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Reducing Greenhouse Gas Emissions from U.S. Transportation

Prepared for the Pew Center on Global Climate Change

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PEW CENTER ON Global CLIMATE CHANGE

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

Transportation is vital to our economy and quality of life. But it is also the primary cause of U.S. oil dependency, and is responsible for more than a quarter of U.S. emissions of the greenhouse gases that are warming our planet. This report examines whether we can substantially reduce greenhouse gas (GHG) emissions from U.S. transportation. Report authors David Greene and Steve Plotkin provide three plausible scenarios of technology, policy, and public attitudes that result in cost-effective GHG reductions throughout the transportation sector. The High Mitigation Scenario shows we can reduce GHG emissions from transportation by as much as 65 percent below today's levels by 2050. In order to do so, we need action on three fronts: targeted public policies, technological progress, and commitment from Americans as consumers and citizens.

- **Technology.** Substantial improvements in fuel economy and GHG emission performance are achievable today just through greater utilization of existing technology. By 2035, the fuel efficiency of the U.S. light-duty fleet can improve dramatically (50 mpg for conventional gasoline vehicles and 75 mpg for hybrid vehicles)—if new standards and/or market pressures push vehicle designers to do so. Using a fuel mix of electricity, biofuels, and hydrogen could significantly reduce the number of gasoline-powered passenger vehicles on the road by 2050. Technological advances in other vehicles including trucks, buses, and airplanes could improve the efficiency of those modes substantially. In fact, technologies exist today to reduce GHG emissions from freight trucks by 30 to 50 percent, with even greater reductions achievable over the next several decades.

- **Policy.** To achieve deep reductions in GHG emissions and oil dependence, public policy must be multi-faceted, flexible, and adaptive. We need to level the playing field for, and spur advances in, low-carbon fuels, advanced vehicles, and lower-emitting transportation modes. Policies are needed to pull technology that exists today into the marketplace, support technological development for the future, and correct market failures that have solidified our dependence on fossil fuels. This will require a combination of performance standards, pricing mechanisms, and research, development, demonstration, and deployment. We need to begin now with the many policies we know to be effective and cost-effective, and adapt as we learn how technologies and policies perform in the real world.

- **Public attitudes.** The extent to which we can achieve climate protection and energy security depends on what Americans do in the public square and in the marketplace. If as citizens we support the necessary public policies, and as consumers we choose advanced technologies, then public policy, technological progress, and market success will be mutually reinforcing.

We can succeed if we begin now and sustain our efforts over time. This is of course a considerable challenge, but one that we must take on with great urgency.

Executive Summary

This report examines the prospects for substantially reducing the greenhouse gas (GHG) emissions from the U.S. transportation sector, which accounts for 27 percent of the GHG emissions of the entire U.S. economy and 30 percent of the world's transportation GHG emissions. Without shifts in existing policies, the U.S. transportation sector's GHG emissions are expected to grow by about 10 percent by 2035, and will still account for a quarter of global transportation emissions at that time. If there is to be any hope that damages from climate change can be held to moderate levels, these trends must change.

This report shows that through a combination of policies and improved technologies, these trends can be changed. It is possible to cut GHG emissions from the transportation sector cost-effectively by up to 65 percent below 2010 levels by 2050 by improving vehicle efficiency, shifting to less carbon intensive fuels, changing travel behavior, and operating more efficiently. A major co-benefit of reducing transportation's GHG emissions is the resulting reductions in oil use and improvements in energy security.

This report develops three scenarios of improved transportation efficiency and reduced GHG emissions through 2050, with both technological progress and policy ambition increasing from the first to the third scenario. The three scenarios show GHG reductions of 17, 39, and 65 percent from 2010 emissions levels in the year 2050.

Passenger Cars and Light Trucks

Light-duty vehicles (LDVs)—passenger cars and light trucks—account for nearly three fifths of the total energy use and GHG emissions of the U.S. transportation sector. Currently, the average fuel economy of new LDVs is 26 miles per gallon (mpg) on Environmental Protection Agency (EPA) vehicle certification tests, or about 21 to 22 mpg when adjusted for on-road conditions. Existing fuel economy standards and GHG emission standards require that this average rise to over 35 mpg (about 29 mpg on-road) in 2016—a 35 percent improvement. By 2035, if new standards or market pressures push vehicle designers to accelerate their efforts to improve fuel efficiency, a new midsize car might attain about 50 mpg on-road or more with a conventional drivetrain and 75 mpg on-road with a hybrid-electric drivetrain.

The average efficiency of the cars and trucks on the road will grow more slowly, because it takes about 15 years to turn over the entire fleet. But by 2035, the LDV fleet could attain an on-road fuel economy of about

34 to 41 mpg, rising to 45 to 59 mpg by 2050. That is much higher than today's fleet (21 mpg) or the 29.3 mpg projected by the Energy Information Administration's (EIA) *Annual Energy Outlook 2010* for 2035, which assumes no new incentives to improve fuel efficiency.

Shifting to alternative fuels can also bring significant reductions in GHG emissions and oil use. While there are many potential alternative fuels including natural gas, the fuels that will likely play the greatest role in the future are electricity, liquid fuels from biomass, and hydrogen:

- **Electricity** has recently reappeared as a strong contender, thanks to the development of lithium-ion batteries and plug-in hybrid electric vehicles (PHEVs). PHEVs with electric ranges of 10 to 40 miles overcome the range limitations of pure electric vehicles (by allowing the vehicle to shift to gasoline operation when the battery is depleted). Battery cost and lifetime remain issues, and the GHG benefits of PHEVs depend on the extent to which the electric grid is decarbonized. The Low and Mid Mitigation Scenarios assume 1 and 3 million PHEVs will be on the road in 2035 (between 0.3 and 1 percent of total LDVs expected in that year), with the number rising to 10 to 20 million by 2050 (3 and 6 percent of total LDVs). The scenarios assume carbon intensity reductions in the electricity sector, so that PHEVs will play a substantial role in reducing transportation GHG emissions.

- **Liquid fuels from biomass** offer another strong opportunity. Certain types of biomass fuels can virtually eliminate GHG emissions (on a lifecycle basis) from the vehicles in which they are used. Two key remaining issues are reducing biomass fuel costs and preventing adverse land use impacts. In the Low and Mid Mitigation Scenarios, advanced biofuels production rises to 20 to 30 billion gallons by 2035 and 35 to 45 billion gallons by 2050 (with an additional 15 billion gallons of corn-based ethanol in both years), replacing 19 and 25 percent of gasoline consumption in 2035.

- **Hydrogen** remains a strong prospect, although earlier enthusiasm has waned. Hydrogen fuel cell vehicles (FCVs) emit no GHGs or other pollutants, although their lifecycle emissions depend on how the hydrogen is produced and distributed. FCVs have already demonstrated ranges of 300 miles, while refueling nearly as quickly as gasoline vehicles. However, hydrogen requires a new refueling infrastructure and the vehicles remain very expensive. Hydrogen vehicle penetration was only included in the High Mitigation Scenario for this report.

- **Alternative Fuels in the High Mitigation Scenario.** Whereas the alternative fuel mix was specified in the Low and Mid Mitigation Scenarios, a range of plausible combinations of alternative fuels was considered for the High Mitigation Scenario. These include a vehicle fleet that is 40 percent or more hydrogen fuel cell vehicles or one that is about one-third or more battery electric and PHEVs, and uses fuel blended with 25 percent advanced biofuels.

In the future, the success of alternative fuel vehicles, and the substitution of significant quantities of gasoline and diesel fuels, will depend on several factors:

- The new vehicles and fuels must become cost competitive.
- A research, development, demonstration, and deployment (RDD&D) program must be sustained and robust.
- Major mistakes (such as safety problems) on the part of vehicle designers and fuel providers must be avoided.
- Government and/or industry must subsidize elements of the new fuel system until it becomes self-sustaining.
- Gasoline and diesel prices must remain high due to sustained high world oil prices or government's willingness to use taxes or other pricing policies.

Trucks and Buses

Freight trucks carry 70 percent of the dollar value and over a third of the total ton-miles of U.S. freight. They emit 17.5 percent of total U.S. transportation carbon dioxide (CO_2, the predominant GHG) emissions. Two-thirds of trucking's energy use and GHG emissions are from heavy-duty long-haul tractor-trailers. Two recent studies have concluded that practical technologies and logistical changes could reduce the fuel use and GHG emissions of a tractor-trailer by 40 to 50 percent within about 10 years. Technologies are also available to reduce fuel use and GHG emissions from other medium- and heavy-duty vehicles by 30 to 50 percent. This report's three scenarios envision medium- and heavy-duty truck on-road fuel economy improving by 30 to 40 percent by 2035 and 40 to 55 percent by 2050.

Commercial Air Transportation, Rail, and Shipping

Air transportation accounts for about 10 percent of U.S. transportation GHG emissions. The impact of aviation emissions on the climate is still not well understood, however, because it depends not only on CO_2 emissions but also on the extent of the additional effects of other airplane emissions in the upper atmosphere. For new aircraft, reductions in CO_2 emissions of 25 to 35 percent should be achievable over the next decade or two through engine, propulsion, and airframe improvements. Aircraft are also able to use alternative fuels. Lastly, there is the potential to improve operating efficiency by 5 to 10 percent through advanced air traffic management and efficient flight planning.

Rail carries 40 percent of U.S. freight (in ton-miles) while using only 2 percent of transportation's energy and producing 2 percent of transportation GHG emissions. Rail energy intensity could be reduced by 15 to 30 percent over the next two decades and by 20 to 40 percent by 2050 through improved locomotive efficiency, greater use of regenerative braking, reductions in the empty weight of rolling stock, and improved operations. Comparable improvements are possible for domestic and international shipping.

Highway System Efficiency

Improving the operating efficiency of the transportation system could reduce its GHG emissions by several percent. The possible steps include driving more efficiently; improving freight logistics, route choices, and trip-making choices; increasing vehicle occupancy rates, smoothing traffic flow, and improving speed management. In the long run, automated control of long-haul truck travel could reduce emissions and improve highway safety. For most system efficiency strategies, the co-benefit of reduced traffic congestion and increased highway capacity substantially exceed the GHG benefits.

Shifting Traffic to More Energy-Efficient Modes

Moving passenger and freight movement to more efficient modes is well worth pursuing, but can be expected to yield only moderate reductions in GHG emissions and fuel use.

Currently, public transit supplies only about 1 percent of total passenger-miles in the United States and, on average, is only modestly more energy-efficient than personal vehicles. However, many transit systems with high occupancy rates and efficient designs use much less energy and have much lower GHG emissions than personal vehicles. Strategies to promote transit in order to reduce GHG emissions must focus on improving the efficiency of current systems and promoting the most efficient systems.

The best opportunities for shifting truck freight traffic to more efficient rail and ships involve improving intermodal transfers and improving freight logistics to make them more attractive to shippers. However, it will be difficult to attain large reductions in GHG emissions from mode shifts because of growing demands for just-in-time delivery and trucking's scheduling flexibility and ability to handle small shipments and short distances cost-effectively. The three scenarios project that improved logistics will reduce overall freight shipments by 0, 2.3, and 5.0 percent by 2035 compared to the report's baseline, and remain constant at that level of reduction through 2050.

Moving Towards Compact Development

Reversing the United States' longstanding trends towards lower density development by promoting compact, mixed-use development would reduce the growth of travel and yield other benefits. Compact development shortens trip lengths and promotes walking, bicycling, and public transit.

