mobility in a climate constrained world

JOHN B. HEYWOOD

The context and the challenge[1]

Mobility has always been valued. For most of history, it has meant moving people and goods at the speed a person could walk, a horse could move, an ox could pull a cart, or a boat propelled by sails or oars could travel through the water. Only in the nineteenth century when we harnessed the energy in fossil fuels were we able to move people and goods at a much faster pace. The invention of the petroleum-fueled motor vehicle at the end of the nineteenth century and the airplane at the beginning of the twentieth opened up opportunities for greatly increased speed and travel choice. Roads provided choice that railroads could not, and airplanes only needed runways on which to arrive and depart.

As a result of these innovations, the twentieth century became a "golden age" for mobility. The volume of personal travel and goods moved grew at unprecedented rates. By the end of the century, individuals who in earlier centuries would have spent their lives within a hundred kilometers of where they were born thought nothing of traveling to distant continents on business or for pleasure. Raw materials, manufactured goods, and food from half a world away became widely available. The world's various populations and geographic regions did not participate evenly in this twentieth-century expansion of mobility. At the start of the twenty-first century, the average citizen of one of the wealthier nations could act as though distances were almost irrelevant. But average citizens in many of the world's poorer countries still transported themselves and their goods as their ancestors did.

People everywhere desire ever-increasing mobility, both for its own sake and because it enables them to overcome the distances that separate their homes from the places where they work, shop, go to school, do business, visit friends and relatives, and explore different places. Businesses desire mobility because it helps them overcome the distances that separate them from their sources of raw materials, from their suppliers and their markets, and avoid the impacts of congestion. A growing concern, however, is that today's mobility systems rely on one source of energy—petroleum. And the tension between humankind's desire for mobility and its concerns about the negative impacts associated with exercising that mobility raises fundamental questions about its future.

During the latter half of the twentieth century the negative consequences of enhanced mobility became evident on a regional and even global scale. Pollution

1
Source: WBCSD 2004.

produced by the internal combustion engines that powered hundreds of millions of motor vehicles began to degrade air quality in more and more cities. The exploration, extraction, transportation, and refining of oil to power transportation vehicles began to damage the environment on an increasing scale. Noise from vehicles on land and in the air, carrying people and goods, disturbed the peace of tens of millions of people. And it is now generally acknowledged that emissions of carbon dioxide from the burning of fossil fuels, a large share of which is transportation-related, is affecting the climate of our planet.

We are now being forced to question whether the extraordinary trends in mobility that have characterized the past fifty years are "sustainable." The World Business Council for Sustainable Development defines "sustainable mobility" as "the ability to meet the needs of society to move freely, gain access, communicate, trade, and establish relationships without sacrificing other essential human or ecological values today or in the future." (WBCSD 2001). With that definition, our current mobility trends are unsustainable.

Put simply, there are too many of us, we use far too much of our available resources, and we use it in ways that are irreversibly damaging our environment. There is too much consumption for our planet's health. And this high consumption is growing year by year due to population growth, increasing affluence, increasing urbanization and suburbanization, and ever-expanding expectations. Yet, mobility is almost universally acknowledged to be one of the most important elements in a desirable standard of living.

Most of us in the world's richer countries like our transportation systems, and much of the rest of the world aspires to have what we have. But people are increasingly aware that their enhanced mobility has come at a price. This price includes the financial outlay that mobility users must make to mobility providers to permit them to supply such systems and the services. But it goes well beyond this. Enhanced mobility has brought with it congestion, risk of death and serious injury, noise, disruption of communities and ecosystems, increased air and water pollution, and emission of climate-changing greenhouse gases.

The World Business Council for Sustainable Development carried out a major project, "Mobility 2030: Meeting the Challenges to Sustainability" (WBCSD 2004), which identified seven major goals where significant progress is needed to make transportation more sustainable:

1. Ensure that the emissions of transport-related conventional pollutants do not constitute a significant public health concern anywhere in the world.
2. Limit transport-related GHG emissions to sustainable levels.
3. Significantly reduce the total number of road vehicle-related deaths and serious injuries from current levels in both the developed and the developing worlds.
4. Reduce transport-related noise.
5. Mitigate congestion.
6. Narrow the "mobility opportunity divides" that inhibit the inhabitants of the poorest countries and members of economically and socially disadvantaged groups within nearly all countries from achieving better lives for themselves and their families.
7. Preserve and enhance mobility opportunities for the general population of both developed and developing-world countries.

This is an extremely demanding agenda. Our challenge is to make progress on individual pieces of this agenda, and at the same time track how well we are doing in the context of this broad set of goals. As we confront these challenges, it is useful to ask: What are the truly fundamental transportation "unsustainables"? A decade ago I was involved in a US National Academies study of this issue (NRC 1997), which concluded there were two such unsustainables. One was the climate change risk from CO_2 emissions, to which transportation is an important contributor. The other was the degradation of ecosystems and the reduction in biodiversity that result from transportation's emissions and infrastructure impacts. These are fundamental because ever-increasing mobility is inevitably making these two risk areas worse. They both link strongly to transportation's vast demand for energy. In this essay, I review how we can reduce transportation's energy consumption and greenhouse gas emissions, and thus its impact on climate change. This involves far more than just a focus on the WBCSD study's second goal of reducing GHG emissions. In parallel, we must pursue goals six and seven because enhanced mobility is essential to continued economic growth in all parts of the world. And progress must be made on the other goals if improving levels of mobility are to continue to be a major enabler for economic and social progress.

Size, growth, and complexity

Our transportation systems in the developed world move people by cars, buses, trains, and airplanes. In developing countries, bicycles and two and three wheelers are widely used, also. Freight is shipped primarily by road and rail, about equally by weight; air freight is growing rapidly. Large (heavy-duty) trucks dominate road freight transport. Transportation systems can be thought of as urban, national, or regional in scale. Figures 1 and 2, show the current status and future projections of key statistics by region and mode for personal transportation and freight. Steady growth that compounds year after year at rates of a few percent per year is evident. Currently, the developed and developing parts of the world are comparable in scale but growth rates in developing countries are higher. These projections (WBCSD 2004) are largely driven by growth in population and per capita income. By 2050 these measures of transportation activity are projected to be double what they are today.

These numbers indicate just how "big" transportation has become: the number of vehicles now in use, the mileage they travel, the weight of goods shipped. Currently, with some 6.8 billion people on the earth and 800 million vehicles, the average distance traveled is 5,000 km per year per person (with a range from 20,000 km/yr/person in the US to 3,000 in Africa). At present, the developed world countries dominate vehicle use but large parts of the developing world are catching up. Freight transport corresponds to 8 tonne-kilometers per person per day. Transportation fuel use is close to 3,500 liters or 1,000 gallons per person per year of which almost half is gasoline, one-third is diesel, and one-sixth jet fuel summing to two-thirds of total world petroleum production of about 82 million barrels per day (a barrel contains 42 US gallons). These consumption rates are so large they are unimaginable. Not only is the current scale vast but, growth rates of a couple of percent per year over several decades will make the scale even larger.

