Trade-offs among performance, size, and fuel consumption in light-duty vehicles will be a critical policy challenge.

Energy Efficiency in Passenger Transportation

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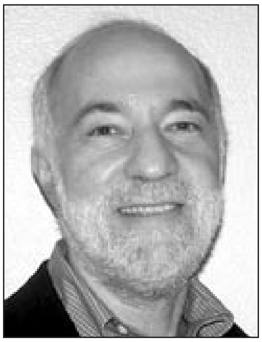

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Transportation accounts for approximately one-third of greenhouse gas (GHG) emissions in the United States, two-thirds of oil consumption, and about half of urban air pollution (Davis et al., 2008; NRC, 2006; EPA, 2008). In addition, GHG emissions are increasing faster in transportation than in any other sector, making it a prime target for changes in energy and climate policy. As a result of increased use of energy-intensive modes of transport, especially private cars and trucks, bus and rail transit now account for less than 3 percent of passenger travel in the United States.

Reducing oil use and GHG emissions in transportation is difficult for two basic reasons: (1) as a derived demand linked to almost all other economic activity, travel demand has proven to be both strong and inelastic; and (2) unlike other large energy-using sectors that can operate with a variety of commercial fuels, vehicles operate almost exclusively on oil-based fuel.

Introducing new fuel-efficient propulsion technologies and low-carbon fuels has been difficult because of poor coordination between fuel and vehicle industries, the necessity of large upfront investments in infrastructure, and entrenched consumer expectations and habits. To make matters

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worse, petroleum production is becoming *more* rather than *less* carbon intensive as easily accessed, high-quality reserves are depleted, and producers tap into remote sources of fossil energy that require additional refining to upgrade fuel quality.

Despite this rather bleak scenario, there are many attractive opportunities for reducing oil use and GHG emissions. In this article we focus on the largest component of the transportation sector, light-duty vehicles,[1] which account for more than half of the oil consumption and almost a quarter of GHG emissions in the United States (EPA, 2008). In addition, we define energy efficiency to include: (1) improvements in conventional vehicles and the introduction of advanced, high-efficiency propulsion technologies based on non-petroleum fuels; (2) changes in "on-road" operational practices; and (3) system improvements that result in decreased vehicle use.

Improvements in Conventional Vehicles

Internal Combustion and Compressed Ignition Engines

Incremental improvements in conventional vehicles include more efficient combustion (e.g., variable valve systems, gasoline direct injection, cylinder deactivation, and homogeneous-charge compression ignition), turbocharging, smart cooling systems, reduced engine friction, more efficient transmissions (e.g., 5- and 6-speed automatic, automated manual, and continuously variable systems), lightweight materials and designs, and "slippery" aerodynamics.

Efficiency can be improved by 10 to 15 percent in the near term (by 2020) and by an additional 15 to 20 percent in the longer term (2030) with improvements in conventional vehicles with internal combustion engines (ICEs) (NRC, 2009). The use of diesel (compressed-ignition) engines could provide small additional improvements. Most studies have shown that the fuel savings from these improvements far outweigh their higher cost (Lutsey and Sperling, 2009).

Electric-Drive Propulsion Technologies

Much greater GHG reductions are possible with electric-drive propulsion technologies. These include hybrid gasoline-electric vehicles (HEVs), plug-in hybrids (PHEVs) that use electricity and petroleum fuels, battery electric vehicles (BEVs), and hydrogen-powered fuel-cell vehicles (HFCVs).

HEVs are fueled by gasoline but are propelled by ICEs coupled with electric motors and batteries. Usually both systems can drive the vehicle, with the ICE being used for recharging the batteries. The primary efficiency benefits of a gasoline hybrid are realized by using the electric motor and battery to eliminate idling, provide regenerative braking, downsize engines, and create more efficient engine operating conditions. A wide variety of hybrid technologies are possible, from simple systems that reduce fuel use by 4 to 6 percent by eliminating engine idling to more complex systems with bigger batteries, such as the Toyota Prius, that reduce fuel use by 30 percent. Another 10 percent in efficiency could be gained with a diesel engine, but at considerably higher cost.

