More Sustainable Transportation:

The Role of Energy Efficient

Vehicle Technologies

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Background

This report provides an overview of how anticipated changes in engine, transmission, and vehicle technologies, and vehicle weight, size and performance expectations, are likely to impact petroleum consumption and greenhouse gas emissions from personal transportation. It also reviews how fuels changes could impact these challenges. Obviously, this is a formidable agenda and quantitative estimates are speculative. While data on these questions is available relating to the U.S. and the rest of the developed world, much less information is available on likely future vehicle technology and vehicle types relevant to the developing world. This overview focuses on light-duty passenger vehicles (cars and light trucks), though some 40% of land transportation energy is used in freight transportation.

Personal transportation in the developed world is highly dependent on the automobile. There are about 800 million light-duty vehicles, cars and light trucks used largely for personal transportation in the world today. While the majority of these are in OECD countries, the developing world is following this developed world personal transport path at an accelerating rate. In the U.S., there are approximately 240 million light-duty vehicles: about 135 million cars, and about 105 million light-trucks. Gasoline use by U.S. cars and light trucks (pickups, SUVs, and vans) account for approximately 44 percent of U.S. oil consumption and some 10 percent of world oil consumption. The U.S. Energy Information Administration (EIA) estimates that sixty percent of the liquid fuels used in the U.S. will be imported and an increasing fraction of this supply will come from the Middle East and Organization of Petroleum Exporting Countries (OPEC). This pervasive and growing use of oil indicates that most of the world's nations have become vulnerable to availability and price fluctuations in the oil market.

Increasing consumption of petroleum leads inexorably to greenhouse gas emissions which contribute to global climate change. The transportation sector is the largest contributor among the end-use sectors of our economies 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, and tailpipe CO_2 emissions from LDVs are now about 22 percent of the total U.S. CO_2 emissions. Worldwide, transport GHG emissions are projected to grow at a rate of some 2 percent per annum. This unrelenting increase in the consumption of oil in personal transportation vehicles presents extremely challenging energy and environmental problems.

Advances in vehicle technologies and fuels are expected to contribute greatly towards reducing use of petroleum and CO_2 emissions from transportation. My own group at M.I.T. has been involved in a substantial research effort focused on these issues for the last several years. A report has recently been completed which summarizes our findings [1]. While we have primarily analyzed the situation in the United States, comparative studies in major European countries have also been completed [2]. These studies have examined the potential for improved propulsion system and vehicle technologies, the introduction of alternative fuel streams to augment mainstream petroleum-based fuels, plausible time scales and rates at which production volumes of improved technologies could increase, how changes in the weighting of the vehicle attributes—performance, size, and on-the-road fuel consumption—affect the impact these technology improvements would have. Especially, we have examined the impacts that changes in these vehicle technologies, fuels, vehicle purchase and use criteria, would have on the fuel consumption and GHG emissions of the U.S. in-use vehicle fleet. Our findings thus cover a wide range of topics: they allow us to provide a comprehensive summary, set of conclusions, and recommendations.

An important issue to keep in mind is that petroleum use and greenhouse gas emissions are increasing steadily in the U.S., in the rest of the developed world, and especially in the developing world, due to seemingly inexorable growth in land and air, passenger and freight transportation demand. Our first challenge is to offset this growth.

Opportunities for Reducing Vehicle Fuel Consumption

Figure 1 illustrates the energy flows in an average size U.S. car in urban driving. Vehicle fuel consumption can be improved by reducing losses in the propulsion and non-propulsion systems. A summary of these fuel consumption reduction opportunities is given below. Details can be found in Kasseris and Heywood [3] and Kromer and Heywood [4].

The opportunities available over the next 25 or so years include: improvements in vehicle aerodynamics yielding a reduction in drag by about 25%; improvements in tire rolling friction where a similar reduction is plausible; and significant vehicle weight reduction. Vehicle size and passive safety issues are critical here. Technically-based weight reduction can probably achieve a 20% reduction in curb weight. Additional weight reduction can be achieved by vehicle redesign and size reduction. The total potential for weight reduction over this timeframe is about one-third.