A recent National Research Council study and two other recent studies conclude that GHG emissions could be reduced by 10 percent or more by 2050 if 75 to 90 percent of all new development were "compact." Because of competing priorities at the local level, however, the scenarios in this study achieve reductions in travel and GHG emissions of 0.5 to 2.0 percent by 2035 and 1.5 percent to 5.0 percent by 2050.

Policies to Promote GHG Mitigation

GHG emissions are a classic example of an environmental externality, a problem that markets generally fail to solve without the assistance of public policy. Just as there is no one technology that can achieve the necessary emission reductions from transportation, there is no single policy that can bring them about. Some of the policies that could play major roles are described below.

Fuel Economy and GHG Standards

Experience in the United States and other major automobile manufacturing nations has shown that fuel economy or emission standards can make large, cost-effective reductions in GHG emissions. In 2009, the United States set standards requiring an average of about 35 mpg (EPA certification test values) for the combined fleet of autos and light trucks to take effect in 2016, and new standards for the 2017 to 2025 period are being developed. Separate standards for medium and heavy-duty trucks are also being developed.

Renewable and Low-Carbon Fuels Standards

Renewable or Low-Carbon Fuels Standards are policies intended to displace oil use, reduce the carbon content of fuels, and stimulate innovation that will bring down the costs of low-carbon fuels. At present, the federal Renewable Fuels Standard requires that 36 billion gallons (about 12 percent of gasoline consumption) of renewable fuels be sold for highway use by 2022. Twenty-one billion of the 36 billion gallons must be either "advanced" or cellulosic biofuel with 50 percent and 60 percent lower lifecycle GHG emissions, respectively, than gasoline. California has a Low-Carbon Fuels Standard (LCFS) that requires a 10 percent reduction of lifecycle GHG emissions.

Pricing Transportation

Putting a price on carbon is a critical component of a comprehensive GHG mitigation policy. Carbon pricing will increase energy efficiency, promote low-carbon fuels, encourage environmentally beneficial travel choices, and motivate innovation. But pricing carbon will not be sufficient for transportation for a variety of reasons. First, consumer markets for energy efficiency do not appear to respond efficiently to energy prices. In addition, governments play key roles in providing and operating transportation infrastructure, and in shaping the geography in which travel takes place. Also, the private sector underinvests in all RDD&D, including for low-carbon transportation.

There are major opportunities to change the way transportation is paid for, without increasing its total cost, so as to encourage GHG mitigation. Examples include pay-at-the-pump (PATP) or pay-as-you-drive motor vehicle insurance, conversion of the motor fuel excise tax to a comprehensive energy user fee indexed to average vehicle efficiency, congestion pricing, and pricing parking. Feebates, a graduated rebate to vehicles with lower GHG emissions offset by fees on vehicles with higher GHG emissions, can be an effective complement to or potential replacement for emission standards.

Vehicle and Fuel Transition

GHG emission reductions of more than 50 percent below current levels are likely to require a transition to a completely different source of energy for transportation, such as electricity or hydrogen. Strong, durable, and adaptable public policies will be needed to overcome the "lock-in" of petroleum-fueled, internal combustion engine technology. Performance standards that stimulate innovation in all competing technologies and fuels are important, but some fuel and technology-specific policies are also needed to ensure that promising technologies are developed sufficiently for consumers and society to make judgments about their costs and benefits. RDD&D support is critical. Deployment assistance should be provided to the extent that societal benefits exceed public investment. All policies must be continually reevaluated and adjusted based on new information and experience.

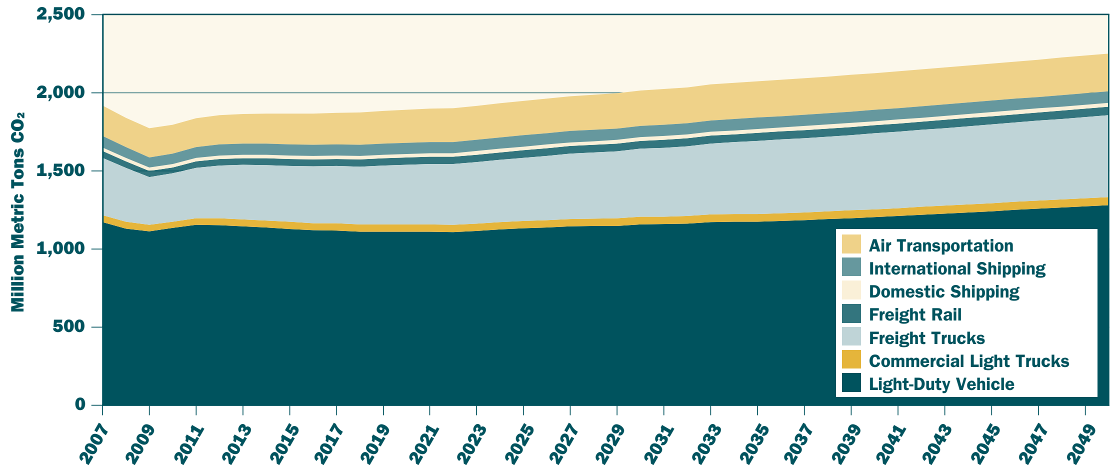
Mitigation Potential: Scenarios for 2035 and 2050

Three scenarios were developed to illustrate a range of GHG mitigation potential for the U.S. transportation sector through 2050, depending on public attitudes about climate change, the extent of technological progress, and the scope and forcefulness of public policies. The Base Case is the EIA's 2010 AEO Reference Case projection, extrapolated from 2035 to 2050. The Base Case includes relatively high energy prices, as well as existing emission standards and a substantial increase in renewable fuel use. Nevertheless, transportation's CO_2 emissions increase

28 percent from 1.8 gigatons in 2010 to 2.3 gigatons in 2050 **(Figure ES-1).** Heavy-duty truck emissions increase the most (0.2 gigatons) and the fastest (a 70 percent increase over 2010).

Figure ES-1

U.S. Transportation CO_2 Emissions AEO 2010 Reference Case Projection to 2035 and Extrapolation to 2050



The combined impacts of the policies and measures are shown in **Table ES-1** by mode, mitigation scenario, and year. All three scenarios incorporate a price on carbon, obtained directly from a carbon tax or indirectly from a carbon cap-and-trade system. The Low Mitigation Case includes post-2016 GHG emissions standards for LDVs requiring reductions of about 2 percent per year. The scenario includes an energy efficiency indexed highway user fee, modest improvements in energy efficiency in non-highway modes, and little additional alternative fuel use beyond the Base Case (which includes the U.S. Renewable Fuel Standard).

The Mid Mitigation Case reflects a greater public commitment to reducing GHG emissions, more rapid technological progress, and a tolerance for some additional innovative pricing policies. Emission standards are more stringent, and public commitment is reflected in greater reductions from energy-efficient driving, land use strategies, an acceptance of feebates, and minimum liability PATP vehicle insurance.

The High Mitigation Case assumes rapid technological progress and aggressive emission standards. Public urgency about addressing climate change is reflected in greater effectiveness of policies such as eco-driving, land use policies, and the acceptance of congestion pricing and more comprehensive PATP insurance. In the High Mitigation Case, a transition to electric and/or hydrogen vehicles is well underway by 2050. Finally, automated highways are introduced by 2050 on major routes.

Table ES-1

Percentage Changes in **GHG Emissions** by mode from Low, Mid, and High Mitigation Scenarios with respect to 2010 levels. Oil savings is with respect to business-as-usual.

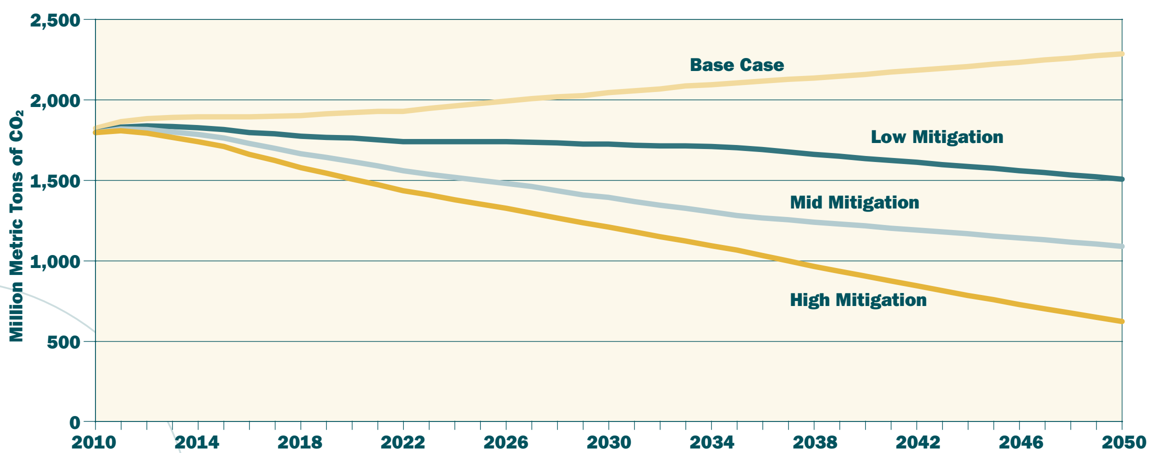
	2035				2050			
	BAU	Low	Mid	High	BAU	Low	Mid	High
Total Impact From All Policies Strategies	14.6%	–6.50%	–29.8%	–41.5%	23.6%	–17.2%	–40.1%	–65.9%
	Percentage change for each mode							
Light-Duty Vehicles	3.50%	–17.4%	–40.4%	–50.6%	12.8%	–24.9%	–48.5%	–73.4%
Commercial Light Trucks	23.1%	0.10%	–26.1%	–37.2%	29.2%	–12.3%	–38.7%	–61.3%
Freight Trucks	51.6%	27.9%	0.10%	–12.1%	69.5%	20.8%	–6.30%	–37.9%
Freight Rail	33.5%	19.0%	3.80%	–7.20%	38.8%	–3.50%	–14.4%	–45.2%
Domestic Shipping	18.7%	1.1%	–12.4%	–23.1%	23.1%	–6.40%	–30.5%	–51.6%
International Shipping	7.70%	–7.1%	–15.0%	–22.7%	8.70%	–11.7%	–32.1%	–43.2%
Air Transportation	26.3%	8.4%	–20.3%	–44.4%	30.7%	–29.8%	–47.2%	–77.2%
Total GHG Emissions (MMT CO_2e)	2,106	1,703	1,279	1,065	2,285	1,507	1,090	622
Annual Oil Savings below BAU (mmb)	—	900	1,800	2,300	—	1,700	2,600	3,700

Note that each mode is according to the definition by the U.S. EIA; Total GHG Emissions do not include miscellaneous emissions as defined by the U.S. EIA. Negative numbers mean there is a decrease in GHG emissions compared to emissions in 2010. Also note that the percentage reduction by mode is the percentage reduction for that mode, not for the whole sector. Estimates of oil savings are approximate.

The emission reductions below 2010 levels achieved in 2050 by these scenarios range from 17 percent in the Low Mitigation Case to 65 percent in the High Mitigation Case (**Figure ES-2**). Technological improvements to vehicle energy efficiency, low-carbon energy sources, and all other strategies make roughly comparable contributions to GHG mitigation in the High Mitigation Case. No single technology, policy, or mode is able to

Figure ES-2

U.S. Transportation CO_2 Emissions in the **Three Mitigation Scenarios**



accomplish a 65 percent reduction in total transportation GHG emissions. Achieving reductions of that magnitude requires a comprehensive strategy, with strong public support, sustained by rapid technological progress.