Improvements in conventional vehicles can deliver a 10 to 15 percent improvement in fuel use and lower emissions by 2020.

The next level of vehicle electrification is PHEVs, which carry a much larger battery pack that is rechargeable from an external source of electricity. PHEV batteries can be sized to power all-electric driving for 60 miles or more, and they can reduce petroleum consumption by up to 75 percent over gasoline vehicles, depending on the size of the onboard battery. The corresponding reduction in GHG emissions depends on the GHG intensity of the electricity used to charge the battery. PHEVs are likely to be introduced into the U.S. market in modest numbers beginning in 2011, but the development of a mass market for them will require batteries that last for 10 years or more and cost much less than today's batteries.

Fully electrified vehicles use batteries and/or fuel cells (and possibly ultracapacitors),[2] do not have combustion

[1] "Light duty vehicles," here and in most regulatory frameworks, include passenger cars and light trucks (including minivans, pick-up trucks, and sport utility vehicles) with Gross Vehicle Weight Ratings of less than 8,500 pounds.

[2] Fully electric vehicles could alternatively use electricity from overhead or adjacent wires or wires in the pavement, as some buses and most urban rail vehicles do.

engines, and have a "tank-to-wheel" vehicle efficiency at least twice that of conventional gasoline vehicles. A large number of small companies already sell small BEVs, and many major automotive companies have plans to start selling them in small numbers beginning in about 2011. In the foreseeable future, mass-market BEVs will be small, similar in size to the Mercedes Smart, with driving ranges of up to about 120 miles per charge.

Hydrogen Fuel Cell Vehicles

HFCVs convert hydrogen into electricity. Fuel cell systems are 2 to 3 times as energy efficient as combustion engines and emit no GHGs—although, like electric cars, their life-cycle GHG emissions depend on how the hydrogen is produced. Most major automotive companies have large fuel-cell development programs and have built and tested demonstration fleets. The principal challenges are the durability and cost of fuel cells, the cost of storing hydrogen in fueling stations and on board the vehicle, and the deployment of a hydrogen supply and fueling infrastructure.

Summary

Table 1 shows plausible levels of reductions in petroleum use and GHG emissions from improvements in vehicle technology (NRC, 2009). The evolutionary improvements described above can reduce fuel consumption of a gasoline ICE vehicle by up to 35 percent in the next 25 years. Diesel ICE vehicles will also continue to be more efficient, but the gap between diesel and gasoline engines is likely to narrow. Hybrid vehicles have a greater potential for improvement and can deliver deeper reductions in vehicle fuel consumption, although they continue to depend on petroleum (or alternative liquid fuels, such as biofuels). BEVs and HFCVs represent a leap forward in efficiency but will be considerably more expensive initially. They offer the additional advantages of zero oil use and zero tailpipe emissions and, if electricity and hydrogen can be produced with few GHG emissions, they would also dramatically reduce total life-cycle GHG emissions.

TABLE 1 Plausible Reductions in Petroleum Use and GHG Emissions from Improvements in Vehicle Efficiency in the Next 25 Years

	Petroleum Consumption (gasoline equivalent)		Greenhouse Gas Emissions (per distance traveled)	
Propulsion System	Relative to Current Gasoline ICE	Relative to Gasoline ICE in 2035	Relative to Current Gasoline ICE	Relative to Gasoline ICE in 2035
Current gasoline ICE	1	—	1	—
Current diesel engine	0.8	—	0.8	—
Current hybrid	0.75	—	0.75	—
Advanced gasoline ICE	0.65	1	0.65	1
Advanced diesel engine	0.55	0.85	0.55	0.85
Advanced hybrid (HEV)	0.4	0.6	0.4	0.6
Plug-in hybrid (PHEV)	0.2	0.3	0.35–0.45	0.45–0.7
Battery electric vehicle (BEV)	none	—	0.35–0.5	0.55–0.75
Hydrogen fuel cell vehicle (HFCV)	none	—	0.3–0.4	0.45–0.60

Sources: Bandivadekar et al., 2008; NRC, 2009.

