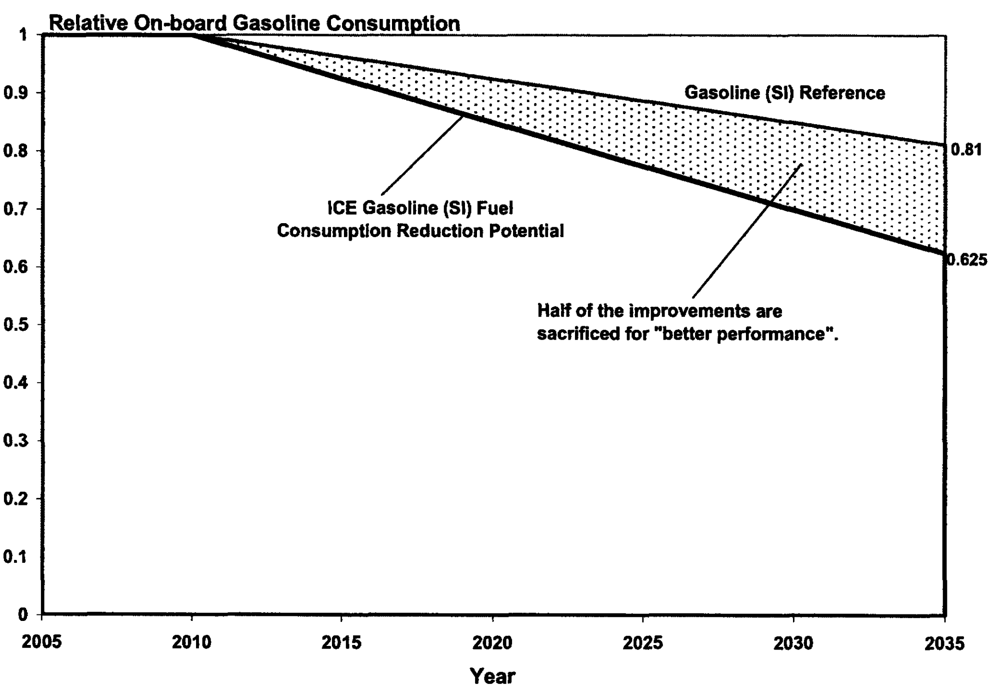
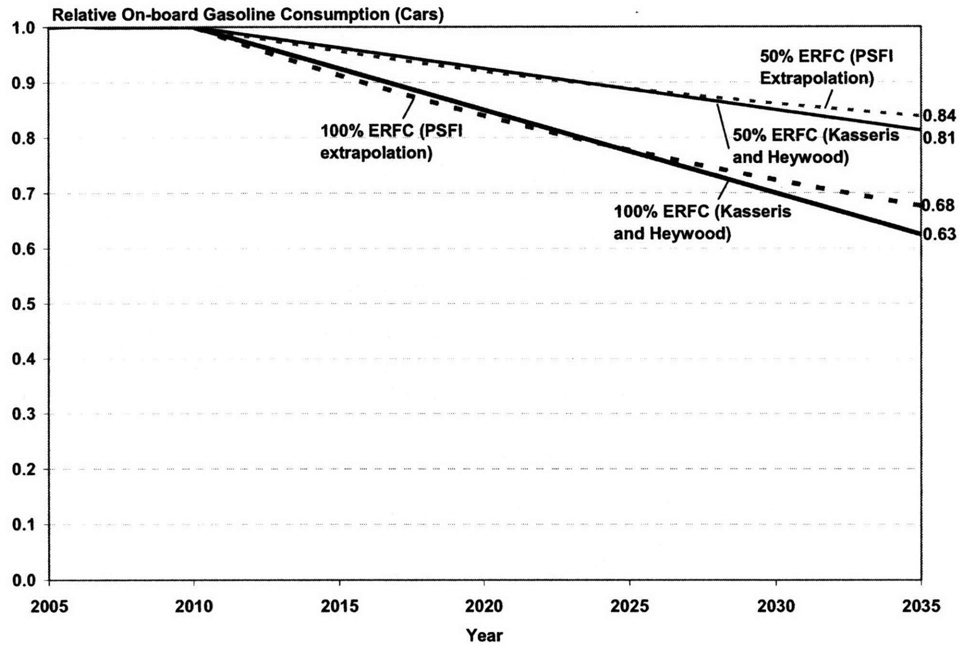


Figure 29 Relative on-board gasoline-equivalent fuel consumption at 50% ERFC

Figure 30 compares the relative on-board fuel consumption values derived from extrapolation of the PSFI trend with the technology assessment work of Kasseris and Heywood for 50 percent and 100 percent ERFC. For 100 percent emphasis on reducing fuel consumption, PSFI extrapolation underestimates 2035 fuel consumption reduction by about 8 percent for cars and 13.7 percent for light-trucks. For 50 percent emphasis on reducing fuel consumption, PSFI extrapolation underestimates 2035 fuel consumption reduction by about 3.7 percent for cars and 5.3 percent for light-trucks. As a result, the performance extrapolation based on the PSFI equation will be somewhat overestimated.



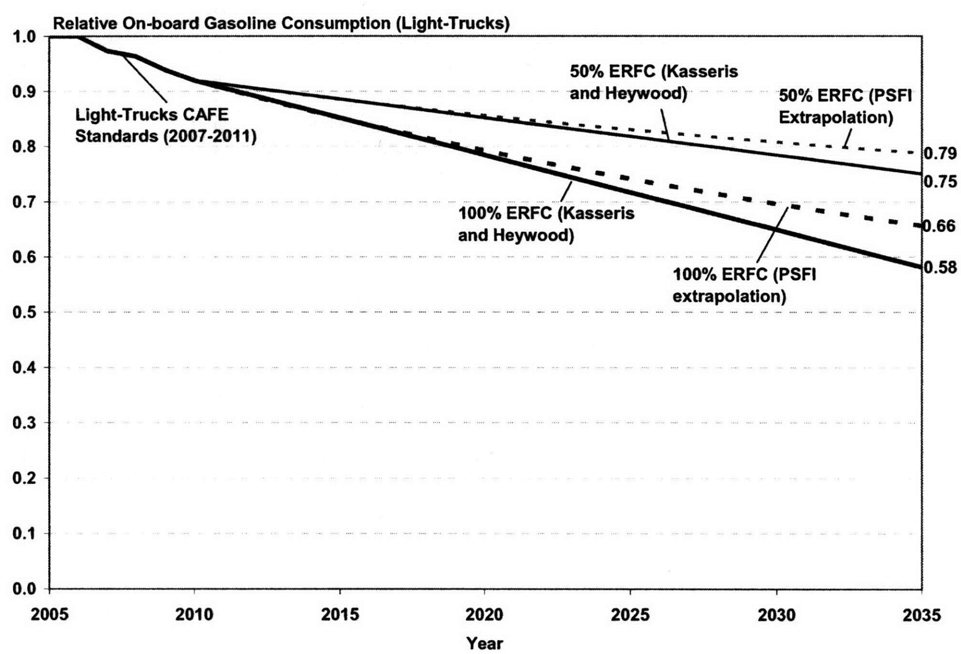


Figure 30 Comparison of PSFI Extrapolation with Technology Assessment Results from Kasseris and Heywood

Using Equations 1, 2, 3 and 4, we can estimate the HP/WT ratio and 0-100 kmph acceleration time for different values of ERFC. 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 of technical improvement is used to increase the HP/WT ratio in accordance with PSFI trend. Kasseris and Heywood assume a 20% weight reduction in vehicle weight by 2035 for 100% ERFC case. When ERFC is below 100%, the corresponding weight reduction is also multiplied 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 3. The results, shown in Table 7 and Table 8 allow us to gain a better appreciation for the fuel consumption benefits being traded off for better horsepower and acceleration.

Table 7 Passenger Car Performance-Fuel Consumption Trade-off for Different Degrees of Emphasis on Reducing Fuel Consumption (ERFC)

	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

Table 8 Light-Truck Performance-Fuel Consumption Trade-off for Different Degrees of Emphasis on Reducing Fuel Consumption (ERFC)

	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

We can estimate the potential fuel use reductions that could materialize if more emphasis were placed on reducing fuel consumption in the future, as opposed to little or no emphasis being placed today. Thus, no emphasis placed on fuel consumption reduction (0% ERFC) becomes our

No Change Scenario. As can be seen in Figure 31, 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*.

When the fuel efficiency benefits are used fully to reduce fuel consumption, the LDV fleet fuel use can be reduced by as much as 26 percent from No Change scenario in 2035 by gasoline ICE vehicles alone. Table 9 lists the light-duty vehicle fleet fuel use in 2035 for different values of ERFC. Each 25 percent increment in ERFC represents approximately 50 billion liters of fuel saved in year 2035.

Table 9 U.S. Light-Duty Vehicle Fleet Fuel Use in 2035 for Different Degree of Emphasis on Reducing Fuel Consumption (ERFC)

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

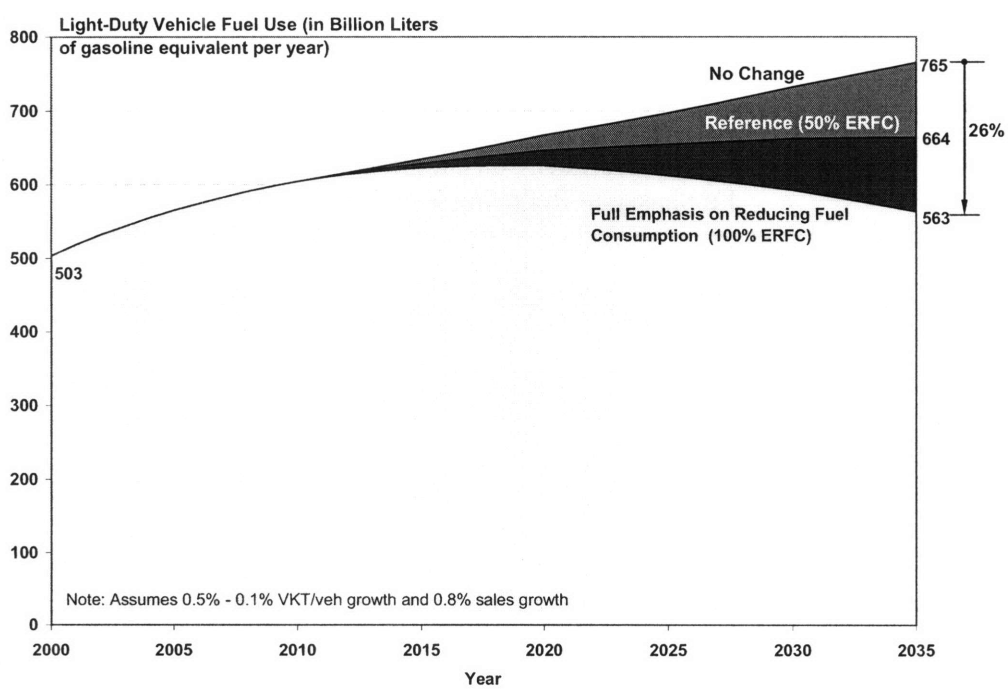


Figure 31 U.S. LDV Fleet Fuel Use with Full Emphasis on Reducing Fuel Consumption

Relative On-Board Fuel Consumption of Different Propulsion Systems

Kasseris and Heywood [2007] and Kromer and Heywood [2007] evaluated the potential of different vehicle technologies to reduce the fuel consumption of cars and light-trucks. The projected improvement in vehicle fuel consumption as per their assessment is shown in Table 10. Note that the relative improvement values are calculated based on the improvement in fuel consumption of a 2035 vehicle comparable in performance to a current ICE gasoline vehicle.

Table 10 Projected Improvement in Vehicle Fuel Consumption

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

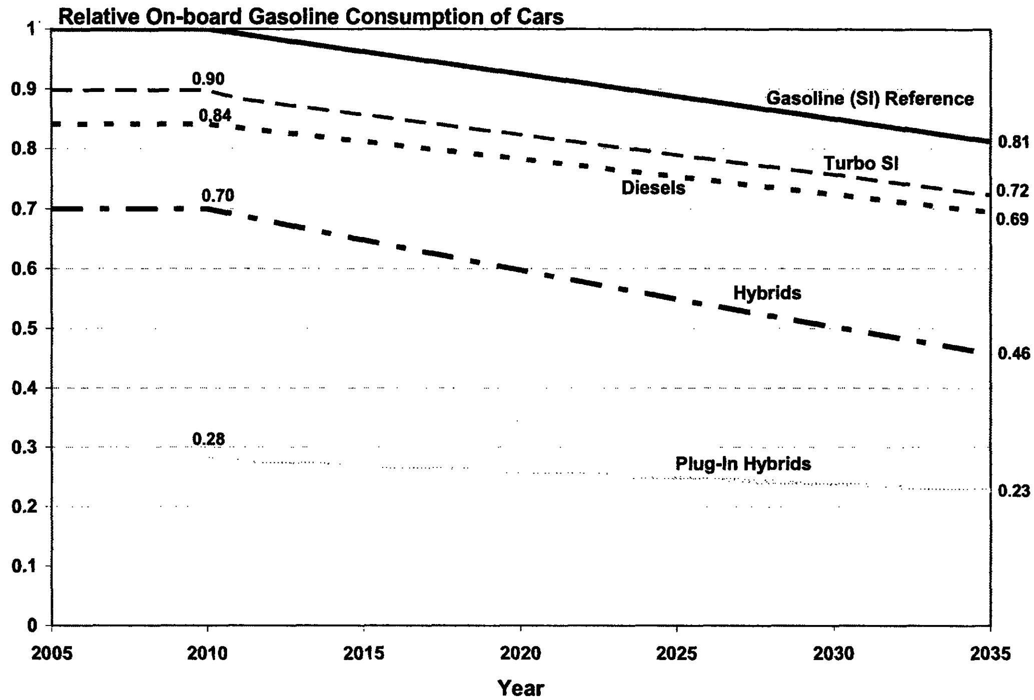
1.01 l/100 km of electricity usage in addition to gasoline not included

Battery electric vehicle (BEV) and hydrogen fuel cell vehicle (FCV) do not consume any petroleum during vehicle operation, and hence energy consumption per kilometer driven is a more appropriate comparison when these vehicles are included. Table 11 shows a comparison of tank-to-wheel energy consumption expressed in MJ per km of vehicle travel for different propulsion systems.

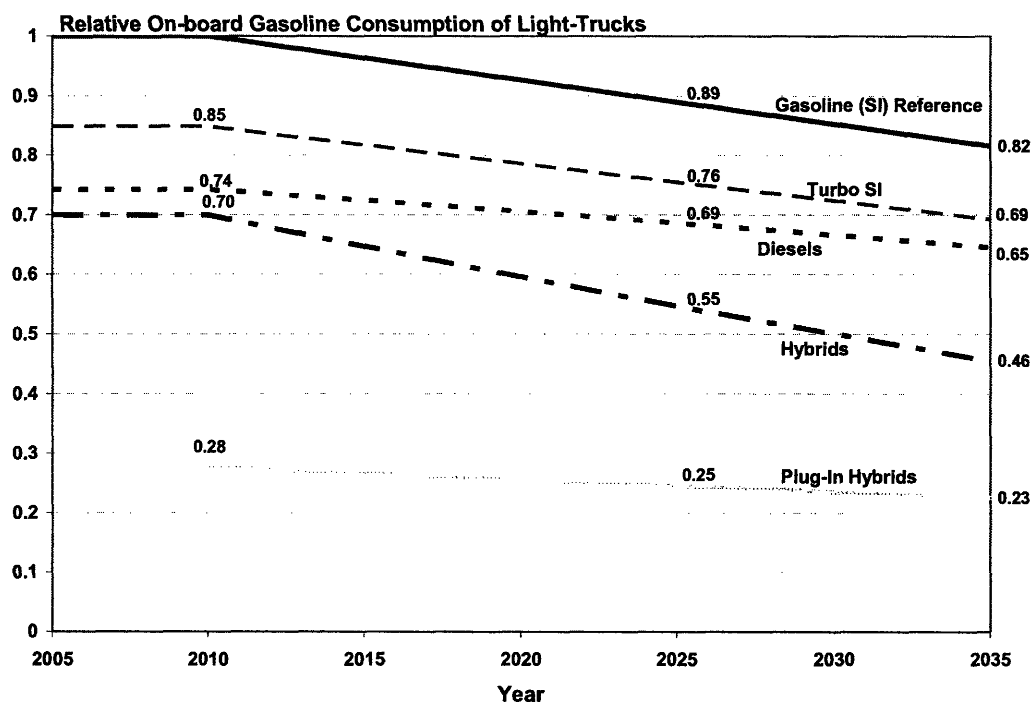
Table 11 Tank-to-Wheel Energy Use

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

For use in the fleet model, we assume that future reductions in fuel consumption start in year 2010 since the product plans for the next two years have already been finalized. Also, the reference case assumes a 50% emphasis on reducing fuel consumption. Using the information in Table 10 and Equation 4, the relative on-board gasoline equivalent fuel consumption for different propulsion systems in the reference case can be calculated for years 2010-2035 as shown in Figure 32.



(a) Cars



(b) Light-Trucks

Figure 32 Relative on-board gasoline-equivalent fuel consumption at 50% ERFC for different propulsion systems

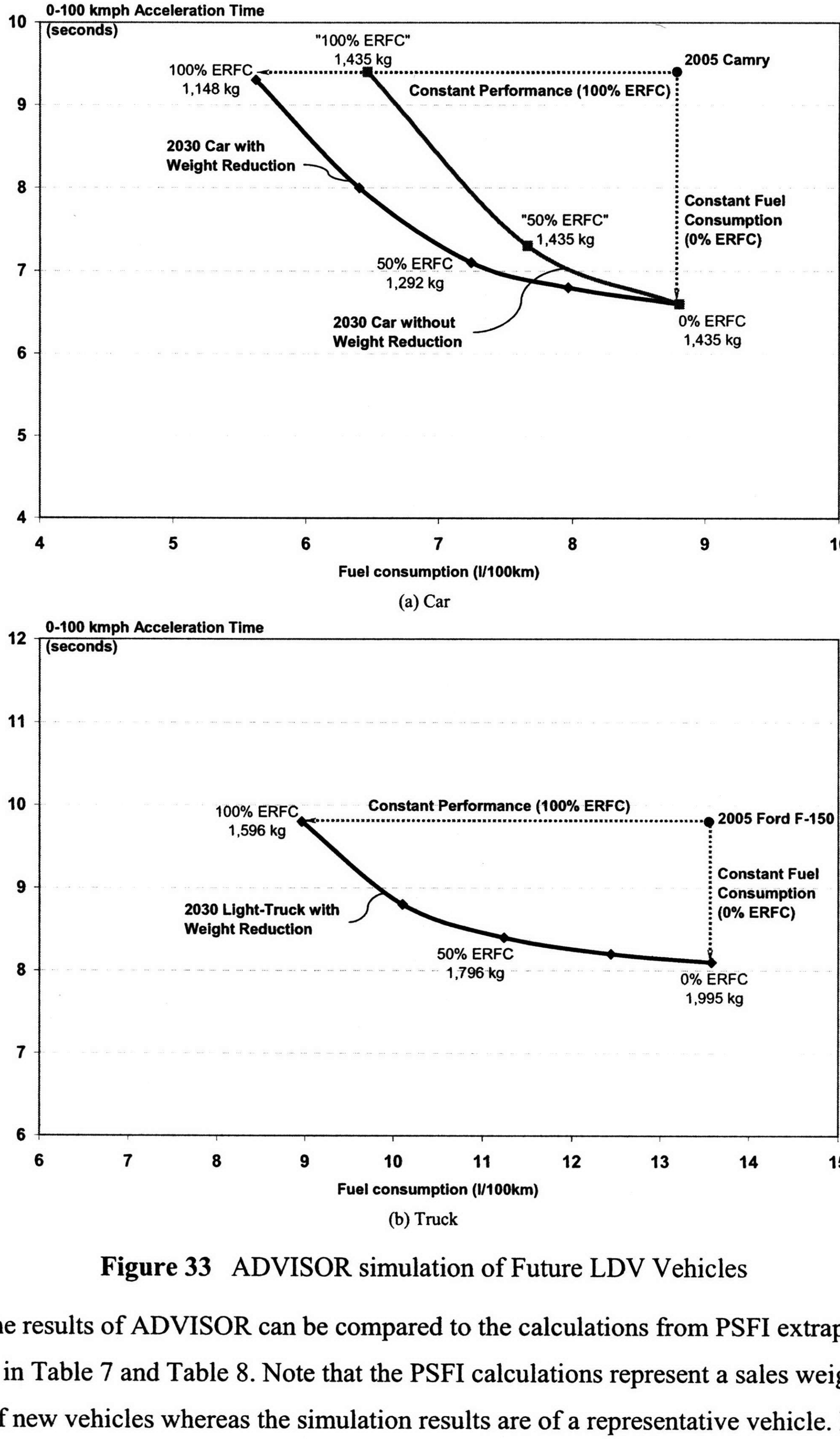
Comparison of ERFC Approximation and Advisor Simulations

The concept of *emphasis on reducing fuel consumption* (ERFC) variable is intended for all types of propulsion systems. For example, we expect that a 50% ERFC for gasoline ICE vehicle will distribute the gains in fuel efficiency evenly between improved performance and reduced fuel consumption. It is possible in case of vehicles with electric motors, such as hybrids, that gains in performance could be realized without much deterioration in fuel consumption. Similarly, the *performance-size-fuel consumption index* (PSFI) is based on an empirical trend observed from gasoline ICE powered vehicles. It is not clear if the PSFI trends can be extrapolated in the future for diesel, hybrid or plug-in hybrid vehicles.

The relationship between performance and fuel consumption can be explored further by running vehicle simulations. Kasseris and Heywood [2007] and Kromer and Heywood [2007] projected the plausible reduction in fuel consumption of future light-duty vehicles. Using the same methodology, Figure 33 shows the impact of vehicle weight reduction and performance on fuel consumption of *future* representative light-duty vehicles.

When adjusted for improvements in vehicle technology without any weight reduction, the simulation indicates a 26 percent reduction in vehicle fuel consumption at constant performance as shown in Figure 33 (a). If only 50 percent of the emphasis is placed on reducing fuel consumption, the 0-100 kmph acceleration time reduces from 9.4 seconds to 7.3 seconds, and the vehicle fuel consumption reduces from 8.8 l/100 km to 7.7 l/100km. When no emphasis is placed on reducing fuel consumption, the simulation shows a reduction in acceleration time to 6.6 seconds.

Assuming a reduction in vehicle weight from 1435 kg to1148 kg at 100% ERFC would bring down the fuel consumption of future car by over 36 percent Thus, the impact of reducing vehicle weight by 20 percent is to reduce the fuel consumption from 6.5 l/100km to 5.6 l/100 km or approximately 14 percent. At 50% ERFC with 10 percent reduction in vehicle weight, the simulation indicates vehicle fuel consumption of 7.2 l/100km at 0-100 kmph acceleration time of 7.1 seconds, or a 6.5 percent reduction in fuel consumption from the 50% ERFC case with no weight reduction. Figure 33 (b) shows a similar trade-off between performance and fuel consumption for a future light-truck.