Transportation will remain a cornerstone of the U.S. economy and a fundamental contributor to Americans' quality of life to 2050 and beyond. The enormous value to society of the mobility of people and commodities must be preserved. Because rates of technological progress and future energy prices are uncertain, the GHG mitigation strategy for transportation must be adaptable. This can be accomplished by monitoring technological progress to insure that policies remain cost effective, taking advantage of faster progress when it occurs, and adjusting to disappointments accordingly. This report presents a demonstration of the likely feasibility of reducing future GHG emissions from transportation by up to 65 percent below 2010 levels by 2050. Greater or lesser reductions may turn out to be appropriate in the future. Fortunately, there is a great deal that can be put in place with confidence today—both short-term policies that will achieve reductions right away, and long-term policies that can be adjusted as the future unfolds.

1. Introduction

1.1 Study Focus

There is an urgent need to slow and eventually reverse the growth of human-made emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) throughout the world, given strong and growing evidence of climate change. Reducing GHG emissions from all sectors must begin now in order to minimize climate impacts. While the role of GHGs in changing global climate is well established, there are disagreements about what might constitute unacceptable damage and a range of projected temperature changes and resulting impacts. Many governments in developed countries have called for GHG emissions to be cut by up to 80 percent by 2050 in order to stabilize atmospheric concentrations of GHG. Because transportation accounts for about a fifth of global GHG emissions (and a higher percentage in industrialized nations), reducing emissions from this sector must be a key part of a global strategy to combat climate change. And because the U.S. transportation sector is by far the largest GHG emitter among the world's transportation sectors, and is expected to see CO_2 emissions grow by about 10 percent by 2035 (EIA, 2010a) under business as usual, it must play a leading role in this strategy.

The U.S. transportation sector faces three major challenges in any attempt to change the trends that are causing ever higher GHG emissions:

- First, although technology to improve vehicle efficiency is available and is being used in vehicles now, vehicle manufacturers have directed much of the potential of the technology to purposes other than fuel economy, such as making vehicles larger and more powerful.
- Second, any attempts to shift from petroleum fuels to lower-carbon alternatives such as hydrogen or electricity must overcome a long-entrenched fuel production and distribution infrastructure, petroleum-fueled vehicle technology honed over a 100-year period, and fuels that have excellent characteristics for transportation.[1] Past attempts to bring new fuels and new technologies into

1. Gasoline and diesel fuel are liquids that are easily stored, easily transported, energy dense, and currently being manufactured with low sulfur content and other characteristics that allow stringent emission controls.

the U.S. marketplace have largely failed. In addition, the cost and performance of incumbent technologies and fuels against which these new options compete change over time, creating a moving target that can affect viability and adoption of new fuels.

- Third, the U.S. population and economy are expected to continue to grow, increasing both freight and personal travel. For example, the Energy Information Administration's (EIA) *Annual Energy Outlook 2010* (AEO2010) Reference Case projects the real Gross Domestic Product (GDP) to double and population to grow by 85 million persons by 2035 compared to 2008 (EIA, 2010a).

The purpose of this report is to identify ways the United States can reduce GHG emissions from the transportation sector substantially over the next 40 years. The report outlines technologies and measures that would allow U.S. transportation to become more energy efficient and less carbon-intensive, reducing both its GHG emissions and its dependence on petroleum fuels. It develops three scenarios that diverge from "business as usual," based on the assumption that the United States is willing to change the incentives and regulations that affect the design of vehicles, the types of fuels that are used, the choices made by individuals and businesses in purchasing and using vehicles, and how communities and their transportation infrastructure are built and used.

Projecting the potential of longer-term technologies and measures can be difficult, given large uncertainties over such factors as the costs of new technologies and the degree of consumer acceptance of new approaches. This report attempts to illuminate these uncertainties and to suggest alternative options for achieving GHG emission reductions. One conclusion is that there are multiple pathways to achieving substantial reductions. Another is that a strong research, development, demonstration, and deployment (RDD&D) program will be crucial. In addition, the progress of technology development must be monitored, and the strategy continually updated based on new evidence. Given the urgency of the problem, the uncertainties do not excuse inaction. Fortunately, there are enough alternative pathways that one can be reasonably assured of success if the United States commits to a strong effort to reduce emissions.

1.2 Global Energy Challenges Facing Transportation

1.2.1 Global Transportation Demand

Unless major changes are made, transportation demand and its resulting oil use and GHG emissions seem destined to continue the explosive growth of the past few decades, concentrated largely in the developing world. This growth will put enormous pressure on world oil supplies and could lead to growing use of heavy oil, oil sands, liquid fuels from coal, and other carbon-intensive fuels that will exacerbate GHG emissions.

In China, India, and other developing nations, burgeoning wealth and a rising middle class, rapid urbanization, and massive additions to road infrastructure are creating enormous demands for personal vehicles, public transportation, and freight transportation. Alongside the overall rise of urbanization,[2] cities have "spread out faster than they have grown in population (Barker, et al., 2007)." This has greatly increased the demand for travel and produced low-density living patterns not easily served by transit. Also, motorized personal vehicles are widely viewed as status symbols as well as being faster, more flexible and convenient, and more comfortable than public transportation (Barker, et al., 2007). As a result, the world auto fleet increased from about 50 million vehicles to 580 million vehicles between 1950 and 1997, growing five times faster than the growth in population (Barker, et al., 2007). It continues to grow at a startling pace. China is a spectacular example: vehicle sales increased from 700,000 in 2001 to 1.1 million in 2002 and 1.7 million in 2003 (Barker, et al., 2007).[3] In 2009, China was reported to have become the world leader in domestic auto sales, at *13 million per year* (BBC News, 2010).

Aside from travel within metropolitan areas, intercity and international travel is also growing rapidly. The main drivers are increased recreational travel as incomes grow; international trade agreements that have lowered trade barriers; and greater willingness of workers to migrate to other cities and even other countries (WBCSD, 2004). Intercity travel, mostly by auto and air, now accounts for about one-fifth of total travel in the United States (WBCSD, 2004). In Europe and Japan, high-speed trains are a part of the intercity travel mix; bus and lower speed rail dominate intercity travel in the developing world.

Freight transportation, driven by globalization and the rapid development of industry in China and the other developing nations, is also a major consumer of energy, at over two-fifths of global transportation energy use (WBCSD, 2004). Freight transportation energy use is pushed upwards by pressure to increase speed and reliability

2. About 75 percent of people living in the industrialized world and 40 percent in the developing world now live in urban areas (Barker, et al., 2007).
3. This includes light-, medium-, and heavy-duty vehicles except mopeds, scooters, motorcycles, and farm vehicles.

and by just-in-time manufacturing and distribution, which favors truck and air transportation, the most energy-intensive modes.

Forecasts to 2030 confirm that the rapid growth in transportation demand, oil use, and GHG emissions over the past few decades is expected to continue. For example, the EIA's International Energy Outlook 2009 (IEO2009) projects that, without changes in ongoing trends, the transportation energy demand of the nations outside of the Organization for Economic Cooperation and Development (OECD) will grow by about 90 percent from 2006 to 2030, an annual growth rate of 2.7 percent (EIA, 2009a). Even with expected slower growth in the developed nations,[4] the total growth for the world transportation sector for 2006 to 2030 will be 39 percent, growing from about 92 quadrillion Btus (quads) in 2006 to 128 quads in 2030.[5] The International Energy Agency (IEA) forecasts are even more bullish on transportation growth—its baseline forecast has transportation energy increasing by nearly 50 percent in 2030 and a remarkable 100 percent by 2050, compared to 2007 levels (IEA, 2009b).

Most of this new consumption of 36 to 46 quads in 2030 is expected to be oil, placing pressure on the world's oil supply capacity. If conventional sources fail to meet this demand, the most likely alternatives will be heavy oil, oil sands, oil shale, and liquids from natural gas and coal. These are carbon-intensive fuels that would add to GHG emissions. The IEA forecast foresees a move to high-carbon fuels after 2030, and its estimated transportation GHG emissions for 2050 are about 113 percent higher than those in 2007 (16 gigatons[6] versus 7.5 gigatons) compared to a 100 percent growth in energy use.

Uncertainties in the cited projections include the following:

- **The future price of oil.** Oil prices have been extraordinarily volatile over the past few years and decades (see **Figure 3**). Projections of future prices vary dramatically, depending in part on whether oil consumption grows only moderately, or whether it jumps by more than 40 percent by 2030, as many forecast.
- **The pace of technology development.** Promising technologies could make insignificant or major contributions depending on the success of efforts to reduce costs and improve performance.
- **The future pace and form of urbanization.** The pace has been extraordinarily rapid in China, India, and other developing nations. The form of future urbanization (i.e., the density, reliance on transit, and availability of nonmotorized transportation) is crucial to future GHG emissions.

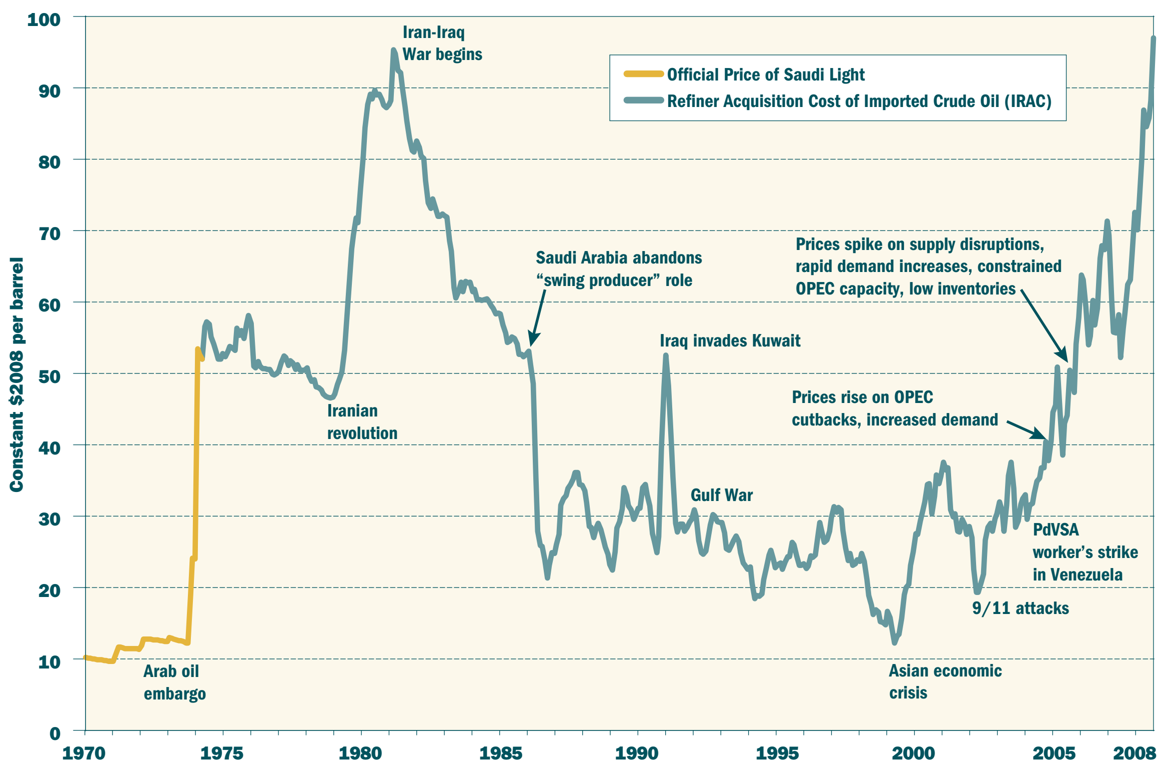
4. Transportation energy consumption in the OECD nations is expected to grow only slowly – 0.3 percent per year, or about 8 percent for the period (EIA, 2009a).
5. In comparison, the total energy consumption of the United States in 2008 was about 100 quads (EIA, 2010a).
6. One gigaton is one billion tons.