Note: Estimates are based on the assumption that vehicle size and performance (e.g., power-to-weight ratio, acceleration) remain at current levels, that electricity is produced with the current energy mix, and that hydrogen is produced from natural gas. Considerably larger reductions are possible if vehicle weight and power, as well as the carbon intensity of electricity, hydrogen, and biofuels, are all reduced.

Gains from Improvements in Vehicle Technologies

An obvious way to reduce fuel consumption is to reduce the weight of the vehicle. A common rule of thumb is that a 10 percent reduction in weight can reduce fuel consumption by 5 to 7 percent, when accompanied by appropriate engine downsizing at constant performance. Still further reductions are possible with reductions in power and vehicle size, both of which have increased dramatically since the early 1980s. Today's average car accelerates from a standstill to 60 miles per hour in about 9.5 seconds. An average car in the mid-1980s required 14.5 seconds—and was much lighter.

Improvements in efficiency do not automatically translate into reductions in oil use and GHG emissions. From the mid-1980s to the early 2000s, efficiency improved considerably in a technical sense (measured as output per unit of energy input), but fuel consumption per vehicle mile did not change. This apparent anomaly occurred because efficiency gains were consumed by increases in vehicle size and improvements in performance (An and DeCicco, 2007; Lutsey and Sperling, 2005). As long as vehicle manufacturers compete on, and consumers continue to expect, improvements in performance, government intervention will be necessary to promote or require reductions in fuel consumption. Making trade-offs among performance, size, and fuel consumption will be a critical policy challenge.

Still further reductions in GHG emissions are possible if fuels themselves are changed. If energy efficiency in the extraction and processing of fuels is improved, or if lower carbon feedstocks are used to produce fuels, then total energy use and GHG emissions would be lower (Table 2). Indeed, the energy and GHG intensity of electricity and hydrogen varies considerably. In California, for instance, only 15 percent of the electricity consumed in the state is generated from high-carbon coal, compared to more than 80 percent from coal in many other states.

We can reasonably assume that the carbon intensity of electricity and other fuels will decrease over time as incentives and requirements for renewable electricity and low-carbon fuels are put into place. The same

TABLE 2 Estimated Incremental Cost of Advanced Vehicles in the Next 25 Years Relative to a Baseline 2005 Standard Gasoline Vehicle

	Conservative Incremental Retail Price[a] (2007 dollars)		Optimistic Incremental Retail Price[b] (2007 dollars)	
Propulsion System	**Cars**	**Light Trucks**	**Cars**	**Light Trucks**
Current gasoline ICE	0	0	0	0
Current diesel ICE	1,700	2,100	1,500	1,900
Current hybrid vehicle	4,900	6,300	4,400	5,700
Advanced gasoline	2,000	2,400	1,800	2,200
Advanced diesel	3,600	4,500	3,000	4,000
Advanced hybrid vehicle (HEV)	4,500	5,500	2,500	3,000
Plug-in hybrid (PHEV)	7,800	10,500	3,900	5,300
Battery electric vehicle (BEV)	16,000	24,000	8,000	12,000
Hydrogen fuel cell vehicle (HFCV)	7,300	10,000	4,500	6,200

[a] Bandivadekar et al., 2008; NRC, 2009.

[b] Based on technology, learning, and longer-term engineering cost reductions: 10 percent cost reduction from gasoline and diesel technologies; midterm battery costs based on Kalhammer et al. (2007), Kromer and Heywood (2007), and EPRI (2002); midterm fuel cell vehicle costs based on NRC (2008), and Kromer and Heywood (2007).

