Assessing the Fuel Consumption and GHG of Future In-Use Vehicles

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Abstract - Over the next several decades, substantial reductions in greenhouse gas emissions from transportation will be required. The targets—an 80% reduction by 2050—are challenging. Thus, we need quantitative methodologies for assessing the impact of changes in vehicle technology and use, and of fuels, on transportation energy consumption and GHG emissions. This paper describes an appropriate methodology for creating plausible future transportation scenarios and assessing their impacts. It focuses on light-duty vehicles (cars and light trucks), in the U.S. and European context. The factors that must be included are: more efficient propulsion systems; vehicle weight changes; performance, size and other vehicle attributes; and now rapidly the deployment of these improved technologies can grow over time. The methodology combines engineering assessments of vehicle performance for the different propulsion and vehicle technologies, a model of the in-use vehicle fleet, and the availability of the various possible fuels. The findings show there is significant potential for reducing petroleum consumption and GHG emissions through improvements in engines, transmissions, vehicle weight reduction, and alternative fuels.

Keywords – alternative fuels, GHG emissions, transportation energy, light-duty vehicle assessment, vehicle fleet modeling

1. INTRODUCTION

As the world's nations consider how best to set targets for reducing greenhouse gas emissions, assessing the opportunities for reducing the transportation sector's contribution is especially important. Transportation contributes about 25% of energy-related global greenhouse gas emissions and that contribution is growing faster than other sectors [1]. Reducing emissions from the transportation sector is more challenging because internal combustion engine technology and petroleum-derived fuels completely dominate our land-based transportation systems, and these technologies and fuels, and the types of vehicles we now use, have developed and been optimized over many decades. In the world's developed countries, most people like the mobility and freight distribution services that their transportation systems provide and do not want these services curtailed. In developing countries, where transportation demand is growing rapidly, planners lack of resources and inability to manage the market's response to that escalating demand (for many reasons) makes reducing GHG emissions especially challenging.

The options available for reducing transportation's fuel consumption and GHG emissions include: more efficient mainstream drivetrains (engines and transmissions), transitioning to more efficient and thus lower GHG emitting alternative propulsion systems, bringing in alternative lower-GHG-emitting fuels and electricity, reducing vehicle weight and drag, moderating vehicle performance expectations [2], adopting eco-driving behaviors [3], increasing vehicle occupancy, reducing the amount of driving, expanding use of public transportation and non-motorized trips, infrastructure management and control [4], etc. This paper focuses on powertrain and vehicle technologies, and alternative fuels opportunities. It describes a methodology for assessing the impacts of various evolving powertrain and vehicle options and fuels scenarios, on future in-use vehicle fleet fuel consumption and GHG emissions. It enables the quantitative comparison of the impacts of various scenarios. A quantitative assessment of our plausible GHG reduction options is essential to developing effective strategies and policies.

2. METHODOLOGY

2.1 Overview

A quantitative model for assessing the impacts on the GHG emissions of a given country or region of different evolving transportation technology and fuels scenarios needs the following components:

(a) A vehicle analysis capability that, for given propulsion system and vehicle technologies (and architectures) can predict the vehicle's fuel consumption and GHG emissions over specified drive cycles.
(b) A model for the dynamics of the in-use vehicle fleet, which includes vehicle sales and scrappage rates, and annual mileage driven.
(c) Specification of new or improved technology introduction timeframes and deployment rates of these technologies as a function of time.
(d) The resolution of the vehicle fuel consumption, performance and acceration, vehicle size, trade-off that, for given powertrain and vehicle technologies affects the improvement in fuel consumption actually achieved.
(e) Quantitative scenarios for the fuel (or energy) streams anticipated to be available over the appropriate timeframe and the GHG emissions

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associated with the production and distribution of those fuels.

We have developed such a methodology for the United States context and for several major European countries, [2], [6], for the respective light-duty vehicle (LDV) fleets. The overall structure of the in-use LDV fleet model is given in Figure 1 [2], which shows the required inputs, and the logic sequence of the outputs: the make-up of the LD vehicle stock; the LDV fleet kilometers travelled; the fleet fuel use; and the fleet GHG emissions. The several components of this methodology will now be reviewed. Additional details can be found in references [2] and [5].

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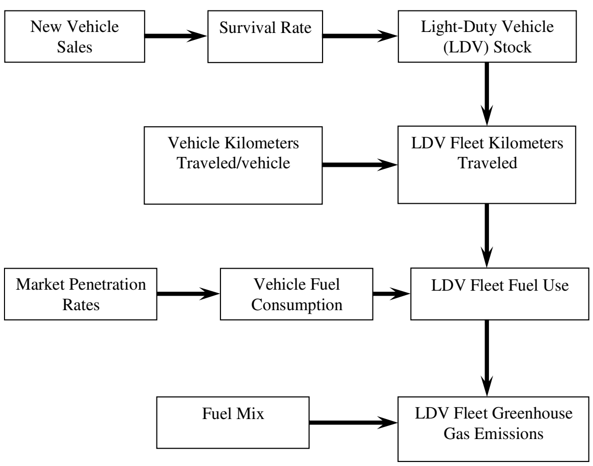


Fig. 1. Fleet Model Overview

2.2 Vehicle simulations

Advances in vehicle technologies and fuels are expected to contribute greatly toward reducing use of petroleum and CO_2 emissions from transportation. Current vehicle propulsion is dominated by internal combustion engines (ICEs) that release the chemical energy in fossil fuels by combustion converting it to mechanical energy. Gasoline-powered spark-ignition (SI) engines dominate the U.S. light-duty market, but diesel-powered compression ignition (CI) engines are widespread in European light-duty vehicles, and dominate the heavy-duty market globally.

There are several different pathways along which vehicle technologies may evolve. In the nearer-term, continuing improvement of ICE-based vehicles will occur, and it is anticipated that electric and fuel cell vehicles will be developed. While the basic architecture of ICEs has not changed significantly over the last several decades, engine technology has improved steadily during this period, and such improvements are likely to continue [7], [8]. Because it takes 15-plus years for the light-duty vehicle fleet to turn over, and alternative powertrains are only just penetrating the market, it is expected that mainstream ICEs will continue to be the dominant light-duty vehicle propulsion system for the next two decades.