- **Energy prices and economic growth rates (both global and for individual countries),** which also create uncertainty in future freight traffic patterns, energy use, and GHG emissions.
- **The policy decisions made by developed and developing economies.** Policies that seriously address GHG mitigation will also greatly reduce transportation energy use and petroleum demand.

Figure 3

World Oil Price Variations and Associated Events, 1970-2008

(Prices adjusted by CPI for all urban consumers)



Source: EIA, 2008

1.2.2 Climate Change Impacts

The scientific evidence is clear that human activity is already causing the world's climate to change and that continued human-made GHG emissions would cause even greater changes. The need to begin reducing emissions of CO_2 and other GHGs from all human-made sources—including the transportation sector—is supported by many independent scientific sources.

The 2010 America's Climate Choices report by the U.S. National Academy of Sciences (NAS, 2010) makes it clear that the earth's climate is changing and that these changes are in large part due to human activity.

The NAS concludes that climate change is occurring, caused largely by human activities, and presents a serious threat to a "broad range of human and natural systems" (NAS, 2010).

A report by the U.S. Environmental Protection Agency (EPA) in 2010 identified a number of climate change indicators already evident today. For example, sea surface temperatures have been warmer in the last three decades than any other time since large-scale measurement began in the late 1800s, and Arctic sea ice in 2009 was 24 percent below the 1979 to 2000 historical average. In the United States, seven of the top 10 warmest years on record for the lower 48 states have occurred since 1990 (EPA, 2010e). To mitigate future climate impacts, curbing GHG emissions from all sectors including the transportation sector must begin now.

1.2.3 Energy Security and Oil Dependence

An improvement in energy security is a major potential co-benefit of reducing transportation's GHG emissions. The U.S. transportation system's dependence on petroleum makes the U.S. economy vulnerable to significant excess economic costs on the order of hundreds of billions of dollars per year (Greene, 2010a), and interferes with U.S. national security and foreign policy objectives (CFR, 2006). A comprehensive strategy of increased energy efficiency, alternative energy sources, and increased domestic supplies of energy for transportation can achieve meaningful energy independence (NCEP, 2004), reducing economic harm from supply shocks and high oil prices. Mitigating transportation's GHG emissions can make the single most important contribution to achieving that goal because transportation consumes 70 percent of all U.S. petroleum use (EIA, 2009d, tables 2.1e and 1.3).

Because of the importance of oil to the U.S. economy, the lack of economical substitutes, and the concentration of the world's oil resources in the Organization of the Petroleum Exporting Countries (OPEC[7]), the U.S. faces higher oil prices than a competitive market would produce. Together with oil price shocks, these high prices cost the U.S. economy hundreds of billions of dollars each year in lost economic production and in the transfer of wealth from U.S. oil consumers to foreign oil producers. In 2008 alone, the estimated economic cost of oil dependence was half a trillion dollars: $350 billion in wealth transfer, $150 billion in lost GDP (Greene & Hopson, 2009).[8]

7. The current members of OPEC are Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, and Venezuela. All have nationalized oil resources operated by national oil companies.

8. When oil producers can use their market power to raise prices, there is a transfer of wealth from oil-importing to oil-exporting economies. The amount is equal to the quantity of oil imported multiplied by the difference between the market price and what the price would have been in a competitive market. Higher, non-competitive oil prices also reduce an economy's ability to produce output due to the increased economic scarcity of a key resource: petroleum. Thus, GDP shrinks. When there is an unexpected large increase in oil prices, there is a further, temporary loss of GDP due to the disruptive effect of the price shock (Greene, 2010a).

The oil dependence problem is not likely to improve in the future unless the United States implements a comprehensive strategy to reduce oil demand and increase domestic supply of liquid fuels (Greene, 2010a). Because of depletion of oil resources in non-OPEC countries, OPEC's global market share is expected to increase from 44 percent today to 52 percent in 2030 (IEA, 2009b, p. 85), increasing the cartel's market power. Even during a severe global recession, OPEC was able to keep world oil prices high. Prices remained at over $90 per barrel for much of 2008 (EIA, 2009d, table 5.21), before dropping to $40 per barrel and rising again into the $70s in August of 2009.

A recent study for the U.S. Environmental Protection Agency (EPA) estimated the energy security benefit of reducing U.S. oil consumption at $12.38 per barrel, or about $0.30 cents per gallon of gasoline (Federal Register, 2009, p. 24917).[9] With about 20 pounds of CO_2 emitted per gallon of gasoline, this energy security benefit is equivalent to a carbon price of approximately $33 per metric ton of CO_2.

Reducing petroleum consumption has an additional climate change mitigation benefit—reducing the need to use shale oil and other alternative petroleum resources, which have lifecycle GHG emissions 10 to 100 percent greater than from conventional petroleum (Brandt & Farrell, 2007).

1.3 U.S. Transportation

1.3.1 U.S. Transportation Energy Use and GHG Emissions

The U.S. transportation system is a major source of GHG emissions. It was responsible for 31 percent of global transportation energy use and GHG emissions in 2006. In 2030, the U.S. transportation sector is expected to use one quarter of global transportation energy, even though the U.S. transportation sector is expected to grow at only a fraction of the rate of growth of non-OECD countries.

The United States has the world's largest transportation system. In 2006, Americans traveled 5.2 trillion person-miles in vehicles and moved 4.6 trillion ton-miles of freight (BTS, 2009b, Tables 4-3 and 4-4). This travel consumed 28.6 quads of energy (EIA, 2009a, Table F3), all but about 4 percent in the form of petroleum products (EIA, 2009b, Table A2)—more energy than used in that year by the entire economies of all but two nations, China (73.8 quads) and Russia (30.6 quads) (EIA, 2009a, Tables F13 and F11).

The U.S. transportation system's annual GHG emissions in 2008 were 27 percent of total U.S. GHG emissions, second in sectoral emissions behind the electric power industry's 35 percent (EPA, 2010b). CO_2 is

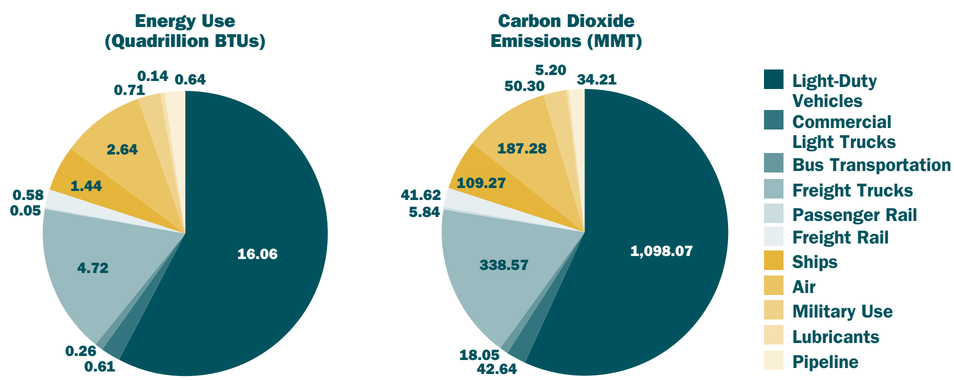
9. This estimate is probably a substantial underestimate in that it includes only economic effects, not national security or military costs caused by petroleum dependence (Leiby, 2008).

transportation's dominant GHG, representing about 95 percent of its total global warming potential (DOT, 2010a).[10] As with its energy consumption, the U.S. transportation sector's CO_2 emissions are greater than the total national emissions of virtually any other nation, China being the sole larger emitter (EIA, 2010a; EIA, 2010b).

Highway vehicles (light-, medium-, and heavy-duty vehicles) dominate the U.S. transportation sector's energy consumption and CO_2 emissions (EIA, 2009b). In 2007, they emitted 78 percent of total transportation CO_2 emissions (EIA, 2009b, Table A19) and accounted for 80 percent of the sector's energy use (EIA, 2009b, Table A7). Air transportation was second (see **Figure 4**) with about 9.5 percent of energy use and emissions, although air transportation's effect on global warming is magnified by the warming effect of jet engine contrails (see Section 2.3).

Figure 4

2008 U.S. **Transportation Energy Use** (in Quads) and CO_2 Emissions (in million metric tons)



Source: EIA, 2010

For the past three decades, transportation has had the highest growth rate in energy consumption and GHG emissions of all U.S. end use sectors, primarily because the other sectors were more successful in improving their energy efficiency. Key reasons for this rapid growth include:

- Automakers used technologies that could have improved fuel economy to instead provide better acceleration, greater safety, larger size, and other features.
- The fuel economy standards in place from 1975 to 2008 had more lenient standards for light-duty trucks than for passenger cars. That helped stimulate a shift in development and sales of the less efficient trucks, which grew from 17 percent of new light-duty vehicle (LDV) sales in 1980 to about 50 percent (EPA, 2009a).[11]

10. Global warming potential (GWP) is the measure of a GHG in an equivalent unit based on the ability of the gas to trap radiation.
11. Light-duty truck share has been relatively stable at about 50 percent since the 2002 model year (EPA, 2009a).

- Deregulation of passenger air travel yielded lower fares and more options, expanding demand.

- "Just-in-time" manufacturing and distribution methods favored truck freight transportation over rail and demanded frequent deliveries, spurring the growth of heavy-duty truck transportation.[12]

However, recent forecasts suggest the transportation sector may not continue to be the fastest growing end use sector in the United States. The new *Annual Energy Outlook 2010* (AEO2010) Reference Case by the U.S. EIA projects that the sector's energy consumption will grow by about 21 percent from 2008 to 2035, compared to growth of nearly 33 percent for the commercial sector (EIA, 2010a).[13] Similarly, the EIA projects growth in CO_2 emissions to be about 10 percent over the same period compared to 24 percent for the commercial sector (EIA, 2010a). These shifts reflect the increasing importance of the service sector in the U.S. economy and the expected effect of new corporate average fuel economy (CAFE) and GHG standards.

Other highlights of the AEO2010 forecasts for the transportation sector, for 2008 to 2035, are as follows:

- LDV travel is expected to continue rising at 1.7 percent per year, or 53 percent during the period. Travel by freight trucks[14] is expected to grow just as rapidly.

- Air travel, which has slowed to 0.7 percent per year growth during the past decade (Davis, Diegel, & Boundy, 2009), is expected to accelerate to 1.3 percent per year.

- Rail and domestic shipping is expected to grow at 0.8 and 0.7 percent per year, respectively.

- Energy consumption and CO_2 emissions by rail and shipping is expected to grow nearly as rapidly as travel by these modes, with only modest gains in efficiency foreseen.