Why worry about the future, and especially about how the energy that drives our transportation might be affecting our environment? The reason is the size of these systems, their seemingly inexorable growth, and the environmental damage our transportation systems do. They use petroleum-based fuels (gasoline, diesel, and aviation fuel) on an unimaginable scale. When these fuels are burned inside engines, the carbon in these fuels is oxidized to the greenhouse gas carbon dioxide, and thus the amount of carbon dioxide entering the atmosphere from using these fuels is likewise immense. Transportation accounts for 25 percent of worldwide greenhouse gas emissions. As the countries in the developing world rapidly motorize, the increasing global demand for fuel will pose a

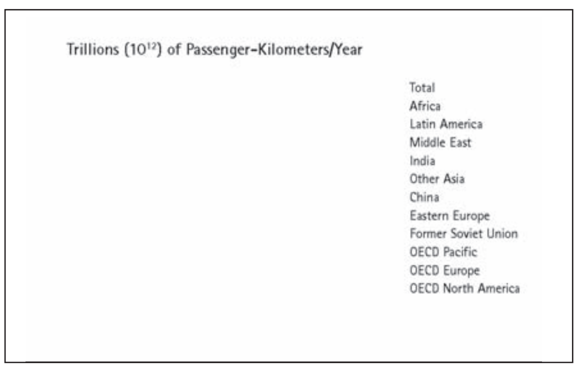


Figure 1(a)

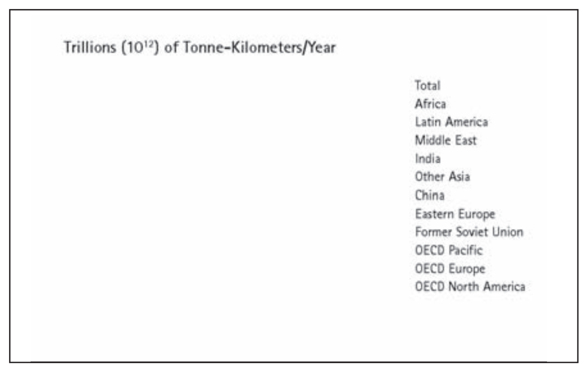


Figure 2(a)

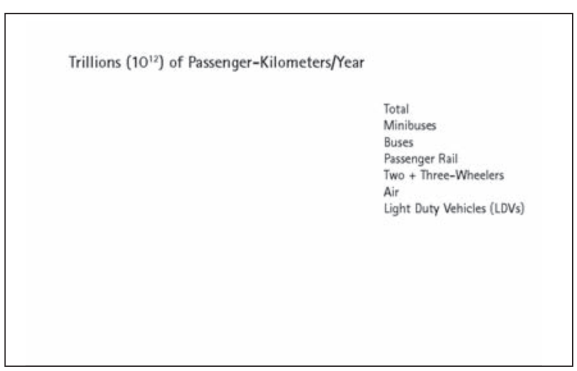


Figure 1(b)

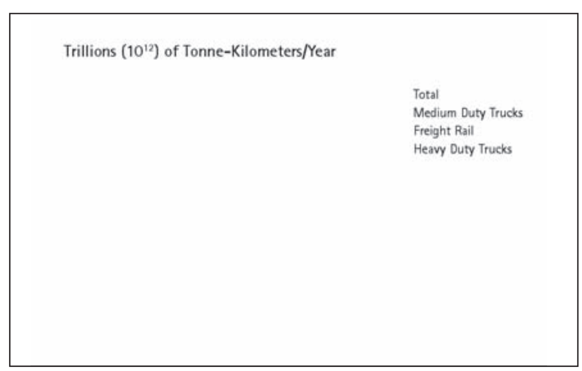


Figure 2(b)

Figure 1. (a) Personal mobility activity by region; (b) Personal mobility activity by mode; out to 2050 (WBCSD 2004).

Figure 2. (a) Freight transport activity by region; (b) Freight transport activity by mode; out to 2050 (WBCSD 2004).

major fuel-supply challenge. It will also significantly increase the concentration of greenhouse gases in the atmosphere. The US light-duty vehicle fleet (automobiles, pickup trucks, SUVs, and vans) of some 250 million vehicles currently consumes close to 600 billion liters (150 billion gallons of gasoline) per year. If other nations burned gasoline at the same rate, world consumption would rise by a factor of almost 10.

Several countries have used fuel economy or CO_2 emission targets or standards as a strategy for reducing transportation's energy consumption and greenhouse gas emissions. Figure 3 shows proposed European Union and US fuel economy and GHG requirements. Since hydrocarbon fuels derived from petroleum are 87% carbon by weight, the fuel economy or fuel consumption, and the CO_2 emissions that result from burning that fuel, are linked in a straightforward way: burning 1kg of fuel releases 3.2kg of CO_2. Typically, the reductions in GHG emissions these targets or regulations will require are some 30% by 2020, just over 10 years away. In 25 years (by 2035) a factor of two reduction is thought to be plausible. Looking farther ahead to 2050, estimates indicate that at least a 70% reduction from today's GHG emissions levels would be required to reduce emissions sufficiently to keep CO_2 levels in the atmosphere below 550 ppm (IPCC 2007), a concentration viewed by many as the best we are likely to be able to achieve to hold down global warming. All of these targets, nearer-, mid- and longer-term, are extremely challenging because changes (whether through deployment of better technology or implementing effective conservation) *on this large a scale* takes significant effort, time and money.

Our options for change

As we look ahead, what opportunities do we have for making transportation much more sustainable, at an acceptable cost? Several options could make a substantial difference. We could improve or change vehicle technology to make it much more efficient; we could change how we use our vehicles so we consume less fuel; we could reduce the size and weight of our vehicles; we could use different fuels with lower GHG footprints. We will most likely have to do all of these to achieve the drastic reductions in transportation's energy consumption and greenhouse gas emissions now judged to be necessary.

In examining alternatives, we have to keep in mind these aspects of our existing transportation system. First, it is well suited to its primary context, providing mobility in the developed world. Over decades, it has had time to evolve so that it balances economic costs with users' needs and wants. Second, this vast optimized system relies completely on one very convenient source of energy—petroleum. And it has evolved technologies—internal-combustion engines on land and jet engines (gas turbines) for air—that well match vehicle-operating characteristics with this energy-dense liquid fuel. Finally, vehicles last a long time so changing impacts take a long time. Constraining and then reducing the local and global impacts of transportation energy use will take decades.

Let's look at the efficiency with which we use energy in our vehicles. Efficiency ratings can be misleading: what counts is the fuel consumed in actual driving. Figure 3 shows the energy flows in a typical mid-size car during urban driving. Only about 16% of the fuel energy actually drives the wheels: this overcomes the aerodynamic drag, the tire rolling resistance, and accelerates the vehicle. Vehicle fuel consumption can be improved by reducing losses in both the propulsion system and the rest of these vehicles. (Kasseris and Heywood 2007). Today's automobile gasoline engine is about 20 percent efficient in urban driving though it

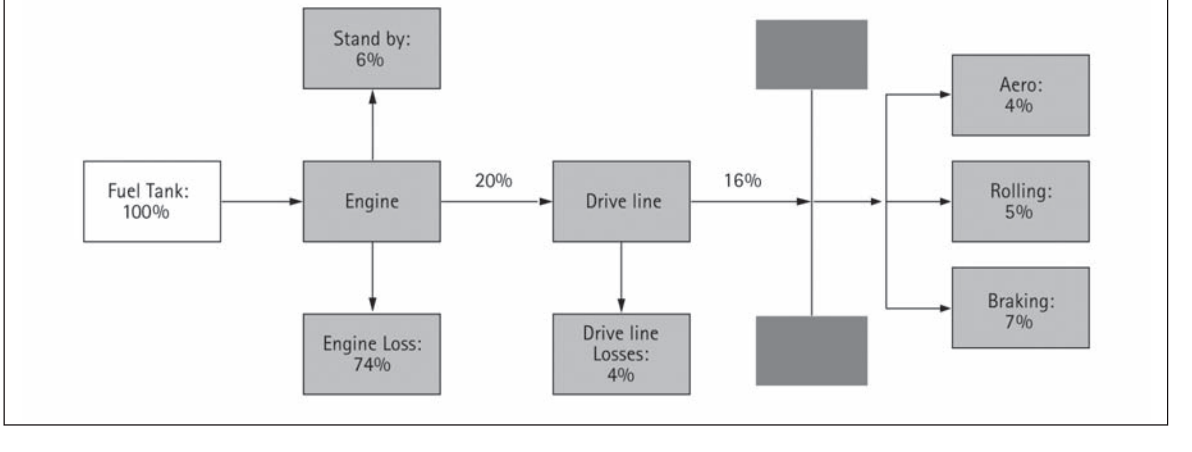


Figure 3. Energy flows from fuel tank to vehicle wheels in a typical current passenger car in urban driving (Bandivadekar et al. 2008).