Propulsion system improvements include both engine and transmission improvements. Transmissions will become more efficient by moving from four and five speeds to six and seven speeds, and using automated mechanical or continuously variable designs. Thus, the efficiency of (automatic) transmissions is likely to improve from around 80% today to over 90% in the future.

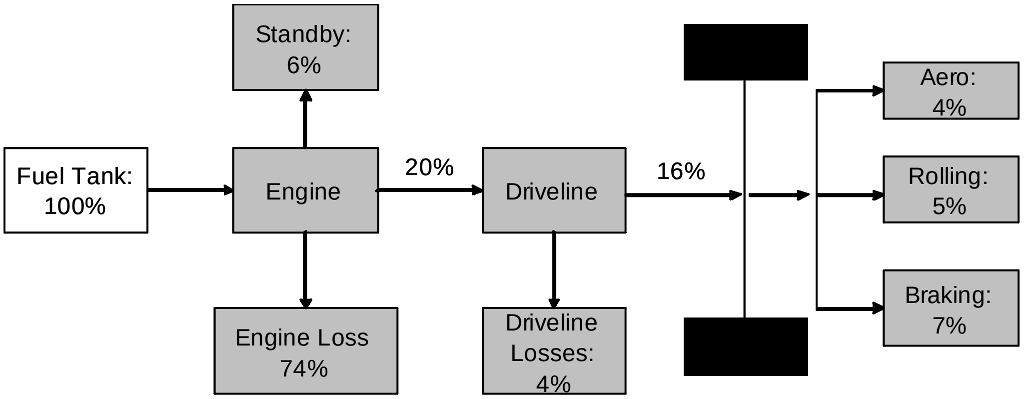

Figure 1 Vehicle Energy Flow in an Urban Driving Cycle [1]

Standard gasoline spark-ignition engines are continuing to improve the power per unit volume levels they can produce and their typical operating efficiency, by some 1% or so per year on average. Improvements come from friction reduction, variable valve control, cylinder deactivation, direct-injection of fuel into the cylinder, increasing compression ratio, and more sophisticated engine sensing and control. Increasingly this type of engine is being turbocharged to increase engine output and thus allow significant engine downsizing, which improves average engine efficiency. Diesel engines also have power and efficient improvement potential, though not as great as that available to gasoline engines. Future diesels will need effective emissions treatment technology in their exhausts for particulates and NO_x air pollution control, which adds significant cost, and some fuel consumption penalty. Thus, future turbocharged gasoline and diesel engines will be much closer in their power per unit engine size (or displaced volume) and their average driving efficiency.

Hybrid electric vehicles (HEV) are now being produced and sold in modest volume (a few percent of the market). Current hybrids comprise a battery pack, electric motor, a generator, electric power controls, and a sophisticated transmission. Most current configurations use a parallel hybrid arrangement where the transmission can decouple the engine or the motor from the wheels, and a control strategy that switches off the engine at idle and low loads and recovers some 90% of the braking energy through regeneration. These “charge-sustaining hybrids” improve fuel consumption significantly, the magnitude of the improvement depending on type of driving (e.g., low-speed urban, or high-speed highway) and other key details. In the future, with improved hybrid technology, vehicle fuel consumption improvements above current mainstream gasoline engine vehicles in 40-50% range appear feasible. “Electric drive” augmented by an on-board internal combustion engine is an inherently attractive propulsion system for the future. It is, however, about $2000 more expensive.