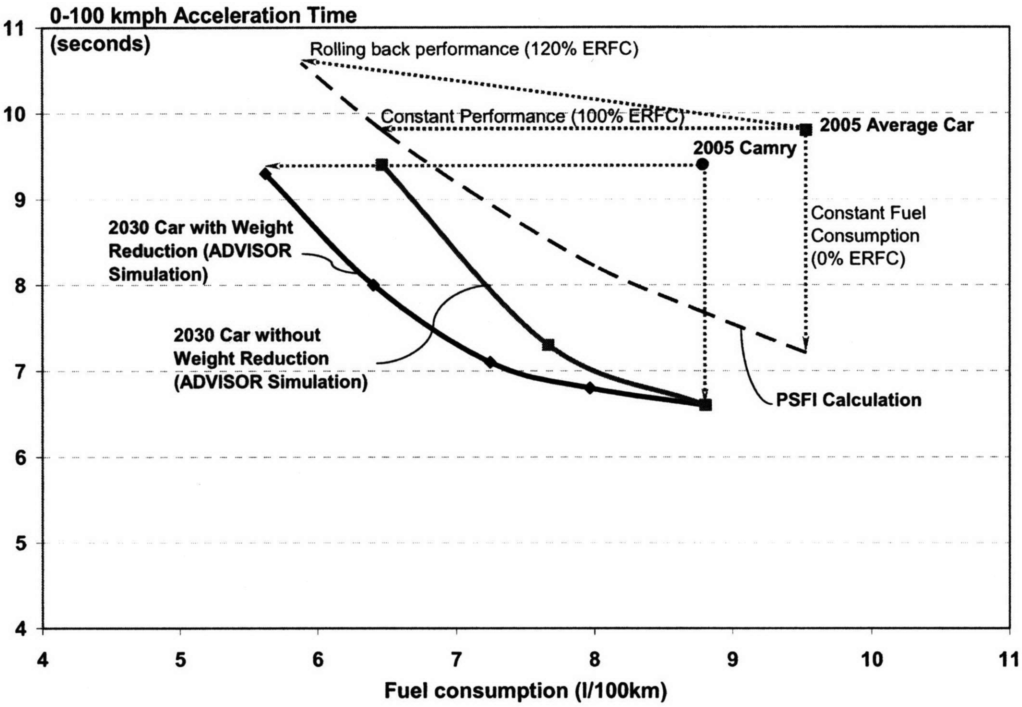


(a) Car

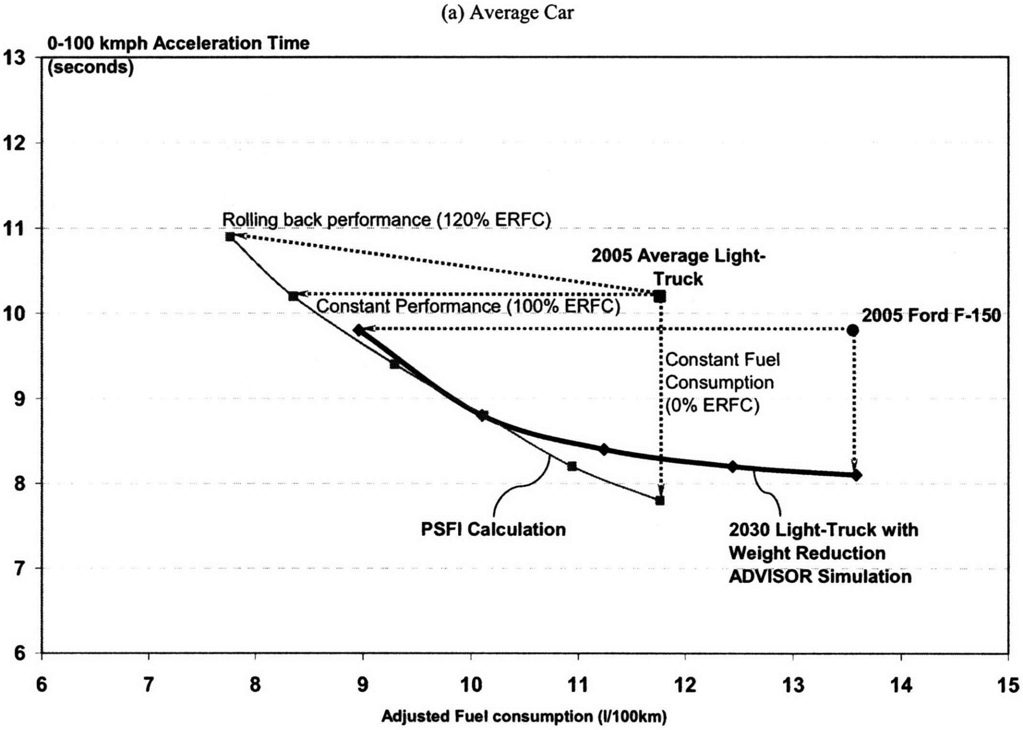
(b) Truck

Figure 33 ADVISOR simulation of Future LDV Vehicles

The results of ADVISOR can be compared to the calculations from PSFI extrapolation discussed in Table 7 and Table 8. Note that the PSFI calculations represent a sales weighted average of new vehicles whereas the simulation results are of a representative vehicle. Figure 34 shows this comparison.



(a) Average Car



(b) Average Light-Truck

Figure 34 Comparison of ADVISOR Simulations with PSFI Extrapolation

By comparing the simulated fuel consumption of different vehicles at 50% ERFC, we can evaluate the utility of ERFC and PSFI in evaluating this trade-off empirically. Recall from Table

6 that using the PSFI relationship, the 0-60 mph acceleration time for 50% ERFC in a 2035 gasoline ICE car is found to be 7.3 seconds. The corresponding sales-weighted unadjusted fuel consumption is 6.8 l/100 km or 8.1/100 km adjusted. The fuel consumption of future vehicles with comparable acceleration performance is shown in Table 10. Note that this is not an entirely accurate comparison since we are using the broad sales weighted average performance and fuel consumption for current gasoline vehicles with a single simulation of future vehicles. Never the less, they provide us with an additional approach to the performance-size-fuel consumption trade-off.

From Table 12, we can see that the performance-size-fuel consumption trade-off scales linearly as predicted by PSFI relationship in case of ICE only vehicles such as gasoline, turbocharged gasoline and diesel vehicles. In the case of hybrid vehicles, it is possible to achieve a higher level of acceleration performance without yielding back most of the gains made in fuel consumption reduction. This is primarily because the hybrid propulsion system utilizes a smaller engine for the same performance, eliminates idling, and actively manages to keep engine use in the higher efficiency areas of its engine map.

Table 12 Comparison of Projected Fuel Consumption using ERFC approximation and ADVISOR Simulation

Propulsion System	Adjusted l/100km for 100% ERFC	0-60 mph time in seconds	Using ERFC		Using ADVISOR simulations	
			Adjusted l/100km*	Relative to current gasoline	Adjusted l/100km*	Relative to current gasoline
Current Gasoline	8.8	9.3[4]	8.8	1	8.8	1
2035 Gasoline	5.6	6.8[1]	8.0	0.91	8.0	0.91
		7.1-7.3[2]	7.1	0.81	7.2	0.82
		8.0[3]	6.3	0.72	6.4	0.73
2035 Diesel	4.7	7.5[2]	6.1	0.69	6.0	0.68
2035 Turbo Gasoline	4.9	7.1[2]	6.3	0.72	6.3	0.72
2035 Hybrid	3.1	7.4[2]	4.1	0.46	3.3	0.38
2035 Plug-In	1.5[#]	7.3[2]	2.0[##]	0.23	1.65[###]	0.19

* Gasoline Equivalent.
# 0.65 l/100 km of electricity usage in addition to gasoline not included
0.84 l/100 km of electricity usage in addition to gasoline not included
0.7 l/100 km of electricity usage in addition to gasoline not included

1: 25% ERFC
2: 50% ERFC
3: 75% ERFC
4: 100% ERFC

Summary and Outlook

This chapter introduced the concepts of Performance Size Fuel Economy Index (PSFI), and Emphasis on Reducing Fuel Consumption (ERFC). The impact of steadily rising vehicle performance on fuel consumption reduction was evaluated by using these indices. It is found that performance improvements during the past twenty years have been responsible for the growth in light-duty vehicle fuel use. It was 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.

Finally, the relative reduction in fuel consumption from emerging vehicle technologies was calculated, and the sensitivity of these propulsion systems to the performance-size-fuel consumption trade-off was evaluated. The next chapter evaluates the likely range of market penetration of these alternative propulsion systems in the US light-duty vehicle over the next thirty years.

Chapter 5

Impact of Vehicle Technology Implementation Rates

The last decade has seen market introduction of hybrid electric vehicles (HEVs), a renewed interest in diesel vehicles in the US market, and increasing curiosity about 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 the conventional gasoline vehicles in the marketplace will determine the long-term trajectory of light-duty vehicle fuel use. This chapter explores the challenges facing a greater market penetration of these alternatives, the likely scale of market penetration, and their impact on fleet-wide fuel use over the next thirty years.

First, a discussion of specific barriers to new propulsion systems and alternative fuels is presented. Next, some of the approaches to forecast market penetration of new vehicles technologies are discussed. The following section describes the supply side constraints to expansion of new vehicle technologies. The next section describes the growth of diesel vehicles in Europe and ethanol flexible-fuel vehicles in Brazil as examples of introduction of new vehicle technologies. Finally, scenarios of market penetration of new propulsion systems in the U.S. light-duty vehicle (LDV) market, and their impact of fleet fuel use are discussed.

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]. Some of the main barriers include:

- High first cost for vehicle: The initial purchase price of the vehicle plays a large role in consumers' choice while selecting a new vehicle, since it typically represents the largest component of the life-cycle cost of owning and operating the vehicle. Table 13 lists the retail price increment for different vehicles over a comparable 2035 ICE gasoline vehicle [Kromer and Heywood, 2007]. The retail prices for vehicles are assumed to be 1.4 times the estimated original equipment manufacturer (OEM) costs or twice the manufacturing costs [Vyas et al. 2000].

Table 13 Estimated Incremental Retail Price over 2035 ICE Gasoline Vehicle

Propulsion System	Estimated Retail Price Increment in 2007 Dollars
Turbocharged Gasoline ICE Vehicle	700-850
Diesel ICE Vehicle	1700-2100
Gasoline Hybrid Vehicle (HEV)	2600-3300
Gasoline Plug-In Hybrid Vehicle (PHEV)	5200-6000
Hydrogen Fuel Cell Vehicle (FCV)	5000-7000
Battery Electric Vehicle (BEV)	9500-14000

Purchasing a PHEV, FCV or BEV could entail a cost premium as large as 35-70%, thereby greatly reducing the number of consumers willing to consider these vehicles at the time of purchase.

- 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 high pressures and stored in larger fuel tanks. Similarly batteries for PHEV or BEV add a substantial amount of 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 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 0.8 times that of a comparable gasoline vehicle with same sized fuel tank.

- Safety: Thermal runaways are the main concerns for the 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 is in the area of fueling and storage of hydrogen. Unlike gasoline vapor, gaseous hydrogen is prone to auto-ignite with even small amount of static electricity. Hydrogen is also liable to explode in confined spaces such as enclosed garages and tunnels. Hence, preventing leaks of hydrogen from fueling stations and on-board storage tanks will be of paramount importance. Unless new scientific breakthroughs are realized, the storage of hydrogen on-board is likely to be in high pressure (700 bar) 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: Unfamiliarity with new vehicle technology may lead to doubts about the reliability in the consumers' mind. The initial experience with Hybrid Electric Vehicles (HEV) has proven that electric propulsion systems can be reliably integrated with the conventional engine-transmission systems. Durability of batteries in the case of PHEV and BEV 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 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 and size reductions to addressing durability concerns by early 2010's.

- High fueling cost compared to gasoline: A gasoline price of 3.00 dollars per gallon at the pump is equivalent to about 25 dollars per GJ. Electricity for PHEV/BEV will be cheaper on energy basis if it costs less than 9 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 dollars per GJ, provided distribution and dispensing costs could be roughly halved from their current value [Kramer et al., 2006]. Ethanol from corn currently receives a subsidy of 51 cents a gallon or 6.3 dollars per GJ. The cost of producing a gallon of ethanol from cellulosic material such as switchgrass is currently estimated to be around $2.25-2.75 depending upon the feedstock cost and ethanol conversion efficiency [NREL, 2006a].

- Lack of refueling infrastructure: There are currently about 175,000 refueling stations serving gasoline across US. A large number of these refueling stations are also capable of serving diesel fuel. According to the Alternative Fuels Data Center maintained by the Department of Energy, there were 1154 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 centralized hydrogen production model is estimated to be between 0.7 – 1.5 Million dollars [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 in to an established market: There are more than 2 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 offer a tough competition to any alternative powertrain. A remarkable amount of engineering effort and learning has undergone in 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 undergo learning and economies of scale, making their task of breaking in to the light-duty vehicle market 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 can 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 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.
- Consumers may also have questions about potential for fuel savings realized for adopting a costlier technology. From vehicle manufacturers' perspective, undertaking a major vehicle redesign when consumers' preference for increased fuel economy is unclear is a risky endeavor.

The above discussion indicates some key challenges and uncertainties that advanced vehicle technologies and fuels need to overcome. The next two sections will consider the difficulty in projecting the market penetration rates of new technologies from demand and supply side considerations.

Demand side modeling

The literature on modeling technology diffusion is very rich, and no attempt is made here to review the entire literature. Instead, this section introduces some of the common modeling approaches that can be used to estimate the market penetration rates of new vehicle technologies.

Early work on modeling the dynamics of technological substitution models established the usefulness of logistic type growth of new technology [Mansfield, 1961; Fisher and Pry, 1971; Blackman, 1974]. Their observation that substitution of one technology by the other tends to grow exponentially in the early years and follows an S-curve has been applied to different industries and products subsequently [Grübler, 1991].

A simple diffusion model, such as Fisher and Pry model, does not contain a direct relationship to underlying product characteristics and an economic rationale for consumers for making the choice to purchase new technology over old. Discrete Choice Models use the principle of utility maximization to estimate the probability of consumer making a choice between competing alternatives [Ben-Akiva and Lerman, 1985]. The remainder of this section describes the discrete choice modeling approach and its application to estimate market penetration rates of alternative propulsion systems.

Individual Logit Model

Let us say that there are two vehicle options: the conventional gasoline spark-ignition Internal Combustion Engine (ICE) and Gasoline ICE-hybrid (HEV) so that the choice set is C_j = {ICE = 1, HEV = 2}. For the sake of convenience, let us say that consumer i makes a choice based on three attributes of the vehicles: price in dollars (X_{jP}), cost of fuel consumption in dollars per kilometer (X_{jF}), and maximum torque generated by the powertrain configuration in kg-m (X_{jT}). The utility derived by consumer i from choosing car j is

$U_{ij} = V_{ij} + \varepsilon_{ij}$ where,

$V_{ij} = \beta_{iC} + \beta_{iP}X_{jP} + \beta_{iF}X_{jF} + \beta_{iT}X_{jT}$

In general, $v_{jn} = \sum_{a=1}^{A} \beta_{na} X_{jna}$ (5.1)

where,

X_{jna} are vehicle attributes such as price, fuel economy, acceleration, horsepower, range, luggage space etc.

β_{na} are the *weights* or preference of consumers for each attribute included in the model

ε_{jn} is the stochastic component of the model, assumed to be identically and independently distributed (Type I extreme value distribution), $\varepsilon_n = \varepsilon_{jn} - \varepsilon_{jn}$ is logistically distributed.

The probability of HEV being chosen by person i from the choice set C_j is given by

$$P(HEV|\ C_j) = \Pr(U_{jn} \geq U_{in}),\ \forall j \in C_n$$

$$= \Pr(U_{jn} \geq U_{in}),\ \forall j \in C_n$$

$$\Pr(V_{i2}+\varepsilon_{i2} \geq V_{i1}+\varepsilon_{i1}) = \Pr(\varepsilon_{i1}-\varepsilon_{i2} \leq V_{i2}-V_{i1}) \quad (5.2)$$

In the logit model, the error terms ε_{i1} and ε_{i2} are assumed to be independent and identically Gumbel distributed (Type I extreme value distribution), and the difference between the error terms ($\varepsilon_i = \varepsilon_{i1} - \varepsilon_{i2}$) is assumed to be logistically distributed i.e.

$F(\varepsilon_i) = \dfrac{1}{1+e^{-\mu\varepsilon_i}}$, where $\mu > 0$, $-\infty < \varepsilon_i < \infty$ and

$$f(\varepsilon_i) = \frac{\mu e^{-\mu\varepsilon_i}}{\left(1 + e^{-\mu\varepsilon_i}\right)^2} \tag{5.3}$$

The choice probability under the logit model for HEV is then given by:

$$P_i(HEV) = \frac{1}{1 + e^{-\mu(v_{i2} - v_{i1})}} = \frac{e^{\mu v_{i2}}}{e^{\mu v_{i1}} + e^{\mu v_{i2}}} \tag{5.4}$$

Generalizing the above approach, the probability of vehicle type j being chosen by person n from the choice set C_J is given by

$$\begin{aligned} P(j|C_J) &= \Pr(U_{jn} \geq U_{in}, \text{ for all } j, j \neq i) \\ &= \Pr(V_{jn} + \varepsilon_{jn} \geq V_{in} + \varepsilon_{in}) \\ &= \Pr(\varepsilon_{jn} - \varepsilon_{in} \leq V_{in} - V_{jn}) \end{aligned} \tag{5.5}$$

When offered a choice between competing J vehicle powertrains, the *aggregate* probability of certain vehicle type j being preferred over others is given by:

$$P_j = \frac{e^{\sum_{a=1}^{A} \beta_a X_{ja}}}{\sum_{j=1}^{J} e^{\sum_{a=1}^{A} \beta_a X_{ja}}} \tag{5.6}$$

In the U.S. light-duty vehicle (LDV) market, two distinct classes of vehicles, namely cars and light-trucks, are sold. Cars can be further classified as sedans and wagons, and light-trucks can be classified as sport utility vehicles, minivans and pick-up trucks. Each of these categories can be further divided into small, medium, and large size sub-category. Within each category, the vehicles share certain attributes and attract a consumer base whose utility functions are similar. A nested logit model can be used in such cases where the choice set can be deconstructed in to nests in which consumers have similar preferences. Greene et al. [2004] formulated a nested logit model for estimating the potential of hybrids and diesels in the U.S. LDV market. In the nested logit model formulation used by Greene et al.:

$$u_{ij} = b\left(A_i + \sum_{l=1}^{K} \beta_l X_{il} + \varepsilon_{ij} \right) \tag{5.7}$$

where,

- u_{ij} is the ranking score for the i^{th} make and model for the j^{th} individual,
- β_l the weight of the l^{th} attribute, X_{il} , and
- ε_{ij} is the j^{th} individual's random component for the i^{th} make and model
- A_i is a constant term reflecting value
- b is the coefficient of price (price slope)

The probability that a consumer will choose a vehicle from class k is based on the expected utility of class k defined as:

- $$U_k = \frac{1}{b}\ln\left(\sum_{i=1}^{n_k} e^{u_{ik}}\right) \tag{5.8}$$

The probability that consumer will choose a vehicle from class k, and the probability of choosing the i^{th} make from the k^{th} class can then be determined from applying equations 5.8 and 5.7 respectively to equation 5.6.

Estimation of attribute coefficients (β) is tricky.

Discrete choice models offer an elegant path to modeling the plausible market penetration rates of advanced propulsion systems based on vehicle attributes. The validity of such a model will depend upon the ability to estimate the weights or preferences (β) assigned to different attributes. The βs normally have to be estimated from a procedure such as maximum likelihood method using data obtained from consumer survey results, or from other methods.

For propulsion systems that are already available in the market, a choice model may be able to estimate these values based on existing market shares. For propulsion systems that are not available, it will be necessary to resort to stated preferences. Cook [1996] developed a measure of product value based on ideal, nominal and worst level of attributes, assuming these levels are already known or can be established based on expert surveys.

Consumer preferences are also likely to vary between different propulsion systems. For example, diesel vehicles are able to deliver a better torque at low speeds, which is preferred by a certain class of customers who have to tow large loads. Vehicles with electric propulsions systems such as electric or fuel cell vehicles might be able to accelerate faster than conventional ICE vehicles, but their ability to sustain performance at high loads might be lower than ICE vehicles. In such cases, neither appropriate data nor appropriate market segmentation is available, and the resulting parameter estimation will be highly biased.

Can β be aggregated for all consumers, or are early buyers different from majority buyers?

People buy vehicles for a number of different reasons which are often not captured explicitly by demand models. This is particularly true with the early adopters of the technology. Heffner et al. claim that *beliefs, values and social status* all play a vital role in consumer's decision to purchase a certain type of vehicle [2007]. They may choose a particular type of vehicle, for example, to make a statement about the viability of an advanced technology, or to demonstrate their commitment to environmental attributes of vehicles [Maynard, 2007]. For example, studies of hybrid consumers in California during 2004-2005 revealed that consumers may be willing to trade off some functionality in return for the image benefits gained from ownership of hybrid vehicles. It is, however, too simplistic to explain the initial sales of hybrid vehicles based on image alone [Heffner et al., 2005; Heffner et al., 2007].

The Argonne national Laboratory has developed a new vehicle choice model called Advanced Vehicle Introduction Decisions (AVID) to take into consideration the preferences of early majority of buyers of advanced vehicle technologies [ANL, 2005]. AVID model distinguishes between an early group consisting of early adopters and early buyers, and the later majority. They estimate that the early group accounts for 15 percent of new vehicle sales market, and its members are more likely to consider advanced fuel efficient technologies than the later majority. This distinction is helpful for modeling purpose because if the preferences of majority were applied, then new vehicle technologies would show little market penetration until those vehicles were available across all categories.

Cao and Mokhatarin reviewed nine different models for consumer models of conventional vehicles and six different models of alternatively fueled vehicles [2004]. While they concede that previous forecasts of choice models have yielded lackluster results, they also point out that the usefulness of these forecasts is not in the actual numerical results, but in preparing scenarios of market penetration of different vehicle technologies.

Finally, customer preferences about different vehicle attributes can change dramatically over a long period of time. For example, vehicle quality and safety considerations have become far more important over time as shown in Table 14 [DOE, 2007]. Over a period of 25 years the relative importance of fuel economy compared with quality and safety has gone down, although fuel economy seems to be gaining traction in the wake of increasing gasoline prices since year 2004.

Table 14 Trends in Vehicle Attribute Preference [DOE, 2007c]

Q: Which one of the following attributes would be most important in your choice of your next vehicle?

Year	Fuel Economy	Dependability	Low Price	Quality	Safety
1980	42%	31%	14%	4%	9%
1981	20%	40%	21%	7%	12%
1983	13%	38%	30%	11%	9%
1985	8%	41%	29%	12%	10%
1987	4%	44%	31%	8%	14%
1996	7%	34%	11%	19%	29%
1998	4%	36%	5%	20%	34%
2000	11%	33%	11%	22%	24%
2001	11%	30%	8%	22%	30%
2004	22%	26%	10%	19%	23%
2005	12%	33%	7%	21%	28%
2006	20%	28%	7%	20%	26%
2007	21%	30%	7%	17%	24%

Source: http://www1.eere.energy.gov/vehiclesandfuels/facts/2007_fcvt_fotw484.html

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. Primarily this could 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. Engineering and development of a "new" propulsion system have to take considerations about 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 fifteen years to become available across all market segments. Figure 35 shows the deployment of different engine and transmission technologies in the US 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 ten to fifteen years to penetrate to half of new vehicles, whereas automatic transmissions, having reached half of the market by 1950, required twenty more years to be available in 90% of the vehicles.

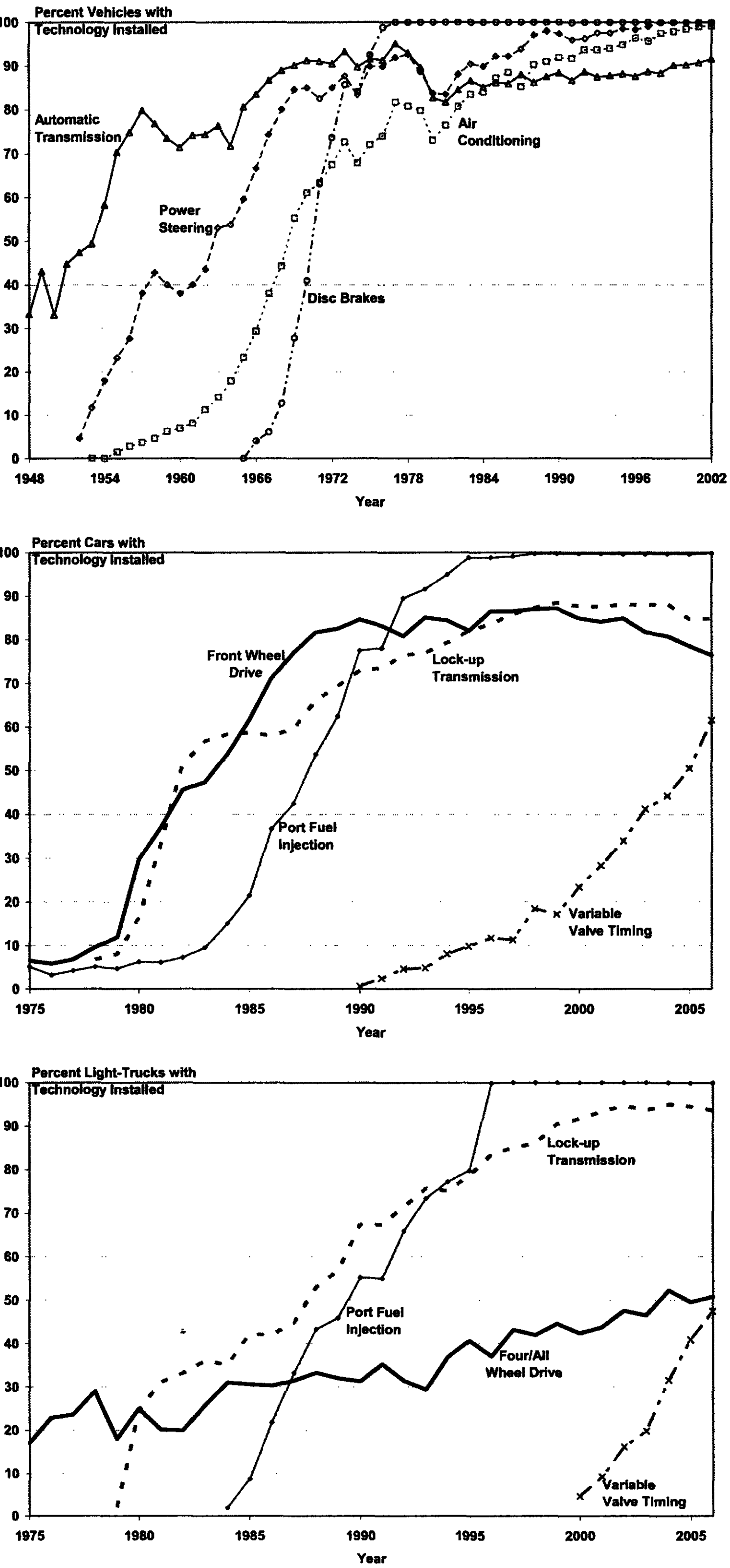


Figure 35 Technology Deployment in New Vehicles, 1948-2006 [Ward's 2003; Heavenrich, 2006]

Based on a broad survey of technological change in automobile industry, Nakicenovic [1986] observed that it took 10 to 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 components or sub-systems shown in Figure 35. 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 battery 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: [Priddle, 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."*

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

- <u>Capital investment required</u>: 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 twelve to eighteen 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 15]. Note that this does not include the costs of engineering and development of these vehicles.

Table 15 Estimated Tooling and Equipment Investment to Convert Brownfield Sites to Produce Hybrids and Diesels (in 2004 Dollars)

		Capital Costs in 2004 Million Dollars	
		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 dollars respectively. For comparison purpose, the US Census Bureau estimates that the annual capital expenditure of motor vehicle manufacturing sector is about 20 billion dollars [US Census, 2007].

- 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 four to ten 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 on the critical path for 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 timescales 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 16.