is 35 percent efficient at its best operating point. But many short trips with a cold engine and transmission, amplified by cold weather impacts and aggressive driving, significantly worsen fuel consumption, as does substantial time spent with the engine idling. These real-world driving phenomena reduce the engine's average efficiency so that only about 10 percent of the chemical energy stored in the fuel actually drives the wheels. Amory Lovins, a strong advocate for much lighter, more efficient vehicles, has stated it this way: with a 10 percent efficient vehicle, and with a driver, a passenger and luggage—a payload of some 300 pounds, about 10 percent of the vehicle weight—"only 1 percent of the fuel energy in the vehicle's tank actually moves the payload!" (Lovins et al. 2005). Surely we can do better!

When we do our energy and GHG accounting as we use vehicles, we must include what it takes to produce the fuel from crude oil and distribute that fuel, to drive the vehicle through its lifetime of 100,000–150,000 miles (150,000–240,000 kilometers), and to manufacture, maintain and dispose of the vehicle. These three phases of vehicle operation are often called well-to-tank (which accounts for about 15 percent of the total lifetime energy use and greenhouse gas emissions), tank-to-wheels (75 percent), and cradle-to-grave (10 percent). We see that the energy required to produce the fuel and the vehicle is not negligible. This total life-cycle accounting becomes especially important as we consider fuels such as biofuels or hydrogen that do not come from petroleum, and new types of vehicle propulsion systems. It is what gets used and emitted in this total sense that matters.

We will explain shortly that improving existing light-duty vehicle technology can do a lot. By investing more money in increasing the efficiency of today's engines and transmissions, decreasing vehicle weight, improving the tires and reducing drag, we can bring down fuel consumption by about one-third over the next 20 years or so years—an improvement of some 3 percent per year. This reduction in fuel consumption would cost about $2,000 per vehicle: at likely future fuel prices, this amount would not increase the overall lifetime cost of ownership. Such incremental improvements have occurred steadily over the past 25 years, but we have purchased larger, heavier, faster cars and light trucks and thus have effectively traded the direct fuel consumption benefits we could have realized for these other attributes. Though most obvious in the US, this shift to larger more powerful vehicles has occurred and continues elsewhere as well.

What engine or propulsion system choices do we have? We can continue to use spark-ignition engines, fueled with gasoline or a biofuel such as ethanol. We can also use diesel engines, which are more efficient, using diesel or biodiesel. Hybrid electric vehicles (HEVs), with an internal combustion engine and a battery and electric motor, are another growing, more efficient option. During the next decade or so plug-in hybrid electric vehicles could become a viable option, using any of these liquid fuels along with electricity to recharge the batteries from the electric grid. Longer-term, after 2030, widespread use of fuel cell vehicles using hydrogen, and battery electric vehicles using electricity, are possible but might well be much more expensive. In addition vehicle weight reduction and reduced tire rolling resistance and drag are likely to occur and augment any propulsion system improvements. Note that a smaller, lighter, more efficient engine and transmission in a lighter-weight vehicle compounds the positive benefits of these improvements in especially advantageous ways.

Standard gasoline spark-ignition engines are continuing to improve their power per unit displaced volume, and their typical operating efficiency, by some 2% per year. Improvements come from friction reduction, variable control of the engine's valves, cylinder deactivation when the engine is lightly loaded, direct-injection of fuel into the engine's cylinder, increasing the engine's compression ratio, and more sophisticated sensing and control of engine operation. Increasingly the gasoline engine is being boosted by raising the intake air pressure with a turbocharger to increase engine output. This allows significant engine downsizing, which improves average engine efficiency. Diesel engines also have power and efficiency improvement potential, though not as great as that available to gasoline engines. Future diesels will need effective emissions treatment technology (traps and catalysts) in their exhausts to control the air pollutants particulates and NO_x. This will add significant cost and some fuel consumption penalty. Thus, future turbocharged gasoline and diesel engines will be much closer in how they operate, their power per unit engine size (or displaced volume) and their average driving efficiency. Importantly, this future gasoline engine will be significantly cheaper—about half the cost—of the competing diesel.

Hybrid electric vehicles (HEV) are now being produced and sold in volumes that are 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 either 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 reductions relative to gasoline engine vehicles in the 40–50% range appear feasible. "Electric drive" augmented by an on-board internal combustion engine is inherently an attractive propulsion system for the future. It is, however, likely to be $2,000–$3,000 more expensive than its improved conventional counterpart. (Bandivadekar et al. 2008).

A plug-in hybrid vehicle (PHEV) is a hybrid-gasoline electric vehicle with a much larger battery that can be recharged from the electric grid. The vehicle would use an advanced battery pack (e.g., lithium-ion battery technology) in a configuration similar to that of the conventional hybrid. Above a threshold battery state-of-charge (SOC), the PHEV operates in "charge depleting" (CD) mode, where it uses the electrical energy in the onboard battery to meet the vehicle's power demands. When it reaches its minimum SOC threshold, the vehicle switches to "charge sustaining" mode, which is equivalent to vehicle operation in a conventional HEV. Both liquid fuel energy and electricity are used to drive the vehicle. Note that any electricity used on the vehicle consumes 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 much too expensive for broad market appeal, and it will need "green" electricity if it is to provide significant additional greenhouse gas reduction potential beyond what charge-sustaining hybrids can provide.

The battery-electric vehicle sources all of its energy from off-board electricity and is charged from the electric grid. The BEV will require a trade-off between vehicle size, cost, and range. The typical 400–mile vehicle range of today's conventional multipurpose vehicles appears implausible in an all-electric vehicle from a cost and weight perspective; even a 200–mile range is daunting. BEVs do not seem a viable large market contender at present, though they are being pursued as a small city or urban car opportunity.

Fuel cells for vehicle propulsion applications employ the proton-exchange membrane (PEM) fuel-cell system to power an electric motor, which drives the vehicle, usually in a series configuration. A fuel cell operates like a battery in that it transforms chemical energy in the hydrogen fuel into electricity. Its key difference from a battery is that the fuel (hydrogen) and oxidizer (air) are supplied continuously to the cell's electrodes. In a fuel-cell hybrid configuration a battery, which stores electrical energy, improves the overall system performance and allows regenerative braking. This hybrid battery uses the same high-power lithium-ion battery now starting to be used for conventional hybrid vehicles. 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 electrolyte membrane materials, by catalyst requirements, and by the complex systems management needed for fuel-cell operation. In addition to this need for improved fuel-cell systems, developing an onboard hydrogen storage system that offers adequate vehicle range, is a major cost, size and weight problem. Of course, producing and distributing hydrogen—creating the hydrogen infrastructure—is a major challenge, too.

Transmissions also matter greatly. Automatic transmissions are popular in the United States primarily due to their ease of use and smooth gear shift, and their sales volume is growing elsewhere. Transmission efficiency is likely to improve in the near to mid term by increasing the number of gears as well as by reduction of losses in bearings, gears, sealing elements, and hydraulic system. While four speed transmissions dominate the current US market, five-speed transmissions are becoming standard. Six-speed automatic as well as automated manual transmissions are already present in some cars and are likely to become standard over the next decade. Luxury vehicles have started deploying seven and eight speed transmissions, which could become standard in the mid-term. Future transmission efficiencies of 90–95% are anticipated. This is a significant improvement over the previous generation of transmissions.