Gasoline hybrid-electric vehicles (HEVs) offer a mid-term solution. HEVs typically combine a high-power battery and electric motor with a downsized ICE to capture additional energy efficiency benefits. Currernt HEVs are not charged from an external electric supply and have limited ability to drive the vehicle in an all-electric mode. Plug-in hybrid vehicles (PHEVs) have a larger battery pack onboard that can be charged from an external electricity supply, and are typically capable of driving 20-60 kilometers on electricity alone. Because they obtain a portion of their energy from the electric grid, PHEVs move further along the path towards vehicle electrification. Full electric vehicles are being introduced.

Fuel cell vehicles (FCVs) running on hydrogen provide another non-ICE propulsion system alternative. Initially, FCVs are expected to be hybrids with a powerful onboard battery.

The fuel consumption reduction potential of these different propulsion technologies are compared by analyzing reference vehicles whose size and performance are held constant, usually at the level of today's models. We have used (for the U.S.) the Toyota Camry with a 2.5-liter gasoline engine, as a close-to-average car, and the Ford F-150 with a 4.2-liter gasoline engine, as a representative light-truck. The Camry and the F-150 are currently the best-selling U.S. light-duty vehicles. Our vehicle system simulations were performed using ADVISOR^R software. ADVISOR is a backward-facing simulation [9].

To develop performance models of future vehicles, the evolution of the major individual vehicle components was first estimated using engineering scaling laws [9]. This evaluation entailed an assessment of vehicle characteristics such as weight reduction, aerodynamic improvements, tire friction reduction, and engine/propulsion system and transmission improvements, as well as electrical system and architecture/control arrangements for hybrids. The resulting vehicle system simulation was then run over different driving patterns (drive cycles and performance tests) to obtain the vehicle's operating characteristics: fuel consumption, 0 – 60 mph (0 – 100 km/h) acceleration times, etc.

The following propulsion systems have been studied: the naturally-aspirated gasoline-fueled spark-ignition engine vehicle (NA-SI); the turbocharged spark-ignition engine vehicle; the compression-ignition diesel vehicle; the gasoline hybrid-electric vehicle (HEV); the plug-in hybrid (PHEV); the fuel cell hybrid vehicle (FCV); and the battery-electric vehicle (BEV).

Figure 2 shows the average fuel consumption (adjusted on-the-road values obtained from the combined U.S. urban and highway test cycle values for these propulsion systems normalized by today's naturally-aspirated gasoline vehicle [2]. These vehicle assessments were done at the same vehicle performance (today's average level) and size. Anticipated vehicle weight reduction (20% by 2035) is included. These numbers in Figure 2 represent the relative fuel consumption of the average new vehicle for each propulsion system sold in that year. Note how the projected fuel consumptions of all these various propulsion-technology vehicles steadily improve over time, but do so at different rates. HEVs and PHEVs show substantial benefits and faster rates of improvement (but at increased vehicle cost [2]). The fuel consumption for PHEVs is based on the gasoline usage and does not include the electricity used. For a PHEV with a 30-mile (50 km) electric range, about half the miles travelled are gasoline-fueled and about half electric. Each electric mile requires between one-third to one-fourth the gasoline energy for each gasoline mile.

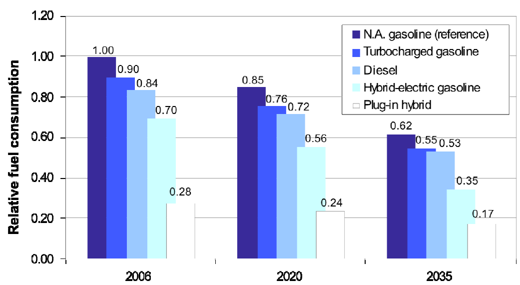


Fig. 2. Relative fuel consumption of future cars, by powertrain type (at 100% ERFC).

2.3 Weight and Drag Reduction

Vehicle weight reduction presents an important opportunity to reduce fuel use in the transportation sector. By reducing the mass of the vehicle, the inertial forces that the engine has to overcome are less, and the power required to move the vehicle is thus lowered. Reducing the vehicle's aerodynamic drag and tire rolling resistance also improve fuel consumption. Opportunities for reducing these vehicles resistances also exist.

In the United States, today's sales-weighted average new light-duty vehicle weight is 1,880 kg (4,144 lb), and has been increasing slowly but steadily at a rate of about 1% per year since the early 1980s. Since the mid-1980s, the popularity of larger and heavier light-trucks, especially sport utility vehicles (SUVs), was partly responsible for this upward weight trend. Weight increase within vehicle classes or segments also takes place. One reason for this is "feature creep"; the increasing number of new features that have been introduced into vehicles that improve utility such as comfort and safety, but also add weight. Steadily increasing vehicle weight has been the trend, except under special circumstances such as between 1976 and 1982 in the U.S., when automakers reduced the average weight of new vehicles in response to the "energy crisis," and the enactment of federal Corporate Average Fuel Economy (CAFE) regulations. With new U.S. CAFE standards recently legislated, interest in vehicle weight reduction is intensifing.

While it is clear that vehicle weight reduction can reduce fuel consumption, the precise relationship is not so obvious. On average in the U.S., every 100 kg weight reduction will achieve a reduction of 0.69 L/100km in fuel consumption. Many studies describe the vehicle fuel consumption reduction benefit associated with lightweighting. It varies from 4.5-8.0% for every 10% reduction in vehicle weight. Factors that affect this relationship include the size and type of vehicle, the drive cycle used, and the type of powertrain. Simulations of representative vehicle models were run using AVL© ADVISOR vehicle simulation software of recent model-year Toyota Camry and the Ford F-150 truck, to represent the average U.S. car and light truck [2].