Table 16 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 on board 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. The definition of market competitive technology used by Schafer et al. is somewhat vague. It is assumed here that for a technology to be market competitive, it must be available across a wide 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 16 represent the 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. Table 17 shows an early 2006 survey of major vehicle manufacturers and their timetables for launching a hydrogen fuel cell vehicle. The table suggests that a commercial mass market fuel cell vehicle is at least 12-15 years away.

Table 17 Fuel Cell Vehicles: Current Timetable for Launch [Adamson and Crawley, 2006]

Manufacturer	Year	Number	Notes
DaimlerChrysler[8]	2012 2015	10,000	Initial Launch Mass Market
Ford Motor Company	2015		Commercial Readiness
General Motors	2010-2015 2025		Commercial Viability Mass Market
Honda	2010[9] 2020	12,000 (US) 50,000 (US)	Start of Production
Hyundai	2010		Road tests in 2009
Toyota	2015		Will cost $ 50,000

In the second stage of technology implementation shown in Table 16, penetration across new vehicle market is meant to represent a timescale 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 timescale reflects the expectations about large scale viability of these propulsion systems based on engineering and cost constraints, and are similar to the timescales required by major vehicle technologies to achieve a large market share. Figure 36 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 years 2012-2015.

The third stage of technology implementation represents the actual use phase of these vehicles. A meaningful reduction in fleet fuel use is not realized until a large number of more fuel efficient vehicles have been driven for several years. This can happen over a timescale of the median lifetime of vehicles, which is around 15 years.

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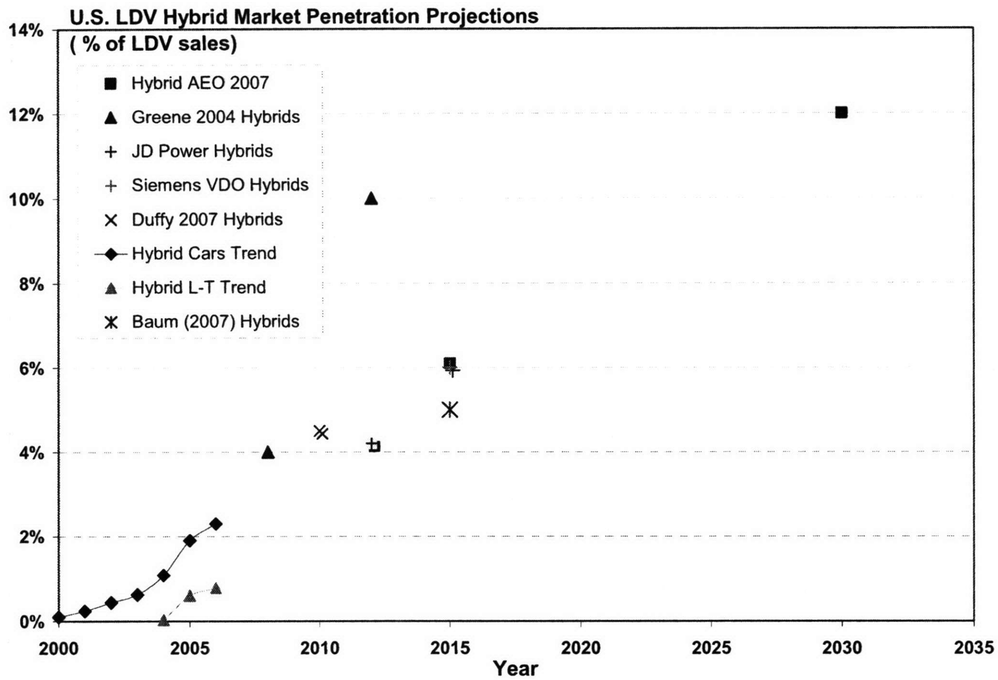
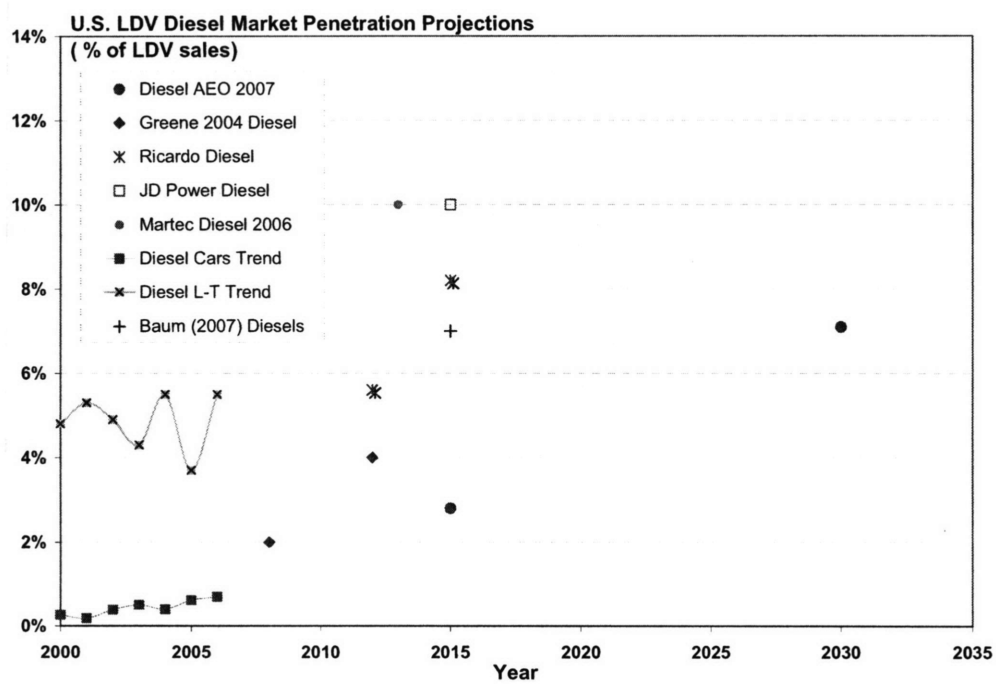
[8] At the time of survey Chrysler was a part of DaimlerChrysler.
[9] Honda has announced that it will start leasing its hydrogen fuel cell vehicle in parts of California in year 2008 at a price of 600 dollars per month [Sabatini, 2007].

Thus, the three phases summarized in Table 16 provide a rough estimate of the timescales to 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.



(a) Hybrid Market Share Projection



(b) Diesel Market Share Projection

Figure 36 Various Forecasts of U.S. Light-Duty Vehicle Diesel and Hybrid Market Penetration

Two Examples of "New" Propulsion System Introductions

This section presents two examples of market penetration of different propulsion systems in a gasoline ICE dominated market. The first is the growth of diesel vehicles in Europe and the second is the growth of ethanol fueled vehicles in Brazil. These case studies can yield some insights into projecting the future market share of advanced propulsion systems in the U.S. light-duty vehicle market.

Growth of Diesel Vehicles in Europe

After stagnating in the single digits for several decades, the diesel engine powered vehicles have increased their market share in Western Europe to about 50% in 2005 in the past twenty five years. This success has neither been monotonic nor been uniform across different European markets as shown in Figure 37.

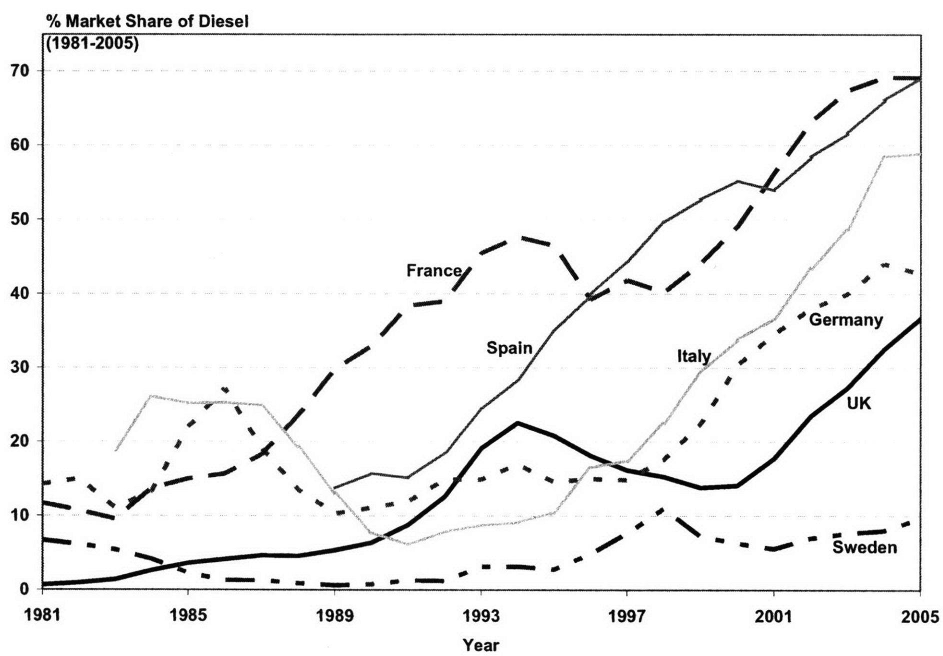


Figure 37 Market Share of Diesel Vehicles in Major European Countries (1981-2005)

Diesel vehicles became popular in France in the 80's, and continued their growth in the 90's. The German auto market, on the other hand, saw the market share of diesels rise very rapidly in early part of the eighties only to see it decline back to its 1980 market share by the end of the decade. This difference is partly explained by the differential taxation of diesel and gasoline as well as lower car taxes on diesel vehicles in France. Figure 38 shows the difference between gasoline and diesel taxes in four different countries. Notice that Germany started to match the (gasoline-diesel) price gap through differential taxation only since mid-nineties.

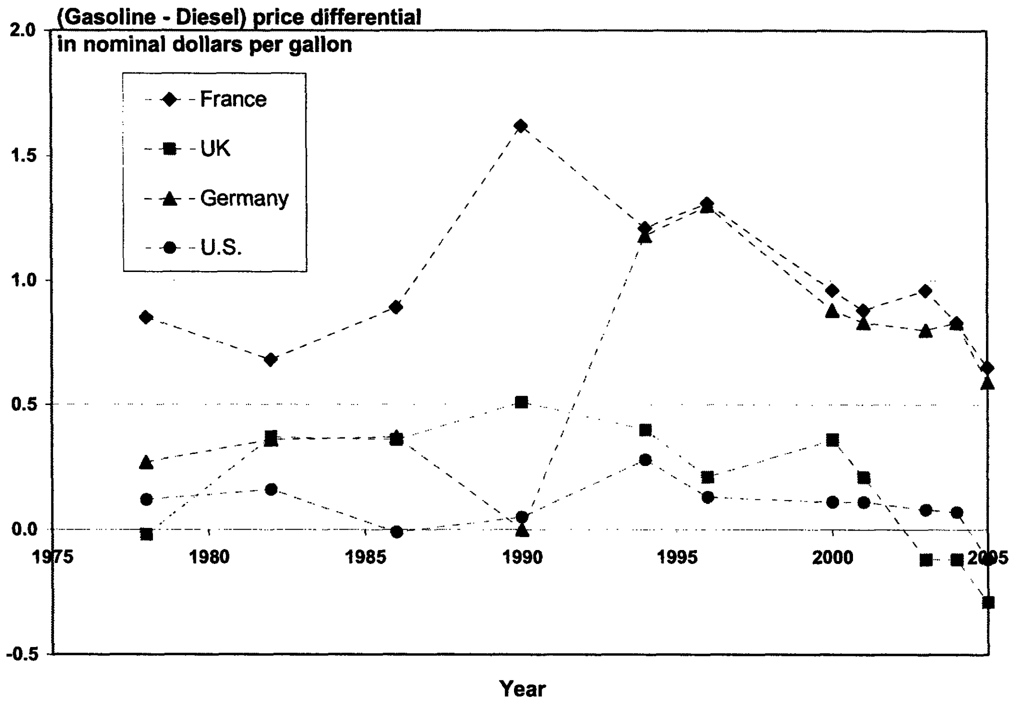


Figure 38 Difference Between Gasoline and Diesel Prices in Four Different Countries (1978-2005)

Some have argued that it is the industrial and tax policy of some European nations, chiefly France, has led to vigorous interest in diesels [Jackson and Loehr, 2005]. Others maintain that the diesel technology has improved dramatically over the same period, and is largely responsible for diesel growth story [Penny, 2002]. For example, the greater demand for diesel vehicles in countries such as Italy and Spain occurred after the introduction of direct injection in the early 90's and common rail injection systems in the late 90's.

Diesel vehicles have traditionally faced the challenge of meeting increasingly stringent emissions standards. Note the dip in diesel market share in UK, Germany and France from 1994-1998. Much of the loss of market share was attributed to the particulate emissions from diesel vehicles. This forced the vehicle manufacturers to speed up the development of particulate traps for diesel exhaust [Ng, 2006]. In the end, the rapid growth of diesels in France, Spain, Italy, Belgium and Austria helped the diesels gain a third of the western European market by 2000.

In July 1998, the association of European car and truck manufacturers (ACEA) made a voluntary commitment to reduce new car CO_2 emissions to achieve a new car fleet average CO_2

target of 140 g/km (~ 40 miles per gallon) by 2008 – which represents a 25% reduction from 1995 or a 33% improvement in fuel economy [ACEA, 2002]. European vehicle manufacturers have used dieselization as a strategy to meet this objective. Countries such as the United Kingdom have established a graduated system of excise duty based on CO2 emissions per kilometer [ECMT, 2007]. A similar proposal is under discussion in Sweden which has seen market share of diesel vehicles double from 9.7% in 2005 to 19.4% in 2006.

Having already achieved a fifty percent market share in Western Europe, it is not clear if there is room for diesel vehicles to grow further. As the market share of diesel vehicles has increased, the governments in different countries have began to loose out on tax revenue due to preferential taxation of diesel vehicles and fuel, and may choose to remove the differential pricing scheme. As Europe moves towards more stringent NOx emissions standards (Euro-6), diesel vehicles will likely incur an additional cost penalty due to exhaust treatment. As a result, the market share of diesels in Western Europe is expected to saturate between 55-60% in the coming decade [Rutecki, 2005; J.D. Power, 2006].

Ethanol powered vehicles in Brazil

Brazil is the second largest producer of ethanol in the world after U.S., and the use of ethanol as transport fuel is not new to Brazil[10]. The escalation of oil prices in the 1970's posed a serious balance-of-payment problem for Brazil. At the same time, world sugar prices were declining rapidly in 1975 after having shot up in the early part of the decade. This prompted the use of ethanol from sugarcane as a transport fuel at a large scale [Geller, 1985]. The 1975 government program called "ProAlcool" set the price of pure alcohol below gasoline price and offered a tax incentive on purchase of ethanol-only vehicles. The program also offered generous loans of up to 30% of total capital expenditure for ethanol production [Moreira and Goldemberg, 1999]. In addition, the *ProAlcool* program mandated the Brazilian oil company Petrobras to purchase all ethanol manufactured in Brazil, and install ethanol pumps at every fueling station in the country. As a result of these policies, the sales of ethanol only vehicles took off starting in 1979. By 1985, 96% of the new vehicles sold in Brazil were ethanol only vehicles [ANFAVEA, 2006].

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[10] For a fascinating discussion of Brazilian policies to promote use of ethanol from 1931-1985, and the decision-making process behind those policies, see MIT PhD dissertation of Maria Helena de Castro Santos [Castro Santos, 1985].

In 1986, Saudi Arabia gave up its role as a swing producer of crude oil, and allowed the oil prices to collapse. At this point, it became prohibitively expensive for the Brazilian government to continue to subsidize ethanol production, even though the cost of producing ethanol had halved from about 140 dollars per barrel in 1981 to 70 dollars per barrel in 1989 [Moreira and Goldemberg, 1999]. Absent government support, the farmers steered sugarcane production away from ethanol and towards sugar. The resulting shortages of ethanol dramatically altered the attractiveness of alcohol only vehicles, and their market share dropped below 30% in early 90's. By 1996-97, alcohol only vehicles accounted for only 0.1% of new vehicle sales in Brazil (Figure 39).

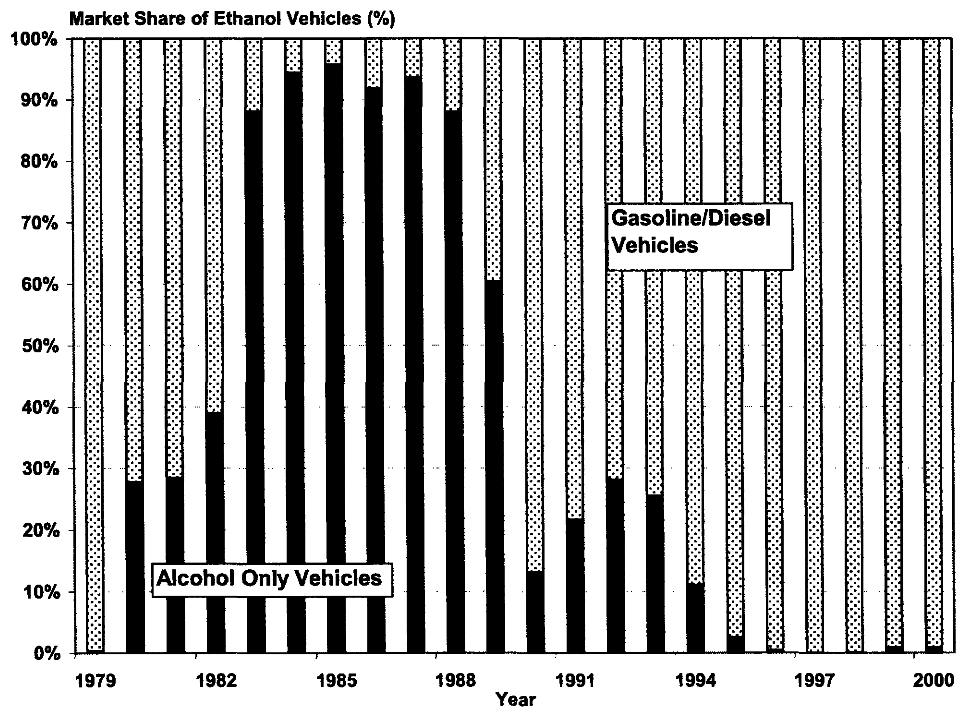


Figure 39 Market share of Alcohol, and Gasoline Vehicles in Brazil (1979-2000)

In spite of the spectacular boom and bust in alcohol only vehicles, ethanol in Brazil continued to retain several advantages. Firstly, the improvement in technology and learning enabled the cost of producing ethanol to drop below 50 dollars per barrel by year 2000. The government also continued its preferential tax treatment of alcohol as a transport fuel, while ratcheting the amount of ethanol to be blended in gasoline up to 22%. This set the stage for introduction of Flexible-Fuel Vehicles (FFVs) at the same time when global oil prices were once again in an upward trend.

Several factors have contributed to the rapid market penetration of FFVs in Brazil. First, the FFVs are capable of taking in any blend of gasoline and ethanol. Second, while FFVs require many vehicles components to be modified, they do not require an overhaul of vehicle production and assembly operations. Third, although FFVs cost typically only about 200 dollars more than their conventional gasoline only counterpart, the Brazilian government gives the FFVs the same preferential tax treatment as alcohol only vehicles. Finally, for the customers, FFVs provide a convenient hedge against increasing fuel prices. Since the *ProAlcool* program ensured availability of ethanol at all pumping stations, consumers are now free to choose the fuel that is cheaper at the time of filling up their tank. As a result, the sales of FFVs have skyrocketed after their introduction in May 2003 (Figure 40).

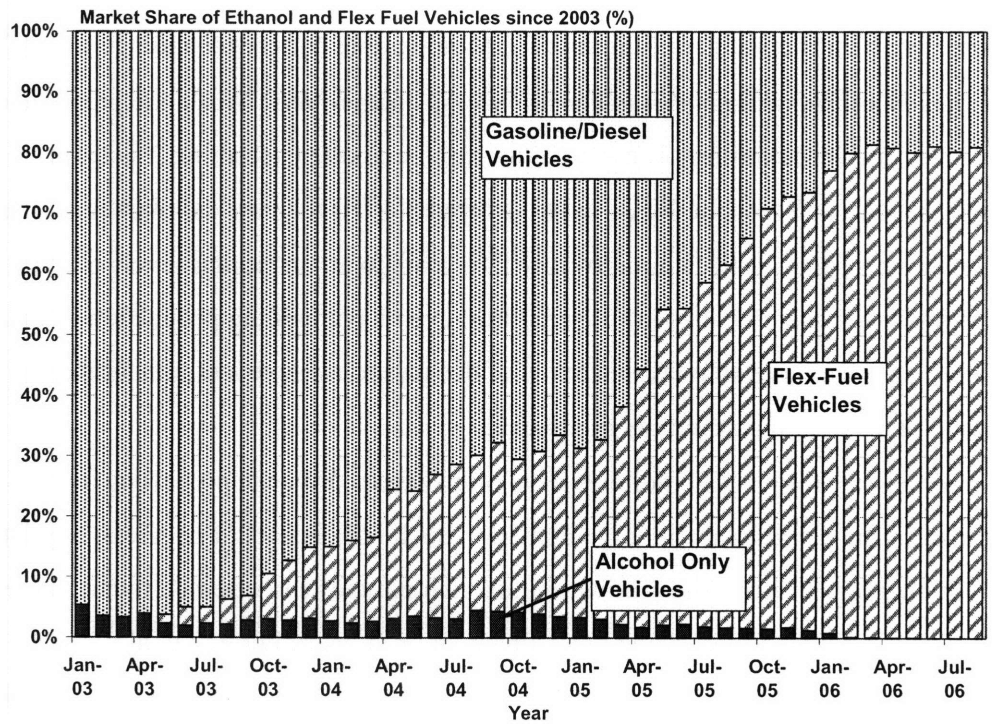


Figure 40 Market share of Alcohol, Gasoline and Flex-Fuel Vehicles in Brazil since 2003 [ANFAVEA, 2006]

In spite of the long history of ethanol fueled vehicles, the growth in new FFV sales in Brazil is rather impressive. As of August 2006, there were 7 brand names selling at least 41 different models of FFVs. The current light-duty vehicle market size in Brazil is around 1.6 million units per year, with FFVs accounting for over a million units in 2006. Based on the previous experience however, it would be premature to conclude that Flex-Fuel Vehicles represent the future of personal transportation in Brazil. It would be even more optimistic to conclude that Brazil's success can be replicated elsewhere, especially in the United States where the new car market is nine-to-ten times as large as Brazil.

Lessons from Europe and Brazil

The main lessons from the roller coaster ride of ethanol fueled vehicles in Brazil, and somewhat less volatile growth of diesel vehicles in Europe appear to be as follows:

- ***Availability of <u>market competitive</u> technology is critical***: Without development of common rail injection systems or sensor and electronic control units, neither diesel vehicles nor flex-fuel vehicles would have gained popularity. In either case, the absolute cost premium of the technology option was small relative to the realized benefit. Some caution is warranted in extrapolating these trends to a plug-in hybrid, for example, since the same can not be said as emphatically about the status of lithium-ion or comparable battery technology in 2007.
- ***Timescales to substantial market penetration vary quite widely***: While the presence of a market competitive technology is essential for rapid market penetration, it is hardly a sufficient condition. So, while FFVs have cornered 3/4th of the new car market in Brazil within a matter of four years, it took twenty five years to attain similar levels of market penetration with diesel vehicles in France. Thus, even a compelling propulsion technology alternative can be expected to take a couple of decades to achieve a dominant market position depending on costs and complexity of change.
- ***Policy matters!***: Strong public policies have often been a driver in propelling a new vehicle technology in the marketplace in large numbers. Such policies could be fiscal, regulatory, or some combination thereof. The motivation for such policies can often be found in the need of national governments to meet some other financial or industrial policy goal. Finally, sustained policy efforts are needed to sustain the growth of new technology beyond the early adopters to an early majority of consumers.
- ***Setbacks are to be expected***: Either due to changes in the level of policy support or other market conditions, the growth in new vehicle technology can be set back several years to a decade. Concerns about particulate matter saw the growth in diesel vehicles in Europe stall for much of late 1990's. Alcohol fueled vehicles all but disappeared in the 1990s from Brazil. It is important to note that once the exogenous conditions were addressed, diesel and ethanol powered vehicles resumed their growth in the marketplace.

Scenarios of Market Penetration Rates

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, 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 13 and Table 10, 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 a thousand dollars. Presently, the market share of turbocharged gasoline vehicles in Europe is about 14% as compared to less than half of one percent in the United States. The market share of turbocharged gasoline vehicles is expected to top 22% by year 2010 in Europe. While the turbocharged gasoline vehicles have been slow to take off in the United States, market shares similar to those projected in Europe by the early 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. The 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 to 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 formation 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 all but disappeared from new vehicle sales mix, as shown in Figure 41. While diesel sales in the 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.