A plug-in hybrid vehicle (PHEV) is a hybrid-gasoline electric vehicle with the ability to recharge from the electric grid. The vehicle uses an advanced (e.g., lithium-ion) battery pack in a parallel hybrid configuration similar to that assumed for the conventional hybrid. Above a threshold battery state-of-charge (SOC), the PHEV operates in “charge depleting” (CD) mode in which it uses the onboard battery to meet the vehicle’s power demands. When it reaches its minimum SOC threshold, the vehicle switches to “charge sustaining” (CS) mode which is equivalent to vehicle operation in a conventional HEV. Both petroleum-based energy and electricity are used to drive the vehicle. Note that the electricity used on the vehicle requires about three times as much primary energy when it is produced from fossil fuels. Plug-in hybrid technology is being developed, but at present is too expensive for broad market appeal, and needs “green” electricity if it is to provide significant additional greenhouse gas reduction potential.

The battery-electric vehicle sources all of its energy from off-board electricity and is charged from the electric grid. The BEV requires a trade-off between cost and range. A 400-mile range vehicle is currently implausible from a cost and weight perspective, and even a 200-mile range is daunting. BEVs do not seem a viable large market contender at present.

Fuel cells for vehicle applications employ the proton-exchange membrane (PEM) fuel-cell system to power an electric motor usually in a series hybrid configuration. The battery characteristics are currently based on the same high-power lithium-ion battery increasingly used for the conventional hybrid vehicle. Fuel-cell vehicles must overcome a number of technological challenges and greatly reduce their cost before they can come to market in significant volumes. In particular, fuel cell performance and durability are limited by the properties of present-day membrane materials, by catalyst requirements, and by the complex systems management needed for fuel-cell operation. In addition to improved fuel-cell systems, developing an onboard hydrogen storage system, which offers adequate vehicle range, is a major cost, size and weight problem. The combination of improved vehicle technology and high fuel-cell efficiency enables a 10,000 psi storage gaseous hydrogen system to offer a driving range on the order of 400 miles with a 150 liter tank.

Performance of these Technologies

We have projected the performance and costs of these various propulsion system and vehicle technologies out to 2035, which corresponds to about 25 years from now. These projections in the U.S. context, which are illustrative are shown in Tables 1 and 2 [1]. Substantially better fuel consumption (at constant vehicle performance or acceleration, and size) is projected, but at higher cost. Vehicle weight reduction (20% in these vehicles) costs some $700. Note that in Europe and Asia where average size and weight is some two-thirds that in the U.S., the weight reduction potential is unlikely to be as great. Also, in Europe, about half of the light-duty vehicle fleet is diesel so the average fleet fuel efficiency is already higher in both an absolute and relative sense.

Table 1 Projected Improvements 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

Table 2 Incremental retail price increase of current and future propulsion technologies

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

Note that the vehicle’s lifetime fuel savings that go with these improved-fuel-consumption propulsion systems, when appropriately discounted, offset the increase in vehicle cost within a few years depending on the details and price of fuel. But to date, this positive social economic outcome result has only pulled incremental technology improvements into vehicles. It has not as yet created a strongly growing market for radically new and significantly more efficient technologies such as hybrids, though high fuel prices and lower diesel fuel taxes than gasoline along with better drivability have in Europe pulled in the diesel.

Table 1 shows the vehicle fuel consumption projections, what we call “tank to wheels.” It is then important to complete the life cycle analysis by including the energy consumption and GHG emissions of the fuel cycle and vehicle production cycle. The vehicle production cycle currently adds about 10% to the energy and GHG emissions burden. Some 25 years ahead, this will rise to between 15-20% due to increasing use of new and lighter weight materials which are more energy intensive, and through reductions in vehicle use fuel consumption. The fuel production and distribution cycle with petroleum fuels adds about 20% (with diesel less than gasoline); hydrocarbon fuels from non-conventional petroleum sources are likely to add about twice that.