The simulations revealed that with acceleration performance and size unchanged, for every 100 kg weight reduction, the adjusted, combined city/highway fuel consumption could decrease by 0.40 L/100km for cars, and 0.49 L/100km for light trucks in the United States. In other words, for every 10% weight reduction from the average new car or light truck's weight, the vehicle's fuel consumption reduced by 6.9% and 7.6%, respectively.

Vehicle weight reduction can be achieved by a combination of: (1) use of lightweight material; (2) redesigning the vehicle to minimize weight; and (3) downsizing the new vehicle fleet by shifting sales away from larger and heavier vehicles.

Typically, about three-quarters of a vehicle's weight is incorporated in its powertrain, chassis, and body, and the bulk of this is made of ferrous metals. Other major materials found in an average automobile in the United States include aluminum and plastics or composites. The use of aluminum and high-strength steel (HSS) as a percentage of total vehicle mass has been increasing over the pasts two decades, while the use of iron and mild steel has been declining.

Other material candidates include magnesium, and polymer composites such as glass- and carbon-fiber-reinforced thermosets and thermoplastics. A comparison of these options is given in Table 1. Of these candidates, aluminum and HSS are more cost-effective at large production volume scales, and their increasing use in vehicles is likely to continue. Cast aluminum is most suited to replace cast iron components, stamped aluminum for stamped steel body panels, and HSS for structural steel parts. Polymer composites are also expected to replace some steel in the vehicle, but to a smaller degree given high cost inhibitions. With aggressive use of lightweight materials, net weight savings of 20-45% can be obtained and has been demonstrated in concept vehicles [2].

Redesigning or reconfiguring the vehicle can also achieve weight savings. For example, the marked decline in vehicle weight in the U.S. in the early 1980s was partly achieved by changing vehicles from a heavier body-on-frame to lighter-weight unibody designs. Although most cars now have a unibody design, the potential exists for smaller sport-utility vehicles

Table 1. Comparisons of alternative lightweight automotive materials.

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

to follow suit. Another way to minimize weight is to minimize the exterior dimensions of the vehicle while maintaining the same interior space, or to remove features from the vehicle.

Secondary weight savings can also be realized by downsizing subsystems that depend on the total vehicle weight. As the vehicle weight decreases, the performance requirements of the engine, suspension, brake and other subsystems and are lowered, and these can be resized accordingly. Secondary weight benefits depend on the vehicle subsystem being considered. We have assumed that the amount of secondary weight savings possible by vehicle redesign to be half the benefit achieved with material substitution. So, for every incremental kilogram of weight reduction from material substitution, one can expect to achieve a further 0.5 kg weight savings with weight-minimizing redesign [2].

Vehicle size reduction, is the third way to reduce vehicle weight. Vehicle size correlates with weight. By shifting sales away from larger and heavier vehicle types, reduction in the sales-weighted average new vehicle weight can be obtained. This can be done by shifting to smaller vehicles *across* vehicle segments or by downsizing vehicles *within* each vehicle segment. In the U.S., if cars were downsized to midsize, and midsize to small, weight savings of 9-12% could be achieved. For other vehicle segments including SUVs and pickups, such a size shift could produce weight savings of about twice this percentage.

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

While engine and vehicle technology have steadily improved over the past 25 years and vehicles have become more efficient the average fuel consumption of new vehicles sold in the U.S. each year has not changed significantly. The higher efficiencies achieved have been used to offset the negative impacts of increasing vehicle size, weight, and power on fuel consumption. This ever-increasing performance and size imposes a penalty on vehicle fuel use.

Since the mid-80s, the average fuel consumption of U.S. light-duty vehicles (LDVs) has remained nearly constant. Despite the fact that powertrain and thus vehicle efficiency have steadily improved. Improved powertrain efficiency has been utilized to offset the negative impact on fuel consumption of increasing vehicle acceleration and power, size, weight, or some combination thereof. Then, the actual fuel consumption is less than would be achieved at constant vehicle performance and size. Obviously, the fuel consumption trend that is realized in practice will depend on the degree of emphasis placed on reducing actual fuel consumption.

To better understand the influence of the performance-size-fuel consumption trade-off, we have introduced a variable we call *Emphasis on Reducing Fuel Consumption,* or ERFC for short.

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

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

Kasseris and Heywood [9] assumed a 20% reduction in vehicle weight by 2035 for the 100% ERFC case. When ERFC is below 100%, the corresponding weight reduction is scaled by ERFC. Thus, the 2035 ICE gasoline vehicle with 50% ERFC would be 10% lighter than the current ICE gasoline vehicle, and so on. The corresponding improvement in acceleration performance can also be calculated [5].

Figure 3 shows an example of this trade-off between vehicle acceleration performance, weight, and fuel consumption for a 2030 mid-sized U.S. car with steadily improving more efficient technology. The vertical line in the figure is for an ERFC of zero: there is no improvement in fuel consumption. The horizontal line shows an ERFC of 100%. Performance does not change and fuel consumption improves by 37%. The 50% ERFC point is about halfway in between.

The fuel consumption versus performance trade-off has played out very differently in Europe, when compared to the U.S. where over the past 25 years, ERFC has been less than 10%. The ERFC in the four largest European passenger vehicle markets (Germany, Italy, France, and the UK) has been about 50% [6].

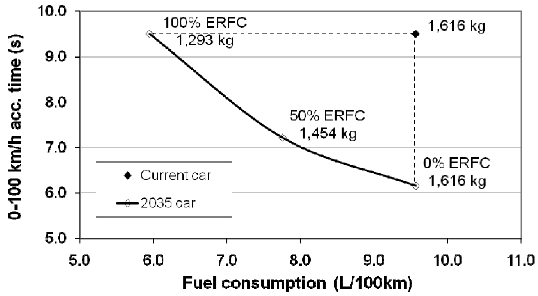


Fig. 3. Trade-off between acceleration performance and fuel consumption in the average new U.S. gasoline cars in 2035, as a function of Emphasis on Reducing Fuel Consumption (ERFC).