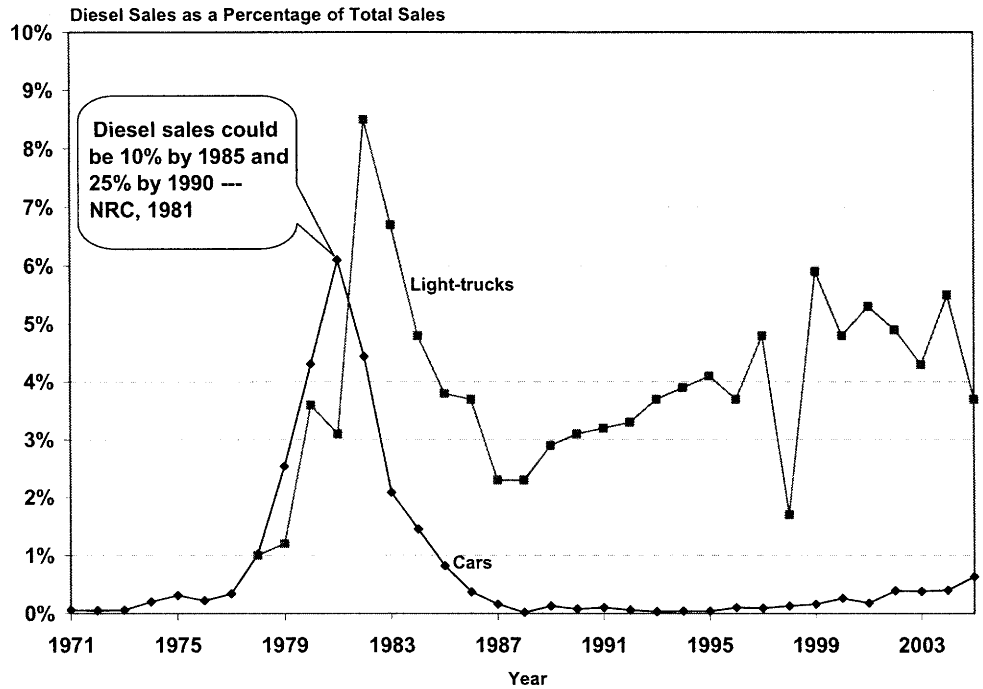


Figure 41 Market Share of Diesel Vehicles in US (1971-2005) [Davis and Diegel, 2007; NRC 1982]

As discussed in the previous section, diesels have penetrated the European markets rapidly, especially since arrival of common rail injection systems in the 1990s. They have failed, however, to make any progress in the U.S. market due their inability to meet the strict criteria air pollutants standards in California and other states which adopted California standards. The emissions standards for NOx and hydrocarbon emissions in Europe have been less stringent in Europe than in the U.S. in the past (Figure 42). While the Euro V and VI standards for gasoline engines approach the U.S. Tier II Bin5 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 1970s and 1980s diesel engines, the new clean diesel still needs to overcome the *perception* of diesel as a smoky, noisy engine. The reduced emissions from clean diesels come at a fuel economy penalty of 2-3%, and an added cost of several hundred dollars. This added cost of 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 in diesel car market in the U.S.

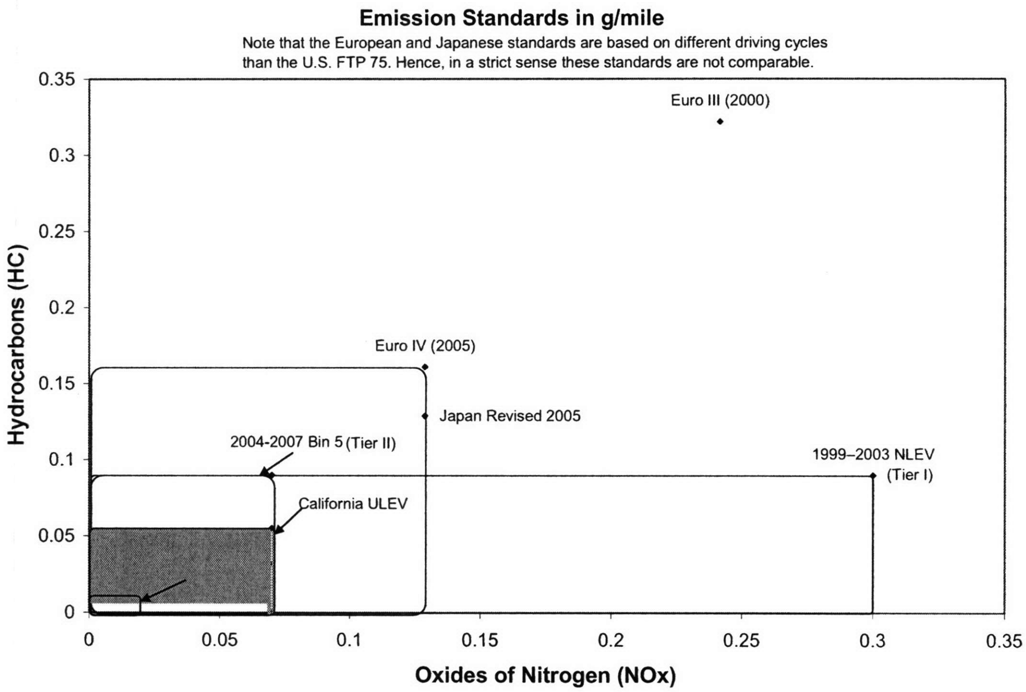


Figure 42 Emission Standards for NOx and Hydrocarbons from Motor Vehicles

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. Over this period the awareness about hybrid technology has grown rapidly. While hybrid vehicles still sell at a large premium 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 vehicle. 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.

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. Toyota Motor Corporation announced in July 2007 that it has plans to test several PHEVs on road in Japan, US, and Europe [Toyota, 2007]. General Motors intends to put its Chevrolet Volt Plug-In Hybrid Concept vehicle in production around 2010 [GM, 2007]. Ford Motor Company has announced a partnership with Southern California Edison Company to test twenty 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 2015-2017 timeframe [Kromer and Heywood, 2007; DOE, 2007a].

Based on the discussion so far, three scenarios for market penetration of different propulsion systems in the U.S. LDV market are described below. These scenarios are meant to be representative of plausible evolution of technology in the U.S. LDV market to illustrate the impact of new vehicle technologies on fleet fuel use, and lack a predictive component. As shown in Figure 43, the three scenarios explore three possible directions in which the U.S. light-duty vehicle market can evolve.

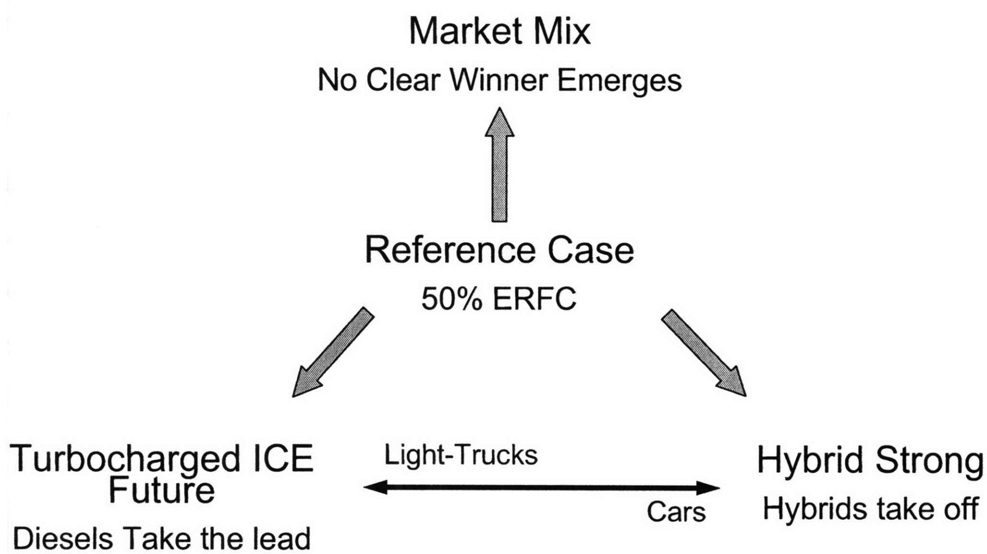


Figure 43 Scenarios for Market Penetration Rates of Advanced Propulsion Systems

The *market mix* scenario represents a muddling through in to the future as no particular propulsion system dominates the LDV market over the next three decades. The *turbocharged ICE future* represents a continuing dominance of internal combustion engines, but with an increasing emphasis on turbocharged gasoline engines as well as advanced diesels. The *hybrid* *strong* scenario presents the possibility that gasoline hybrids and plug-in hybrids emerge as the dominant powertrain combinations.

Following along the lines of the reference scenario described in Chapter 4, the three scenarios assume that increases in fuel efficiency are utilized evenly between reducing fuel consumption and increasing vehicle performance (50% Emphasis on Reducing Fuel Consumption). The fleet model can model both a linear and S-shaped growth in market shares up to year 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 16 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.

Market Mix – No Clear Winner Scenario

A plausible scenario is that no clear winner emerges, and the LDV market in the U.S. 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 modest proportions. Plug-in hybrids (PHEVs) establish a niche for themselves among primarily 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 a 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 taking over majority of new gasoline vehicles sales around 2040 as shown in Figure 44.

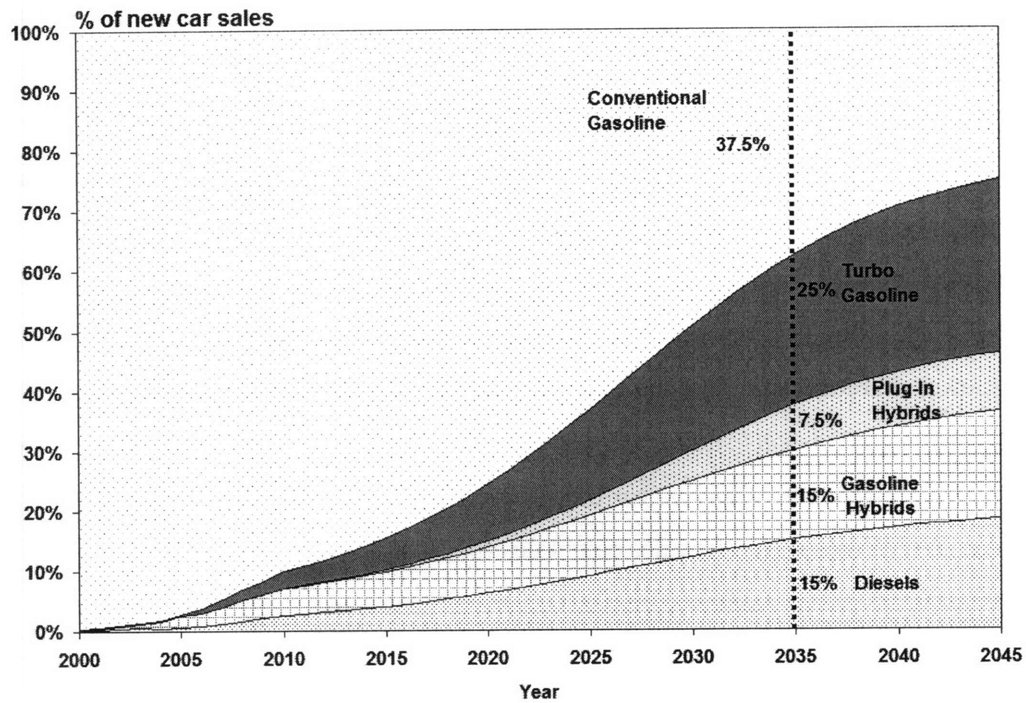
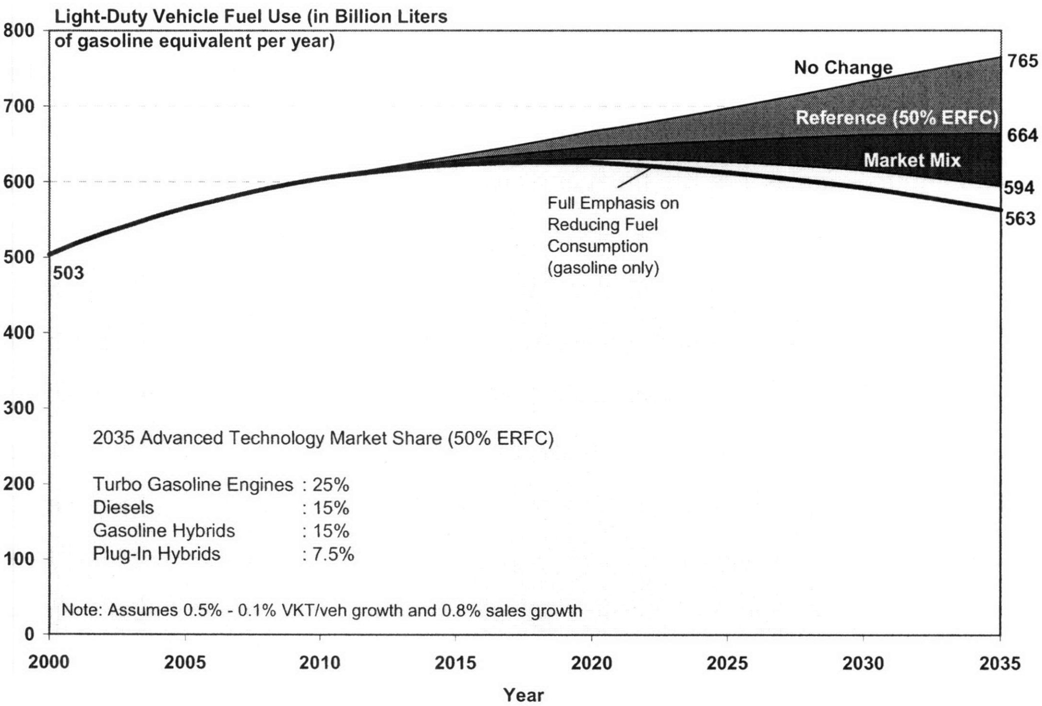


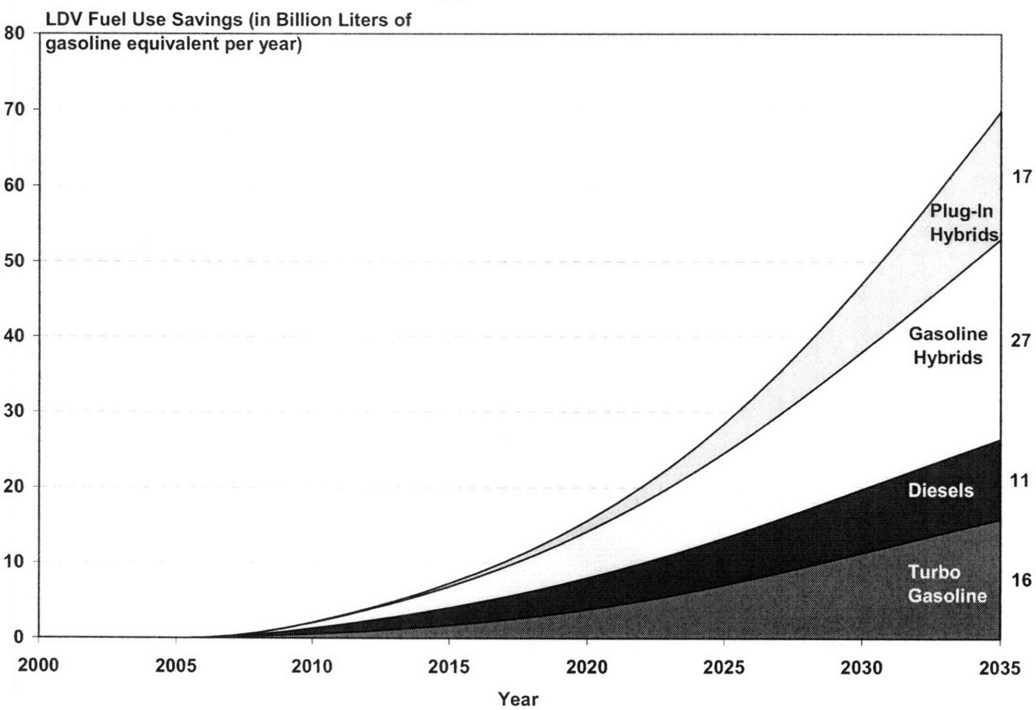
Figure 44 Market Mix – No Clear Winner Scenario

Figure 45 (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.

Figure 45 (b) shows the contribution of different propulsion systems in reducing LDV fuel use. The cumulative fuel savings over this 25 year period are 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 indeed quite strong. The GHG emission reductions realized from PHEV are not as high is discussed in Chapter 6.



(a) LDV Fuel Use



(b) Contribution of different propulsion systems in fuel savings

Figure 45 LDV Fuel Use under Market Mix Scenario

Turbocharged ICE Future Scenario

In a 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 markets. Diesel vehicles under this scenario could garner approximately 40 percent of the market share by 2035, and their market share could approach 50 percent by mid-century (Figure 46). This represents a forty-year compounded annual growth rate of 12 percent for diesel cars and 6 percent for diesel light-trucks. Turbocharged gasoline vehicles follow similar growth pattern, and take over conventional gasoline vehicles sales by 2030, and eventually replacing all conventional gasoline vehicles by 2040. Notice that under this scenario more than 50 percent of new vehicles sold in 2025 have alternate propulsion system.

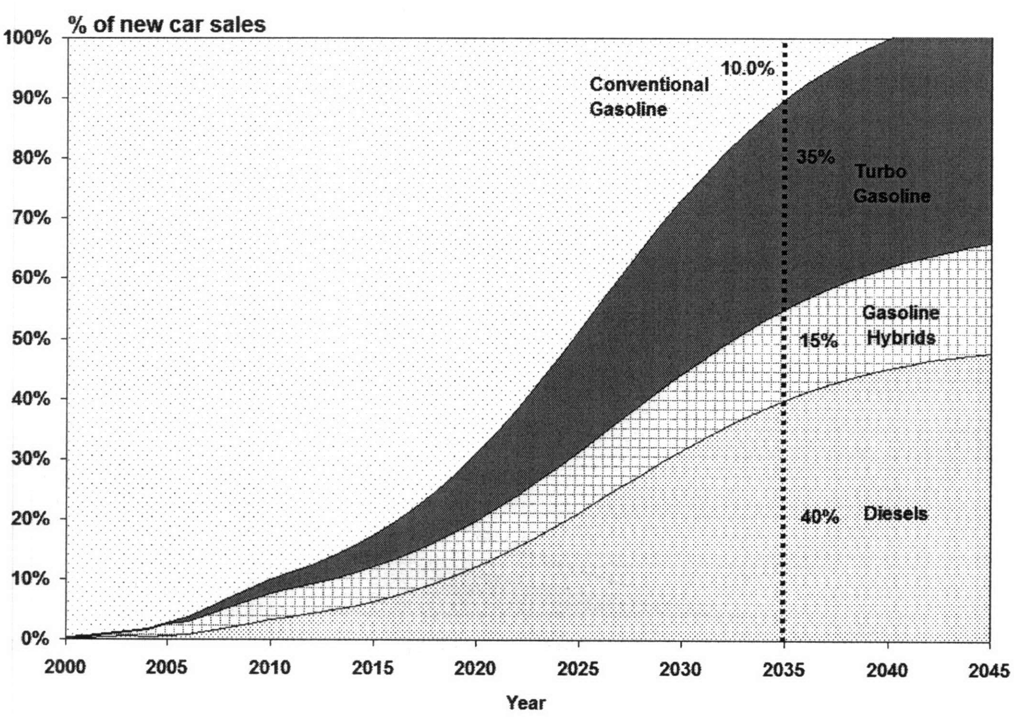


Figure 46 Turbocharged ICE Future Scenario

LDV fleet fuel use under the Turbocharged ICE Future scenario is shown in Figure 47. Fleet fuel use in 2035 in this scenario is approximately 12% lower than the reference case. When compared with Market Mix scenario, the 2035 fleet fuel 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 start to diverge significantly only after 2025.

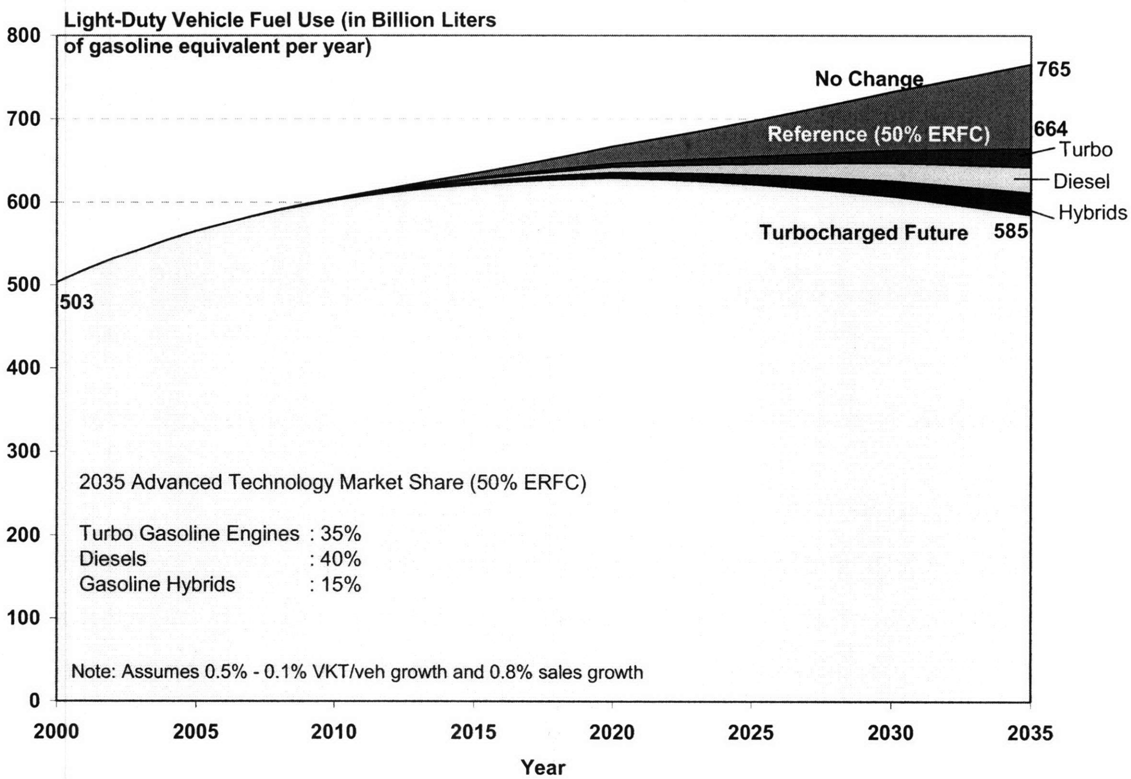


Figure 47 LDV Fuel Use under Turbocharged ICE Future Scenario

As the market share of diesel fueled vehicle grows, the amount of diesel fuel as a fraction of LDV fuel increases dramatically. In 2005, diesel fuel accounted for approximately 2 percent 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 percent on 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 48). 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 a turbocharged ICE Future scenario, a large change in the quantity of diesel fuel demanded for LDV applications will likely 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 modest.

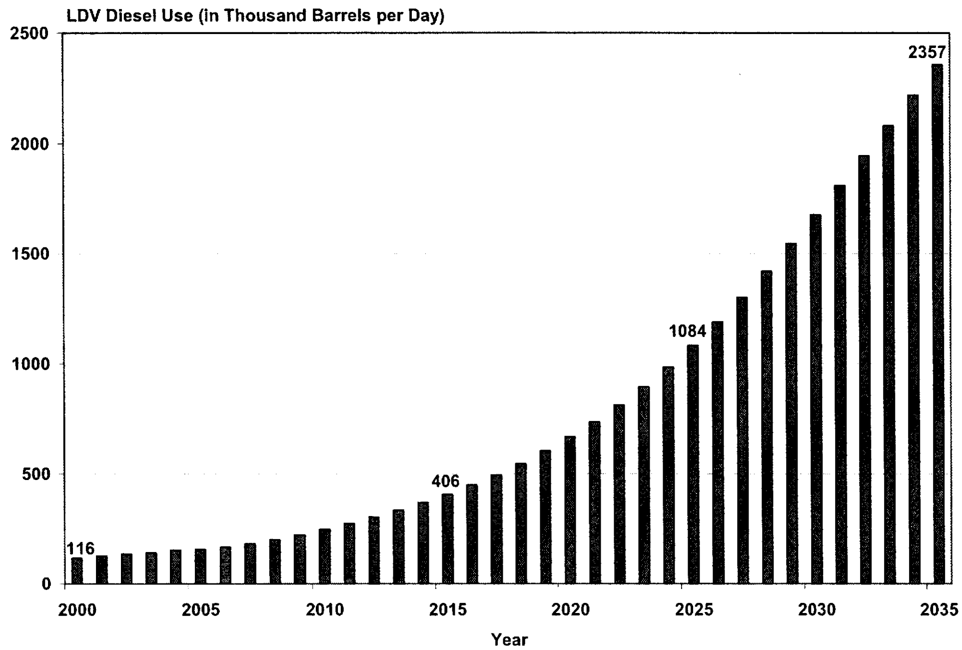


Figure 48 U.S. LDV Diesel Demand for Turbocharged ICE Future Scenario

Hybrid Strong Scenario

In a Hybrid Strong scenario, hybrid vehicles emerge from their current niche 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 forty-year compounded annual growth rate of 8 percent for hybrid cars and 11 percent 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 percent by 2035 and 20 percent 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 percent of the new vehicle sales in the U.S. LDV market are conventional ICE gasoline vehicles as shown in Figure 49.