Note: To obtain the price increments of an advanced technology vehicle relative to a future (improved) ICE vehicle, subtract $2000 (car) or $2,400 (truck) for the conservative projections.

forceful efforts that are being made to improve vehicle efficiency will eventually carry over to energy suppliers. With low-carbon electricity and hydrogen, it would be possible to reduce life-cycle GHG emissions from new vehicles by 80 percent or more by 2050.

Cost Considerations

Advanced vehicle and fuel technologies require large initial costs—especially for the development of electricity and hydrogen storage systems and fuel cells. Based largely on studies at MIT (Bandivadekar et al., 2008), a National Research Council (NRC) committee estimated the cost of future vehicles, presented as incremental increases in retail prices relative to a 2005 baseline gasoline ICE vehicle (shown in the left-hand columns of Table 2). These estimates depend on rates of engineering development and technology deployment and are subject to considerable uncertainty. The right-hand columns show a somewhat more optimistic estimate of future costs.

Table 2 shows that improved gasoline and diesel engines and gasoline hybrids would cost 10 to 30 percent more than typical current gasoline vehicles. The price difference is estimated to shrink to 5 to 15 percent in the midterm future. Longer term options such as plug-in hybrid and fuel-cell vehicles are estimated to cost 25 to 30 percent more than a future gasoline vehicle. Full-sized BEVs with standard performance would be much more costly, and thus most future BEVs will likely be small city cars with reduced ranges.

The additional cost of fuel-saving technologies will largely be offset by fuel savings over the lifetime of the vehicle, but not in all cases. Longer term options such as PHEVs and HFCVs are estimated to pay back 50 to 70 percent of the increase in cost at $2.50 per gallon. At $5.00 per gallon, all technologies except diesel vehicles and (full-size) BEVs would fully pay back the initial retail price increase.

Overall, the estimates in Table 2 suggest that evolutionary improvements in gasoline ICE vehicles are likely to be the most cost-effective option for reducing petroleum consumption and GHG emissions in the near term. As advanced technologies improve, and if larger reductions in oil use and GHG emissions are deemed necessary (and supported by incentives, regulations, and other policies), then PHEVs, BEVs, and HFCVs will gradually be introduced.

Market Penetration

Advanced-technology vehicles face many barriers to capturing market share, such as high initial cost, safety concerns, fuel availability, reliability and durability concerns, and lack of awareness. Because all advanced technologies will be competing against steadily improving gasoline ICE vehicles, market penetration rates are likely to rise slowly unless fiscal and/or regulatory policies are changed dramatically.

The NRC study of energy efficiency (2009) developed plausible estimates of market share for advanced vehicles (Table 3). If, as indicated below, aggressive climate and energy policies are adopted, the market shares of advanced-technology vehicles are likely to be much higher.

In December 2007, Congress passed a law requiring that fuel economy for new light-duty vehicles be improved by 40 percent by 2020 (from an average of 25 mpg to 35 mpg). California, followed by 12 other states, has adopted a law that would require even greater reductions (roughly 40 mpg by 2020), but these state laws are under litigation and federal review and have not been implemented as this article goes to press. Many other programs and policies to accelerate improvements in vehicle efficiency and reductions in emissions are also in various stages of implementation.

TABLE 3 Plausible Light-Duty Vehicle Market Shares with Advanced Technology by 2020 and 2035

Propulsion System	Plausible LDV Market Share by Given Model Year	
	2020	2035
Turbocharged gasoline	10–15%	25–35%
Diesels	8–12%	15–30%
Gasoline hybrids (HEVs)	10–14%	15–40%
Plug-in hybrids (PHEVs)	1–3%	7–15%
Hydrogen fuel cell vehicles (HFCVs)	0–1%	3–6%
Battery electric vehicles (BEVs)	0–2%	3–10%

Source: NRC, 2009.