Vehicle weight reduction is another obvious way to improve fuel consumption. Figure 4 shows the dependence of fuel consumption on vehicle weight in the US light-duty vehicle fleet. A commonly used rule of thumb is that a 10% reduction in vehicle weight can reduce fuel consumption by 5-7%, when accompanied by appropriate engine downsizing, at constant performance. Weight reduction in vehicles can be achieved by substituting lighter-weight materials, and by vehicle redesign and downsizing. Downsizing a passenger car by one vehicle size-class can reduce vehicle weight by approximately 10%. However, vehicle size is an attribute that consumers value.

Tire rolling resistance reduction is also a fuel consumption reduction opportunity, and could reduce consumption by a few percent. Note that new tire technologies can be introduced into the much larger market of replacement tires and thus achieve

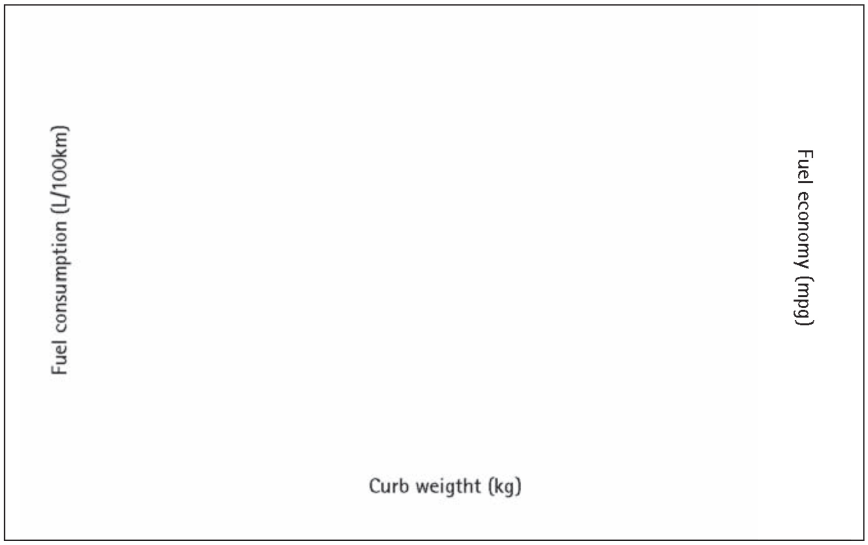


Figure 4. Light-duty vehicle fuel consumption as a function of vehicle weight for US model year 2005 vehicles (Cheah et al. 2008).

benefits faster than if implemented in new cars alone. Tire pressure monitoring and proper inflation levels are useful fuel efficiency opportunities also.

In highway driving, at least half of the energy required to propel the vehicle is used to overcome the aerodynamic drag. Thus, reductions in aerodynamic drag can achieve meaningful reductions in fuel consumption. A 10% reduction in drag can achieve up to a 2% reduction in average vehicle fuel consumption. Significant reductions in drag from current levels are feasible through vehicle steamlining.

GHG emission reductions from gasoline and diesel ICE vehicles and HEVs are proportional to reductions in petroleum consumed. Further reductions in GHG emissions could be achieved if the effective carbon content of fuels can be lowered through the use of low carbon-emitting biofuels. For PHEVs, BEVs and FCVs, the well-to-tank emissions produced during the generation and supply of electricity and hydrogen strongly affect the ultimate GHG emission reduction potential. Electricity production efficiency improvements, as well as increased contributions from nuclear, renewable sources, and fossil fuels with carbon capture and sequestration, could lower the well-to-tank emissions from electricity generation: plug-in hybrids would then be an attractive option for reducing both petroleum and GHG emissions.

Let's explore our fuel options in more detail. Our current transportation systems—land, water, and air—overwhelmingly use petroleum-based hydrocarbon fuels. These fuels dominate because they are liquids, have very high energy density, and fit well with today's engine technologies: spark-ignition engines, diesels, and gas turbines. An illustration of their attractiveness is that when refueling our cars today, fuel energy flows through the nozzle we hold in our hand at the rate of 10 MW providing another 400 miles of driving with a 5 minute refueling time.

Since petroleum-based fuels dominate the transportation sector, they have developed very large-scale refining and distribution systems. More than 300 billion gallons of refinery products are distributed across the US each year, some one-third of world production. The ability of alternative fuel streams to be compatible with and integrated into these refining and distribution systems is obviously a critical aspect of their attractiveness.

What are the possible alternatives? Natural gas use in transportation varies from less than 1% of vehicles almost everywhere, to about 10% in a couple of countries where tax policies have made it an economical option. Natural gas has attractive engine combustion characteristics but it is a gaseous fuel that must be compressed and then stored in high-pressure tanks on the vehicle. The drawbacks of a gaseous fuel (lower specific engine power, reduced driving range, compression work in vehicle fueling, vehicle interior space impacts of fuel storage tanks, extra cost, methane emissions) more than offset the attraction of the lower carbon-to-hydrogen ratio of this fuel. Furthermore, demand for natural gas in other applications is rising rapidly, as is its cost. As a widely used vehicle fuel, it prospects do not seem promising.

Oil sands (e.g., tar-like deposits in Canada) and heavy oils (more dense oils from Venezuela) are already contributing a growing fraction (about 5%) to liquid transportation fuels. Over time, other non-petroleum sources of hydrocarbon fuels, such as natural gas conversion to a liquid, oil shale, and coal, are likely developments. These pathways can produce high-quality transportation fuels, and volumes from such sources are expected to steadily increase. However, the carbon dioxide emissions during the production of these fuels are higher than those from petroleum-based fuel production due to the significant energy required to make them, and their higher carbon content.

Liquid transportation fuels derived from biomass have the potential to contribute significantly to supplying energy for our vehicles. Sources of biomass include corn, prairie grasses, switchgrass, miscanthus, forest, and municipal wastes, and other dedicated fuel crops. End products include ethanol, biodiesel, and, potentially, gasoline- and diesel-like fuels. Critical questions that need to be resolved are the availability of suitable land for these crops, the greenhouse gas releases that occur as land uses change, fertilizer and water requirements, land degradation over time, water pollution issues, and the net energy requirements during production. There is substantial potential for an important biofuel contribution to transportation but the extent of that opportunity still needs extensive evaluation. In the US maybe some 20% of transportation's energy could come from biofuels in about 20 years time.

Biofuels, electricity, and hydrogen, require a different type of life cycle analysis in transportation since the fuel production and distribution cycle is now the dominant component. Biofuel impacts 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 depend on how the electricity is generated. When generated from fossil fuels, electricity's 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—low GHG emissions—electricity for transportation with, say, plug-in hybrids, and when would such green electricity become available? Hydrogen faces similar questions: how could it be made and distributed with low GHG emissions? Any hydrogen produced in the nearer-term, would most likely come from natural gas, and overall has energy consumption and GHG emissions levels that are not much different from those that would result from using petroleum-fueled vehicles.

Performance of these vehicle technologies

We have projected the performance and costs of these various propulsion system and vehicle technologies out some 25 years. These projections for the mainstream powertrain vehicles are shown in figure 5. (Bandivadekar et al. 2008) Substantially better fuel consumption (at constant vehicle performance, and size) is anticipated, but the costs increase. The vehicle weight reduction (20% in these vehicles) costs some $700. Note that in Europe and Asia where average vehicle size and weight is some two-thirds that in the US, the weight reduction potential may well be less. Also, in Europe, about half of the passenger vehicle fleet is diesel so the average fleet fuel efficiency is already higher.