Biofuels, electricity, and hydrogen, require a different type of life cycle analysis since fuel production and distribution cycle is now the dominant component. Biofuels vary from being comparable to the full life-cycle GHG emissions of gasoline-fueled vehicles for corn grain ethanol, to better than gasoline-fueled vehicles (sugar cane ethanol in Brazil), to potentially significantly better when based on cellulosic biomass conversion. Electricity's energy and GHG burdens vary substantially since they are dependent on how the electricity is generated. When generated from fossil fuels the burden is substantial, and the much more efficient use of electricity on the vehicle is essentially offset by the inefficiencies in electricity generation at the power plant and in distribution. Important questions are: what are the plausible sources of green electricity for transportation with, say, plug-in hybrids, and when would such green electricity become available? Hydrogen faces the same questions: how could it be made and distributed with low GHG emissions? Any hydrogen produced in the nearer-term, for example from natural gas, has energy consumption and GHG emissions levels that are not much different from those that would result from using petroleum fueled vehicles.

Figure 2 shows a comparison of the vehicle petroleum consumption and well-to-wheels GHG emissions of these various future propulsion systems, in mid-size lighter-weight cars in the U.S. context, for 2035. On this time scale, the GHG emissions per vehicle vary by about a factor of two. Improvements in mainstream engines, transmissions, vehicle weight and drag, decrease petroleum consumption, by some 30-40%. Plausible quantities of biofuels provide an additional 5% benefit. Hybrid technology provides a significant additional 40% step. While plug-in hybrids and fuel cells with hydrogen significantly reduce or remove petroleum consumption, in any transition build-up phase their GHG emissions impacts are no better than conventional gasoline charge-sustaining hybrid levels.