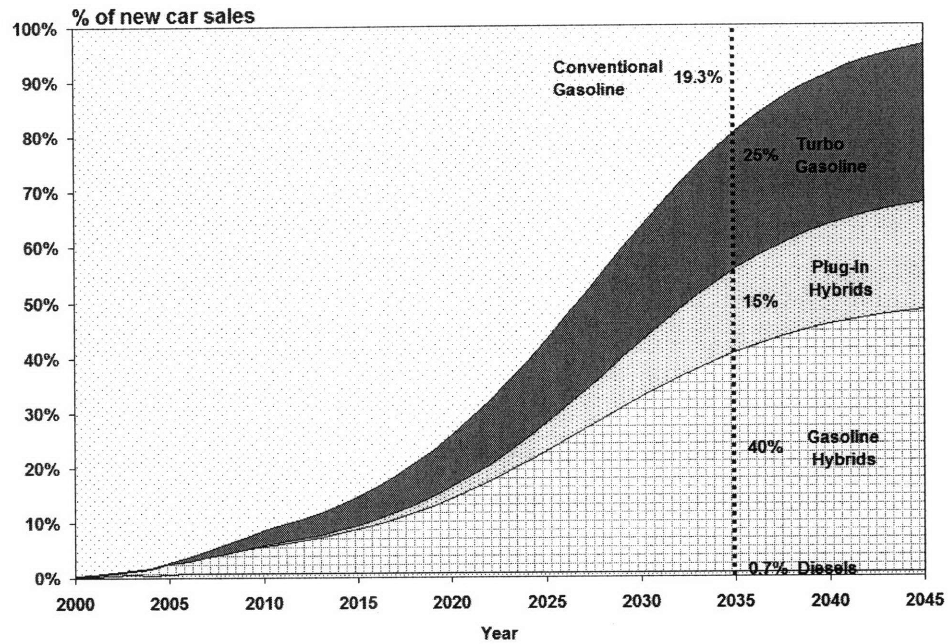


Figure 49 Hybrid Strong Scenario

When compared with the previous two scenarios, Hybrid Strong scenario achieves the greatest reduction in fuel use (Figure 50). Not only is the 2035 fuel use in this scenario lower by 18 percent from the reference case, this is the only scenario among the three which has lower 2035 fuel use than the case with 100 percent 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 Hybrid Strong scenario are more than 1040 billion liters, 60 percent of which come from gasoline hybrid vehicles.

Hybrid Strong scenario also demonstrates the potential of plug-in hybrid vehicles to reduce petroleum use in a relatively short period of time. Even though the market share of PHEVs in this scenario is only 5 percent by 2025, compared with 15 percent 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 percent.

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 percent ERFC and a substantial penetration of advanced vehicles, growth in the LDV fleet fuel use over the next decade has already been committed.

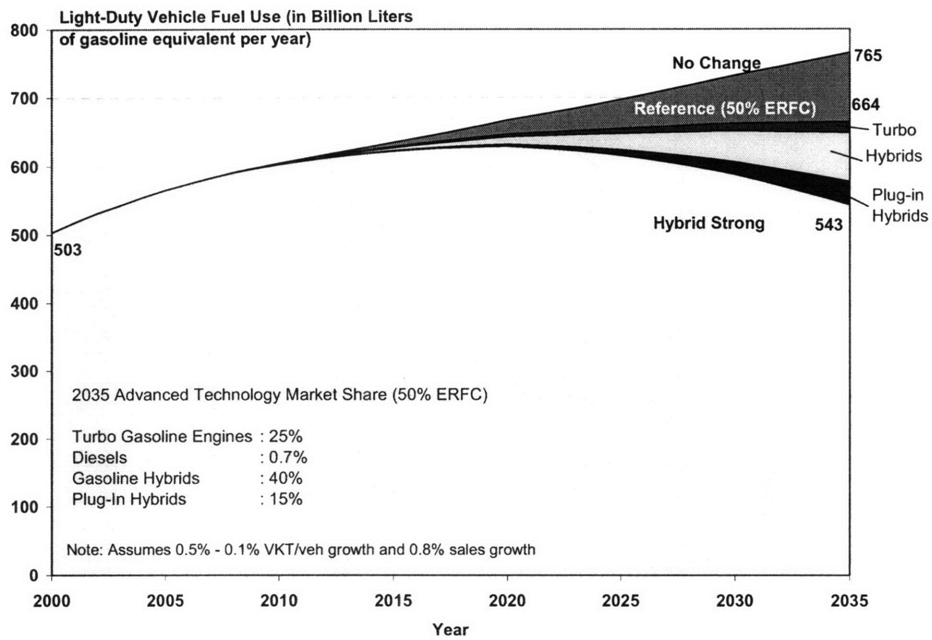


Figure 50 LDV Fuel Use under Hybrid Strong Scenario

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

Table 18 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	11	11	11.2	11	11	634	697	765
Reference	50%	10.6	9.8	9	11.1	10.3	9.5	629	655	664
Gasoline only	100%	10.2	8.6	6.9	11	9.7	8	623	612	563
Market Mix	50%	10.3	9	7.5	11	9.9	8.5	621	626	594
Turbocharged Future	50%	10.3	8.9	7.4	11	9.8	8.4	621	622	585
Hybrid Strong	50%	10.3	8.5	6.2	11	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 fleet fuel consumption from No Change in 2035. This is reflected the fleet fuel use across scenarios in year 2015. None of the scenarios achieve more than 2% reduction in LDV fleet fuel use by 2015 when compared to 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 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.

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

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 heavy-duty applications. Therefore, there is a reason to believe that diesel and hybrid vehicles will penetrate at different rates in passenger car and light-truck market. This scenario is evaluated by combining the market penetration rates from Turbocharged ICE Future and Hybrid Strong scenarios. The market penetration rates from the Hybrid Strong scenario are applied to the cars and from the turbocharged ICE Future are applied to the light-trucks.

Figure 51 shows the results of this combined scenario. As can 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/100km. It should be noted that the results of this scenario match very closely with the gasoline only (100% ERFC) scenario.

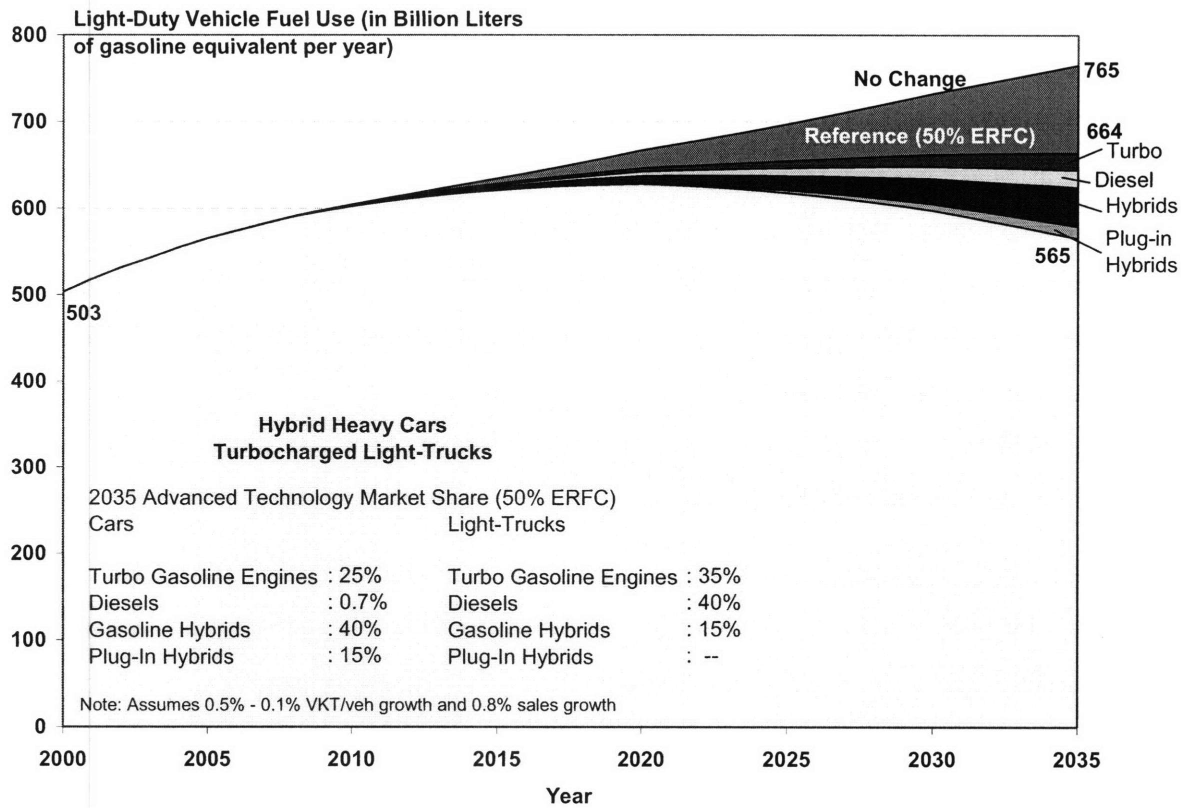


Figure 51 LDV fleet Fuel Use under Hybrid Strong Cars and Turbocharged Light-Trucks Scenario

2) Increasing the emphasis on reducing fuel consumption in the Hybrid Strong scenario

Hybrid Strong scenario, which resulted in the most fuel savings of all scenarios, assumes a 50 percent emphasis on reducing fuel consumption. In a world of ever increasing concerns about impacts of climate change and petroleum security, a larger emphasis may be placed on reducing fuel consumption. Figure 52 shows the impact on LDV fleet fuel use when ERFC is increased from 50 percent to 75 percent and 100 percent.

LDV fleet fuel use in year 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 percent ERFC. Figure 52 shows that by increasing the emphasis on reducing fuel consumption from 50 percent to 100 percent, the 2035 fleet fuel use could be reduced by a further 10 percent from No Change scenario. This represents a cumulative fuel savings of 850 billion liters over the fuel savings in Hybrid Strong scenario with 50 percent ERFC.

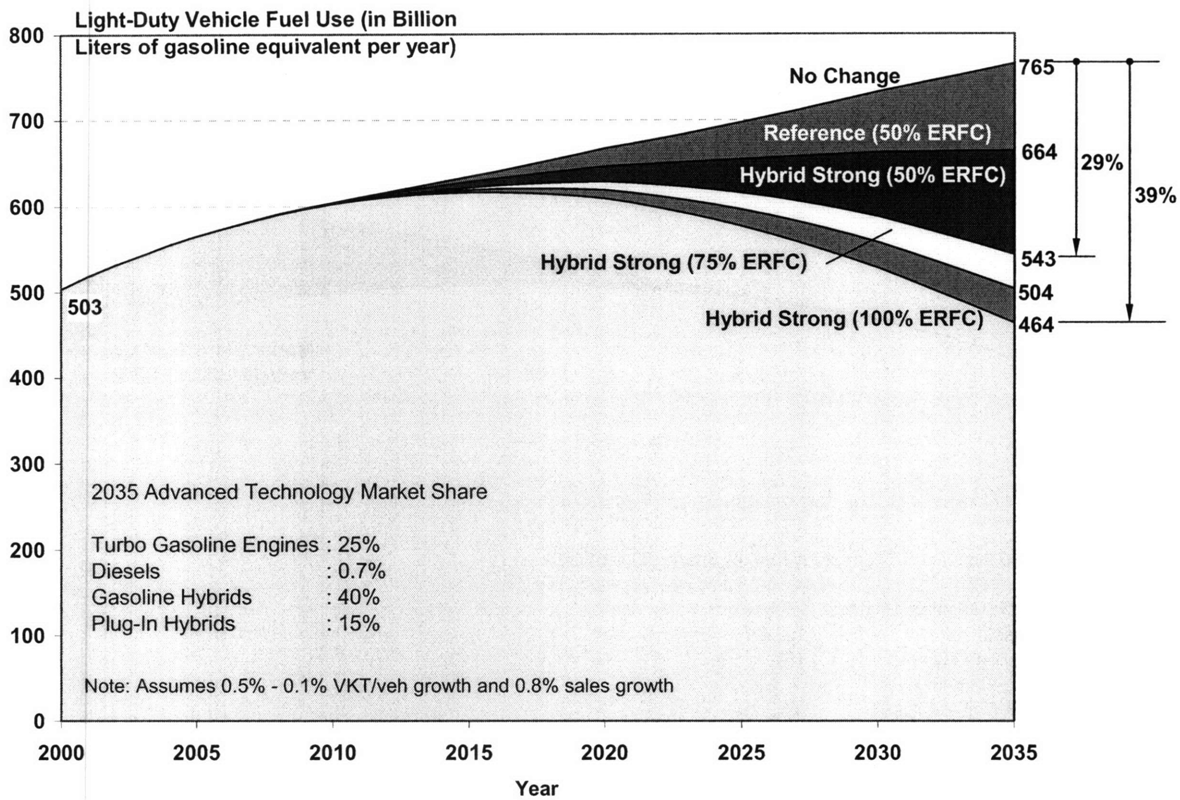


Figure 52 Increasing the Emphasis on Reducing Fuel Consumption in the Hybrid Strong Scenario

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 can expect introduction of commercial FCVs by 2020. In the initial years, the number of fuel cell vehicles will be small enough so that fueling infrastructure will not be a major issue. As FCV technology improves and costs come down, fuel cell vehicles can be expected to enter the market in increasing number. In the illustrative scenario here, the market penetration rate of hydrogen fuel cell vehicles is similar to that of plug-in hybrid vehicles, except for the 10 year time lag in introduction of FCVs.

Since FCVs do not consume any petroleum during vehicle operation, they can have a relatively quick impact of fleet fuel use. Figure 53 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 may have a bigger 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.

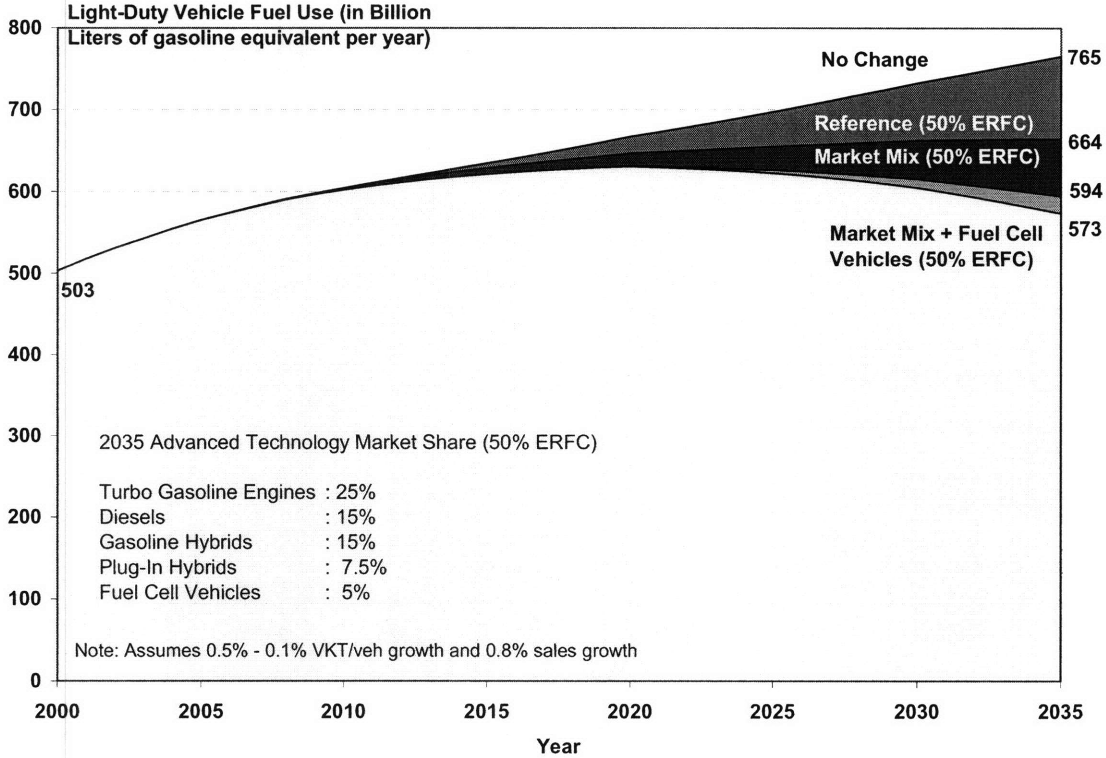


Figure 53 Impact of Hydrogen Fuel Cell Vehicles on LDV Fleet Fuel Use

Conclusions

The discussion on market penetration rates of new propulsions systems and various scenarios of LDV fleet fuel use reveal that:

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 has already been baked-in the cake.
2. Uncertainties in consumer demand makes undertaking major vehicle redesigns a risky endeavor for vehicle manufacturers. This, when coupled with the high initial cost and strong competition from mainstream gasoline vehicles, means that market penetration rates of low-emissions diesels, and gasoline hybrids are likely to be slow in the U.S. 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 new vehicle market than 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 percent below fuel use in year 2000.
4. The long delay between 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 term and long term impacts must be understood properly in this context. 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 deep reductions in long-term fuel use, advanced vehicle technology introduction needs to start as early as possible.
5. For similar levels of market penetration, gasoline hybrid vehicles look promising vis-à-vis diesels in terms of reducing fleet fuel use. Market Mix scenario with a small amount of plug-in hybrids produces results that are similar to that of turbocharged ICE Future with a large market penetration of diesel vehicles.
6. Shifting the emphasis on reducing fuel consumption from 50 percent to 100 percent in mainstream ICE gasoline vehicles alone can produce fuel use reductions equivalent to about 80 percent market penetration of advanced vehicle technologies.

Summary and Outlook:

This chapter discussed a variety of issues concerning the likely scale and impact of advanced propulsion systems. By taking both supply and demand side constraints on building up vehicle production rates, three plausible market penetration scenarios were developed. These scenarios indicate that substantial potential exists to reduce light-duty fleet fuel use over the next three decades. 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 or diesels can capture more than half of the new vehicle market by 2035, and all the advances in technology are used to emphasize reduction in fuel consumption.

This and the previous chapter focused on the impact of vehicle technology. To understand the life-cycle fuel use and greenhouse gas impacts, it is necessary to track the changes in fuel mix as well. The following chapter will discuss the role of changing fuel mix on reducing petroleum use and greenhouse gas emissions from light-duty vehicle fleet.

Chapter 6

Impact of Fuels

Over ninety-seven percent of the energy used in the U.S. transportation sector comes from petroleum, and transportation accounts for over 2/3 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 content of transportation fuels have also provided a boost for this search.

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 the Alberta province of Canada, oil shale in Green River Formation of the western U.S., and coal in Northwestern states of U.S.) have the added attraction of being in North America, and thus enhancing security of supply. Considerable uncertainty exists however in the economic and environmental viability of these resources. Non-conventional oil projects are more capital intensive than conventional oil production, and thus more susceptible to volatility in the global oil market. At the same time, the lifecycle 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 type of biomass resource available and corresponding conversion technology to produce liquid transportation fuel. So far, the worldwide production of liquid fuels from biomass has come from annual crops such as corn (maize), wheat, and sugarcane. There is potential to harvest woody perennials such as poplar, as well as herbaceous perennials such as switchgrass. Agricultural residues and organic waste matter may also be able to contribute as feedstock 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 fuel 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 all 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, the greenhouse gas emissions from production and distribution of hydrogen and electricity vary widely depending upon the source.

This chapter will evaluate 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. The following few sections contain a brief discussion of each of these fuels and their well-to-tank greenhouse gas emissions. The rest of the chapter will focus on evaluating the well-to-wheel greenhouse gas emissions impact of different vehicle and fuel scenarios.

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. 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 not mobile when mined and must be processed. Commercial exploitation of tar sands has been ongoing since 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, 2007].

Figure 54 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 the potential of oil sands to grow up to 6 million barrels per day by 2030 [O&GJ, 2006].

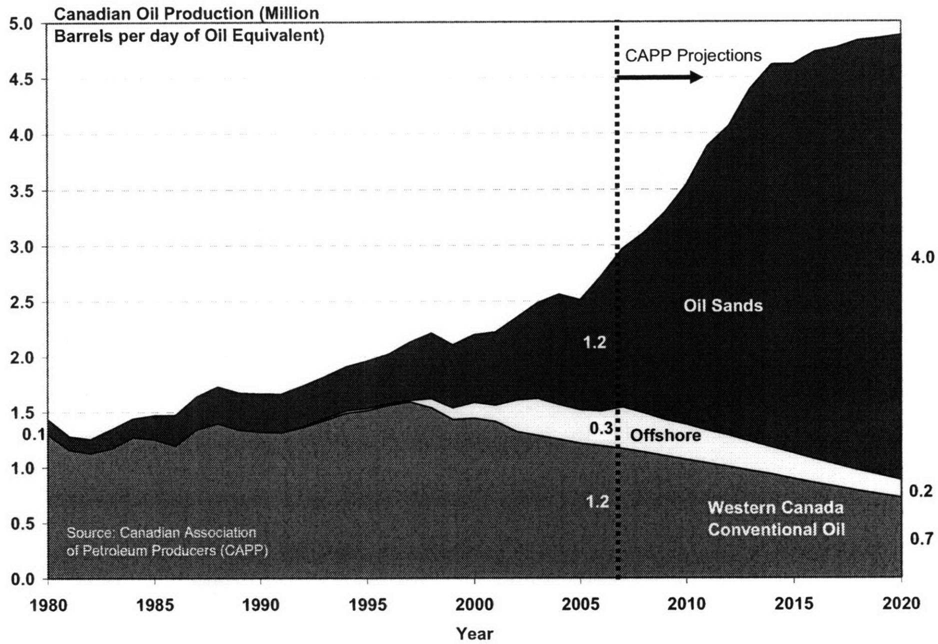


Figure 54 Oil Sands versus Conventional Oil Production in Canada [CAPP, 2007]

The growth in Canadian oil sands in subject to oil prices (>50 \$/bbl), natural gas usage (< 1 Mcf/bbl at a price of <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. Table 19 shows the estimated capital expenditure in different non-conventional liquid fuels facilities, their current scale of production, and estimated greenhouse gas emissions during production.

Table 19 Estimated capital expenditure in non-conventional liquid fuels facilities [2006-2010]

Fuel	**Estimated Capital Expenditure (\$ per barrel/day of production capacity)**	**Estimated CO_2 emissions in kg per GJ of fuel produced (well-to-tank)**	**Current Production (mbd)**
Conventional Oil (including natural gas liquids)	7,000 - 30,000	~ 21	83
Oil Sands	40,000 - 60,000	~ 35 - 40	1.2
Ultra Heavy Crude	30,000 - 45,000	~ 35 - 40	0.5
Gas-to-Liquids	50,000 - 80,000	~ 30 - 50	<0.1
Coal-to-Liquids	60,000 - 90,000	~ 100	0.2
Sources: IEA Energy Technology Perspectives, 2006; IEA World Energy Outlook, 2006			

In the reference case scenario of 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 55. The EIA estimates a low case estimate of 1.9 million barrels per day and a high case estimate of 4.4 million barrels per day in 2030.

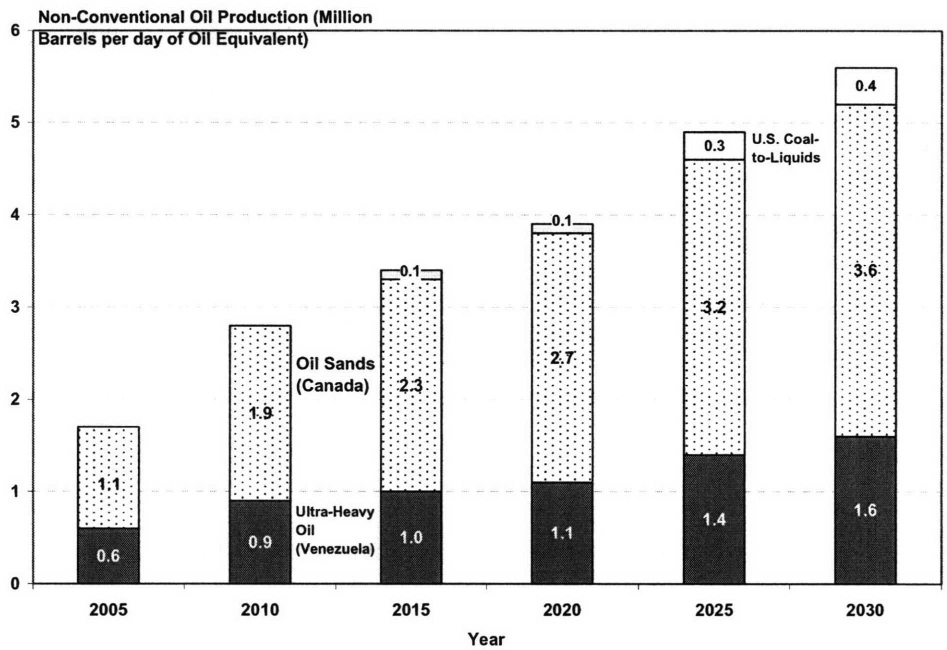


Figure 55 Non-Conventional Oil Production from U.S., Canada and Venezuela [EIA, 2007c]

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 U.S. If 80% of these exports comprise synthetic crude oil (SCO) derived from tar sands, then the U.S. imports of tar sands could exceed 2.5 million barrels per day by 2025.

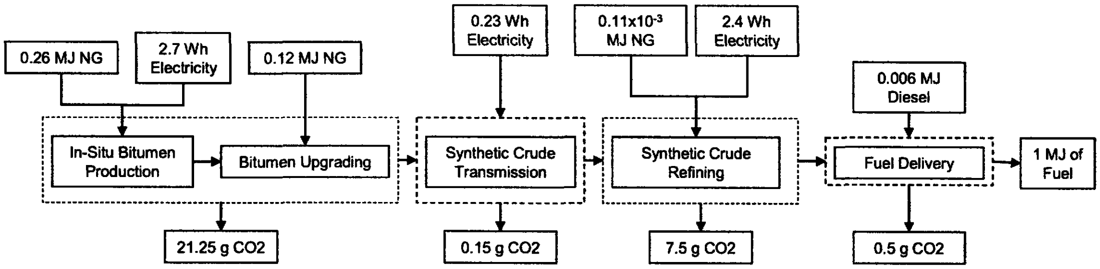
Figure 55 also shows the growth in other non-conventional liquid fuels that are likely to impact North American market. According to the EIA, the production of ultra-heavy crude from Venezuela could range from 0.8 million barrels per day in low case to 2 million barrels per day in the high case in 2030. The production of coal-to-liquids in the U.S. could range from 0.4 million barrels per day in 2030 under the reference scenario to 1.6 million barrels per day under the high price scenario. 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 greenhouse gas 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 much 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 4 tons of material needs to be removed to separate the 2 tons of oil sands needed to produce a barrel of SCO. As concerns about above ground impact grows and available bitumen resources get deeper, new production technologies have emphasized in-situ production of bitumen. The most common processes such as steam assisted gravity drainage (SAGD) involve steam flooding to loosen up bitumen so that it can flow through the pipes for further upgrading. As a result, energy consumption and GHG emissions from in-situ production of bitumen are 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 majority of processes, hydrogen is supplied by reforming natural gas on site. Consumption of natural gas and the resulting CO_2 emissions can also become a constraint on further development of oil sands projects.