Overall, these improved future vehicles with these different powertrain options would cost some $2,000 more for a gasoline engine vehicle, $2,500–3,000 for a turbo-gasoline vehicle, $3,500–4,300 for a diesel and $4,500–5,500 for a hybrid, all relative to current mainstream gasoline-engine equivalents. Plug-in hybrids and fuel cell vehicles would probably cost $6,000–8,000 more; battery electric vehicles $10,000–20,000 more, depending on range. At present vehicle concepts with battery systems with significant on-board electrical storage capacity are clearly not yet ready for the mass market.

For the mainstream technology vehicles, the vehicle's lifetime fuel savings that go with these improved-fuel-consumption propulsion systems, when appropriately discounted, would offset these increases in vehicle cost at current fuel prices. But to date, this positive overall economic outcome has only pulled lower cost technology improvements into vehicles. It has not as yet created a strongly growing market for new and significantly more efficient technologies such as hybrids, though high fuel prices and lower diesel fuel taxes than gasoline, along with better diesel vehicle drivability, have pulled in the diesel to close to 50% of the new vehicle market in Europe.

It is then important to complete the full 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 that are more energy intensive, and through reductions in vehicle use fuel consumption. The fuel production and distribution cycle with petroleum fuels adds about 20%; hydrocarbon fuels from non-conventional petroleum sources like oil sands are likely to add about twice that.

Figure 6 shows a comparison of the vehicle petroleum consumption and well-to-wheels GHG emissions of these various future propulsion systems, in a mid-size lighter-weight US car 25 years ahead. On the petroleum consumption scale, plug-in hybrids,

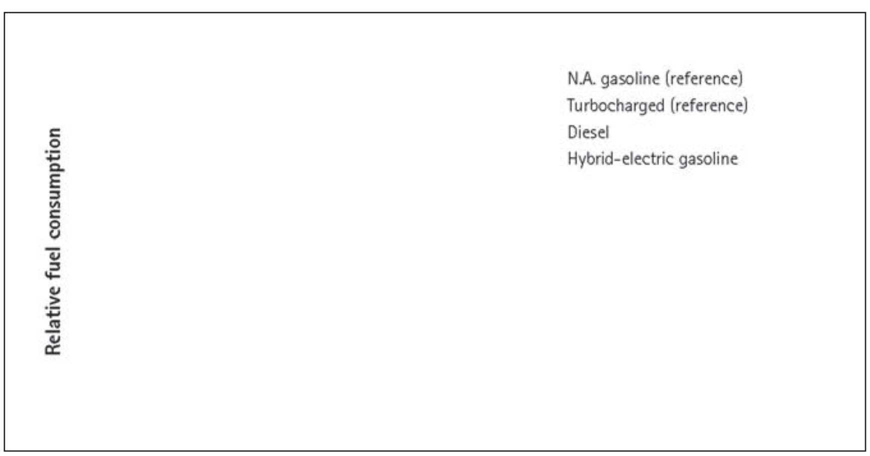


Figure 5. Relative fuel consumption of present and future vehicles with different advanced powertrains for 2006, 2020, and 2035 (Bandivadekar et al. 2008).

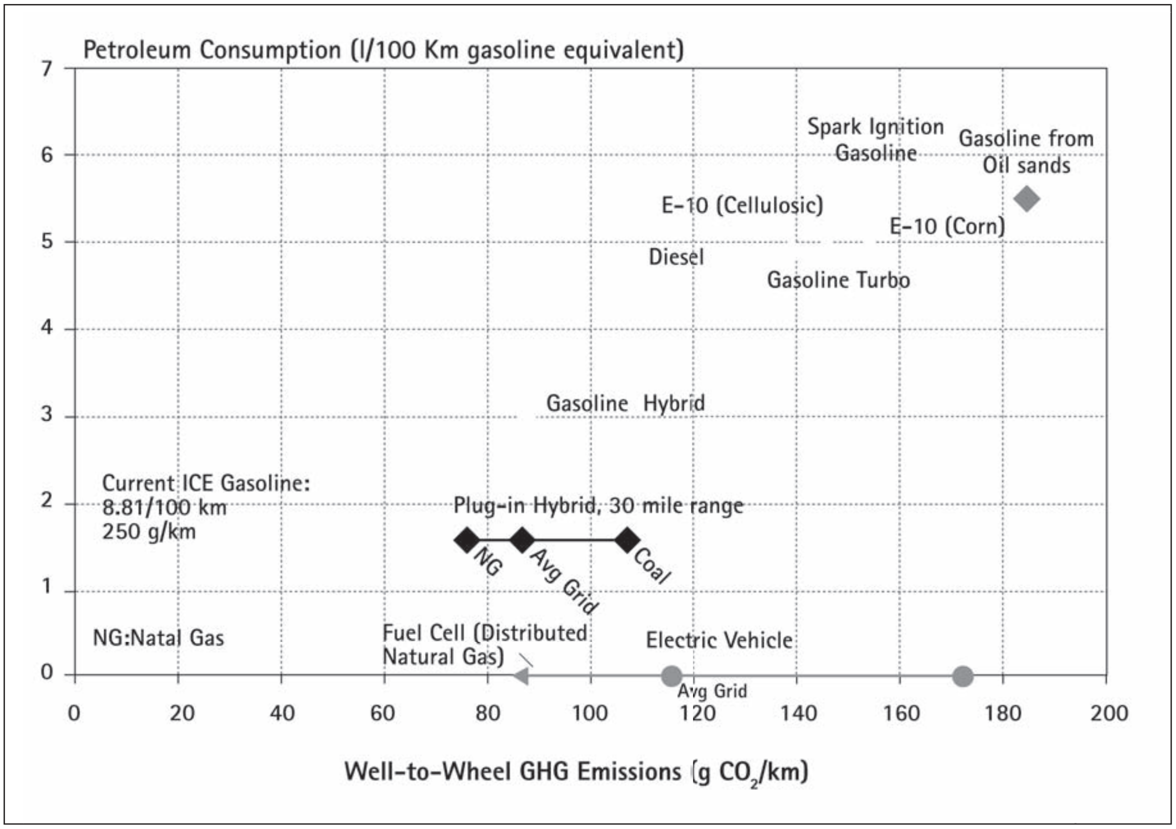


Figure 6. Petroleum consumption and well-to-wheels greenhouse gas emissions of future (2035) cars with various different propulsion systems and fuel sources (Bandivadekar et al. 2008).

fuel cells, and electric vehicles give significantly lower fuel consumption. But of course these vehicles also use electricity from the grid or hydrogen from a new production and distribution infrastructure. These additional energy requirements on the energy supply side reduce the GHG emissions reductions. With electrical supply systems, which are based on coal and natural gas (as in the US), the additional vehicle GHG emissions benefits are offset by the electrical generation emissions. With nuclear and renewable electricity generation the picture is much better. Battery electric vehicle emissions for a standard size vehicle are significantly worse in large part due to the added weight of the substantial battery pack required for adequate driving range. We see that future GHG emissions per vehicle could eventually be reduced to about one-third of the emissions from a current vehicle. Improvements in mainstream engines, transmissions, and reductions in vehicle weight and drag, decrease petroleum consumption by some 30–40%. Plausible quantities of biofuels could provide an additional 10% benefit. Hybrid technology provides a significant additional 40% reduction from these mainstream vehicle levels. While plug-in hybrids and fuel cells with hydrogen significantly reduce or remove petroleum consumption, in any build-up transition phase, their GHG emissions impacts are no better than conventional gasoline charge-sustaining hybrid levels.