One federal program, for example, offers large subsidies for advanced vehicles (e.g., $7,500 for PHEVs with a range of 40 miles), and California and other states have a zero-emission vehicle program, likely to be strengthened in 2010, that requires automakers to supply increasing numbers of advanced vehicles. In addition, many states are considering revenue-neutral "fee-bate" programs that impose large taxes on the sale of gas guzzlers and offer rebates for low-GHG, energy-efficient vehicles. Feebate programs that have been implemented in several European countries since 2007 have effectively shifted consumer purchases toward efficient, low-carbon vehicles.

On-Road Efficiency Improvements

Actual fuel consumption can be reduced without advanced propulsion technology. Large improvements in "on-road" fuel economy can result from improved vehicle maintenance, more efficient ancillary and accessory equipment, and technologies that encourage more energy-conscious "eco-driving" styles.

Improved vehicle maintenance practices, such as inflating tires to the proper level and making sure wheels are aligned and replacing oil and air filters regularly, can ensure that vehicles operate at their designed efficiency levels. Maintenance practices also include the use of low-friction engine oils and low rolling resistance tires. Another change that does not directly impact efficiency but does reduce GHG emissions is replacement of the conventional air conditioning refrigerant, hydrofluorocarbon (HFC)-134a, with lower global warming potential gases like HFC-152a.

Fuel consumption can be significantly reduced by providing more and better information on how driving style affects fuel economy. New vehicles can be equipped with dashboard instruments that provide instantaneous fuel consumption, efficient engine rpm ranges, shift indicator lights, and tire pressure.

On-road fuel consumption can also be reduced by improving equipment not directly related to fuel propulsion, and thus not measured in government fuel economy ratings. Examples include more efficient alternators, air conditioning systems, and ancillary engine systems, such as dual cooling circuits and electric water pumps.

Improvements in actual on-road efficiency depend on real-world conditions (e.g., road, weather, and traffic conditions; driving style; accessory use; etc.). Based on data from the European Conference of Ministers of Transport and International Energy Agency (ECMT and IEA, 2005), as analyzed in Lutsey (2008), such improvements can reduce fuel consumption by more than 10 percent.

System Transformations and Reduced Vehicle Use

For the time being, the greatest reductions in oil use and GHG emissions in the transport sector are likely to come from improved vehicle efficiency and low-carbon fuels. But system transformations could eventually be important. The history of transportation is filled with continuous innovations, most of them small and incremental but some that are cumulative and lead to restructuring and reorganization. For example, impressive transformations have been made in the freight sector in the past few decades. The container revolution, combined with the use of information technologies, has led to huge gains in efficiencies in transporting goods. An integrated, multi-modal freight system has evolved that is far more efficient and less costly than the old system.

Improved maintenance practices, driver education, and ancillary equipment can reduce fuel consumption.

The same cannot be said, however, for surface passenger travel, which has not changed structurally for 80 years. Although, there are more limited-access expressways, and vehicles are safer and more comfortable, the structure, efficiency, and performance of the passenger transport system are largely unchanged. Cars, buses, and rail transit are still the dominant modes of transportation, and all of them have essentially the same functional performance.

Although some interest has been shown in automated highway lanes for cars and trucks using advanced control technologies and sensors, these efforts have faltered in the face of litigation and safety concerns. Information and communication technologies, referred to in the transportation community as intelligent transportation systems (ITS), have been embraced but have led to only incremental changes in current practices. Local governments have learned to use information to improve the management of road use, and travelers have gained access to navigational devices and information services that ease driving tension, reduce destination search times, and provide emergency services, but the net effect has been a very small decrease in driving and energy use.

Thus, there would seem to be opportunities for increasing fuel efficiency through system-level changes, if only because the current pattern of mostly single-occupant vehicle use is so inefficient. The answer, however, is not to expand conventional transit (e.g., full-size buses and rail transport). Today, transit buses in the United States consume about the same amount of energy per passenger mile as light-duty vehicles, largely because of low average ridership (Davis et al., 2008). Rail transit is somewhat better in terms of energy use per passenger mile, but except for New York City and a few other densely populated cities that have heavy ridership during both peak and non-peak hours, transit rail is also characterized by light use for much of the day, which translates to high average energy use per rider.