The concept of Emphasis on Reducing Fuel Consumption (ERFC), which defines what percentage of the improved efficiency from powertrain and other technologies employed in vehicles is used to reduce actual vehicle fuel consumption is clearly an important one. It must, therefore, be included in the assessment methodology. We have shown that significantly larger reductions in future LDV fuel use are possible if the performance-size-fuel consumption trade-off is favorably resolved.

2.5 *In-Use 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 pickups, minivans, and sport utility vehicles (SUVs). New LDV sales in 2006 totaled nearly 16.6 million units, comprising 8.1 million passenger cars and 8.5 million light-trucks, approximately 7% of the total LDV fleet. To evaluate the impact that emerging propulsion systems and fuels could have on total LDV fleet fuel use and greenhouse gas (GHG) emissions, a model of the dynamics of fleet turnover and usage must be developed. This section explains the logic of the LDV fleet model used for this purpose.

The fleet model is a tool to track LDV stock, travel, fuel use, and greenhouse gas emissions [2]. A simplified overview of the fleet model is shown in Figure 1. The model tracks new vehicle sales, market shares of different propulsions systems and their fuel consumption, vehicle aging and scrappage, vehicle stock, vehicle travel, and fuel mix. Historical data from 1960 onward is used to calibrate the model. Here we describe the details of the model's individual building blocks.

Three different public sources of data on U.S. LDVs were used: (1) The Transportation Energy Data Book (TEDB); (2) The EPA Light-Duty Automotive Technology and Fuel Economy Trends reports; (3) The U.S. Department of Transportation report compiled by National Highway Transportation and Safety Administration (NHTSA). Wherever possible, the fleet model uses data compiled from these three sources.

The annual sales of light-duty vehicles in the United States are divided into two categories: cars and light trucks. (This distinction is not used in most of the rest of the world). The share of light trucks in new LDV sales has increased from 15% in 1970 to over 50% in 2005. The growth in the light-truck category, however, has slowed in the past few years. The default setting in our fleet model is to maintain the market share of cars and light-trucks at this current level of 50%.

There are approximately 800 vehicles per thousand people in the United States. There are about 600 vehicles per thousand people in Canada and Western Europe, and fewer than 20 vehicles per thousand people in China. Presently, the number of light-duty vehicles on the road in the United States exceeds the number of licensed drivers. Given this unprecedented level of vehicle ownership, it is unlikely that the growth rate of light-duty vehicle sales will be much faster than the rate of growth in the U.S. population.

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: (1) a logistic function to estimate the survival rate of light-duty vehicles based on the median lifetime of cars and light trucks; (2) a Weibull distribution based on attrition rates of passenger cars; (3) based on engineering scrappage defined as scrappage as scrappage resulting from vehicle aging and accompanying physical wear and tear [2].

For the purpose of our model, the survival rate of new vehicles is determined by using a logistic curve as shown in Equation 1.

$$1 - \text{Survival Rate (t)} = \frac{1}{\alpha + \exp\left[-\beta(t - t_0)\right]} \qquad (1)$$

where, t_0 is the median lifetime of the corresponding model year; t, the age in a given year; β, a growth parameter translating how fast vehicles are retired around t_0; α, a model parameter set to 1. We have kept the median lifetime constant after model year 1990 at 16.9 years for cars and 15.5 years for light trucks. The growth parameter β is fitted to 0.28 for cars and 0.22 for light trucks.

Increase in total vehicle kilometers travelled (VKT) takes place as a result of an increase in the number of vehicles on the road and an increase in kilometers travelled per vehicle. The long-term growth in VKT per vehicle for light-duty vehicles is 0.5-0.6% per year. In the future, the rate of growth in per-vehicle kilometers travelled is assumed to decrease from 0.5% per year between 2005 and 2020, to 0.25% per year in 2021-2030, to 0.1% per year in the years after 2030. This simplifying assumption prevents the distance driven per vehicle from escalating rapidly beyond 30,000 km per year [2].

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

$$VKT = VKT_{\text{new}} \times e^{-ri} \tag{2}$$

The total VKT for a given calendar year, j, is obtained using Equation 3:

$$VKT_j = \sum_i N_{i,j} \times VKT_{i,j} \tag{3}$$

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

Historical new vehicle fuel consumption values from 1975-2005 are taken from NHTSA and EPA data. The model assumes that new vehicles meet the CAFE standards for years 2006-2010. These fuel consumption data are not adjusted for on-road performance. The on-road fuel consumption is higher than the test values because of differences between actual driving conditions and trip patterns, and the test cycles, as well as less than ideal state of maintenance of vehicles and aggressive driving behavior. Allowing for these factors, actual versus test-cycle fuel economy requires an adjustment. A study by the U.S. EPA [10] indicates that the average on-road fuel consumption of new vehicles from 1986-2010 is greater than the test values by about 20%. Our model uses the same value as the IEA Sustainable Mobility project: an average shortfall of 19% in fuel economy or a 22% increase in fuel consumption [11].

We have assumed that future reductions in fuel consumption start in 2010. We estimate the potential fuel use reductions that can materialize if more emphasis is placed on reducing fuel consumption in the future, as opposed to the little or no emphasis placed on it over the past 20 years. Thus, no emphasis placed on fuel consumption reduction (0% ERFC) becomes our *No Change Scenario*. If the average performance and size of future vehicles remains the same as that of today's vehicles (ERFC = 100%), then the fuel consumption of future vehicles is assessed using the vehicle analysis methodology described in Section 2.2. This, however, is an overly optimistic assessment of the fuel consumption/performance/size trade-off. More realistic assumptions, such as an ERFC of 50% or 75%, reduce the fuel consumption of the different future vehicles by less than this constant performance and size amount. For an assumed ERFC, the average on-road fuel consumption of future vehicles (with different propulsion systems and weights) for a given future year (e.g., twenty-five years ahead, in 2035) is estimated using the approach described by Cheah et al. [5]. Then, fuel consumption values for intermediate years are obtained by linearly interpolating between current new vehicle values and these estimated values at a specific future year (such as 2035).