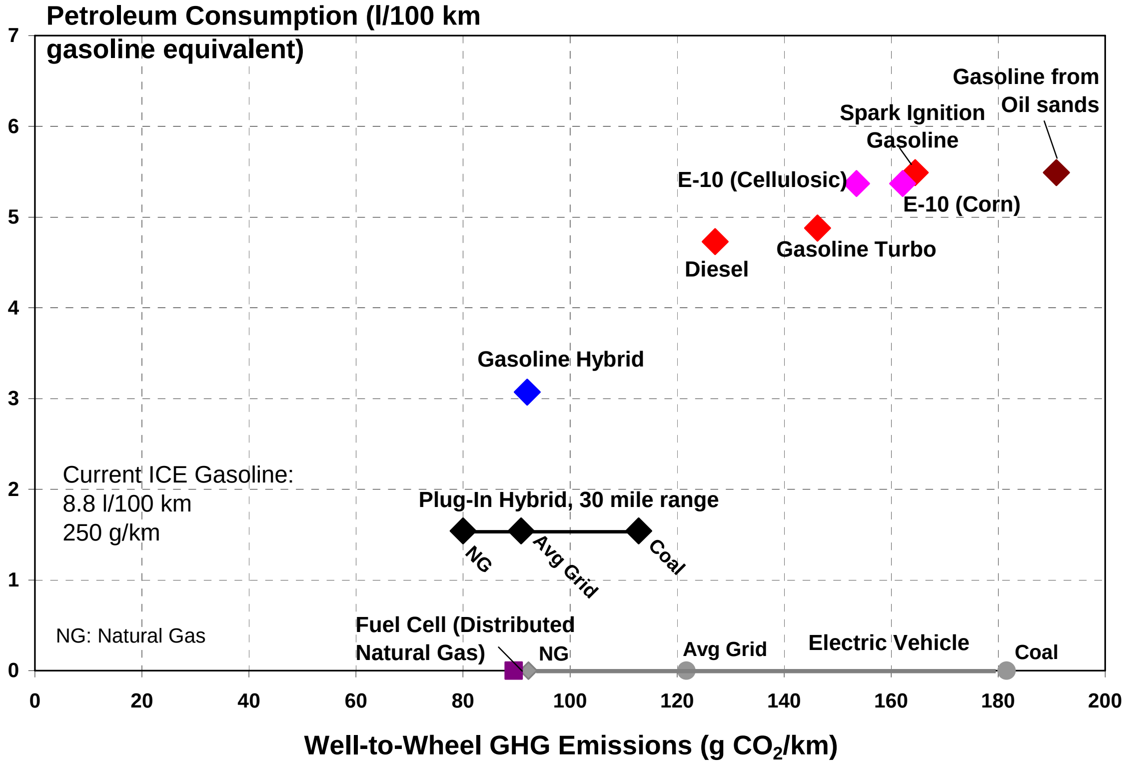

Figure 2 Fuel Consumption and Well-to-Wheel GHG Emissions for Future (2035) Cars

Vehicle Performance, Size, Fuel Consumption, Trade-Off

The previous section compared vehicle characteristics at constant vehicle performance or acceleration, and interior size. That is, as we project into the future these vehicle characteristics do not change. Data from the past two decades show that vehicle performance and size have steadily increased, especially performance. In the U.S., while engines and transmissions have become increasingly more efficient over the past 20 or so years, vehicle on-the-road fuel consumption has remained constant. In Europe, the performance escalation has not been as great, and about half of the efficiency improvements have shown up as vehicle fuel consumption reductions. We have introduced a parameter to quantify this critical trade-off: Emphasis on Reducing Fuel Consumption. This parameter has been zero since the early 1980s in the U.S., and about 50% in the major European countries we have analyzed. To achieve real world reductions in fuel consumption and GHG emissions, we will need to take into account this important trade-off between vehicle performance, size (and thus weight), and fuel consumption. Vehicle purchasers and users have shown a clear preference for increasing vehicle performance and larger size, thus providing market “pull” for these attributes. The automobile companies compete amongst themselves by offering ever-increasing performance and vehicle size, providing the “push.” In the U.S., the emphasis on enhanced performance has been so strong that (with some size increases) a fuel consumption gain at constant performance of some 25% has been lost. In Europe, the emphasis on performance has not been as strong, and some half of the fuel consumption improvements that could have been realized have been achieved.

We have discussed how vehicle weight and size reduction could contribute significantly to reduced petroleum consumption and greenhouse gas emissions. This is an important opportunity, and it adds to what powertrain improvements can do. Direct weight reductions through substitution of lighter materials and basic vehicle design changes (which, for example maximize the interior volume for a given vehicle length and width) enable secondary weight reductions as vehicle components are appropriately downsized. Much of this is straightforward engineering and some of this weight reduction is relatively low cost. A shift in vehicle size distribution away form larger vehicles also reduces average weight and initially can be accomplished by changes in production volumes with existing models. Our estimates indicate that a 20% reduction in sales-weighted average vehicle weight could be achieved over about 25 years. The maximum potential for weight reduction is about 35% but the additional reduction beyond 20% would cost significantly more. These estimates allow for the additional weight of future safety requirements and convenience features. Vehicle weight reductions of 20-35% on their own result in some 12-20 reduction in vehicle fuel consumption.

Impacts on Fleet Fuel Consumption and GHG Emissions

Improved propulsion system and vehicle technology only have impact when vehicles with these technologies are out there in large numbers. Such improved technologies must therefore have strong market appeal, and production volumes must be built up and high production volumes be sustained for 5-10 years to impact a large fraction of the in-use fleet. We have estimated and then compared the impacts of different market penetrations of the different promising propulsion systems with their different fuel consumption and GHG emissions characteristics through use of a vehicle fleet model. The required input information for connecting such scenarios to our fleet model are illustrated in Figure 3. Databases from which to extrapolate many of the various required inputs are available; some of these have been summarized already in Table 1. The assumptions that are critical but difficult to estimate are the market penetration rates or evolving production volumes of these improved and new technologies.