Figure 56 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 quite similar to refining of conventional crude if the refinery is capable of treating a relatively heavy slate of oil.



Adapted from McCulloch et al., 2005

Figure 56 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 20. 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 primarily two reasons: (i) upgrading of SCO to a higher grade product with more hydrogen, (ii) 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 20 Well-to-Tank Emissions from Production of 1 MJ of Fuel from Tar Sands

(a) Current

		All numbers are in **g CO2 per MJ** in tank				
		2005				
#	Source	In-Situ Extraction	Upgrading of Bitumen to SCO	Refining	Transportation and Other	**Well-to-Tank**
1	Flint (2004)	17		11	1	29
2	Alberta Chamber of Resources (2004)	10 – 13	11 – 14	11	1	33 - 39
3	McCulloch (2005)	21		7.3	2.5	30.8
4	OSTRM (2003)	6.5 - 11	8 – 11	11	1	26.5 - 34
5	Syncrude (2005)	19		11	1	31
6	GREET (2006)	31.75 - 34				
7	TOTAL (2003)	10 – 20	6.5	4	1	21.5 - 31.5

(b) Future

		All numbers are in **g CO2 per MJ** in tank				
		2035				
#	Source	In-Situ Extraction	Upgrading of Bitumen to SCO	Refining	Transportation and Other	**Well-to-Tank**
1	Flint (2004)	20 - 29		11	1	32 - 41
2	Alberta Chamber of Resources (2004)	26 - 28		11	1	38 -40
3	McCulloch (2005)					
4	OSTRM (2003)					
5	Syncrude (2005)					
6	GREET (2006)	36 - 46				
7	TOTAL (2003)					

Biofuels

Biofuel is a general term used to encompass a variety of end products generated from biomass as the basic feedstock. Figure 57 shows different possible pathways for producing biofuels from different resources [WBCSD, 2004]. Of these, biodiesel from rapeseed, ethanol from corn in U.S., and ethanol from sugarcane are the most commonly used transportation fuels currently.

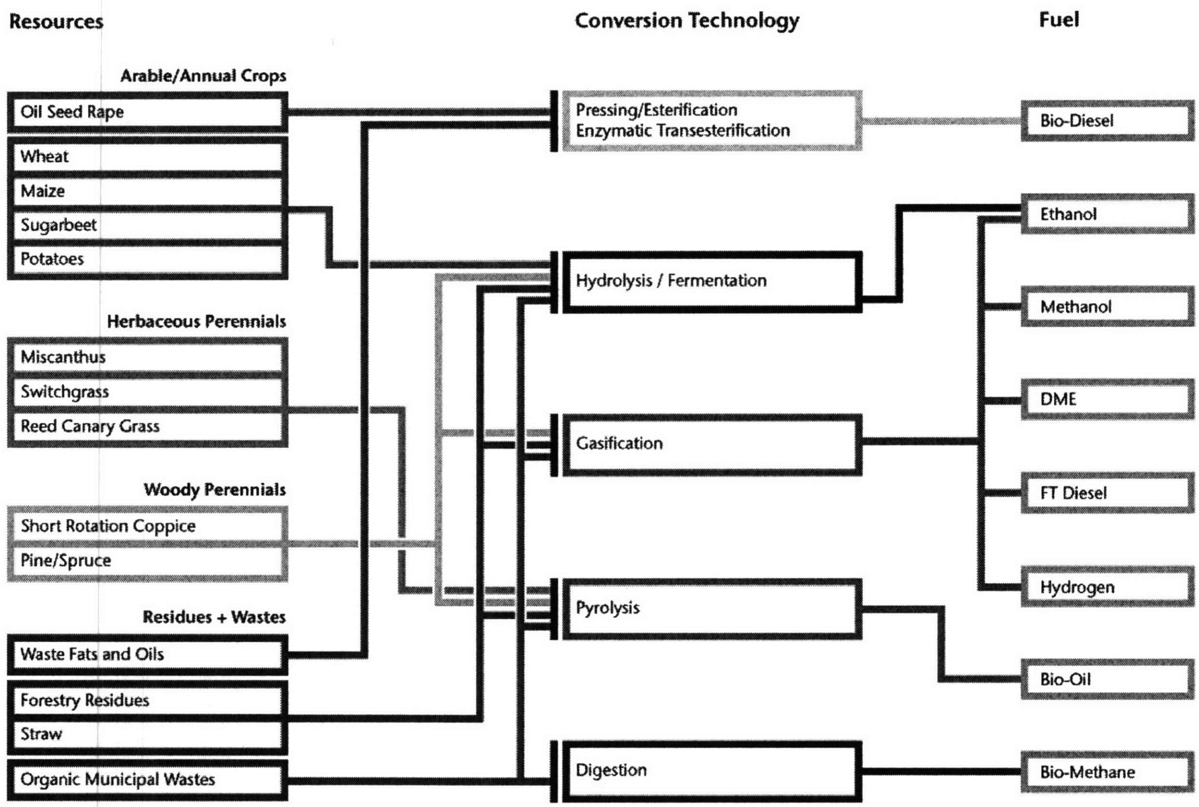


Figure 57 Possible Advanced Biofuel Pathways [WBCSD, 2004]

This chapter discusses only ethanol from corn and cellulosic materials such as switchgrass as biofuel options for the U.S. market. Corn based ethanol has been encouraged in the U.S. since 1970s as a means of displacing petroleum. The oxygenate requirement of the 1990 Clean Air Act along with a 51 cents 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, and was replaced by ethanol. Further growth in corn ethanol was guaranteed by the Renewable Fuels Standard established by the Energy Policy Act of 2005, which requires 7.5 billion gallons of ethanol to be blended in gasoline by 2012 [Yacobucci, 2006].

Current production of ethanol in U.S. 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, contribution from corn ethanol is quite small. The renewable fuels standards requirement of Energy Policy Act of 2005 will ensure that at least 0.5 million barrels per day of corn ethanol (~28.3 billion liters per year) is produced in the U.S. 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 U.S. to 45 billion liters a year by 2011.

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 rest of agricultural markets [NCGA, 2007]. Figure 58 shows the trends in ethanol production in U.S. and the anticipated expansion.

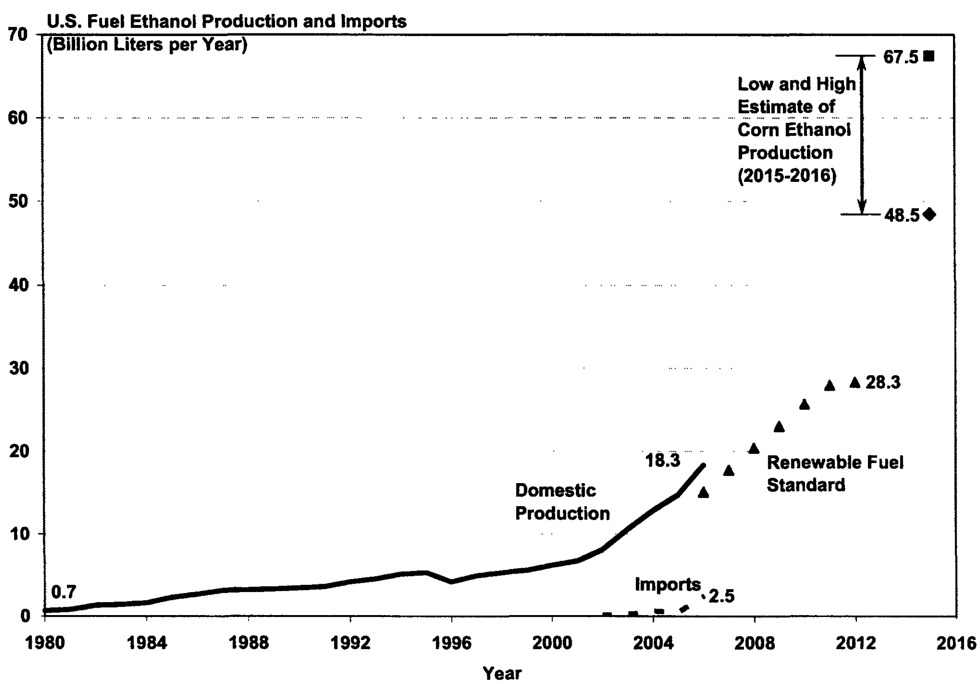


Figure 58 Domestic Production and Imports of Ethanol in U.S. [RFA, 2007; Yacobucci, 2006; NCGA, 2007]

Groode [2007] anticipates that with increases in corn grain yield and ethanol conversion rate improvement, the amount of ethanol from corn in U.S. can plateau between 57-68 billion liters by 2025. In the vehicle fleet model, it is assumed that 70 billion liters of ethanol from corn will be available in year 2035.

In 2006, the Department of Energy identified an agenda for development of 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 bio-ethanol. Finally, the agenda identifies that the next five year phase would entail integration of bio-refineries tailored to meet the demands of regional energy crops. Whether a bio-ethanol industry will develop from such a systematic research agenda is quite uncertain at present.

Currently no commercial facilities process cellulosic material in to ethanol, although several pilot plants to convert ligno-cellulosic material such as corn stover to ethanol have been announced. In February 2007, 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 dollars [DOE, 2007b]. These pilot plants combined are expected to produce 570 million liters (150 million gallons) by 2010.

The Energy Policy Act of 2005 requires blending of 950 million liters (250 million gallons) of cellulosic ethanol starting year 2013. 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 success of the first generation of pilot plants, capital costs and sizing of commercial scale processing plants, as well as availability of providing feedstocks at scale. At present, the capital cost requirements of building a cellulosic facility are expected to be five times as much as those of a comparable corn ethanol facility [Wright and Brown, 2007].

Based on availability of feedstocks and improvements in processing technology, Groode [2007] 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.

While bio-ethanol appears to the fuel of choice in the U.S. currently, a variety of other biomass to liquids pathways are available as shown in Figure 57. Several vehicle manufacturers in Europe have identified gasification of biomass and use of Fischer-Tropsch process to create diesel fuel from biomass as a viable alternative [Choren, 2007]. In a Turbocharged ICE Future scenario, where demand for diesel fuel grows rapidly in the U.S., the Fischer-Tropsch pathway might become attractive.

Energy consumption and GHG emissions in Corn/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 different system boundaries used in various studies. There is general agreement, however that well-to-wheel GHG emissions from production of corn ethanol are close to 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.

Groode and Heywood tested the sensitivity of GHG emissions from production of corn and cellulosic ethanol to the system inputs using a Monte Carlo simulation. They confirmed the conclusions of Farrell et al., and also pointed out the role of geographic variability in corn ethanol emissions as shown in Figure 59.

Groode and Heywood also indicate that future greenhouse gas emissions from corn ethanol could be up to 20% lower due to improvements in agricultural yields and conversion efficiency. Cellulosic ethanol on the other hand can reduce GHG emissions by 90% or more.

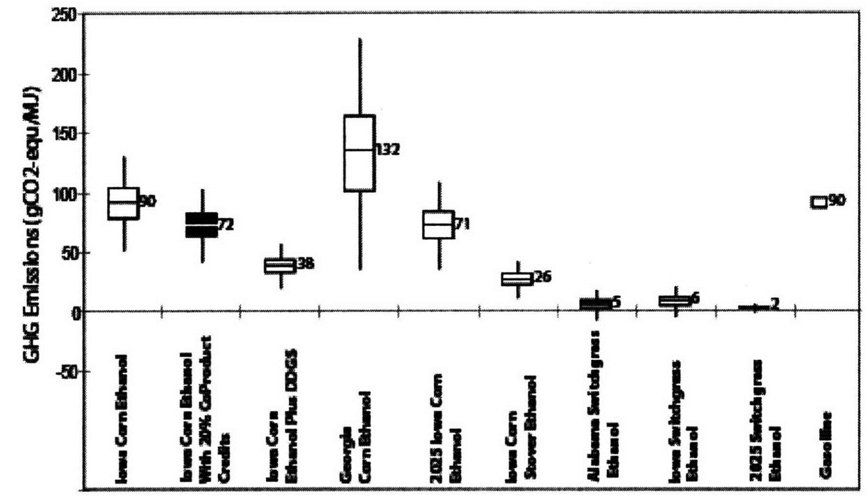


Figure 59 emissions for various corn and switchgrass ethanol production scenarios [Groode and Heywood, 2007]

None of the biofuels, except ethanol from sugarcane in Brazil, are cost competitive with conventional gasoline and diesel even at crude oil price of $65 per barrel [IMF, 2007]. Figure 60 shows the recent trends in price of ethanol in U.S. with and without the blenders credit compared with gasoline prices [EIA, 2007d].

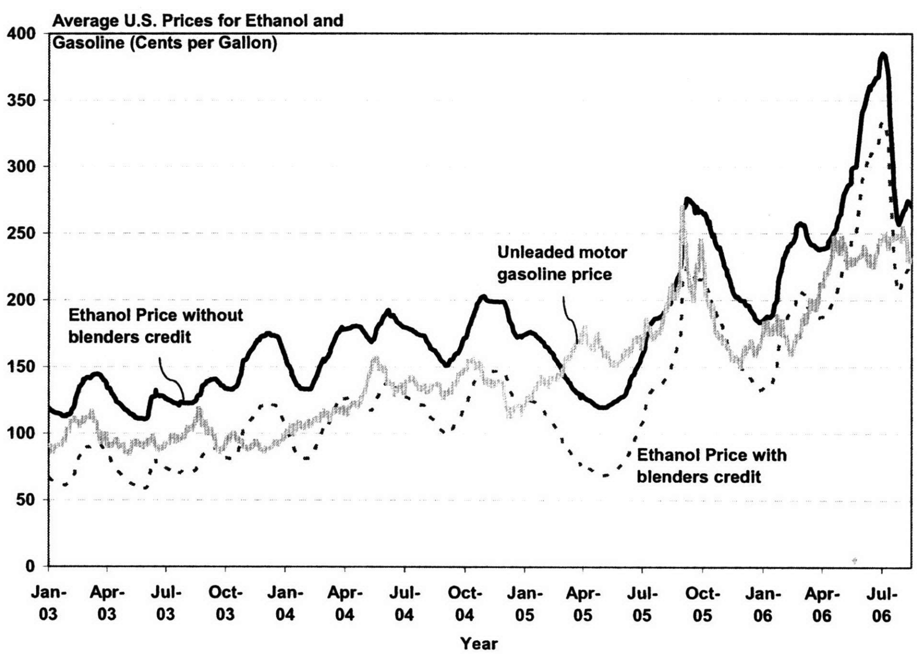


Figure 60 Average U.S. Ethanol and Gasoline Price (2003-2006) [EIA, 2007b]

Figure 60 shows that even with 51 cents per gallon subsidy, ethanol in U.S. is as expensive as gasoline on volume basis. When adjusted for the lower energy density of ethanol, the cost premium for blending ethanol in gasoline is of the order of 20%. 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.

Ethanol is traded as a commodity on futures market in the U.S. Since the size of ethanol market is much smaller than oil, it should be anticipated that any arbitrage in ethanol and oil prices will be exploited by the futures market effectively. Thus, it can be expected that over a long term the price of fuel ethanol on an energy adjusted basis will track the oil price. From this perspective, fuel ethanol is unlikely to work as a hedge against high oil prices.

As a result, biofuel alternatives in the U.S. are a rather costly pathway to reduce greenhouse gas emissions. Figure 61 shows the approximate range of incremental cost and greenhouse gas emissions realized by different ethanol alternatives according to the IEA.

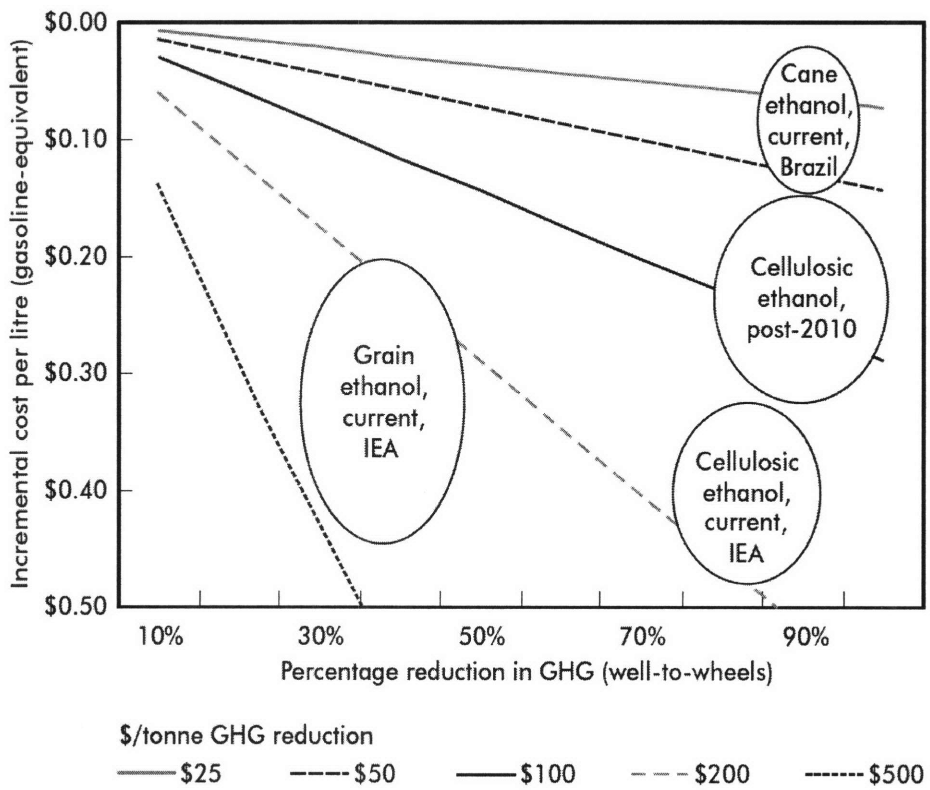


Figure 61 Biofuel Cost per ton of GHG emissions reduced [IEA, 2004]

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 U.S. concluded that [NRC, 2007]:

> *"...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."*

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 biofuels will contribute less than 10-15% of fuel supply by 2035 on energy basis, and will deliver somewhat smaller reduction in greenhouse gas emissions.

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 efficiency of vehicle 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 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 21.

Table 21 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 cars in year 2035. The total electricity demand by plug-in hybrids in year 2035 grows to 59 billion kilowatthours. As the fleet of PHEVs grows, the demand for electricity will by approximately 6 to 10 billion kilowatthours in the decade after that. The current electricity consumption in the U.S. is approximately 3700 billion kilowatthours, and is projected to increase to over 5200 billion kilowatthours by 2035 [EIA, 2007a]. Therefore, plug-in hybrids will represent only 1-2% of electricity demand under this scenario, and their impact on the electricity grid is likely to be small.

In the longer-term, if PHEVs become a substantial fraction of U.S. light-duty fleet, then the additional electricity load due to PHEVs will be a part of the base demand for electricity. As a result, the average electricity grid mix is an appropriate measure for GHG emissions from electric operation of PHEVs.

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, and will 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 be forecourt[11] production. In the longer term, hydrogen could be produced

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

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 compressed hydrogen to the tank of vehicle at 350 atmospheres pressure. If hydrogen is stored at a higher (approximately twice) pressure, then compression work required will increase the CO_2 emissions intensity of hydrogen to approximately 140 g/MJ.

Summary of Fuel Options

The life-cycle emissions factors used to calculate the vehicle fleet GHG emissions are shown in Table 22 [Kromer and Heywood, 2007; Groode and Heywood, 2007; GREET 2007]. 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 use of ethanol during vehicle operation phase ethanol is considered to be zero.

Table 22 CO_2 Emission Factors for different Transportation Fuels

Fuel	**Fuel Cycle** (g CO_2 per MJ in the tank)	**Vehicle Operation** (g CO_2 per MJ used in vehicle)
Conventional Gasoline	21	71
Conventional Diesel	18	76
Gasoline from Oil Sands	38	71
Ethanol from corn	77[12]	0
Ethanol from cellulose	9	0
Electricity	214	0
Hydrogen from Natural Gas	132	0

[12] Includes a 20% co-product credit for dried distillers grains with solubles.

Based on the emissions factors shown in Table 22, and vehicle fuel consumption discussed in Chapter 4, we can estimate petroleum consumption and GHG Emissions of different vehicles. Figure 62 shows fuel consumption and well-to-wheel GHG emissions for future cars using different fuels. Note that compared to today's typical 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.

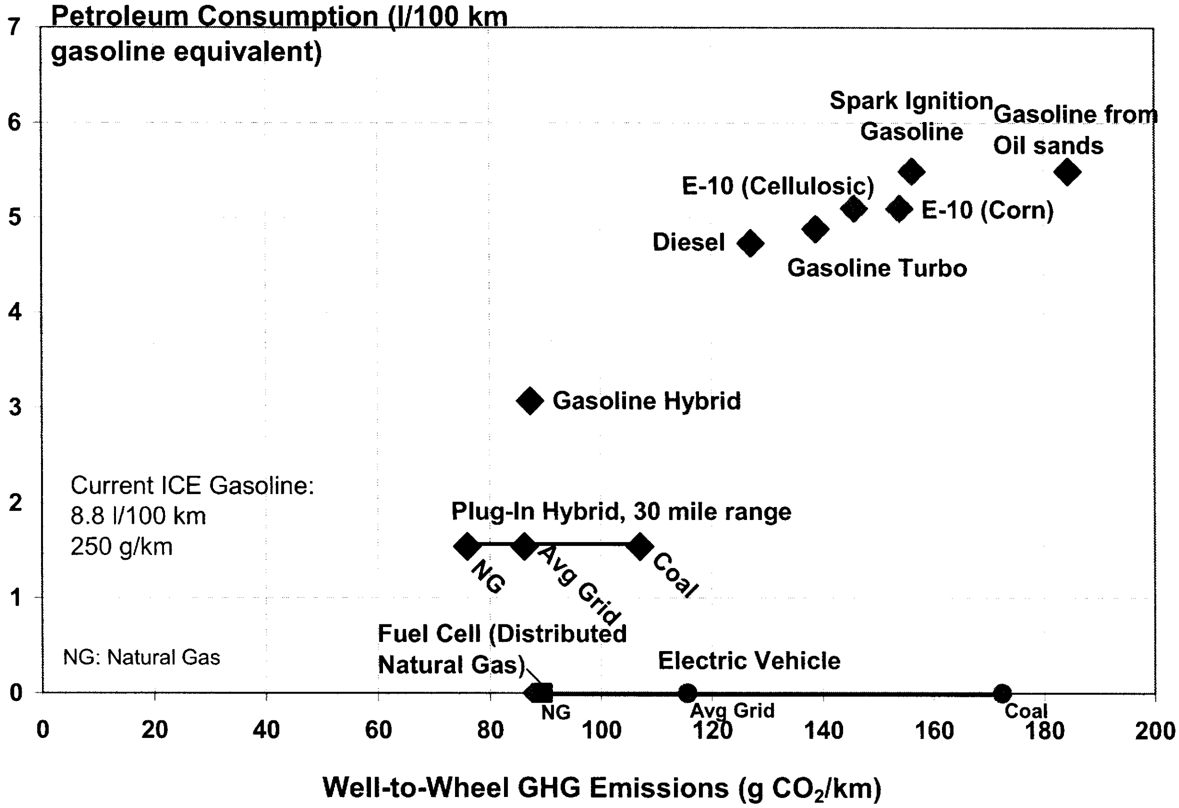


Figure 62 Fuel Consumption and Well-to-Wheel GHG Emissions for Future (2035) Cars

A car running on gasoline derived solely from 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 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 ethanol in E-10 is made from cellulosic material such as switchgrass.

Gasoline hybrids stand out separately from the cluster of improved ICE- only vehicles. The plug-in hybrid vehicle achieves a further reduction in petroleum consumption compared with gasoline hybrid. The GHG emissions reductions achieved by the PHEV charged from average U.S. electricity grid mix are comparable to that of 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 conventional gasoline hybrid or a plug-in hybrid. The primary reason for comparatively poor CO_2 performance of the BEV is due to 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 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 62 indicates that while a variety of vehicle alternatives can displace petroleum from light-duty vehicles, their effectiveness in reducing CO_2 emissions can vary widely. 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.

Impact of Changing Fuel Mix on LDV GHG Emissions

This section will discuss 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.

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 U.S. were from oil sands, approximately 0.6 MBD of oil from tar sands entered the U.S. in 2005. Thus oil sands accounted for approximately 3% of total U.S. petroleum use. If the oil sands exports from Canada to U.S. were to increase to more than 2.5 MBD as explained above, 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 U.S. LDV fleet use would increase from 0.3 MBD in 2005 to 1.1 MBD in year 2035. Figure 63 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 63 also shows the impact on well-to-tank- GHG emissions if up to 2 MBD of oil from tar sands enters U.S. LDV market by 2035.