The fuel use of the entire in-use fleet is calculated by summing up the fuel use of vehicles of the same age, using different technologies, which in turn is calculated by multiplying the number of vehicles in service of that age and technology type by the number of vehicle kilometers travelled, and then by their respective fuel consumption. Fuel use is calculated separately for each propulsion system type in gasoline-equivalent units. Greenhouse gas emissions are calculated on a well-to-wheel basis by multiplying the fuel use by a corresponding well-to-tank and tank-to-wheel greenhouse gas emission coefficient, as discussed in Section 3. Energy use and greenhouse gas emissions from the vehicle manufacturing and disposal stage are also incorporated in the model.

2.6 Deployment of New Technology

The rate of deployment of new propulsion system and vehicle technology in new vehicles is a key input in assessing the in-use fleet's fuel consumption and GHG emissions.

The last decade has seen the market introduction of gasoline-electric hybrid vehicles (HEVs), some renewed interest in diesels in the U.S. market, and increasing exploration of more complex propulsion systems such as Plug-In Hybrid Vehicles (PHEV) and Hydrogen Fuel Cell Vehicles (FCVs). The extent to which these technologies successfully compete with the steadily improving gasoline vehicles in the marketplace will have a significant impact on the long-term trajectory of light-duty vehicle fuel use. Here we discuss the challenges that must be overcome in order to achieve a greater market penetration of these alternatives, and how we assess plausible deployment rates of successful new technologies.

New propulsion systems and alternatively fueled vehicles face many hurdles on their way to market acceptance. The major barriers include: higher vehicle purchase price; reduced driving range with alternative fuels; potential safety issues; worse reliability and durability; uncertain and likely higher fuel cost (including fuel taxes); lack of refueling infrastructure; competing effectively with attributes and functionality of mainstream gasoline-fueled vehicles; higher capital and other fixed costs since learning and economies of large-scale production not yet realized. Also, consumers heavily discount the potential for fuel savings realized when adopting a costlier technology, which increases the auto manufacturer's risk. Even if the demand for an emerging vehicle or propulsion system component is strong, the supply of such systems could be limited. This could be due to constraints in engineering and capital resources, as well as supply chain considerations.

The automobile is a highly complex product, and consumer expectations from a mass-produced vehicle are demanding. As a result, even proven sub-systems or components may take up to 15 years to become available across all market segments. A broad survey of technological change in the automobile industry suggests that it takes 10–30 years after introduction of a new technology before it is deployed on half of new vehicles sold [2]. With respect to emerging technologies such as hybrids, the integration of the new technology into vehicles is more complex, and additional time may be needed to develop components so that they meet traditional safety and reliability requirements.

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. To convert 10% of the US domestic production capacity (~1.3 million vehicles per year) to produce hybrids and diesels each will take a capital investment of approximately $2.2 billion and $1.6 billion, respectively. The annual capital expenditure of the U.S. motor vehicle manufacturing sector is about $20 billion.

As these supply side constraints suggest, the time scales by which new technologies can have an impact on fleet fuel use and GHG emissions are long. This timeline can be split into three stages. In the first stage, a market-competitive technology needs to be developed. For a technology to be market competitive, it must be available across a range of vehicle categories at a low enough cost premium to enable the technology to become mainstream. The time scales for the different propulsion systems to become mainstream alternatives depend on their relative maturity. Turbocharged gasoline engines, diesels, and gasoline hybrids are currently available and thus they are market-competitive. Plug-in hybrid and battery electric vehicles are about to enter into limited production. They could become market-competitive in 5-10 years. The case for a market competitive fuel cell vehicle is more speculative: a mass-market fuel cell vehicle is at least 10 years away.

The second stage of technology implementation is the penetration of that new technology into new vehicle to attain a market share of the order of a fourth to a third of total vehicle sales. Typically, these time scales have been about 15 years: an example is the time it took for diesels to grow to one-third of the new vehicle market in many European countries—some 20 years. Growth in deployment rates of major new technologies in the past have typically been about 10% per year, once an initial 5-10 year period of low-volume production has successfully been completed.

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

By combining these three phases we obtain an estimate of the time before significant impact for new vehicle technologies can occur. There is some overlap between each of the three phases, and thus the net time to impact is thus somewhat smaller than the sum of each stage. For turbo gasoline engine vehicles this is about 20 years; for plug-in hybrids it is some 30 years, with conventional hybrids some 25 years [2].

The barriers and constraints outlined above provide the rationale for our choice of deployment rates of improved mainstream engine, transmission, weight reduction technologies, and significant numbers of advanced propulsion system technologies, such as low-emissions diesels, gasoline hybrids, and plug-in hybrids. Since these deployment rates are critical inputs to our impact assessments, scenarios are generated that encompass a range of assumptions about market penetration rates of different technologies.

An illustration of the deployment rates of the different propulsion systems in U.S. light-duty vehicles out beyond 2035 that we have used in our impact assessments is shown in Figure 4 [2]. In this *Market-Mix scenario* with no clear "winner" (see Section 4), by 2035 HEVs and PHEVs are assumed to account for about one-third of the alternatives propulsion systems. Turbo gasoline vehicles are 40% of the total gasoline engine vehicles. The corresponding compounded annual growth rates range from 6-14%, with the total alternative propulsion systems sales fraction growing at 7% per year over this 25-year period.

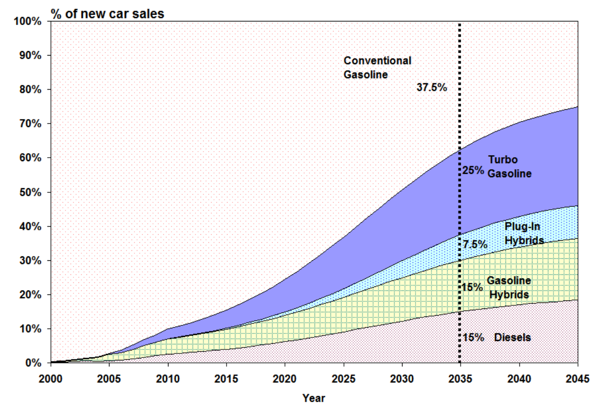


Fig. 4. Market Mix—No Clear Winner Scenario: Deployment rates of the various propulsion systems.