Trade-offs and marketability

So far, we have compared vehicle characteristics at constant vehicle performance or acceleration, and fixed interior size: i.e., 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 US, while engines and transmissions have become increasingly more efficient over the past 20 or so years, on-the-road vehicle fuel consumption has remained constant. In Europe, the performance escalation has not been as great, and about half of the engine efficiency improvements have shown up as vehicle fuel consumption reductions. The emphasis placed on reducing actual fuel consumption is critical. In the US, such emphasis has been close to zero since the early 1980s, while about half the potential fuel consumption benefits have been realized in Europe. Vehicle purchasers and users have shown a clear preference for increasing vehicle performance and larger vehicle size, thus providing market "pull" for these attributes. The automobile companies compete amongst themselves by offering ever-increasing performance and size, providing the "push." In the US, the emphasis on enhanced performance has been so strong that, along with some size increases, a fuel consumption gain at constant performance of some 25% has been lost. In Europe, emphasis on performance has not been as strong, and half of the fuel consumption improvements that could have been realized have actually been achieved.

We have indicated that vehicle weight and size reduction could also 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. 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 at a cost of about $700. The maximum potential for weight reduction in the US is about 35%, but the additional reduction beyond 20% would cost significantly more. These are substantial weight reductions and will require rethinking vehicle design. Vehicle weight reductions of 20–35% on their own result in some 12–20 reduction in vehicle fuel consumption. (Bandivadekar et al. 2008)

Market penetration: a critical issue

Improved propulsion system and vehicle technologies only have impact when vehicles with these technologies are being used in large numbers. Such improved technologies must therefore have strong market appeal, 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. In-use fleet models when given market penetration rates of the different promising propulsion systems with their different fuel consumption and GHG emissions characteristics, can then examine how the overall fleet fuel consumption and GHG emission rates evolve as new vehicles enter the fleet and older cars are scrapped. The assumptions that are critical but difficult to estimate are the market penetration rates or evolving production volumes of these improved and new vehicle technologies.

What governs the rate of deployment of improved powertrain and vehicle technologies and of alternative fuels into the market? Even if the demand for an emerging vehicle or propulsion system technology is strong, the supply of such systems could be limited. This could be due to constraints in engineering and capital resources, as well as in supply chains. The automobile is a highly complex product, and consumer expectations from a mass-produced vehicle are demanding. The development and design of new powertrains and other sub-systems, often in vehicle architecture, is a major time and resource consuming task, and may take some 15 years to become available across all market segments.

Automobile manufacturing is both a capital- and labor-intensive business, and the established industry players are risk averse. It normally takes two to three years for an auto manufacturer to build a new production facility. Thus, to convert 10% of the US domestic production capacity (1.5 million vehicles per year) to produce hybrids would take a capital investment of approximately $2.2 billion, some 10% of the annual capital expenditure of the US motor vehicle manufacturing sector.

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

Table 1. Estimated time scales for technology impact (adapted from Schafer et al. 2006)

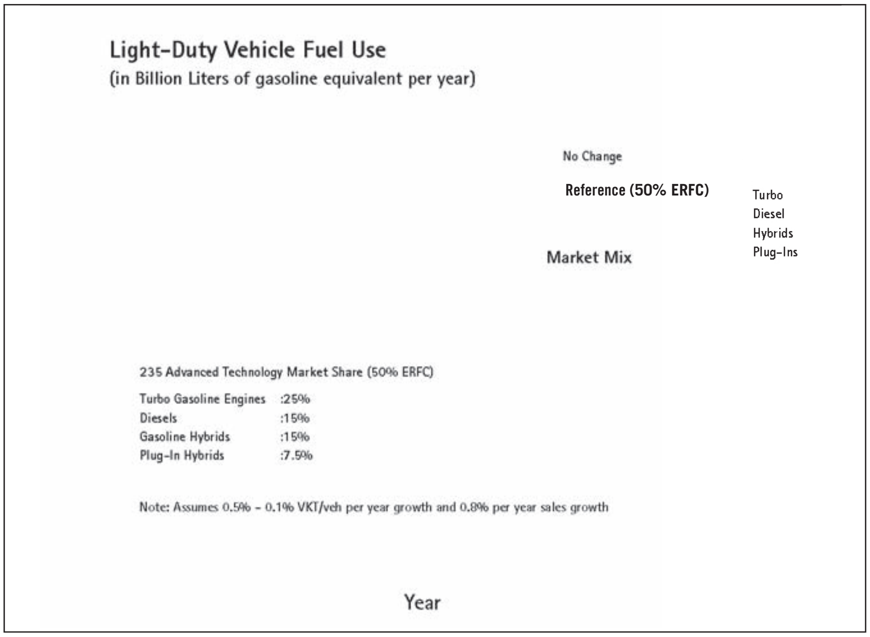


Figure 7. Illustrative scenario that explores the in-use US vehicle fleet fuel consumption impact of increasing numbers of advanced technology vehicles out to 2035. Half the efficiency improvements (50% ERFC) go to reducing vehicle fuel consumption; half offsets performance and size increases. Vehicle weight reduction, 10%. No change shows the impact in fleet size and mileage (Bandivadekar et al. 2008).

As these supply side constraints suggest, the time scales required for new technologies to have a significant impact on fleet fuel use are long. Schafer et al. (2006) split this total time into three stages, as shown in Table 1.

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. Table 1 shows estimates of how long it would take for these different propulsion systems to become available as mainstream alternatives in the market. Of these, only turbocharged gasoline, diesel, and gasoline hybrid powertrain technologies are currently ready to be designed for production. While no concrete product plans have been announced for plug-in hybrid vehicles, several major auto manufacturers have expressed interest in developing a commercial product within the next decade. The situation for a market competitive fuel cell vehicle is more speculative. A survey of announcements from major automakers suggests that a commercial mass-market fuel cell vehicle is at least ten years away.

In the second stage of technology implementation shown in the table, penetration across new vehicle production, represents the time scale for the vehicle technology to attain a market share of some one-third of the total vehicle sales. Broadly, this time scale reflects expectations about large-scale viability of these propulsion systems based on engineering and cost constraints.

The third stage of technology implementation is the build-up in actual use of substantial numbers of these vehicles. A meaningful reduction in fleet fuel use only occurs when a large number of more fuel-efficient vehicles are being driven around. This will happen over a time scale comparable to the median lifetime of vehicles, which is some 15 years.

Overall, we see that the total time scales before significant impacts occur from these new vehicle technologies, are long.

Real world impacts

Figure 7 shows an example of the impact of growing volumes of more efficient vehicles in the US light-duty fleet. This illustrative scenario assumes that production volumes of turbocharged gasoline engine vehicles, diesels, hybrids, and plug-in hybrids all grow steadily from current market shares to the percentages given in the figure by 2035. Many other assumptions are involved, of course. (Bandivadekar et al. 2008) The "no change in technology" line shows the fleet's gasoline consumption rising steadily due to growth in fleet size and mileage. With the "emphasis on reducing fuel consumption" (shown as ERFC) at 50%, half the efficiency improvements are realized as actual fuel consumption reductions. The growing 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 impact calculation are this emphasis on reducing fuel consumption and the percentage of the most efficient technology—hybrids—in the 2035 sales mix. With full, 100%, emphasis on reducing fuel consumption rather than 50%, fleet fuel consumption is reduced by an additional 15% to 505 billion liters per year. If the sales volume of hybrids doubles—i.e., if some 50% of the 2035 new vehicles are hybrids—an additional 10% reduction in fleet fuel consumption to 543 billion liters could be achieved. Combined, these two additions would give an additional 30% reduction relative to the market mix line in figure 7. Note that the impact of these more efficient technology vehicles grows slowly at first, but beyond about 2030 plays an increasingly more substantial role in reducing fleet fuel consumption and GHG emissions as the technology improves and deployment grows.

What we learn from these scenarios is that the inexorable impacts of growth in vehicle-miles traveled can be offset, and fuel consumption and GHG emissions can be leveled off and then pulled downwards.