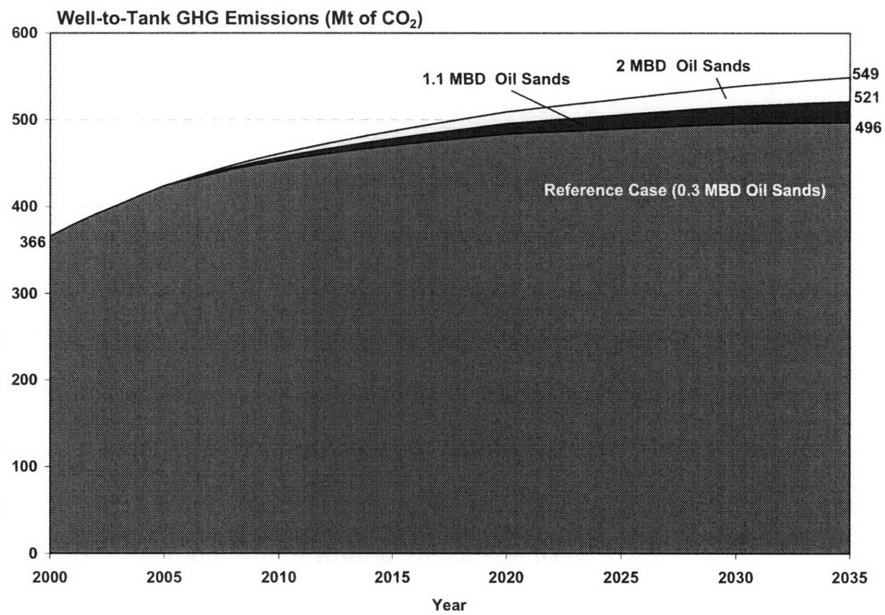


Figure 63 Impact of Increasing Oil Sands on Well-to-Tank GHG Emissions

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 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.

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 product are much higher than those in production of oil sands [EIA, 2007a; Rand, 2007]. If the pursuit of the dream 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.

Two-to-six percent reduction in 2035 well-to-wheel CO_2 emissions 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 chapter, Table 23 lists the projected low and high volumes of contribution for non-conventional oil, corn ethanol and cellulosic ethanol.

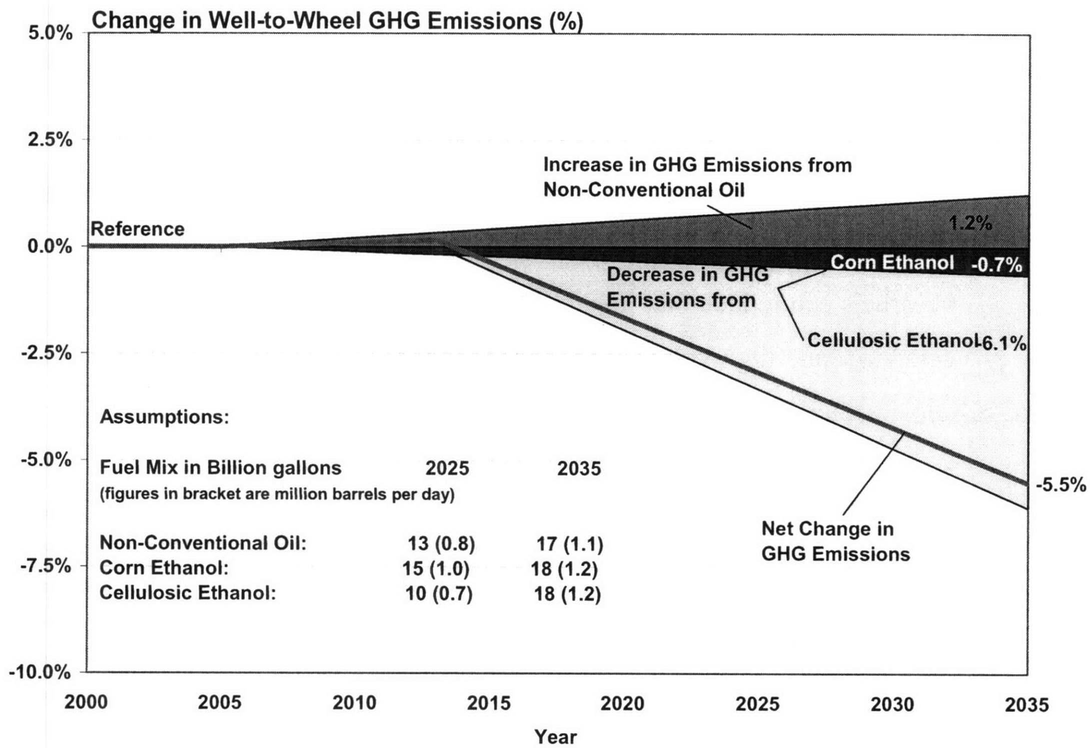
Table 23 Scenarios of Alternative Fuel Mix by Volume

Year	Non-Conventional Oil (MBD)		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

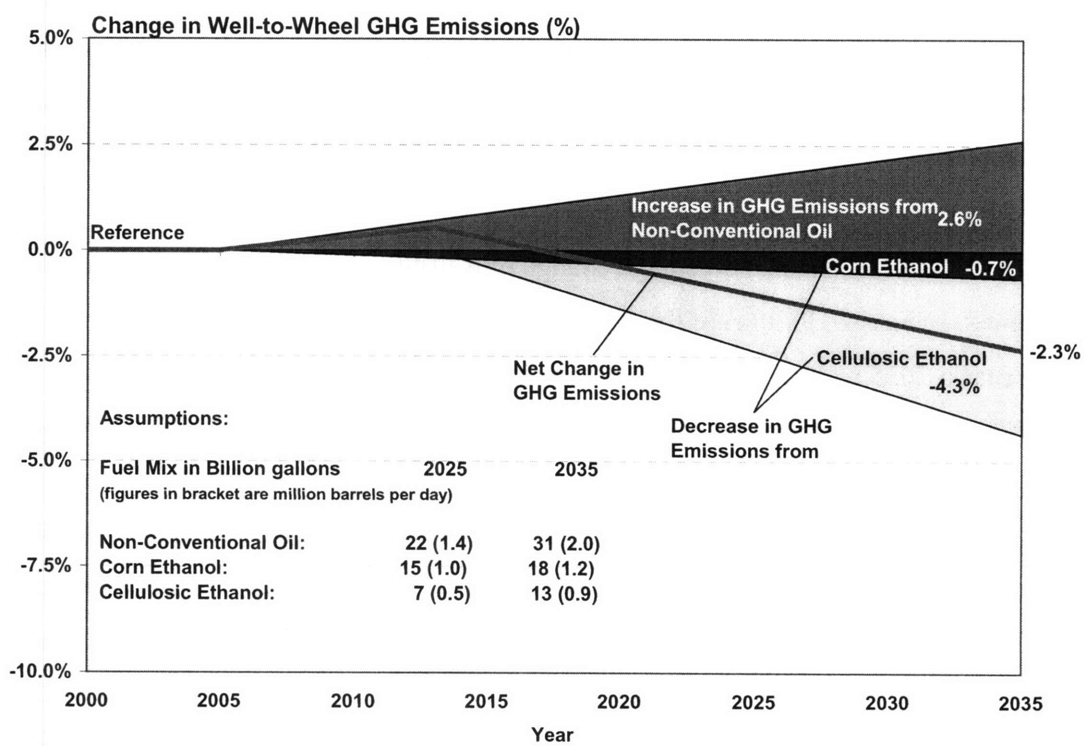
MBD: Million Barrels per Day, 1 MBD = 15.34 Billion gallons per year

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

Figure 64 evaluates the percentage change in well-to-wheel (WTW) GHG emissions from these two scenarios. Part (a) of the figure shows that in a low oil sands, high cellulosic ethanol scenario 2035 well-to-wheel GHG emissions increase by 1.2% from the reference scenario from use of oil sands. Increased use of corn and cellulosic ethanol reduces WTW GHG emissions by 6.8%, leading to a net reduction in 2035 GHG emissions of 5.5% from the reference case. Part (b) of the figure shows high oil sands, low cellulosic ethanol scenario where the net reduction in GHG emissions in 2035 is only 2.3% below reference case. 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 year 2017. Figure 64 indicates that on the net, changes in fuel mix is likely to produce a 2-6% reduction in 2035 WTW GHG emissions compared to reference case scenario.



(a) Low Oil Sands, High Cellulosic Ethanol Scenario



(b) High Oil Sands Low Cellulosic Ethanol Scenario

Figure 64 Net Change in Well-to-Wheel CO_2 Emissions due to Fuel Mix

Summary and Outlook

This chapter 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. This chapter also indicates 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 both energy security and carbon emissions at the same time.

The next chapter will integrate the energy and greenhouse gas emissions produced during manufacturing and disposal of vehicles with the well-to-wheel impacts, and show the combined life-cycle impacts of different vehicle and fuel scenarios.

Chapter 7

Evaluating the Greenhouse Gas Implications of Integrated Scenarios

The previous three chapters described the impact of changing vehicle and fuel technology on U.S. light-duty vehicle (LDV) fleet fuel use. This chapter presents the integrated greenhouse gas emissions (GHG) impacts of different vehicle and fuel scenarios. First, the well-to-tank and tank-to-wheel aspects of vehicle operation are combined with the vehicle production, distribution and disposal stages to gain a complete life-cycle perspective. The results of life-cycle GHG emissions for different scenarios discussed in Chapters 4, 5 and 6 are shown next. The impact of delays in realizing fuel consumption reductions possible in these scenarios is described next. Finally, the relative effectiveness of different vehicle and fuel alternatives in achieving certain policy objectives is evaluated.

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. As part of the Partnership for New Generation of Vehicles (PNGV), the United States Automotive Materials Partnership's Life Cycle Assessment Special Topics Group (USAMP/LCA) conducted a life cycle inventory of a generic 1995 family sedan [Sullivan et al., 1998]. This comprehensive life cycle inventory assembled data from manufacturing and disposal of 644 vehicle components from six major vehicle systems (Powertrain, Suspension, HVAC, Electrical, Body, and Interior). The generic family sedan described in this study was composed from popular U.S. sedans in the 1990s (Chevrolet Lumina, Dodge Intrepid and Ford Taurus). They found that this generic vehicle – weighing 1532 kg and consuming 10.2 liters per 100/km (23 miles per gallon) of fuel – used 133 GJ of primary energy, and was responsible for 7.8 metric tons of greenhouse gas emissions during the production of materials, manufacturing and end-of-life.

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 [2007]. 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 24. 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 light-weighting can be realized through downsizing and enhanced vehicle design/reconfiguration. As a result, the energy and GHG factors in Table 24 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.

Table 24 Energy and GHG Emissions during Manufacturing and Disposal of Light-Duty Vehicles

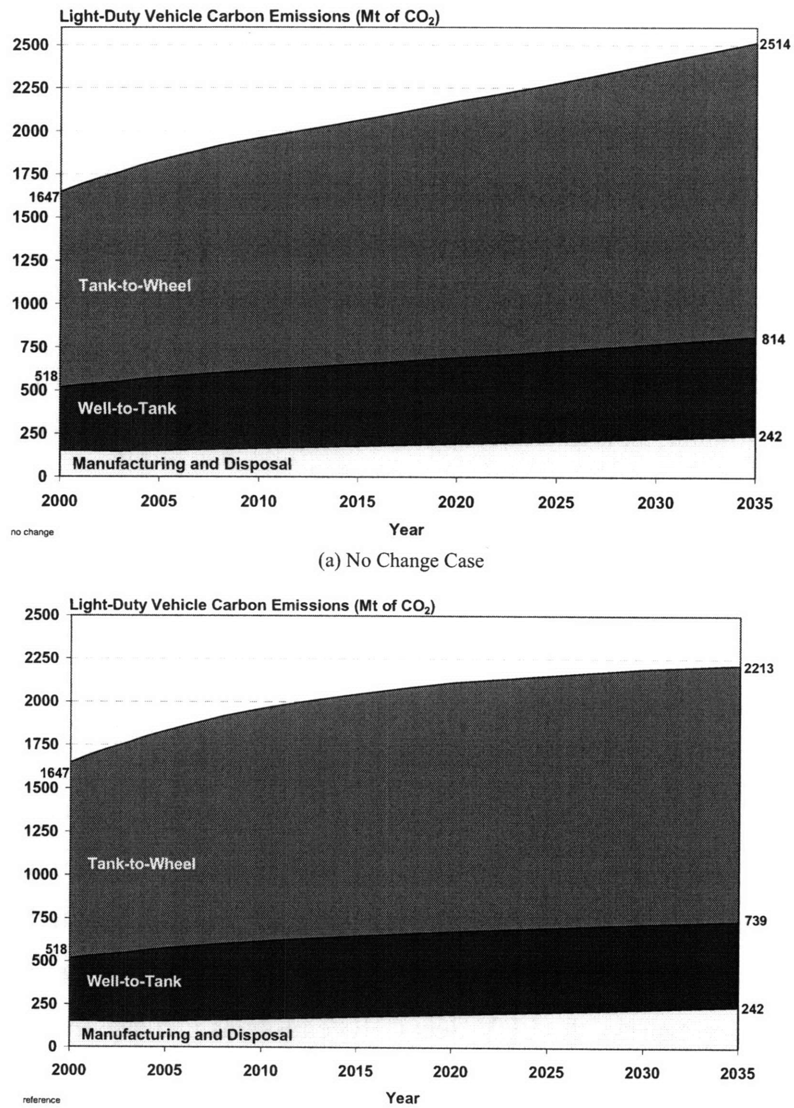
Vehicle	Cars		Light-Trucks	
	Energy (GJ/vehicle)	GHG (metric tons/vehicle)	Energy (GJ/vehicle)	GHG (metric tons/vehicle)
Current Gasoline ICE	96.9	7.7	124.6	10.0
Current Turbo ICE	95.9	7.7	134.3	10.8
Current Diesel ICE	99.0	8.0	128.4	10.4
Current Gasoline Hybrid	113.6	9.1	144.2	11.6
2035 Gasoline ICE	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 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).

Total life-cycle energy and greenhouse gas emissions

The total life-cycle energy and greenhouse gas emissions of the LDV fleet are obtained by addition of well-to-tank, tank-to-wheel and vehicle-cycle energy and GHG emissions. The life-cycle greenhouse gas emissions impacts described in this chapter 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.

Figure 65 shows the U.S. LDV fleet GHG emissions under No Change and Reference case scenarios. In year 2000, the shares of vehicle cycle, well-to-tank, and tank-to-wheel components of total fleet GHG emissions were 9, 22 and 69 percent respectively. The tank-to-wheel GHG emissions in year 2000 from light-duty vehicles are estimated to be 1129 million metric tons which compares well with the EPA estimate of 1105 million metric tons [EPA, 2007]. In a No Change scenario, the LDV fleet GHG emissions increase from 1647 million metric tons in 2000 to 2514 million metric tons, whereas in the reference scenario the fleet GHG emissions plateau around 2213 million metric tons in year 2035.



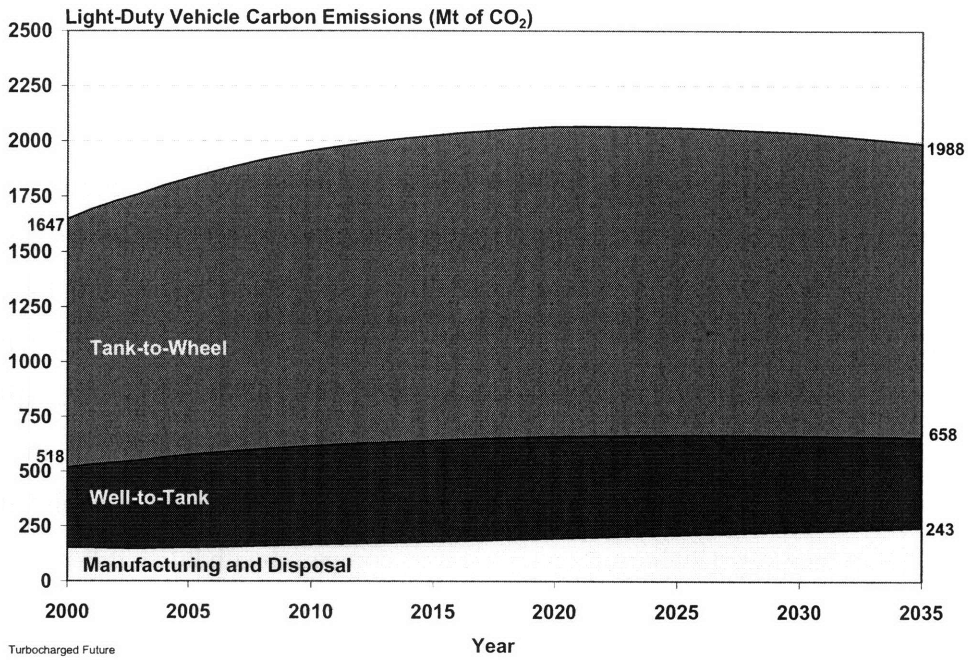
(a) No Change Case

(b) Reference Case

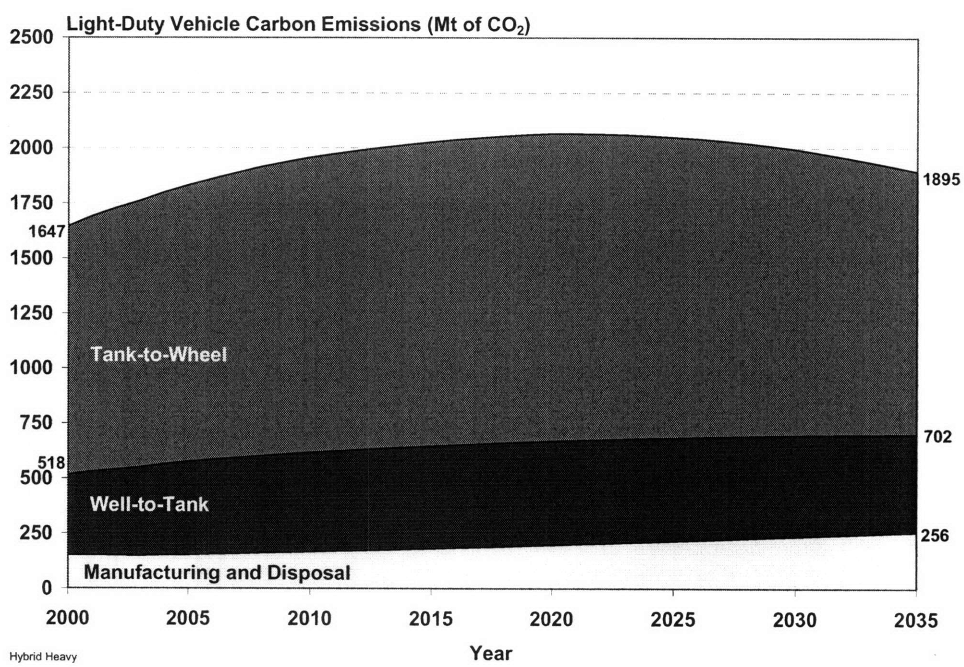
Figure 65 LDV Fleet GHG emissions under No Change and Reference Case Scenarios

Scenarios of LDV Fleet Life-Cycle Greenhouse Gas Emissions

LDV fleet GHG emissions under turbocharged ICE Future and Hybrid Strong scenarios are shown in Figure 66. In both the 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 percent higher in a turbocharged ICE Future and 15percent 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.



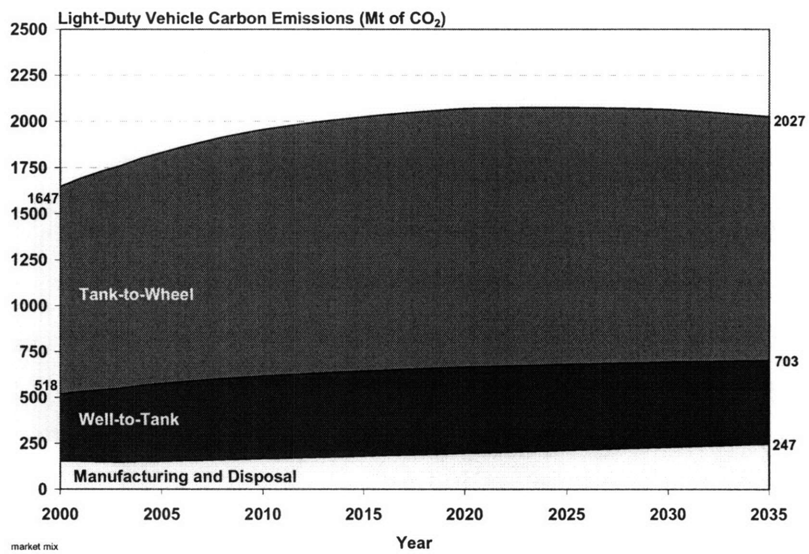
(a) Turbocharged ICE Future Scenario



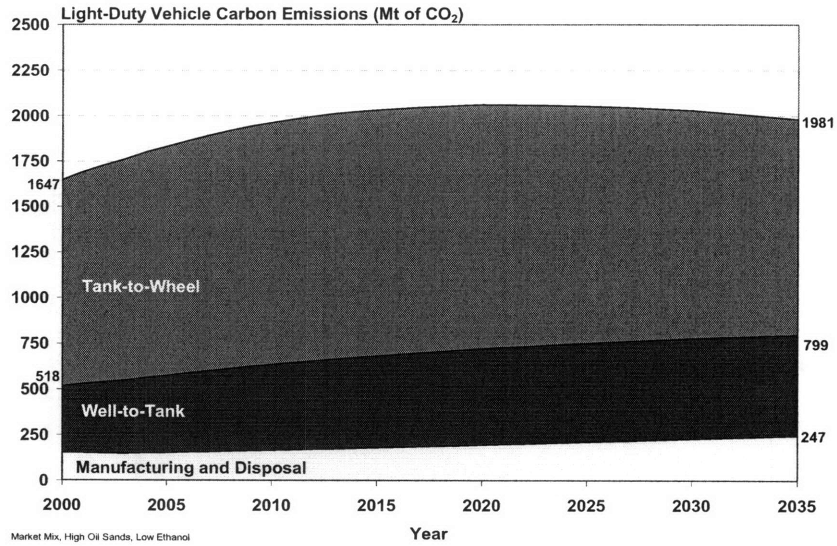
(b) Hybrid Strong Scenario

Figure 66 LDV Fleet GHG emissions under Turbocharged Future, and Hybrid Strong Scenarios

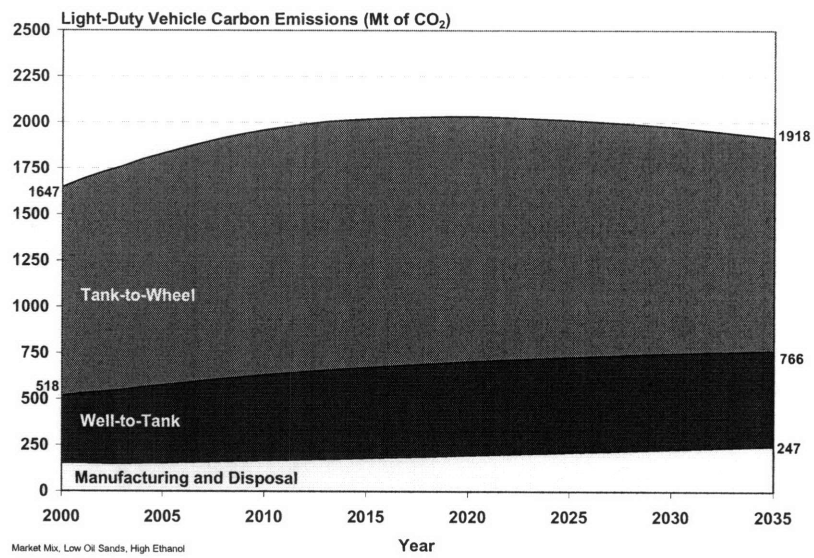
The impact of a changing fuel mix on fleet GHG emissions is shown with the help of market mix scenario in Figure 67. While the fuel use in Market Mix scenario peaks in year 2020, the GHG emissions do not peak until 2024. The 2035 GHG emissions under the market mix scenario (2027 million metric tons) are approximately 9.5 percent below emissions under reference scenario, and 20 percent below No Change scenario. When the fuel mix is changed according to the High Oil Sands and Low Ethanol scenario described in Chapter 6, the LDV fleet GHG emissions in 2035 reduce by an additional 2.3 percent to 1981 million metric tons [Figure 67 (b)]. On the other hand, a Low Oil Sands and High Ethanol scenario reduces the GHG emissions by 5.5 percent to 1918 million metric tons [Figure 67 (c)]. In either case, the maximum yearly emission occur in year 2020, but the peak GHG emissions in High Oil Sands and Low Ethanol scenario are 2060 million metric tons compared with 2033 million metric tons in Low Oil Sands and High Ethanol scenario. Compared with a 22.4 percent share of well-to-tank emissions in the Reference Case scenario, the share of well-to-tank emissions in the fuel mix scenario is between 27 and 28 percent of total life cycle GHG emissions in 2035.