- In contrast, LDVs' energy use and CO_2 emissions is expected to grow much more slowly than their travel growth because of their expected strong efficiency gains and use of renewable fuels—0.4 percent per year (for energy) with no growth in CO_2.[15]

- Energy consumption and GHG emissions for freight trucks will grow vigorously throughout the period (1.2 percent and 1.1 percent, respectively), although somewhat slower than the growth in freight tonnage due to moderate improvement in efficiency.[16]

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12. From 1993 to 2007, truck modal share of U.S. freight ton-miles rose from about 26 percent to about 40 percent; rail rose from about 27 percent to about 40 percent; shipping lost considerable share during this period, from about 24 percent to about 5 percent in 2007 (RITA, 2004; BTS, 2009a).
13. The commercial sector consists of non-manufacturing business establishments, educational institutions, religious organizations, and government.
14. Freight trucks are medium- and heavy-duty trucks.
15. Zero growth for CO_2 emissions assumes both attainment of vigorous renewable fuel standards and no negative consequences from land use changes associated with growing the biomass feedstocks for these fuels (see Section 2.6.3).
16. If expected standards for medium- and heavy-duty vehicles are established, improvements in freight truck efficiency should be considerably higher than forecast by the AEO2010 Reference Case.

The forecast also anticipates that U.S. oil imports will shrink dramatically, from 60 percent of total consumption in 2006 to 45 percent in 2035, the result of a projected 1 million barrels per day (mmbd) increase in domestic production and slow growth in demand. However, this projection could be affected by slowdowns in drilling due to changed safety requirements after the Gulf oil spill in 2010. Whether or not the pre-spill forecast proves accurate, however, the level of imports will remain a significant energy security concern.

1.3.2 Transportation's Mitigation Responsibility

Transportation will have to severely reduce its GHG emissions by 2050 to mitigate the effects of climate change. The three scenarios presented in Section 4 show how different combinations of policies, technologies and behavior could reduce transportation's CO_2 emissions by anywhere from 15 to 65 percent below 2010 levels by 2050. However, at present, it is not possible to determine with confidence precisely how great a reduction the transportation sector can or should make by 2050.

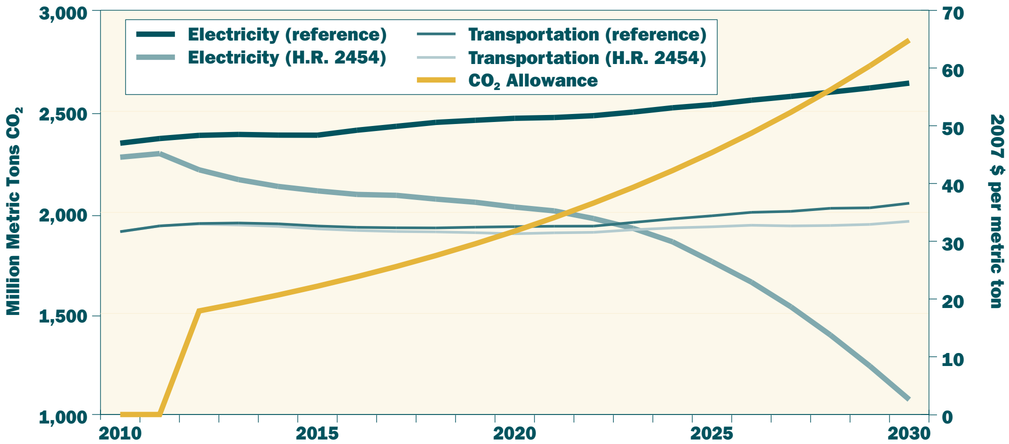
The most economically rational way to determine transportation's "fair share" of GHG emission mitigation would be to insure that the cost of the last ton of CO_2 reduction from transportation was no more and no less than the costs in other sectors of the economy. The easiest way to accomplish this might seem to be via market-based policies (e.g., a tax on CO_2 or a cap-and-trade system) that allowed the market to determine the price of allowances to emit CO_2. That would be true if transportation markets were perfectly competitive and efficient. But they are not. They are affected by political decisions about highways, ports, and other infrastructure, as well as by government regulations and patterns of land development.

In addition, markets for energy efficiency in general and passenger motor vehicles in particular, appear to significantly undervalue future fuel savings. Consumers demand less efficiency than is cost-effective, and firms have less incentive to develop energy-efficient technologies. New technologies that use alternative sources of energy will also need to solve the "chicken or egg" dilemma (who will buy a vehicle that lacks a refueling infrastructure and who will supply a fuel when there are no vehicles to use it?).

As a result, some analyses suggest that market-based policies alone cannot achieve significant reductions in transportation emissions. In an EIA study of an economy-wide carbon cap-and-trade system (EIA, 2009c), a carbon price that rises from \$20 per ton of CO_2 in 2012 to \$65 per ton in 2030 reduces emissions from the electric utility sector by 60 percent while transportation emissions fall by only 5 percent. On the other hand, bottom-up analyses of transportation options have claimed emission reductions of 12 percent (Creyts, Derkach, Nyquist, Ostrowski, & Stephenson, 2007, exhibit 22) to 50 percent (Greene & Schafer, 2003, table 6) compared to projected levels in 2030, at costs of less than \$50 per ton of CO_2.

Figure 5

Estimated Effect of Waxman-Markey Bill on CO_2 Emissions in Electricity and Transportation Sectors



Source: EIA, 2009c

The main difference is that Greene and Shafer (2003) consider a wide range of policies, from fuel economy standards to pay-at-the-pump (PATP) automobile insurance, instead of just pricing carbon. Greene and Shafer are also more optimistic about the pace of development of new technology.

The authors' perspective here is that the sector's "fair share" of overall reductions is substantial. Indeed, transportation's GHG emissions are so large that it would be wise to aim for reductions of at least 50 percent by 2050, while at the same time assuring that policies are cost-effective.[17] The key is to get started now with those policies that can be demonstrated to be cost-effective, and to adjust based on experience and technological progress.

In the following section, a wide array of mitigation options and the evidence for their effectiveness is considered. There is no shortage of actions that can be taken today that will have major impacts on GHG emissions both in the near and the long term.

17. The meaning of cost-effectiveness in this report is that the studies cited support the assertion that under plausible assumptions the technologies and measures considered are likely to pay for themselves in energy savings or other benefits, assuming full lifetime energy costs and discounting at social, rather than individual consumer, discount rates.

2. Mitigation Options

This section assesses a variety of technological and operational options for reducing transportation's GHG emissions. Improving vehicle and system efficiencies, substituting lower-carbon fuels for petroleum, and shifting traffic among modes are all considered. Changing the pricing of transportation, a potentially powerful GHG mitigation strategy, is considered in Section 3.

2.1 Passenger Cars and Light-Duty Trucks Efficiency

Passenger cars and light-duty trucks account for about 60 percent of the energy used for U.S. transportation, and their energy use has grown by 1.4 percent per year over the past several decades (Davis, Diegel, & Boundy, 2009). Meanwhile, the fuel economy of the new LDV fleet has essentially stagnated despite constant improvement in technology, as fuel economy has been "traded away" for other vehicle attributes. **Box 1** discusses this issue.

Box 1. Fuel Economy vs. Other Attributes

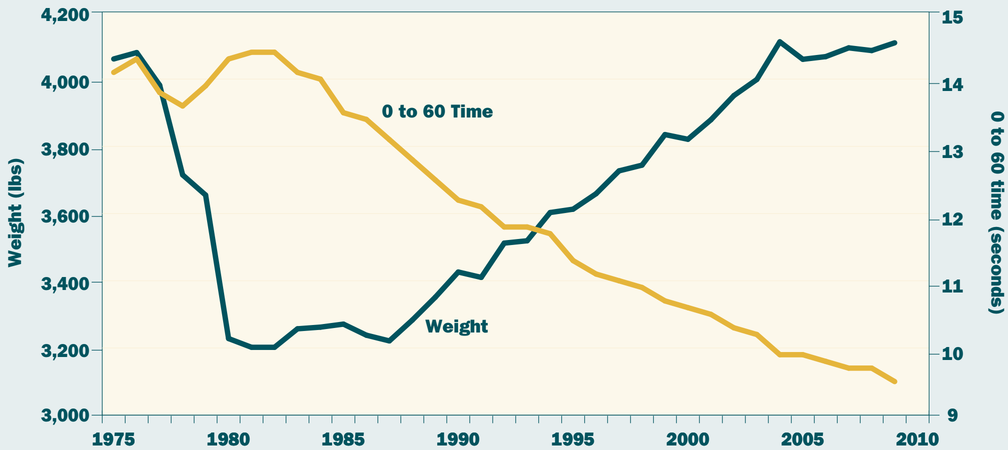
Virtually all studies that project potential future fuel economy gains assume that other attributes such as vehicle acceleration performance and weight remain unchanged (except for weight additions required to satisfy existing safety requirements). In other words, these studies assume that 100 percent of the potential of technology improvements is directed to improving fuel economy rather than to other, competing vehicle attributes such as acceleration performance.

Figure 6 shows EPA data on the average curb weight and 0 to 60 mph acceleration performance of the U.S. light-duty fleet from 1975 to the present (EPA, 2009b). The data show that CAFE standards and escalating gasoline prices led to a sharp drop in vehicle weight from 1976 to 1980; the weight trend reversed in 1987, eventually increasing by 30 percent from its low point. Although some of the weight gains enhanced fleet safety with more crashworthy body structures and added safety equipment, much of the weight and essentially all of the performance gains were due to consumer preferences for size, luxury equipment and performance over fuel economy. Meanwhile, acceleration performance began a similar increase in 1983 that saw 0 to 60 mph acceleration times drop from about 14 seconds to under 10 seconds today. The weight trend seems to have slowed during the last few years; the performance trend has not.

The result of these trends has been to nullify the potential fuel economy gains associated with an equally robust gain in the technical efficiency of the fleet during this period. **Figure 7** compares the on-road fuel efficiency (measured in mpg) and its "weight-normalized" fuel efficiency (measured in ton-mpg). The weight-normalized efficiency, which

Figure 6

Curb **Weight and Acceleration** Performance of New U.S. Light-Duty Vehicles, 1975-2009

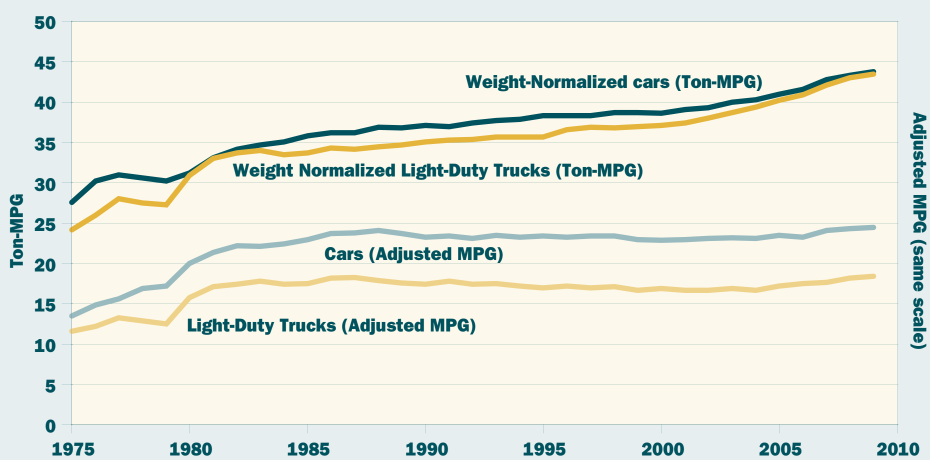


Source: EPA, 2009

measures how efficiently the fleet can move one ton of weight, rises continuously throughout the entire period, reflecting continuous improvement in technology. If the weight-normalized efficiency were also normalized to nullify the effects of changes in performance, the increases in ton-mpg would be much greater. In contrast, the on-road fuel efficiency trend, reflecting both technology and vehicle attributes (e.g., weight and performance), is basically flat after 1987.