Figure 4 shows an example of such an impact calculation for the U.S. light-duty fleet: this scenario assumes that production volumes of turbocharged gasoline engines, diesels, hybrids and plug-in hybrids all grow steadily from current values to the percentages given in the figure by 2035. Many other assumptions are involved and the values used can be found in [1]. The "no change" line shows the fleet's gasoline consumption rising steadily due to growth in fleet size and mileage. With the "emphasis on reducing fuel consumption" (ERFC) at 50% (typical of current European practice), half the efficiency improvements are realized as actual fuel consumption reductions. The increasing thin wedges for each of the more efficient engine/propulsion system technologies are clear. Overall, this scenario reduces the fuel consumption from 765 to 594 billion liters per year, a 22% reduction. The two inputs that have the greatest effect on the scenario output calculation are this emphasis on reducing fuel consumption and the percentage of hybrids in the 2035 technology mix. 100% ERFC rather than 50% reduces fleet fuel consumption by an additional 15% to 505 billion liters per year. With 55% of the 2035 new vehicles hybrids, an additional 10% reduction in fleet fuel consumption to 543 billion liters could be achieved. Combined, these two additions would give up to an additional 30% reduction relative to the market mix line in Figure 4. Note that the impact of new (sometimes called advanced) technology vehicles grows slowly at first, but beyond about 2030 plays a growing and more substantial role in reducing fleet fuel consumption and thus GHG emissions.

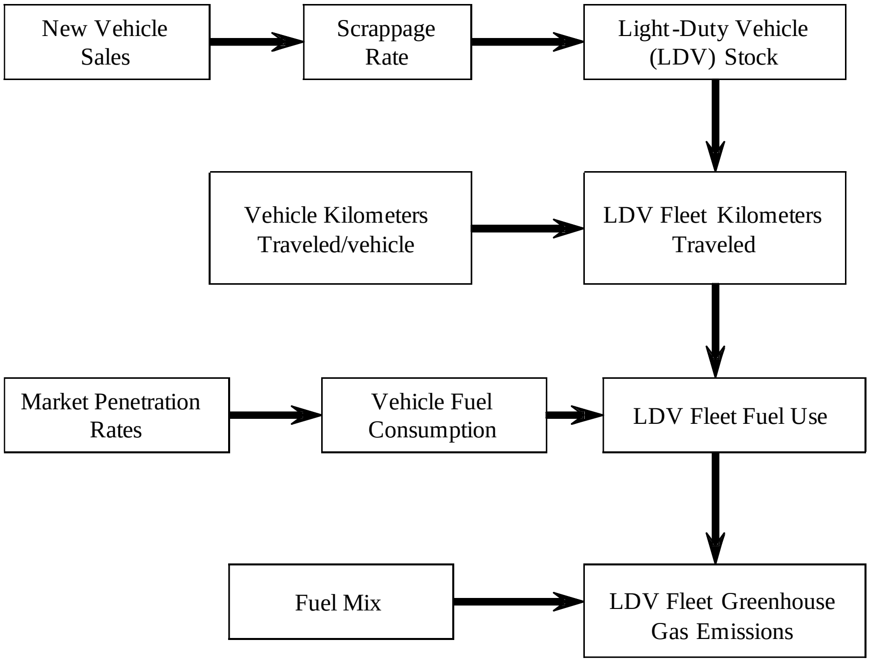

Figure 3 Fleet model overview indicating the required inputs [1]