(a) Market Mix Scenario



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

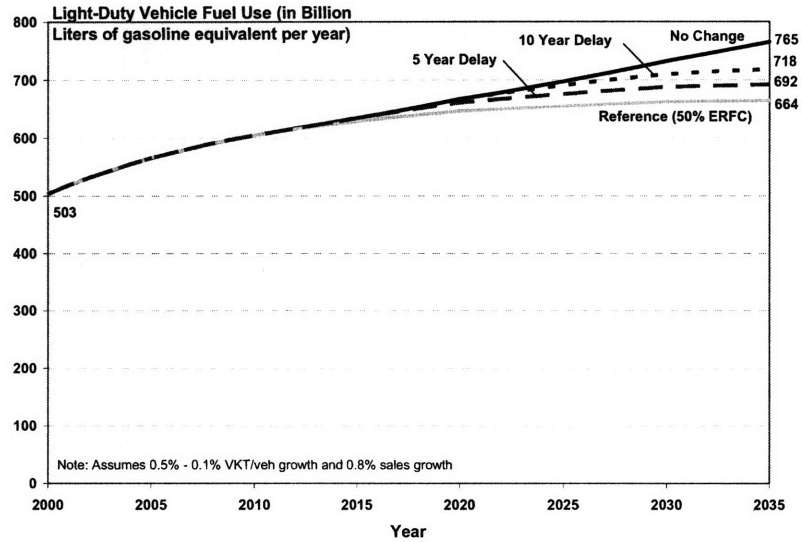


(c) Market Mix Scenario with Low Oil Sands and High Cellulosic Ethanol

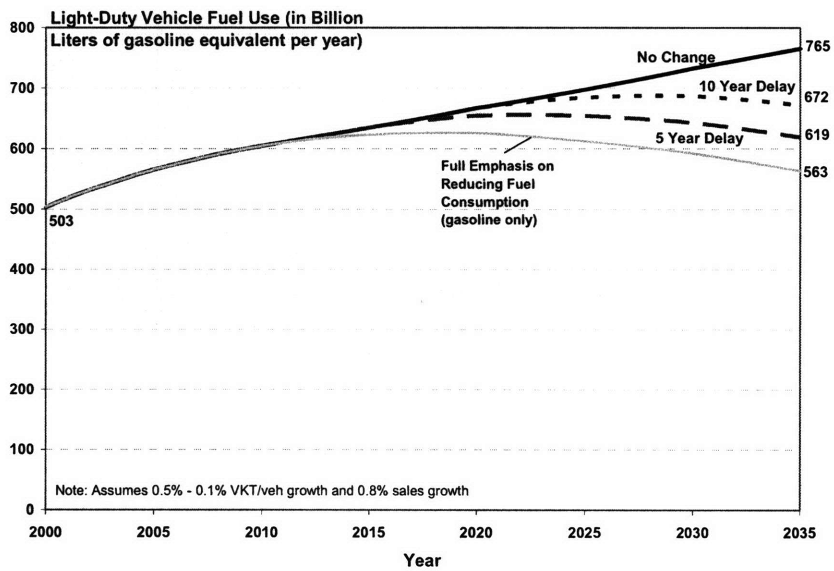
Figure 67 LDV Fleet GHG emissions under Market Mix Scenario with changing mix of non-conventional oil and ethanol

Impact of Delays

A delayed action scenarios represent the consequences of postponing action by five, or ten years on overall fuel consumption and greenhouse gas emissions. The purpose of these scenarios is to investigate the level of additional effort required to contain the vehicle fuel consumption in the Future as opposed to taking action immediately. Figure 68 shows the impact on LDV fleet fuel use if the fuel economy improvements, which begin in year 2010 in reference case or 100 percent ERFC scenarios, are in fact delayed by five or ten years.



(a) Delay with 50percent ERFC



(b) Delay with 100percent ERFC

Figure 68 Effect of Delay in 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 makes it more difficult to address. On the other hand, even small changes made sooner could result in larger benefits than more aggressive actions taken later. This also indicates that 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 is taken now, as opposed to waiting for a *cure-all.*

The next two scenarios compare the market penetration rates of different vehicle technologies at varying emphasis on reducing fuel consumption to achieve a predetermined target. In the first scenario, this target is based on fleet fuel use and GHG emissions, whereas in the second scenario, the target relates to the fuel consumption of new vehicles sold.

Reducing 5 percent of fuel use and GHG emissions below reference case

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 five percent petroleum and GHG reduction in 2025 below the reference case using various different propulsion systems, fuel alternatives, as well as demand-side measures as shown in Table 25.

Table 25 Alternatives considered to reduce an additional 5 percent petroleum and GHG emissions from reference case 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 percent in the reference case
Vehicle weight and size reduction alternatives[13]	• 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 percent per year to zero percent in 2025

[13] 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.

To compare the relative fleet wide impact of different propulsion systems, the market shares each of the of technologies listed in Table 25 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 fuel use and GHG emissions reduction is estimated (Table 26). The market shares required to achieve a 5 percent reduction in GHG emissions are more aggressive than those required to achieve the same reduction in fuel use for all propulsion systems. In the case of plug-in hybrids, the share required to meet the target is increased by a greater extent due to the GHG emissions produced from the electricity consumed by these vehicles, assuming an average U.S. grid mix.

Table 26 Market penetration rates of new propulsion technologies to achieve a 5 percent reduction in fuel use and GHG emissions

Propulsion System	Market Share Required for a 5 percent 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 emphasis placed on reducing fuel consumption (solid bars)
two-thirds emphasis placed on reducing fuel consumption (hatched bars)

From Table 26, 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 Chapter 5 do any of the propulsions systems achieve the required market share except for the case of hybrids with 65 percent 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 percent in the reference case to 88 percent and 93 percent would achieve the 5 percent 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 case ERFC to achieve the same objective (Table 26). 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 case value of 50 percent.

Amongst the fuel alternatives, cellulosic ethanol appears to be an attractive way to reduce both petroleum and GHG emissions. In the reference scenario, ethanol from corn contributes 3 percent of the fuel use which translates into 25 billion and 31 billion liters of ethanol in 2005 and 2025 respectively. Displacing an additional 5 percent 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 nearly seven times higher however, to achieve the same reduction in life-cycle GHG emissions even after assuming a 20 percent co-product credit (Table 27). Thus, if GHG emissions reduction is desired through fuel alternatives, then rapid development of cellulosic ethanol or similar biofuel pathway is critical.

Table 27 Amount of additional ethanol blended in gasoline as a percentage of total gasoline use to achieve a 5 percent 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 percent reduction by altering vehicle weight and size is also challenging (Table 28). In the reference case, the curb weight of new cars and light trucks is assumed to decline by 6 percent from 2010-2025, while vehicle size is kept constant. To realize a 5 percent reduction in fuel use through additional vehicle weight reduction, the sales-weighted average of new vehicle weight must decrease by an additional 12 percent, decreasing from 1,860 kg in 2005 to 1,540 kg in 2025. The same 5 percent reduction in GHG emissions requires an additional 19percent reduction in new vehicle weight, to a fleet average of 1,430 kg by 2025. To realize weight reduction by downsizing without any material substitution, large vehicles[14] – currently accounting for a third of new vehicle sales – would have to disappear from the market to offset 5 percent of fuel use by 2025, while compact or small vehicles must grow from their current 23 percent market share to 90 percent. We can also consider shifting sales away from light trucks to cars to reduce the average vehicle weight. 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 fuel consumption as in cars in 2025.

It is not possible to achieve a similar 5 percent reduction in GHG emissions by downsizing vehicles without material substitution. At best, if small vehicles accounted for the entire market, GHG emissions could be reduced by 4 percent relative to the reference case in 2025. Similarly, if trucks were completely phased out from the new vehicle market in 2025, this would only realize a 3.5 percent reduction in GHG emissions. Thus, even implausible

[14] As defined by the EPA size class.

downsizing changes will likely not achieve the targeted impact within the next 20 years by themselves.

Table 28 Weight/size reductions required to achieve a 5 percent reduction in fuel use and GHG emissions

Weight and Size reduction	Current value in 2005	Required for a 5 percent reduction by 2025
Material substitution		
Fuel use	1,860 kg average vehicle weight	1,541 kg (17 percent reduction)
GHG emissions		1,427 kg (24 percent reduction)
Shifting within classes to smaller vehicles		
Fuel use	23 percent market share of small vehicles	90 percent market share of small vehicles
GHG emissions		> 100 percent market share of small vehicles (maximum 4 percent reduction)
Shifting from light trucks to cars		
Fuel use	44 percent market share of cars	98 percent market share of cars
GHG emissions		> 100 percent market share of cars (maximum 3.5 percent reduction)

Finally, restraining growth in vehicle travel also appears to be an effective alternative to realize nearer term fuel use reduction. Reducing the rate of growth of per vehicle travel from 0.5 percent to zero between 2010 and 2025 – plausible albeit challenging – would reduce the total fuel use and GHG emissions by 6 percent from the reference case in 2025.

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, the market penetration rates of advanced vehicles required to achieve even a five percent 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 upon current performance.

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 percent 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.

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 such strategy described by Pacala and Socolow is to raise the fuel economy of all 2 billion passenger vehicles globally from approximately 30 miles per gallon at present to 60 miles per gallon in fifty 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 percent per year [Yacobucci and Bamberger, 2007]. If these proposals were to be implemented, they would effectively require new vehicles in 2035 to consume half as much fuel per unit distance traveled as in 2006.

More recently, 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].

Here, a scenario which 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 in to consideration. An evaluation of doubling the fuel economy of new vehicles using all three alternatives can be found in Cheah et al. [2007].

Table 29 (a) shows the market share of advanced propulsion systems to double the fuel economy of new vehicles by 2035 when used with evolving mainstream gasoline internal combustion engines. Recall from Table 10 that a 2035 hybrid vehicle is the only technology that is projected to have less than a half the fuel consumption of current gasoline ICE vehicles. As a result, even a hundred percent market share of turbocharged gasoline vehicles or diesels will not achieve a factor of two reduction in new vehicle fuel consumption. If only 25 percent 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 percent ERFC the market share of hybrids needs to be less than half to achieve the same target.

Table 29 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 percent ERFC is shown in Table 29 (b). In any of the three cases shown above, the market share of advanced propulsion systems needs to be substantial in 2035.

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 30, 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-third of the emphasis on reducing fuel consumption in a Hybrid Strong scenario will result in 2035 new vehicles reducing 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 percent market penetration of plug-in hybrids (PHEVs) by 2035. Since PHEVs consume relatively small mount 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.

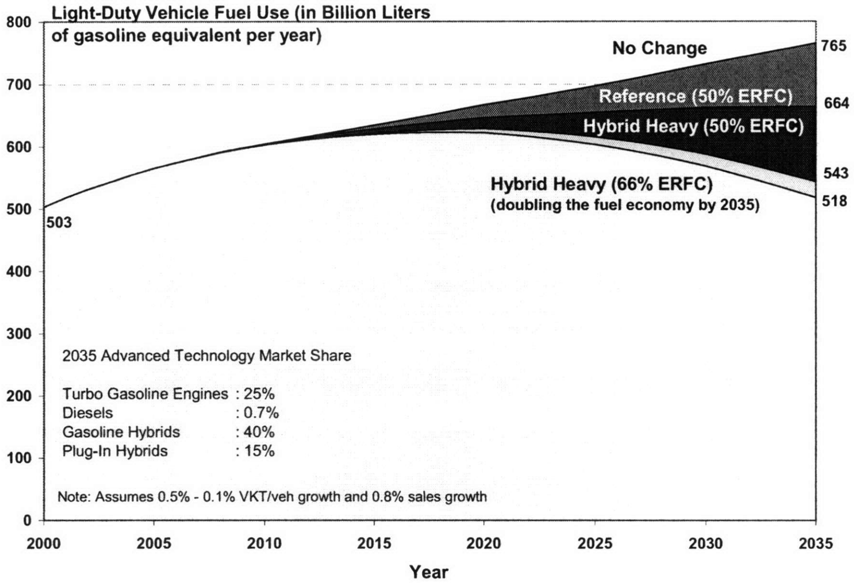
Table 30 Emphasis on Reducing Fuel Consumption (ERFC) required to double the fuel economy of new vehicles in 2035 for different scenarios

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

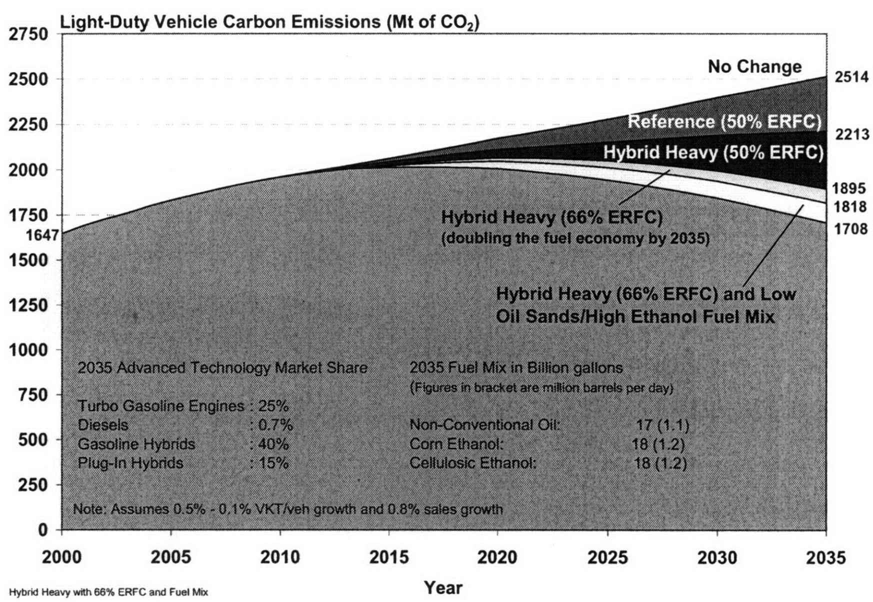
If a doubling of new vehicle fuel economy is achieved by increasing ERFC to 66 percent in the Hybrid Strong scenario, the resulting light-duty vehicle fleet fuel use and CO_2 emissions are shown in Figure 69. The fuel use shown in Figure 69 (a) under this scenario maxes out at 623 billion liters in year 2018, and returns to its 2001 value by year 2035. The corresponding GHG emissions shown in Figure 69 (b) max out at 2047 million metric tons in 2020, and reduce by 28 percent in 2035 compared with No Change scenario.

Adding the Low Oil Sands and High Ethanol fuel mix to this scenario can reduce the 2035 GHG emissions by a further 6 percent to 1708 million metric tons of CO_2. The cumulative

GHG savings of more than 7800 million metric tons of CO_2 compared with No Change and 4900 million metric tons of CO_2 compared with the reference case scenario.



(a) Fuel Use



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

Figure 69 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 percent of baseline vehicle manufacturing costs. While these costs could be recouped during the vehicle operation through fuel savings, the changes necessary to achieve 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 percent 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.

Effect of Reducing Demand

While the goal of this research 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 demand can be lowered by other means. This is illustrated in Figure 70.

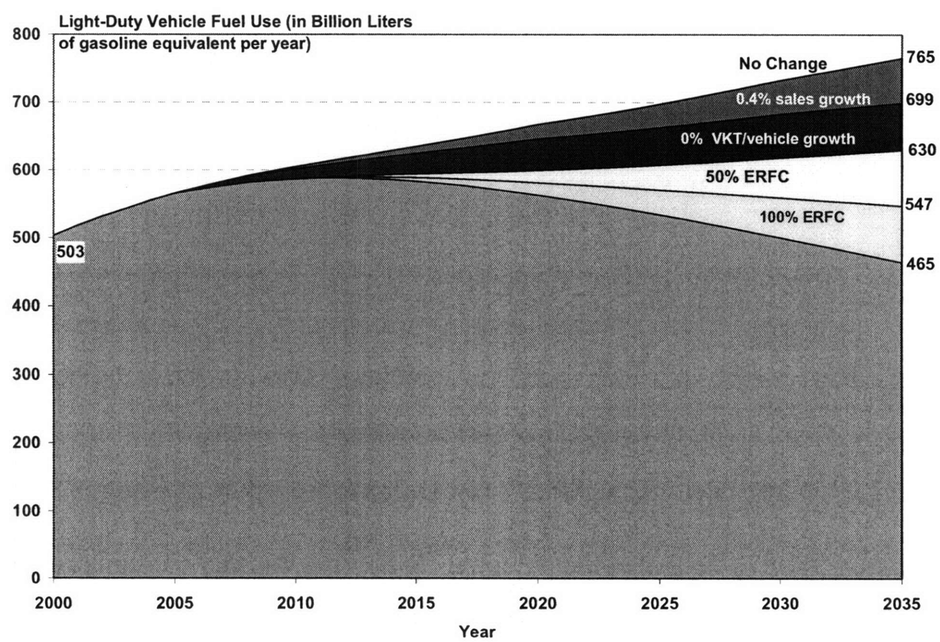


Figure 70 Effect of Reducing Rates of Growth on LDV Fleet Fuel Use

As discussed briefly in chapter 3, halving the sales growth rate from 0.8 percent per year will reduce the 2035 LDV fuel use by approximately 8.6 percent. In addition, if the growth in per vehicle travel could be halted i.e. per vehicle travel were held at today's value, a further 10 percent 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 percent, an additional 26 percent reduction in 2035 fuel use can be realized, therefore bringing the total reduction of more than 39 percent from the No Change scenario.

Note that no advanced propulsion systems are assumed in this scenario. Even the Hybrid Strong scenario with 100 percent ERFC as described in Chapter 5 achieves the same amount of reduction in 2035 fuel use (See Figure 52). 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 (100% ERFC) scenario, this scenario achieves a cumulative additional fuel use reduction of 835 billion liters (5 billion barrels of oil) and 3200 million metric tons of CO_2 emissions over the thirty year period from 2005 to 2035.

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 71 with the help of WBCSD Sustainable Mobility Project (SMP) global fleet model [IEA/SMP, 2004].

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 fleet 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 percent ERFC in the U.S. LDVs, then the global LDV fleet GHG emissions will plateau around 3750 million metric tons 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 time period, without the help from advanced propulsion systems and alternative fuels.

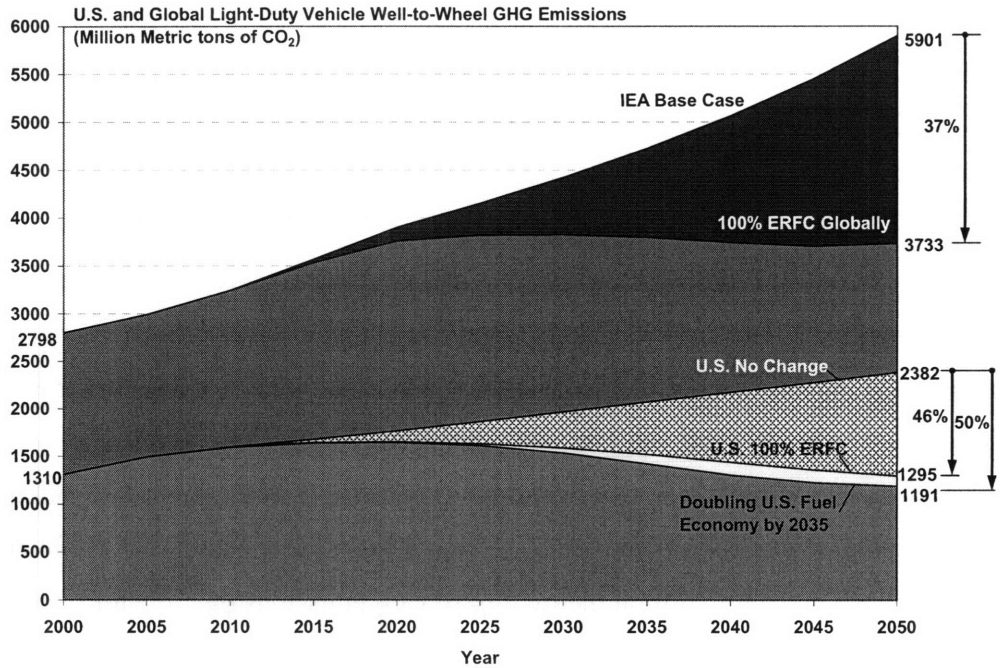


Figure 71 U.S. and Global LDV Well-to-Wheel GHG Emissions (2000-2050)

Figure 71 should highlight 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 provide an additional wiggle room on the global LDV GHG emissions front.

Summary and Outlook

This chapter has integrated the impact of changes in vehicle technology and fuel mix on light-duty vehicle fleet greenhouse gas emissions. The scenario results show that life-cycle GHG emission reductions will likely lag reduction in petroleum use. While up to 35 percent reduction in fleet GHG emissions from a No Change scenario are possible by 2035, the magnitude of changes required to achieve these reductions are daunting. The final chapter will summarize the major results and conclusions from this research.

Chapter 8

Summary and Conclusions

This final chapter will briefly summarize the results of this work and the major conclusions that emerge from it.

Summary

The objective of this thesis was to gain an insight into the possible impact of advanced propulsion systems and fuels on the U.S. light-duty vehicle fleet over the next three decades. As compared with the previous work in this domain, which compares individual vehicle or fuel alternatives, the focus in this thesis was on fleet calculations.

Chapter Two developed the context in which the U.S. light-duty vehicle technologies and policies evolve. The chapter highlighted the complex interactions between the diverse stakeholders, and the need for a coordinated policy approach that spreads the costs and benefits among different stakeholders.

Chapter Three identified the primary trends underlying the growth in LDV fleet fuel use, and introduced the U.S. light-duty vehicle fleet model and its structure. The model results 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 model results indicate that if left unchecked, the U.S. light-duty vehicle fleet fuel use will increase by some 35% between 2005 and 2035.

Chapter Four introduced the concepts of Performance Size Fuel Economy Index (PSFI) and Emphasis on Reducing Fuel Consumption (ERFC). The impact of steadily rising vehicle performance on fuel consumption reduction was evaluated by using these indices. It was also shown that up to 26 percent reduction in future LDV fuel use from a No change scenario is possible with mainstream gasoline ICE vehicles alone if the performance-size-fuel consumption trade-off is resolved in favor of reducing fuel consumption. The chapter further estimated the relative reduction in fuel consumption from emerging vehicle technologies, and also evaluated the sensitivity of these propulsion systems to the performance-size-fuel consumption trade-off.

Chapter Five elaborated on the factors affecting the likely scale and impact of advanced propulsion systems. By taking both supply and demand side constraints on building up vehicle production rates, three plausible market penetration scenarios were developed. These scenarios indicate that substantial potential exists to reduce light-duty fleet fuel use over the next three decades. The LDV fleet fuel use in 2035 could be up to 40% lower than in No Change scenario if advanced propulsion technologies such as hybrids or diesels can garner more than half of the new vehicle market by 2035, and all the advances in technology are used to emphasize reduction in fuel consumption.

Chapter Six showed the role of alternatives to conventional petroleum – mainly non-conventional oil from tar sands and ethanol from biomass – in the U.S. light-duty vehicle fleet. Based on the emissions intensity of fuel mix, the fleet model was extended to calculate the well-to-wheel greenhouse gas emissions. Scenarios of a changing fuel mix revealed that a 2-6 percent reduction in well-to-wheel GHG emissions is possible through fuel mix changes. This chapter also indicated that in general, measures that reduce greenhouse gas emissions also reduce petroleum consumption, but the converse is not necessarily true.

Chapter Seven integrated the impact of changes in vehicle technology and fuel mix on light-duty vehicle fleet life-cycle greenhouse gas emissions. The scenario results show that life-cycle GHG emission reductions will likely lag reduction in petroleum use. While up to 35 percent reduction in fleet GHG emissions from a No Change scenario is possible by 2035, the magnitude of changes required to achieve these reductions are daunting, as all of the current trends run counter to the changes required.

Conclusions

The following conclusions can be drawn from this work:

- At constant performance and increased cost, a 30-50% reduction in light-duty vehicle fuel consumption, and a 25-40% reduction in fleet fuel use is feasible over the next three decades. Whether this reduction in fuel consumption is realized in the vehicles and on-road depends on the relative importance given to vehicle performance, size and fuel consumption. Policies to reduce vehicle fuel consumption should take into account this trade-off between vehicle performance, size and fuel consumption. Placing a greater emphasis on reducing fuel consumption rather than improving vehicle performance can lower the required market penetration rates of advanced vehicle technologies to achieve reductions in fuel use and greenhouse gas emissions. Therefore, addressing the vehicle performance-size-fuel consumption trade-off should be the priority for policymakers rather than promoting specific vehicle technologies and fuels.

- Due to slow rates of fleet turnover, fuel consumption of mainstream technology vehicles will determine the near-term level of fuel use and GHG emissions. The key to reducing near-term light-duty vehicle fuel use and GHG emissions is not *what* specific propulsion or fuel technology to deploy, but *how* to deploy these technologies. In other words, directing the efficiency improvements towards reducing fuel consumption of high-sales-volume vehicles is critical. In the near-term the high volume vehicles will be gasoline ICE vehicles, and efforts to reduce their fuel consumption will yield a greater result in terms of reducing fuel use and GHG emissions.

- Delaying reductions in fuel consumption not only pushes the problem out in time, but the growth during the delay increases the absolute amount of fuel use and emissions that must be reduced afterwards. Fleet calculation shows that even small changes made sooner can result in larger benefits than more aggressive actions taken later.

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

- In the longer-term, the impact of advanced technology vehicles will indeed be far larger than their near term impact. Since the time-scales to impact of new technologies are long, advanced vehicle technology introduction needs to start as early as possible to realize deep reductions in long-term fuel use and GHG emissions. Sustained policy efforts that go well beyond the incentives during the initial market introduction of advanced propulsion systems and fuels will be needed to reduce light-duty vehicle fleet fuel use.

- A greater number of vehicle and fuel alternatives are available to displace petroleum use than to reduce greenhouse gas emissions. For example, plug-in hybrids could, over the longer term, have a large impact on reducing petroleum use, but GHG reductions similar to plug-ins can be achieved by gasoline hybrids at a lower cost. Therefore, policies that selectively promote plug-in hybrids will certainly help to reduce petroleum consumption, but won't be cost effective in reducing greenhouse gas emissions. Similarly, policy incentives that promote development of domestic liquid fuels such as coal-to-liquids may well reduce dependence on petroleum, but the resulting increase in greenhouse gas emissions will largely negate any decrease in GHG emissions from low carbon biomass-to-liquids. Policy efforts, therefore, should be focused on measures that improve both energy security and carbon emissions at the same time.

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