The net improvement from replacing personal vehicles with a suite of mobility services is likely to be substantial.

Clearly, increased load with existing service would result in less energy-intensive travel, but unless there are dramatic changes in land use or dramatic increases in the cost of owning and operating a car, these changes are unlikely. The run-up in gasoline prices in 2007–2008, followed by an economic downturn, did increase annual public transportation ridership by 4 percent, putting transit trips in 2007 and 2008 at a 50-year high (APTA, 2009). Despite these shifts, the aggregate effect of transit is still trivial in terms of reducing overall energy use (Davis et al., 2008).

If, however, ITS and other advanced technologies were used to create new mobility services, and were combined with changes in land use, broader system changes with much larger energy and GHG benefits might be achieved. One can imagine, for example, demand-responsive jitney services that pick up passengers at their homes or offices with only a few minutes notice, dynamic ride-sharing that facilitates carpooling among people with similar origins and destinations (e.g., commuting to the same office or traveling to a sporting event), and smart car-sharing that provides easy access to a variety of vehicles, all combined with more rational management of land use and the expanded use of conventional and bus rapid transit along high-density travel corridors. Such a transport system might provide higher quality service at lower cost for many individuals.

The key to substantial improvements in efficiency is replacement by households of one or more cars—which now cost more than $8,000 per vehicle per year to own and operate. The net improvement (and reduction in carbon footprint) resulting from the replacement of personal vehicles with a suite of mobility services has not been carefully modeled, but is likely to be substantial. The potential benefits would include less energy use and lower GHG emissions, as well as lower cost, less stress, and greater satisfaction. For many people, the combination of being freed of the stress and time demands of driving and having access to convenient services and nearby car-sharing might be more practical than owning and driving a vehicle.

Although a shift toward dense urban corridors would be at odds with long-term trends, changes in individual preferences (e.g., interest in urban amenities), values (e.g., environmental concerns), and costs of vehicle ownership and operation, might encourage change. For this kind of diversified system to evolve, however, there have to be changes not only in people's preferences, but also in policies and institutions that govern land-use management and the provision of transportation services.

Conclusions

Many transportation strategies for reducing energy use and GHG emissions are highly cost effective. When future energy savings are calculated using normal discount factors, improved gasoline and diesel vehicles have the potential to generate cost savings over the lifetime of the energy-saving technology or product. The use of alternative-fuel technologies could lead to far greater efficiency gains while also decoupling passenger transportation from petroleum use. When the full range of benefits, including improved energy security, reduced traffic congestion, and climate change are taken into account, many vehicle-efficiency and GHG-mitigation options seem even more attractive.

Nevertheless, there are considerable barriers to widespread deployment of efficient, low-carbon technologies and practices. Vehicle consumers, in the absence of automotive fuel and climate policies, have historically opted for larger vehicles, more sophisticated accessories, and more rapid acceleration. High fuel prices have led to increased sales of smaller and more efficient vehicles, but only temporarily. Unless policies, behavior, and market circumstances change, efficiency improvements will be implemented slowly.

A number of aggressive policies are under serious consideration, and some are being put into effect. Vehicle GHG standards that require substantial improvements in fuel economy (and greater use of efficient electric-drive vehicles) may also be adopted shortly in many states, and perhaps nationally. Zero-emission vehicle requirements in some states will provide an additional boost, as will low-carbon fuel standards, which have been adopted in California and in more limited form in the European Union and are under serious consideration in other states and at the federal level.

Financial enticements, such as feebates, tax credits for advanced vehicles, and higher fuel prices (e.g., prices resulting from carbon cap-and-trade programs), could provide a further boost by encouraging consumers to embrace more efficient vehicles and by encouraging technology companies to accelerate investment in advanced technologies. The combined effect of these policies would accelerate the development and use of energy-efficient, low-GHG vehicles and transportation systems.

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