But it will take a couple of decades to do this. Actions that directly affect the full in-use vehicle fleet, like reduced driving due to higher fuel prices, can impact emissions faster than new vehicle technology. And, as we have explained, focusing strongly on *reducing on-the-road fuel consumption* rather than allowing vehicle performance and size to escalate is really important.

As an illustrative example of what is needed to get onto this path, 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. (Cheah et al. 2008) It would require that two-thirds of new vehicle production be hybrids, require 75% of the energy efficiency improvements to go into actual fuel consumption reduction instead of increased performance and size (in the US this percent has been zero; in Europe it has been around 50%), and would require on average a 20% vehicle weight reduction. While feasible, this is a challenging, demanding, and time-consuming task.

We might expect our 2020 targets of a one-third reduction (e.g., the US CAFE fuel economy requirements) to be less challenging, but that is not the case. With the target date only some 10 years away, the fuel consumption improvements in the various powertrain technologies available will be correspondingly less, and the time available to build-up significant production levels of these technologies is less too. Thus, the 2020 task turns out to be at least as demanding than this factor of two improvement in 25 years.

Looking much further ahead to 2050, we are learning that more of the same types of incremental improvements will not get us to where we may well need to be—GHG emissions down to some 20–30% of what they are today. That is where plug-in hybrids or fuel cell technologies may well have to come into large-scale use with their different sources of energy—electricity or hydrogen. If these "energy carriers" are produced with really low greenhouse gas emissions, then these energy carriers and the technologies that use them would bring substantial additional GHG emissions reductions. But the time scales for such radical changes in technology and energy carriers to have significant impact are long, several decades, as Table 1 suggests. And success in developing battery and fuel cell technology, and low GHG emitting energy production and distribution infrastructures, is far from certain. Major efforts to explore these options are in progress, as they should be.

Other options

We do have other options. For decades, transportation system improvement opportunities have been studied and some have been implemented. But many have not because of the difficulty in coordinating businesses, local, regional, and national governments, as well as blending new ideas with existing infrastructures.

In passenger transport, the opportunities could be significant because the current pattern of largely single-occupant vehicle usage is inefficient in terms of energy and money. Many studies demonstrate the potential for reducing energy consumption and emissions through use of what we call Intelligent Transportation Systems (ITS) that electronically link vehicles to one another and to the infrastructure, and thereby reduce vehicle use by densifying and reorganizing land-use patterns, enhancing collective modes of travel, substituting information and communication technologies for travel, and enhancing use of non-motorized travel modes. The opportunities are many and compelling, with various co-benefits, such as less travel delay, reduced road infrastructure investment, and less local air pollution. The energy and climate benefits that would result could be significant in the longer term.

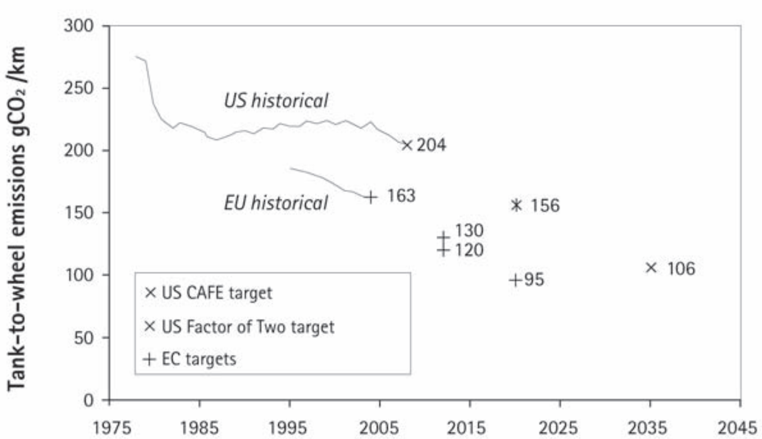
ITS is based on technologies that can sense individual vehicles and their characteristics, such as speed and location within the transportation network. Various technologies are available for doing this: devices that can sense vehicles using specialized roadside infrastructure, the Global Positioning System, or the cellular telephone network. For this information to be of value to more than the drivers of individual vehicles, it must be communicated from the vehicle to the infrastructure or between vehicles to enable the gathering of data about the overall status of the network. Collecting these massive amounts of data and reducing them to a form in which they can be used either to provide information to individual drivers or to manage the transportation network as a whole requires sensing, communicating, computing, analysis, and feedback.

Work on ITS is motivated by the following shortfalls in the performance of our current surface transportation system. Congestion, which reflects insufficient capacity on our highways is a major issue that affects the movement of both travelers and goods. The costs—both financial and environmental—of addressing capacity issues by building or expanding traditional infrastructure can be prohibitive, especially in urban areas where land-use constraints apply. ITS-based concepts can help combat congestion in two ways, through use of traffic information, and dynamic road-use pricing. Highway safety is also a major concern.

In the context of this essay our major issue is the energy and environmental impact of transportation. By smoothing traffic flow, fuel consumption, and emissions per vehicle are reduced. However, if infrastructure use increases as a result of increased capacity, then fuel use and emissions will increase. It is, therefore, important to explore how ITS can be used to improve the transportation system in a synergistic way with the other issues listed above (Sussman 2005).

To achieve a significant reduction in vehicle use and GHG emissions requires a mix of complementary strategies. The changes discussed earlier concerning the efficiency of the vehicle, and these changes in the transportation system to reduce congestion, often assume that current residential and travel patterns will continue. If land use patterns change towards more dense urban occupancy from suburban and rural housing patterns, then vehicle miles would be reduced. If people are willing to live along denser urban corridors, they could be served more efficiently by public transportation. And a significant role for small "city cars" might develop. However, land use patterns for more than 60 years have been moving in the other direction—toward suburban living.

For more diversified transportation systems to evolve, two sets of policy changes would be needed: greater control of land use and greater use of road pricing. These opportunities need to be considered. The net effect of a concerted effort to internalize congestion and environmental externalities, reduce single-occupant vehicle use, and encourage the use of small, efficient neighborhood or city cars for local travel could be large.



Notes:

- For US, unadjusted NHTSA fuel economy numbers used
- US CAFE target = 35 mpg by 2020; US factor of target = Halve 2006 FC by 2035
- Conversion factor = 8,788 gCO2 per gallon gasoline (EPA 2005)
- For EU, historical data for EU-15 passenger cars shown (European Commission 2006)
- Lower EC target in 2012 (120 gCO2/km) includes use of biofuels

Figure 8. Average new vehicle greenhouse gas emissions targets and regulations in the US and Europe.

What can we expect?

Figure 8 shows greenhouse gas emissions targets for light-duty vehicles for Europe and the US. These targets are aggressive in that the time scales proposed for achievement are short, and thus they require faster progress than our factor of two reduction in 25 years. In Europe, achieving these objectives in the near term will be especially difficult because there is less "slack" in the existing in-use vehicle fleet: that fleet is already half diesel (a more efficient engine than the gasoline engine), and average vehicle size and weight are some two-thirds of the US levels. Also, performance escalation in Europe and Japan, which has occurred, has been significantly lower than in the US opportunities for further improvement are, therefore, less.

Figure 9 illustrates our challenge. It shows global and US projections out to 2050 for GHG emissions from light-duty vehicles. Today the US fleet emits about half the global emissions from this mobility sector. Europe and Japan contribute a significant fraction of the rest. Even with aggressive implementation of more efficient technology, emissions are usefully but only modestly reduced from current levels.