Figure 7

Comparing **Weight-Normalized vs. On-Road Fuel Economy** for New U.S. Light-Duty Vehicles



Source: EPA, 2009

The figure shows that the sharp gains in technical efficiency from 1987 to the present have been essentially nullified by the fleet's weight and performance gains. Although fleet fuel economy has been rising since 2005, the 2008 values are similar to the fuel economy values reached in 1987.[18]

18. The on-road values for 2008 are slightly below those for 1987, but the laboratory values are a bit higher than those for 1987. The difference is caused by the rolling in of a new on-road adjustment factor.

The efficiency of passenger cars and light-duty trucks can be improved by:

- Reducing the energy needed to move the vehicle, by reducing weight, aerodynamic drag (the resisting force of air) and rolling resistance (resisting force between tires and the road)
- Improving the efficiency of the drivetrain (engine and transmission)
- Improving the efficiency of accessories such as air conditioning and lights; also, reducing the need for heating and air conditioning by improved insulation, changes in window glass, and more

Weight reduction is critical. A 10 percent reduction will typically yield a fuel economy improvement of about 7 percent at the same performance level (EEA, 2006). Weight reduction can be achieved by design changes and the use of stronger, lighter materials, such as plastics, polymer composites, and lighter metals (especially aluminum, magnesium and lighter, stronger steels). While most substitute materials are more costly than conventional steel, there can be savings from reducing the weight of important vehicle components. A lighter vehicle can use a smaller, lighter, and cheaper engine, with less support structure and lighter suspension and brakes, for instance. Avoiding any compromise with safety is critical to weight reduction efforts and this has been accomplished thus far.[19]

In a design exercise, Lotus Engineering was able to cut the weight of a mass-market crossover utility vehicle by 38 percent (excluding the powertrain) at an estimated cost of less than $1,000 (Lotus Engineering, 2010) through the use of lighter materials and a more efficient design. Lotus estimates that such vehicles could be produced by 2020. They could become widespread in the vehicle fleet by 2030.

More gains could come from the use of carbon fiber-reinforced polymer (CFRP), a strong and light composite.[20] CFRP can be designed to have unique load-bearing properties, so its use has the potential to improve vehicle safety. If the cost of the material can be lowered enough to allow its widespread use, weight reductions of 40 to 45 percent from current levels might be possible. Currently however, its raw material costs are high, and the parts manufacturing process is too slow for mass production. It is also difficult to recycle and repair, and there is concern about its durability for external parts exposed to sunlight.

Reducing aerodynamic drag by 10 percent can yield a fuel economy improvement of about 2 percent (EEA, 2006). Aerodynamic drag force increases with the square of speed (that is, it is four times as great at 60 mph as at 30 mph), so it can be the dominant force on the vehicle at highway speeds. Drag reduction can be obtained by

19. The EPA/NHTSA Final Rule (EPA & DOT, 2010) states that "[t]he agencies believe that the overall safety effect of mass reduction in cars and LTVs may be close to zero."
20. It is used in moderate quantities in the Lotus vehicle (Lotus Engineering, 2010).

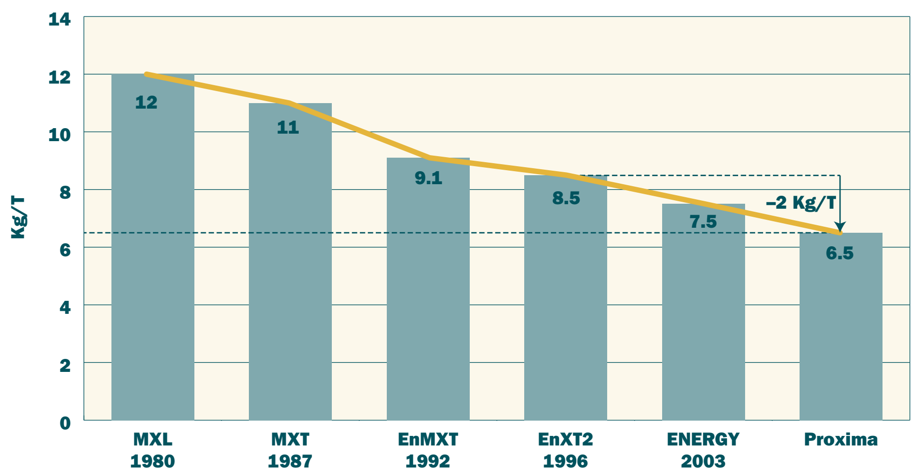
reducing a vehicle's cross-sectional area, improving the fit of body parts, changing the vehicle's shape, smoothing the vehicle's underbody, and other measures. Boxy sport utility vehicles (SUVs) and pickup trucks with open beds have inherently high aerodynamic drag.

A recent MIT study, *On the Road in 2035,* projects that the new car fleet could attain about a 30 percent reduction in aerodynamic drag by 2035 (Bandivadekar, A. et al., 2008).[21] The light-duty truck fleet should be able to attain similar improvements, but from a higher baseline.[22] Success, however, will depend on customer acceptance of the more aerodynamic designs.

Reducing rolling resistance by 10 percent will typically improve fuel economy by about 2 percent.[23] It can be done by improving tire materials, structure, and tread design. **Figure 8** illustrates improvements in rolling resistance in Michelin tires (Michelin, 2010).

Figure 8

Changes in Tire Rolling Resistance for Succeeding Generations of High-Efficiency Michelin Tires



Source: Michelin, 2010

There are substantial opportunities to improve drivetrain efficiencies even for conventional drivetrains and gasoline-fueled engines. For gasoline engines, some key technologies are:

- Direct injection of fuel into the cylinder, as is currently done in modern diesel engines.[24]

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21. Currently, the average coefficient of aerodynamic drag C_D (drag force = CD x Velocity^2 x cross-sectional area) of the new U.S. passenger car fleet is about 0.30, with the best at about 0.25. Some company websites reveal aerodynamic data for some models, but samples of these data are flawed by selection bias by the companies. The aerodynamic drag coefficient of the Toyota Prius is 0.25 (Toyota, 2009). A European version of the Mercedes E-Class Coupe attains 0.24 (Daimler, 2009).
22. Typical minivans have C_{Ds} ranging from 0.36 to 0.40, and pickups and large SUVs tend to have CDs ranging from 0.40 to 0.45 (EEA, 2006).
23. Rolling resistance is the energy (in the form of heat) that is dissipated from the tire's rubber compounds as the tire deforms to make contact with the ground.
24. Current U.S. models that offer direct injection gasoline engines include the Cadillac STS, Audi A3, Volkswagen Jetta, Hyundai Sonata, and Pontiac Solstice sports car.

- Turbocharging with substantial engine downsizing. An exhaust turbocharger uses the engine's exhaust to drive a turbine that pushes extra air into the cylinders, increasing power and torque.[25] 1.4-liter turbocharged engines could replace 2.3 to 2.5 liter four-cylinder engines (SAE International, 2010).
- A variety of other measures, including improved lubricants, lighter weight valve trains, more precise control of the timing and opening of intake and exhaust valves (including shutting down cylinders at low loads), and others.

Improved transmissions can also increase drivetrain efficiency by reducing internal losses and by enabling the engine to operate more at its most efficient speed, generally by increasing the number of transmission speeds. A new generation of six, seven, and eight speed automatic transmissions with fewer parts and lower internal losses have made substantial inroads in the luxury car fleet and will roll into the overall fleet over the next few years. The fuel economy gains from these technologies would be about 4 to 5 percent. Other transmission options with promising efficiency advantages include automated manual transmissions and continuously variable transmissions.

Hybrid electric drivetrains offer a substantial boost in fuel economy, though at considerable cost. Using at least one electric motor, a powerful battery and a control system, hybrids:

- Recover some of the vehicle's energy of motion that is otherwise lost as heat upon braking, by using the motor to slow the vehicle and generate electricity that can be stored in the battery.[26]
- Allow engine downsizing by using the battery and motor to provide extra boost.
- Save energy during idling and deceleration by turning the engine off (using the motor as a powerful starter to allow the engine to be turned back on virtually instantaneously).
- Avoid inefficient modes of engine operation using the motor and battery.

25. Turbocharging is made more feasible by direct injection, which enhances turbocharger operation at low engine speeds and, by cooling the intake air "charge," reduces detonation problems and allows higher compression ratios to be used.
26. This is known as regenerative braking.

- Allow use of engine cycles more efficient than the conventional Otto cycle[27] (the Toyota Prius hybrid uses the Atkinson cycle).[28]
- Allow easier use of efficient electric power steering and air conditioning.

Current "full" hybrid systems that allow most or all of these benefits can boost fuel economy by 40 to 80 percent[29] at a retail price equivalent of about $2,500 to $5,000 for a midsize car (EPA & NHTSA, 2010; Keefe, Griffin, & Graham, 2007; Duleep, 2009; EEA, 2007). Future systems may have a higher percent benefit (by improving system design and component efficiency)[30] at lower cost. *On the Road in 2035* (Bandivadekar, A. et al., 2008) estimates that an advanced hybrid drivetrain will provide a 77 percent improvement in fuel economy over an advanced conventional drivetrain in 2035. However, because the baseline conventional vehicle will be considerably more efficient in 2035, the gallons of gasoline or dollars saved by a hybrid vehicle (or by other advanced vehicles) may shrink. Thus, cost reduction will be important if hybrid drivetrains are to become mainstream.