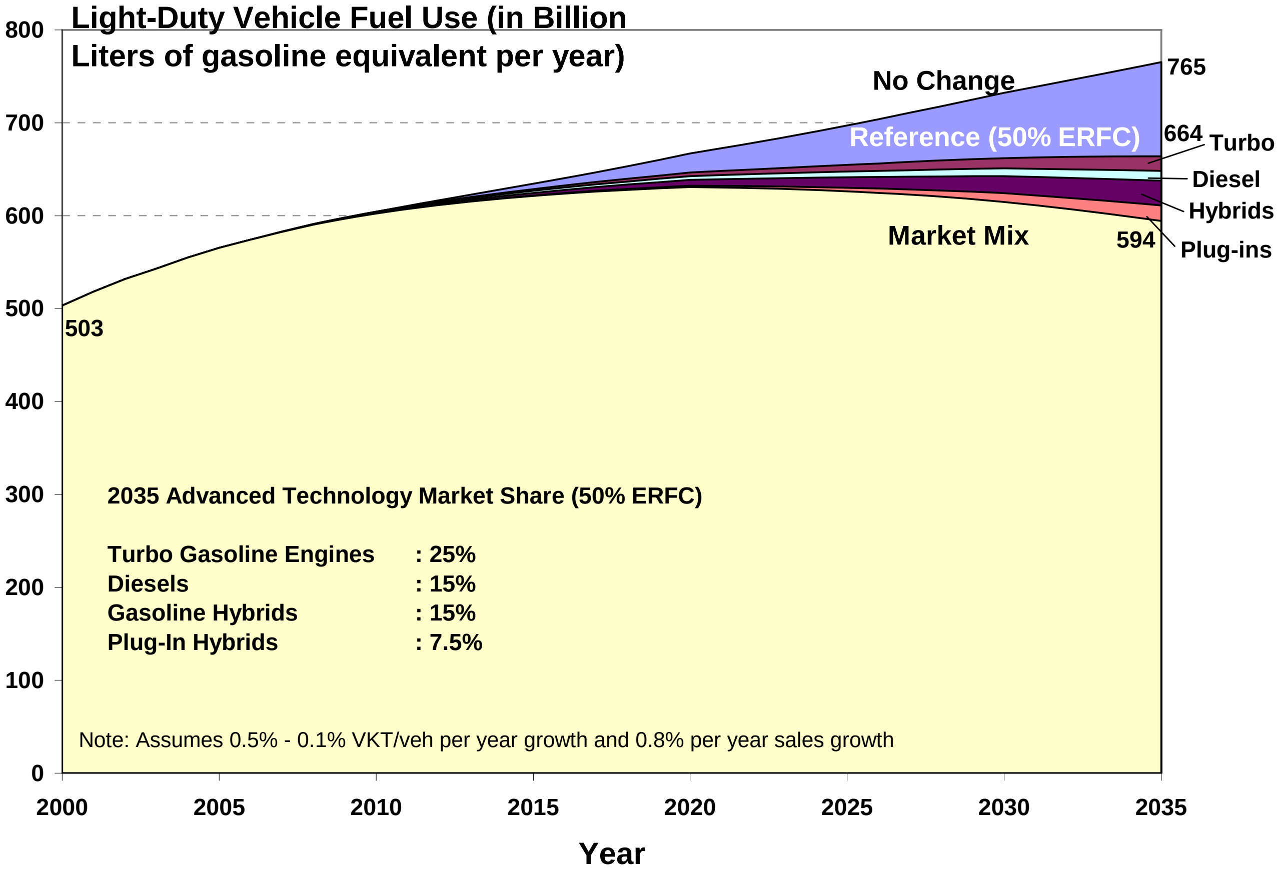

Figure 4 LDV Fleet Fuel Use Savings for Market Mix Case—50% emphasis on reducing fuel consumption ERFC [1]

Additionally, we have analyzed what it would take to halve the fuel consumption, or double the fuel economy, of the new car sales fleet in 2035 [5]. It would require that two-thirds of new vehicle production be hybrids, require 75% of the energy efficiency improvements to go into fuel consumption reduction instead of into increased performance and size (in the U.S. this percent is zero; in Europe it is around 50%), and a 20% vehicle weight reduction, on average. This is a challenging and demanding task.

Summary and Conclusions

Our work at MIT, and that of many others, leads to the following summary and conclusions regarding our options for reducing petroleum consumption and greenhouse gas emissions from the vehicles used for personal transportation.

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

2. At constant vehicle performance and size, a 30-50% reduction in new light-duty vehicle fuel consumption is feasible over the next 20 to 40 years. Such a reduction in fuel consumption can be achieved by a combination of:

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

   - Vehicle weight and drag reductions

   - Plug-in electric hybrids and hydrogen fuel cell hybrids in the longer-term

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

   The nearer-term changes, when combined in appropriate combinations in vehicles, result in vehicle cost increases between about $1500 and $3500 if produced in significant volumes. The additional costs of plug-in hybrids and fuel cell vehicles are uncertain but are anticipated to be significantly higher.