3. FUEL SUPPLY OPTIONS

More than 97% of the energy used in the U.S. transportation sector comes from petroleum, and transportation accounts for more than two-thirds of U.S. petroleum consumption. The desire to diversify away from petroleum has been at the heart of the search for alternative fuels. More recently, efforts to reduce transportation's greenhouse gas emissions have provided a further boost for this search. Petroleum use in land-based transportation is split between gasoline and diesel. In the U.S., light-duty vehicles predominantly use gasoline (diesel is some 3%); diesel dominates heavy-duty vehicle fuel use. In Europe, diesel is a major component of light-duty vehicle fuel use since the fleet has about equal shares of gasoline and diesel vehicles. As in the U.S., diesel also dominates European heavy-duty vehicle fuel use. Since growth in the heavy-duty freight arena is more rapid than in the light-duty fleet, the ratio of diesel fuel demand to gasoline demand is rising.

Non-conventional sources of liquid fuels such as oil or 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 hydrocarbon resources is very large—of the order of several trillion barrels of oil equivalent [12]. Considerable uncertainty exists, however, regarding the economic and environmental viability of these resources. Non-conventional oil projects are more capital intensive than conventional oil production, and thus are more susceptible to volatility in the global oil market. Also the life-cycle carbon emissions associated with the production and use of non-conventional oil sources can be significantly greater than those associated with producing fuels from conventional oil.

Biomass has the potential to provide a renewable and low greenhouse gas-emitting liquid fuel pathway. While there is a diversity in the types of biomass resources and conversion technologies available to produce liquid transportation fuels, the worldwide production of liquid fuels from biomass has been mainly ethanol and biodiesel. The energy and environmental impacts of large-scale cultivation of biomass for fuel production are not yet well understood. There is a growing consensus, however, that biofuels will be a useful part of the future transportation fuel mix.

Hydrogen and electricity are the two energy carriers that could become a part of the transportation “fuel mix” longer term, if corresponding vehicle technologies (viz. fuel cell and plug-in hybrid/ electric) become market competitive. Electricity is familiar and readily available to consumers, but hydrogen will have to overcome the barriers of unfamiliarity and the lack of fueling infrastructure. Both electricity and hydrogen can be produced from a diverse mix of fuel sources. While this has the advantage of source diversity, greenhouse gas emissions from the production and distribution of hydrogen and electricity vary widely depending on the source. These fuels, however, will only significantly reduce GHG emissions from the transportation sector if they are produced on a large scale from low GHG emission sources. Non-conventional petroleum fuels, from oil or tar sands largely in Canada and heavy oil in Venezuela, already constitute about 5% of U.S. petroleum use. Over time (next 20 years) these are expected to grow to 10 - 15%. The fuels produced from these feedstocks are gasoline, diesel, and aviation fuel and thus can be integrated into the petroleum supply and distribution system.

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

In 2007, 10.5 billion gallons of ethanol and 2.5 billion gallons of biodiesel were produced globally, representing approximately 2.2% and 1.6% of the global transportation fuels market on a volume and energy basis respectively. Over time, biodiesel and ethanol production have increased, largely due to government blending mandates and tax incentives. Though global biodiesel production has increased over the past five years, it still represents only 20% of the biofuels market. Though biodiesel production may increase over the next several years, the overall scale of biodiesel production in the short to medium term is still limited by its cost of production, poor land use efficiency, and limited government support. In the U.S., corn-based ethanol currently dominates. While no commercial facilities currently process cellulosic material into ethanol, several pilot plants to convert lignocellulosic material such as corn stover to ethanol are being constructed.

The impact of biofuels on climate change is being increasingly debated: the societal and environmental costs of biofuels are participating contentious. These impacts include increases in food prices around the world, as well as increased water consumption and soil erosion from more energy crop production, and water contamination from increased fertilizer use. The potential for significant GHG emissions from land use changes, especially when forest lands are converted to croplands, is of growing concern as well.

Biofuels have the potential to displace a significant fraction of petroleum use, and provide some reduction in greenhouse gas emissions. However, due to the economic and environmental challenges posed by a rapid expansion of biofuels production, it appears unlikely that bioethanol will contribute more than 10–15% of fuel supply by 2035 on an energy basis, and will deliver a significantly smaller reduction in greenhouse gas emissions.

The use of electricity in light-duty vehicles will grow if plug-in hybrids (PHEVs) or battery electric vehicles enter the market in large numbers. While this would help displace petroleum use, the GHG emissions reductions will depend on the efficiency of vehicles under electric operation and the GHG intensity of the electricity used. The 2007 EIA Annual Energy Outlook reference case projects limited changes 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 only modestly. When losses in transmission (9%) and battery charging (10%) are taken into consideration, the average U.S. emissions rate is approximately 770 gCO_2/MWh or 214 gCO_2/MJ of electricity delivered to the vehicle. The emissions intensity of electricity will vary regionally, and the initially marginal load imposed by plug-in hybrid and electric vehicles will likely be taken up by available spare capacity.

Hydrogen can also be produced from a variety of sources. Currently, industrial hydrogen is produced by steam reforming natural gas. Centralized production of hydrogen will produce less CO_2 emissions compared to distributed production at service stations because it would be more efficient and would lend itself to carbon capture and storage [13]. During any initial start-up phase of hydrogen fuel cell vehicles, however, the demand for hydrogen will be small and the cost effective option will likely be forecourt production. In the much longer term, hydrogen could be produced at distributed locations from renewable electricity, or from coal or biomass with carbon capture and storage. For the time scales under consideration here, distributed steam methane reforming of natural gas will most likely be the source of hydrogen production. Weiss et al. [14] estimated that 130 - 140 g CO_2 will be emitted during production and delivery of one MJ of compressed hydrogen to the vehicle fuel tank.