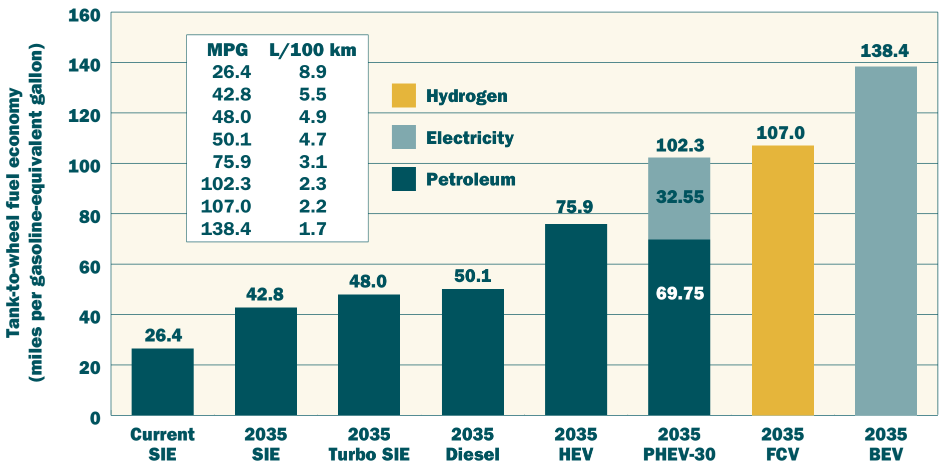
On the Road in 2035 examines efficiency upgrades to a midsize car and a pickup truck, and extrapolates these upgrades to the overall fleet. The baseline midsize car is the 2005 Toyota Camry sedan with a 2.5-liter 4-cylinder engine. The study concludes that average midsize new cars in 2035 could achieve a 20 percent reduction in curb weight, a 25 percent improvement in aerodynamics, and a 33 percent reduction in tire rolling resistance. The study then looked at the potential impact of seven different drivetrain combinations, ranging from "advanced conventional" spark ignition (SI) drivetrains to battery electric and fuel cell drivetrains (**Figure 9**).[31, 32]

The analysis shows dramatic reductions in fuel use. Even the 2035 conventional drivetrain car with spark-ignition (SI) gasoline engine attains a 62 percent improvement in fuel economy (38 percent reduction in

27. The Otto cycle is the conventional thermodynamic cycle, using spark plugs to ignite the fuel, used by virtually all gasoline-powered engines.
28. The Atkinson cycle is a modification of the conventional Otto cycle that changes valve timing in such a way as to allow more mechanical energy to be extracted from each engine cycle, though at the cost of some power. In a hybrid, the power loss is compensated by power from the electric motor.
29. The fuel economy benefit will be somewhat lower for vehicles used for towing, because this requirement will limit the amount of engine downsizing that can be accomplished.
30. However, future improvements in conventional engines and transmissions will reduce some of the energy losses that hybridization targets, limiting the overall efficiency gain that hybrids can achieve.
31. Note that the 2035 fuel economy values assume that all of the potential efficiency benefit of both the load reduction and advanced drivetrain technologies has been applied to improving fuel economy.
32. The adjusted fuel economy values in the figure are likely to overestimate the actual fuel economy most drivers would attain in real-world driving. The U.S. EPA obtains these estimates by adjusting the results of fuel economy tests using dynamometers, machines that allow vehicles to simulate driving while the vehicle remains motionless. This testing simulation requires an adjustment to estimate likely on-road fuel economy. Current EPA guidance for the on-road adjustment is about 0.8 or below for most cars (i.e., one must reduce EPA test results by 20 percent to obtain on-road fuel economy). This adjustment factor can vary depending on the vehicle type, and vehicles with higher fuel economy test values generally have more severe adjustment factors (e.g., 0.793 for a 2010 Toyota Camry and 0.696 for a 2010 Toyota Prius). The larger downward adjustment for high-mpg vehicles reflects the understanding that the lower fuel consumption of these vehicles is more sensitive to on-road conditions, including the energy drain of accessory use or effects of higher weight loading (more passengers and luggage). If these differential EPA adjustment factors were applied to the *On the Road in 2035* estimates of the future fuel economies of different types of drivetrains, the estimated improvements provided by the higher-efficiency drivetrains (e.g., hybrid electric drivetrains) would be reduced.

Figure 9

Fuel Economy Levels of Current and 2035 New Midsize Cars. All Numbers are in On-Road MPG



Source: Bandivadekar, A. et al., 2008

fuel use), saving nearly 2200 gallons of gasoline over a 150,000-mile lifetime. The estimated increase in retail price is $2,000, or $0.92 per gallon saved. However, applying a discount rate of 20 percent to fuel savings, better reflecting consumer behavior, the cost rises to $2.55 per gallon saved.[33]

Many of the other drivetrains appear cost-effective compared to the baseline 2005 vehicle, but to gauge the marginal costs and benefits of further investments in technology, a better comparison is with the 2035 advanced SI engine technology. For example, the 2035 hybrid-electric vehicle (HEV) attains a 65 percent reduction in fuel use compared to the baseline 2005 vehicle, but only 44 percent compared to the advanced spark-ignition engine (SIE)—saving an additional 1,500 or so gallons over its lifetime, but at a price increase of $2,500 over that of the 2035 SIE. This is a marginal cost of about $1.64 per additional gallon save or $4.54 at a 20 percent discount rate. The other advanced vehicles are more expensive still. The conclusion is that, for the 2035 light-duty fleet to gain large numbers of vehicles with drivetrains that are more advanced than the "advanced conventional" drivetrain, some combination of very high fuel prices, strong government purchase subsidies, greater-than-estimated reductions in technology costs, strong shifts in consumer attitudes about the value of fuel savings, and stronger fuel economy standards must occur.

The authors of *On the Road in 2035* are not optimistic that manufacturers *will* direct the full potential of the technologies described in the report towards fuel economy. They acknowledge that the historical record is

33. Vehicle purchasers do not value a dollar of future fuel savings nearly as highly as a dollar spent today for fuel saving technology (see Appendix A). Applying a lower discount rate of 4 percent, which may reflect the value society places on future savings, yields $1.19 per gallon saved. Society thus views the advanced SI vehicle as much more cost-effective than would the average vehicle purchaser.

less than promising. Even in Europe, where fuel prices have been far higher than in the United States and a range of other tax and registration measures promote vehicle efficiency, much of the potential of adopted technologies have gone to performance and other vehicle attributes competing with fuel economy.[34] On the other hand, U.S. policymakers can use policy measures, such as new fuel economy standards, to push for directing new technologies to improved fuel economy (see Section 3.2).

Attaining the *On the Road in 2035* efficiencies would have substantial effects. The AEO2010 Reference Case (EIA, 2010a) projects that LDV energy use will increase by about 7 percent from 2007 to 2035; CO_2 emissions would increase by a similar amount. In this case, new car on-road fuel economy will be 36.0 miles per gallon (mpg) and light-duty trucks will achieve 27.3 mpg in 2035. The stock fleet (that is, both new and older vehicles) will achieve 29.3 mpg. Extending these trends to 2050 would yield a stock fleet of about 33 mpg in that year.

In contrast, new passenger cars with *On the Road* technology would attain 42.8 mpg for gasoline-fueled engines with conventional drivetrains; 48.0 mpg with turbocharging; and nearly 76 mpg with hybrid drivetrains. Equivalent values for light-duty trucks are 27.3 mpg, 32.2 mpg, and 49.0 mpg, respectively.[35] The conventional car will be cost-effective to consumers at gasoline prices well under $3.00 per gallon even with a high discount rate of 20 percent. Sales of hybrids will depend partly on costs. The AEO2009 Reference Case projected 2030 sales of hybrids and plug-in electric hybrid vehicle (PHEVs) at 24 percent of total LDV sales, while AEO2010 projected 2030 sales at 11 percent.[36]

2.1.1 Additional Sources of Reductions in LDV Fuel Use and GHG Emissions

The above discussion focused primarily on improving the efficiency of LDVs by reducing vehicle loads and improving drivetrains. Alternative fuels—biomass liquids, electricity, hydrogen, and other low carbon fuels—can also play a major role in reducing both oil use and GHG emissions, and are discussed in Section 2.6. Reducing LDV use through changing land use, higher fuel taxes, promoting public and nonmotorized transportation, and other measures are also discussed elsewhere (e.g., Sections 2.5.5 and 2.5.6). Additional measures include driving more efficiently (see Section 2.5.4) and changing consumer preferences so that consumers favor vehicles that are inherently more efficient—particularly if policies focus on the least efficient vehicles. For example, moving from a large truck-based SUV with a fuel economy of 14 mpg to a smaller car-based SUV with a fuel economy of 20 to 26

34. From 1995 to the early to mid-2000s, for gasoline vehicles, the percentage of the "potential" gains that actually were used to improve fuel economy ranged from 52 percent in the United Kingdom to 83 percent in Italy (Bandivadekar, A. et al., 2008, Table 18).
35. All of these fuel economy values are on-road values, i.e. they are adjusted downward to reflect the difference between EPA test values and real world conditions. However, they fail to reflect the difference in on-road adjustment factors used by AEO2010 and On the Road – 0.83 vs. 0.81. If On the Road used the 0.83 adjustment factor, its 42.8 mpg estimate for the advanced gasoline conventional drivetrain passenger car would shift to approximately 43.9 mpg; all the other values would also shift upwards by about 2.5 percent.
36. Personal communication, John Maples, Energy Information Administration, March 9, 2010.

mpg will save 320 to nearly 500 gallons per year, far more than the 217 gallons per year saved by shifting from a 29 mpg Toyota Corolla to a 50 mpg Toyota Prius hybrid.[37]

2.1.2 Report Scenarios for Light-Duty Vehicles

Table 2 shows the assumptions about LDV fuel economy for each scenario. Attaining levels of efficiency improvements of any of the scenarios would yield significant reductions in LDV fuel use and GHG emissions, even without use of alternative fuels.

Table 2

Changes in On-Road Fuel Economy and Fleet Mix for LDVs Used in the Low, Mid, and High Mitigation Scenarios.

	2035			2050		
Report Scenario Assumptions for Light-Duty Vehicles	Low	Mid	High	Low	Mid	High
Fuel Economy (% change in mpg compared to reference case)	15%	30%	40%	35%	60%	80%
New Car Fuel Economy (mpg)	48.5	57	64.6	*		
New Light-Duty Truck Fuel Economy (mpg)	31.5	37.2	42.5	*		
Hybrid Electric Vehicle Share (% of LDV fleet)	20%	50%	**	*		
Turbocharged SI Vehicle Share (% of LDV fleet)	30%	30%	**	*		
Advanced SI Vehicle Share (% of LDV fleet)	50%	20%	**	*		
Light-Duty Fleet Fuel Economy (mpg)	34	38	41	45	53	59

** Assumptions related to fuel economy and share of each vehicle type were only made for 2035. These values were then used to calculate the fuel economy change for the LDV fleet related to the reference case. This percentage change was extrapolated to 2050 resulting in the LDV fleet economy used in this report for that year.*
*** There are many way to achieve the fuel economy for the High Mitigation Scenario as discussed previously.*

The Low and Mid Mitigation Scenarios are reachable with a combination of advanced conventional vehicles, hybrid vehicles, and plug-in hybrid vehicles. There are a number of pathways by which the LDV fuel economy and fuel carbon intensity for the High Mitigation Scenario might be achieved. These include a vehicle fleet that is 40 percent or more hydrogen fuel cell vehicles or one that is about 30 to 40 percent battery electric vehicles with an equal proportion of plug-in hybrid electric vehicles using fuel blended with 25 percent advanced biofuels. Indeed, many combinations of electricity, hydrogen, and biofuels could accomplish the mitigation assumptions of the High Scenario. In all cases, however, rapid technological progress, decarbonized electricity or hydrogen, and strong public policies are essential to reaching the High Scenario's level of GHG mitigation. The GHG

37. The truck-based SUV is a 4WD Nissan Armada with an 8-cylinder engine. The car-based SUV is a Chevrolet Equinox with either a 6- or a 4-cylinder engine (2010 fuel economy data from www.fueleconomy.gov). The example assumes 15,000 miles per year for each vehicle.

emission reductions in this scenario can be met, for example, by Case 4 of the NRC's (2008) analysis of maximum feasible transitions to alternative energy sources for LDVs, which focuses on hydrogen fuel cell vehicles.