In summary we see the potential for a 30 to 50 percent reduction in the fuel consumption of light-duty vehicles—cars, SUVs, light trucks—over the next 10 to 25 years. This will come from improving mainstream powertrains, developing new more efficient propulsion systems, and reducing vehicle weight and size. Whether or not we achieve this potential will depend on how we control ever-increasing vehicle performance expectations, and especially how urgently we pursue these technology improvements. The latter will depend on the context for such actions: the price of petroleum, our sense of its availability, our GHG emissions concerns, the comprehensiveness and effectiveness of the policies and regulations we impose to force such change, and our willingness to moderate our demand for mobility. In the nearer-term, 10 to 20 years, it is clear what path we should be on to reduce transportation's petroleum consumption. Mid-term, as we focus increasingly on GHG emissions reduction, the path becomes less clear and the challenge of continuing to reduce petroleum use and GHG emissions increases. We will then have to resolve the questions of how much of a contribution we can obtain from biofuels, the extent to which we can use electricity as a major energy source for our vehicles, and whether or not hydrogen and fuel cells for vehicle propulsion should be our ultimate objective. We are not yet able to resolve these questions, but we need to develop the knowledge base so that as time evolves we develop ever better answers.

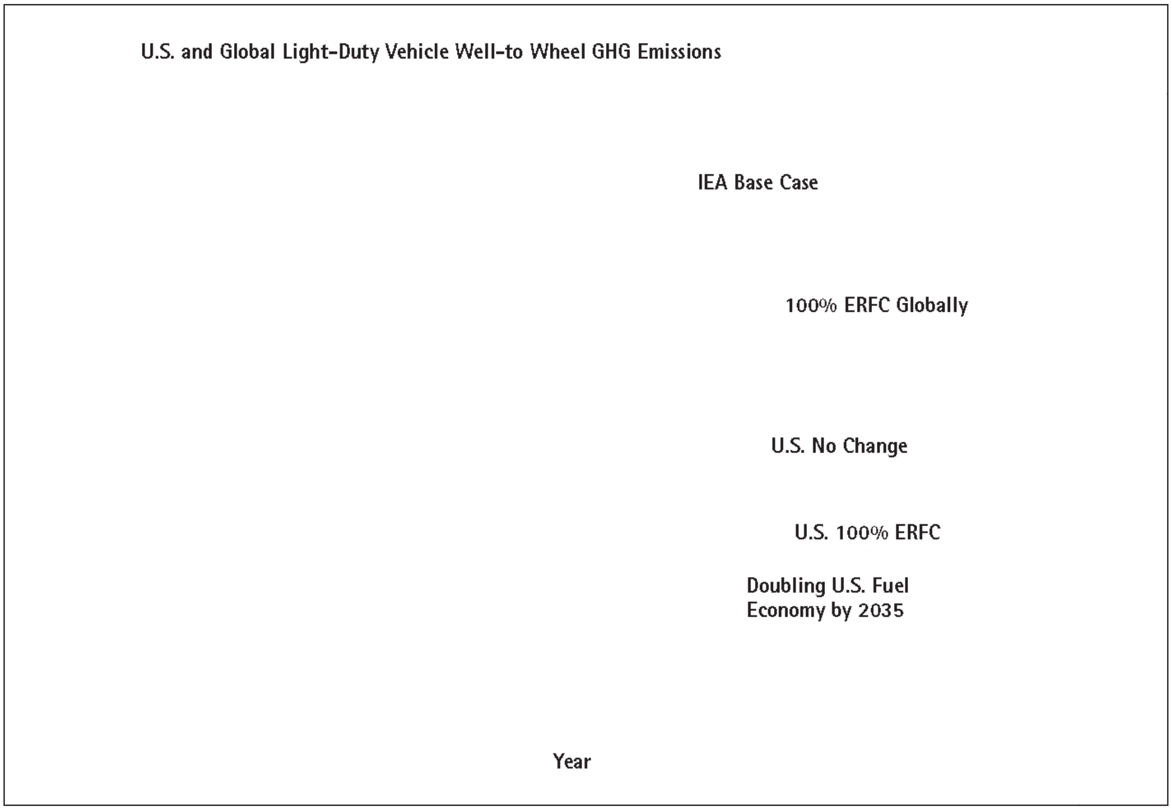


Figure 9. Global and US scenarios out to 2050 showing effects of halving new vehicle fuel consumption by 2035 on in-use vehicle fleet well-to-wheels greenhouse gas emissions. Average vehicle performance and size are held constant (100% emphasis on reducing fuel consumption) (Bandivadekar et al. 2008).

Worldwide demand for transportation services is growing inexorably, and there is no single major development that alone can resolve the growing problems of vehicle fuel consumption and GHG emissions. This essay has explained that progress must come from a comprehensive effort to develop and market more efficient vehicles and more environmentally benign fuels, find more sustainable ways to satisfy demands for transportation services, and prompt all of us who use our vehicles and other transportation options to reduce our travel-related energy consumption. All of these changes will need to be implemented at very large scale to achieve significant reductions in transportation's petroleum and energy use, and GHG emissions. Implementation is likely to increase the cost of transportation to ultimate users, and will require government policies to encourage, even require, moving toward these goals while sharing the burdens more equitably and minimizing total social costs.

Transitioning from our current situation onto a path with declining fuel consumption and emissions, even in the developed world, will take several decades—longer than we hope or realize. We must keep in mind that what matters is effecting changes that will have substantial impact on these issues. We will need much better technology, more appropriate types of vehicles, greener fuel streams, and changes in our behavior that emphasize conservation. We need nearer-term results that get us out of our currently worsening situation. We will need to change to far more sustainable pathways in the longer term. And we will need to pursue all these opportunities with urgency and determination.

Bibliography

Bandivadekar, A., K. Bodek, L. Cheah, C. Evans, T. Groode, J. Heywood, E. Kasseris, M. Kromer, and M. Weiss. "On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions." MIT Laboratory for Energy and the Environment, Massachusetts Institute of Technology, July 2008. http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/.

Cheah, L., A. Bandivadekar, K. Bodek, E. Kasseris, and J. Heywood. "The Trade-off between Automobile Acceleration Performance, Weight, and Fuel Consumption." *Society of Automotive Engineers paper 2008-01-1524.* SAE International Powertrains, Fuels and Lubricants Congress, Shanghai, China, June 23–25, 2008.

Intergovernmental Panel On Climate Change. "Climate Change 2007: Synthesis Report." *Summary for Policy Makers*. Cambridge, UK: Cambridge University Press, 2007.

Kasseris, E., and J. B. Heywood. "Comparative Analysis of Automotive Powertrain Choices for the Next 25 Years." *Society of Automotive Engineers, SAE paper 2007-01-1605, 2007*. National Research Council.

—, "Toward a Sustainable Future: Addressing the Long-Term Effects of Motor Vehicle Transportation on Climate and Ecology". *Special Report* 251, Committee for a Study on Transportation and a Sustainable Environment, Transportation Research Board, National Academy Press, Washington, DC, 1997.

Schafer, A., J. Heywood, and M. Weiss. "Future Fuel Cell and Internal Combustion Engine Automobile Technologies: A 25-Year Life Cycle and Fleet Impact Assessment." *Energy*, vol. 31, no. 12, 2006, 2064–2087.

Sussman, J. *Perspectives on Intelligent Transportation Systems (ITS).* New York: Springer, 2005.

World Business Council For Sustainable Development. *Mobility 2001: World Mobility at the End of the Twentieth Century and its Sustainability.* Report prepared for the Sustainable Mobility Working Group, WBCSD, by the Massachusetts Institute of Technology and Charles River Associates, August 2001. Available online at http://www.wbcsdmobility.org.

World Business Council For Sustainable Development. *Mobility 2030: Meeting the Challenges to Sustainability.* World Business Council on Sustainable Development. Sustainable Mobility Project Report, 2004 (180 pages). Available online at http://www.wbcsd.org/DocRoot/fI311MAvneJpUcnLgSeN/mobility-full/pdf.