The life-cycle emissions factors used to calculate future vehicle fleet well-to-wheels GHG emissions are given in Table 2 [2]. 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 as it grows, cancels out emissions during combustion. As a result, the CO_2 emissions associated with the use of ethanol during vehicle operation are considered to be zero.

Table 2. Energy use and CO_2 emissions factors for different transportation fuels [2].

FUEL	ENERGY (fossil MJ / MJ delivered to tank)	GHG EMISSIONS Fuel Cycle (g CO_2 / MJ delivered to tank)	Vehicle Operation (g CO_2 / MJ delivered from tank to wheels)	Total (g CO_2 / MJ delivered from well to wheels)
Conventional gasoline	0.24	21	71	92
Conventional diesel	0.21	18	76	94
Gasoline from oil sands	0.41	38	71	109
Ethanol from corn	0.68[1]	77[1]	0	77
Ethanol from cellulose	0.09	9	0	9
Electricity (avg. U.S. grid mix)	2.30	214	0	214
Hydrogen from natural gas	0.84	132	0	132

[1]Includes a 20% co-product credit for dried distillers grains.

Based on the fuel cycle emissions factors shown in Table 2, and vehicle fuel consumption calculations discussed in Section 2, we can estimate the petroleum consumption and life-cycle GHG emissions of different types of vehicles. Figure 5 shows fuel consumption and well-to-wheel GHG emissions for future cars using different fuels. Note that compared to today's average car, which consumes 8.8 L/100 km of gasoline and emits 250 g CO_2/km, all future vehicles have the potential to realize a dramatic reduction on both counts. Note also that while the transition from gasoline hybrid to PHEV, then to fuel cell and general purpose BEV, would step petroleum consumption down essentially to zero, the well-to-wheels GHG emissions with the anticipated U.S. electricity and hydrogen supply system change little.

4. ILLUSTRATIVE RESULTS

We now illustrate the use of the methodology described in the previous sections. As explained, the required inputs are: trends in future new vehicles sales, mileage driven per vehicle, and average vehicle lifetime; the evolution of average new vehicle on-road fuel consumption for each powertrain technology over time (at constant performance and size); the emphasis on reducing fuel consumption versus offsetting increased performance (the value of ERFC—which degrades the constant performance and size fuel consumption values); the deployment rates of each different powertrain technology; and (as an option) segmentation of the in-use fleet into different vehicle categories. Many different scenarios have been developed and analyzed, e.g., [2], [5], and that work continues. Here we present some examples of results projected out to 2035, which illustrate the value of such scenario analysis.

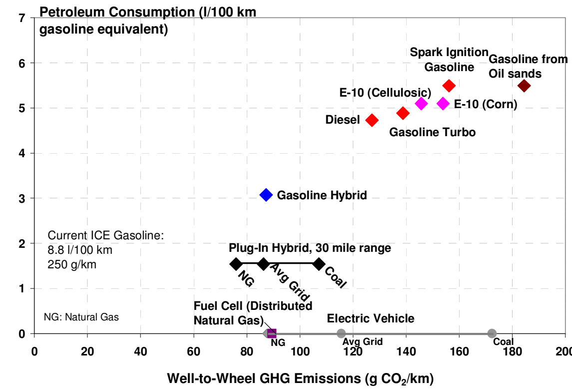


Fig. 5. Fuel consumption and well-to-wheel GHG emissions for future (2035) cars and fuels.

Figure 6 shows the importance of the relative emphasis on reducing fuel consumption parameter. The vertical scale is the projected fuel consumption (ERFC) (billion liters per year) of the in-use U.S. light-duty vehicle fleet out to 2035. The *No Change scenario* shows the effects of modest growth in vehicle fleet size and miles (km) per year individual vehicle travel. It has an ERFC equal to zero: the last 25 years in the U.S, have followed a close to zero ERFC trend as performance has steadily escalated [2]. With no growth in sales and mileage driven, the fleet fuel consumption would change little beyond 2010. However, at least nearer term, there will be increases in performance as the different auto manufacturers compete for market share and customers encourage that trend. The reference case shown in the Figure corresponds to a context where moderate pressure from gasoline price, increases in fuel economy standards, and competitive pressures, combine to prompt steady improvements in the fuel consumption of gasoline engines (as indicated by the left-hand bars in each set in Figure 2). With an ERFC of 50%, the Figure 6 benefits over time are effectively halved. In this reference case, the other "alternative" propulsion systems included in Figure 2 are not deployed to any significant degree. Note that with only gasoline engine improvements (and some vehicle weight reduction), it takes an ERFC of at least 50% to offset the growth levels embedded in this scenario.