3. Policies developed to reduce vehicle fuel consumption will need to take into account the trade-offs between vehicle performance, size (and thus weight), and fuel consumption. Vehicle purchasers and users have shown a clear preference for increased vehicle performance and size providing market "pull" for these attributes. The automobile companies compete amongst each other by offering ever-increasing performance and vehicle size, providing the "push." In the U.S., the emphasis on enhanced performance has been so strong that (with some size increases) no significant fuel consumption gains have been realized over the past 25 years. In Europe, the emphasis on performance has not been as strong, and some half of the fuel consumption improvements that could have been realized have been achieved.

4. Vehicle weight and size reduction could contribute significantly to reduced petroleum consumption and greenhouse gas emissions. Direct weight reductions through substitution of lighter materials and basic vehicle design changes (which, for example maximize the interior volume for a given vehicle length and width) enable secondary weight reductions as vehicle components are appropriately downsized. A shift in vehicle size distribution away from larger vehicles also reduces average weight and initially can be accomplished by changes in production volumes. Our estimates indicate that a 20% reduction in sales-weight average

vehicle weight could be achieved over about 25 years. The maximum potential for weight reduction at plausible but significantly higher cost is about 35%. Vehicle weight reductions of 20-35% on their own result in some 12-20 reduction in vehicle fuel consumption.

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

6. Due to high initial cost and strong competition from mainstream gasoline vehicles, market penetration rates of low-emission diesels and gasoline hybrids (where current production volumes are low) are likely to be slower than is widely believed. As a result, diesels and gasoline hybrids have only a modest, though growing potential for reducing U.S. fleet fuel use before 2025. In Europe, the potential for impact through improved mainstream engines and weight reduction is significantly less due to the fact that roughly half the fleet is already diesel, and vehicle size and weight are some two-thirds of average U.S. vehicle values.

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

8. Alternative liquid transportation fuels are widely viewed as an important and growing contribution to reducing petroleum use and GHG emissions. Currently the Canadian oil-sands reserves are supplying about 3% of total U.S. petroleum use. This could expand to about 10% of total U.S. consumption in 2030. This would increase well-to-tank fleet GHG emissions by about 5%. Both corn-grain based ethanol and cellulosic ethanol from, say, switchgrass displace gasoline, by two-thirds volume for volume. The GHG emissions impacts are substantially different, with corn grain ethanol proving only modest GHG benefits and cellulosic biomass based ethanol potentially providing more substantial GHG benefits. Recent discussions of the GHG penalties associated with land use changes to produce the biomass material suggest that the presumed GHG benefits may only be partly realized. While ambitious targets for ethanol production and use have been set in many parts of the world (e.g., displacing 20% of gasoline by 2020 in the U.S.) it is unclear whether the targets for cellulosic ethanol (comparable volumes to corn ethanol by 2025) can be met, nor what the GHG emissions benefits are going to be. Ethanol is not yet cost competitive with current gasoline prices without significant subsidies.

9. 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, at present a costly and heavy option, might over the longer term have an important impact on reducing petroleum use. However, due to the likely GHG emissions from the electricity production required, the GHG emissions reduction that plug-ins

would achieve are comparable to those available from change-sustaining gasoline hybrids at a lower cost.

- In the U.S., ethanol might displace about 10% of gasoline by 2025. However, as explained in 8 above, increasing the biomass-to-liquids supply near term might help reduce well-top-wheels GHG emissions, but increased use of non-conventional oil is likely to offset this impact. Biofuel contributions are likely to be constrained by land availability and yields.

Thus, policy efforts should be focused on measures that improve both energy security and carbon emissions at the same time.

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