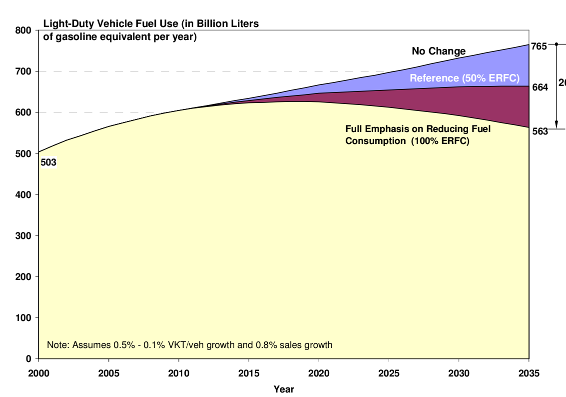
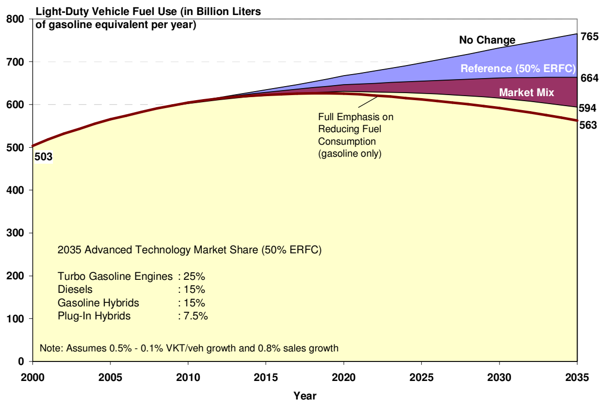
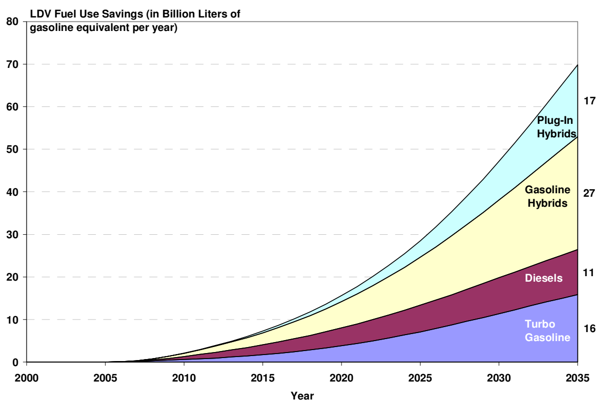


Fig. 6. U.S. LDV fleet fuel for No Change and ICE Reference case, with 50% and full emphasis on reducing fuel consumption.



(a) LDV Fuel Use



(b) Contribution of different propulsion systems in fuel savings.

Figs. 7(a) (b). LDV fuel use under the Market Mix Scenario, and the No Change and Reference Scenarios.

Figure 7 shows the projected gasoline-equivalent-fuel consumption of the in-use U.S. LDV fleet for the *Market Mix scenario* where the sales of the different propulsion systems included grow with time as shown in Figure 4. We do not claim that this is the "most likely" scenario: rather that these different powertrains each have market appeal across the cost versus benefit spectrum, and may well be deployed in response to market pull from different segments of the LDV fleet. Note that the Reference (50% ERFC) scenario from Figure 6 is repeated on Figure 7(a), and the benefit of the Market Mix of alternative powertrains is separately identified. The 50% ERFC market mix approaches the 100% ERFC Reference case of Figure 6. Obviously, higher ERFC than 50% with the alternative propulsion systems of the *Market Mix scenario* would bring total fuel consumption and GHG emissions in 2035 down lower.

Figure 7(b) shows the fuel savings that result from the percentages of different propulsion systems deployed. It makes clear that proportionally, the higher the hybrid fraction and the plug-in hybrid fraction the larger the fuel and GHG emissions reductions that are achieved. These more efficient propulsion systems have an increasing impact on the downturn of these curves beyond 2035. Note that the electricity used in the PHEVs is not included in these gasoline equivalent fuel consumption numbers. In a lifecycle GHG emissions accounting they would need to be evaluated and included.

Additional scenarios have been analyzed in reference [2]. The results from these different fleet scenarios are summarized in Table 3. They show an 18-44% reduction in 2035 average new vehicle fuel consumption from the *No Change Scenario*. In the very near term (~2015), though, all scenarios show similar modest values of new vehicle fuel consumption.

Table 3. Summary of LDV fleet fuel use scenarios.

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

The total life-cycle energy and greenhouse gas emissions of the LDV fleet are obtained by adding together the well-to-tank, tank-to-wheel, and vehicle manufacturing and end-of-life disposal energy and GHG emission reductions. The reductions realized from the *No Change scenario* are substantially less than the fuel consumption reductions described in this section. Several factors contribute negatively, the major ones being: (1) the well-to-tank and manufacturing and disposal emissions are added to the tank-to-wheel emissions, effectively "diluting" the tank-to-wheel reductions; (2) realistic alternative fuels scenarios are dominated over the next two decades by non-conventional petroleum (from oil sands and heavy oil) and corn-based ethanol which (combined) increase GHG emissions; (3) any electricity used (in the U.S. context) has only slightly lower GHG emissions than the equivalent petroleum [2].

5. SUMMARY

This paper has made clear how important it is to assess *quantitatively* the potential impacts of various petroleum consumption and GHG emissions reduction opportunities in our transportation sectors. A quantitative methodology that assesses these impacts has been described. It requires many inputs relating to powertrain and vehicle technologies, alternative fuel streams, deployment rates of improved and new technologies and fuels, and in-use behavior. Many of these inputs are data based: some are assumptions based on judgments. Thus the best use of this methodology is to assess the various opportunities for reducing fuel consumption and GHG emissions through comparing carefully constructed scenarios since differences in the estimated impacts are less sensitive to uncertainties in the assumptions made. Especially this methodology can identify what factors are most important in achieving reductions. One important finding from the illustrative examples discussed is that it substantially more difficult to achieve reductions in GHG emissions from transportation than reductions in petroleum consumption.

ACKNOWLEDGEMENT

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Fig. 1. Fleet Model Overview.

Fig. 2. Relative fuel consumption of future cars, by powertrain type (at 100% ERFC).

Fig. 3. Trade-off between acceleration performance and fuel consumption in the average new U.S. gasoline cars in 2035, as a function of Emphasis on Reducing Fuel Consumption (ERFC).

Fig. 4. Market Mix—No Clear Winner Scenario: Deployment rates of t he various propulsion systems.

Fig. 5. Fuel consumption and well-to-wheel GHG emissions for furture (2035) cars and fuels.

Fig. 6. U.S. LDV fleet fuel for No Change and ICE Reference cars, withi 50% and full emphasis on reducing fuel consumption.

Figs. 7(a)(b). LDV fuel use under the *Market Mix Scenario*, and the *No Change* and *Reference Scenarios.*

Table 1. Comparisons of alternative lightweight automotive materials.

Table 2. Energy use and CO_2 emissions factors for different transportation fuels [2].

Table 3. Summary of LDV fleet fuel use scenarios.