2.2 Freight Trucks and Buses

Freight trucks (medium- and heavy-duty trucks) are the backbone of U.S. freight transportation, carrying 71 percent of the dollar value and 70 percent of the weight of U.S. freight and representing 40 percent of the total ton-miles carried. Trucking has been growing rapidly at the expense of rail and shipping; between 1993 and 2007, truck ton-miles grew by 54 percent, rail grew by 43 percent, and shipping lost 42 percent (BTS, 2009a; RITA, 2004). By 2008, trucking represented 17.5 percent of total U.S. transportation CO_2 emissions (EIA, 2010a). Freight truck vehicle miles traveled (VMT) and energy consumption are projected to grow faster than any other mode. The U.S. EIA projects that truck travel will grow from 241 billion vehicle miles in 2007 to 363 billion miles in 2035, with energy use growing from 2.41 mmbd to 3.11 mmbd. That is a growth rate of 1.7 percent per year and 1.2 percent per year, respectively (EIA, 2010a). The smaller energy growth is caused by an expected increase in fuel efficiency from 6.0 mpg in 2007 to 7.0 mpg in 2035.

There is a wide variety of freight trucks and freight operations, and consequently there are multiple technology options that can be applied to different parts of the truck fleet.

Heavy-duty long-haul tractor-trailers (Class 8 trucks) account for two-thirds of all truck fuel consumption, about 1.6 mmbd of diesel fuel (NESCCAF, 2009). These vehicles already have highly efficient diesel engines (44 to 45 percent efficiency), and generally have streamlined spoilers on their cabs to reduce drag. But there remain potential improvements in turbocharging and supercharging,[38] better thermal management, and waste heat recovery.[39] The U.S. Department of Energy's (DOE) Office of Vehicle Technologies has established a 2013 goal for heavy-duty engines of 55 percent efficiency (Office of Vehicle Technologies, 2008).

Reductions of the aerodynamic drag coefficients (C_D) of about 25 percent can be obtained by improving cab shaping, replacing mirrors with cameras, closing the gap between cab and trailer, and adding a short boat-tailed rear (Cooper, 2000). These improvements can reduce fuel use by approximately 12 percent at 65 mph. Englar (2001) also estimated C_D reductions of 50 percent and higher with pneumatic (air blowing) devices; this benefit is coupled with potential benefits in safety from better braking and roll and stability control. A complete package of aerodynamic improvements for a heavy-duty truck might save about 15 to 20 percent of fuel for trucks operating

38. Turbochargers and superchargers are devices that increase the pressure of air flowing into an engine's cylinders, increasing power output. Turbochargers are driven by the energy in the engine's exhaust stream; superchargers are driven directly by the engine using a belt.
39. Some new Daimler trucks use turbo-compounding, where a turbine extracts waste energy from the exhaust, to achieve about a 5 percent fuel economy boost.

primarily on uncongested highways at an estimated cost of about $5,000, with substantial cost reductions possible over time (Vyas, Saricksl, & Stodolsky, 2002).

Significant fuel use and GHG reductions can also be obtained from improving freight logistics (e.g., improvements in truck routing, avoiding empty return trips, and consolidating shipments), using higher capacity trucks, improving driver behavior, reducing truck idling, and even improving product packaging. For instance, Rocky Mountain double and triple trailers[40] can reduce fuel use and GHG emissions by 17 to 21 percent compared to standard 53-foot trailers (NESCCAF, 2009). More fuel-efficient driving techniques, such as lower speeds, reduced idle time, better gear shifting, and better anticipation of traffic flow to cut down the number of stops and starts can reduce fuel consumption by an estimated 7 percent (McKinnon, 2009). And cab heaters and other devices that allow drivers to sleep comfortably while parked without using the main truck engine could save more than 1000 extra gallons of diesel fuel per year (Gaines & Hartman, 2009).

A consortium of four research and policy organizations recently evaluated a variety of technology packages for long-haul trucks, using simulation analysis (NESCCAF, 2009). The packages consist of various technologies and technology combinations, including cab and trailer aerodynamic improvements, low rolling resistance tires, idle reduction, operational measures (multiple trailers, slower speeds), and advanced engine and drivetrain technologies. The technology packages could reduce fuel use by 18 to 50 percent, with the 50 percent reduction requiring about 5 years to pay off with diesel fuel costs at $2.50 per gallon with a 7 percent discount rate. Crucially, the study only considered technologies that are currently in production or ones with available design specifications.

Some of the technologies and technology packages will pay off within 3 years or less (at a $2.50 per gallon diesel price), which should be attractive to truck owners even without further policy incentives.

Introducing the technologies listed in **Table 3** gradually into the U.S. long-haul truck fleet between now and 2022 could save about one sixth of the expected annual fleet fuel consumption by 2030.

Additional savings can be obtained with more advanced and more expensive technologies. For example, combining a parallel hybrid-electric powertrain, exhaust heat recovery, a speed limit of 60 mph, and an advanced version of the EPA's SmartWay package (with improved aerodynamics and lower rolling resistance) could reduce fuel consumption and CO_2 emissions by about 40 percent with a 5-year payback period at an incremental vehicle cost of about $90,000. Introducing this technology package and others with lifetime net cost savings[41] during the current-2022 period could reduce the 2030 long-haul fleet fuel use and CO_2 emissions by 39 percent.

40. These are trucks with two or three trailers, generally restricted to less populous states, e.g. the Rocky Mountain States (Colorado, Idaho, Montana, Utah, and Wyoming).
41. Assuming a 7 percent discount rate for future fuel savings.

Table 3

Fuel and CO_2 Reduction Options for Heavy-Duty Long-Haul Tractor-Trailers

	Percent Fuel and CO_2 Reduction	Payback Period (Years)
U.S. EPA's SmartWay 2007: aerodynamics, improved tires and idle reduction*	18%	3
Mechanical Turbo Compounding	3%	2
Variable Valve Actuation	1%	0.6
Advanced exhaust gas recirculation	1.2%	1.4
Rocky Mountain Double Trailers (limited by safety concerns)	16–21%	2.1

** SmartWay is an EPA program focused on improving the efficiency of trucking, see www.epa.gov/smartway.*
Source: NESCCAF, 2009.

A recent National Research Council (NRC) report on medium and heavy-duty trucks arrived at somewhat more optimistic results for the 2015 to 2020 time frame—a fuel consumption reduction potential for tractor-trailers of 51 percent (from a package of drivetrain and vehicle technologies and logistical changes), costing about $85,000 per truck. The package has a 3-year payback at $2.50 per gallon diesel fuel (NRC, 2010b).

For delivery trucks, urban buses, and other medium- and heavy-duty vehicles that do a great deal of congested stop-and-go travel, hybrid electric drivetrains can be strongly beneficial. New York City has obtained about a 45 percent improvement in fuel economy as well as improved acceleration by using hybrid buses (Chandler, Eberts, & Eudy, 2006). FedEx achieved a 36 percent reduction in fuel consumption for its E700 diesel hybrid delivery vehicles (Green Car Congress, 2004). In 2006, the United Parcel Service unveiled a hydraulic hybrid[42] delivery truck designed by FEV, Inc. that obtained a 60 to 70 percent improvement in fuel economy compared to its diesel delivery trucks (EPA, 2006).

The NRC study cited above also examined a range of vehicles from box trucks[43] to refuse trucks to transit buses. **Table 4** shows the potential for fuel consumption reduction, capital costs, and breakeven fuel prices associated with packages of fuel-saving technologies. **Table 4** shows that the aggressive technology packages have a wide range of cost-effectiveness. At $2.50 per gallon diesel price, the package for the motor coach will pay off in less than 5 years and the refuse truck's package will pay off in less than 8 years; at the other extreme, the package for the transit bus would require nearly 20 years to pay off—double the lifetime of the bus.

In May of 2010, the Obama Administration called for development of fuel economy and GHG emission standards for medium and heavy-duty trucks (White House, 2010).[44]

42. Hydraulic hybrids are hybrids that store energy as a compressed gas in a storage tank rather than as electricity in a battery.
43. Box trucks are trucks with a rigidly attached boxlike cargo container.
44. Because fuel economy standards for freight trucks will very likely be in place within a few years, even this report's Low Mitigation Scenario assumes that average fuel economy for freight trucks will improve.

Table 4

Fuel Consumption Reduction Potential and Cost-Effectiveness for Seven Medium- and Heavy-Duty Vehicles in 2015

Vehicle Class	Fuel Consumption Reduction	Capital Cost	Breakeven Fuel Price ($/gallon)*
Tractor-trailer	51%	$84,600	1.10
Class 6 box truck	47%	$43,120	4.20
Class 6 bucket truck	50%	$49,870	5.40
Class 2b pickup	45%	$14,710	4.80
Refuse truck	38%	$50,800	2.70
Transit bus	48%	$250,400	6.80
Motor coach	32%	$36,350	1.70

** Calculated assuming a 7 percent discount rate and a 10-year life, excluding incremental operating and maintenance costs associated with the technologies.*

Source: (NRC, 2010b).

Table 5

Percent Change in Fuel Economy for Freight Trucks Used in the Low, Mid, and High Mitigation Scenarios Compared to the Reference Case

Report Scenario Assumptions for Freight Trucks	2035			2050		
	Low	Mid	High	Low	Mid	High
Fuel Economy (% change in mpg)	15%	25%	30%	25%	35%	40%

2.3 Commercial Aircraft

2.3.1 Introduction

Aviation is the largest source of GHG emissions in the transportation sector after passenger vehicles and trucks. Commercial aircraft account for about 2 percent of global primary energy use and 1.5 percent of total CO_2 emissions. Aviation accounts for 11 percent of global transportation energy use and 12 percent of global transportation's CO_2 emissions (IEA, 2009a, ch. 7). U.S. aviation accounts for just over 4 percent of U.S. CO_2 emissions from fossil fuel consumption and 3.5 percent of U.S. anthropogenic GHG emissions (McCollum, Gould, & Greene, 2009, table 1). Today, petroleum fuels provide all of the energy used in commercial aviation, with jet fuel[45] accounting for about 99 percent (McCollum, Gould, & Greene, 2009). Because air travel is projected to grow faster than highway energy use, its relative importance as a source of GHG emissions is expected to roughly double by 2050.

Aircraft fuel consumption and GHG emissions can be reduced by, 1) aerodynamic improvements to the airframe that increase its lift-to-drag ratio,[46] 2) material substitution and design changes that reduce the empty

45. Most jet fuel is a blend of hydrocarbons for use in gas-turbine engines. Kerosene-type jet fuel is the most common type for aviation.
46. The lift-to-drag ratio of an aircraft measures the upward force (lift) produced when the aircraft moves forward through air relative to the resistance to its forward motion created by having to move air out of its way (drag). Higher lift-to-drag ratios are more efficient.

Box 2. Climate Change Effects of Aviation CO_2 Emissions

The impact of aviation emissions on the global climate is significant, but uncertainties remain; the warming effect of aviation CO_2 emissions at cruise altitudes may be three times as great as that of CO_2 emissions at ground level (RCEP, 2002). Water vapor and particulate emissions from aircraft at high altitudes also have an effect by forming contrails that may expand to form cirrus cloud cover. Because cirrus clouds absorb outgoing infrared radiation at a greater rate than they reflect incoming solar radiation, the net effect can be an increase in warming. An estimate for the year 1992 put the total warming caused by aviation emissions at 4.9 percent of the anthropogenic total. If cirrus cloud formation is not considered, aviation's share drops to 3.5 percent, still more than twice aviation's share of global anthropogenic CO_2 emissions (McCollum, Gould, & Greene, 2009, p. 11). Nitrogen oxide (NO_x) emissions increase the formation of ozone, a powerful GHG, while the scavenging of methane by NO_x reduces the global warming impact of aircraft emissions, as does increased reflection of sunlight due to sulfur oxide particles. However, most of these mechanisms are not well understood. The possibility that most of aviation's climate impact may come from sources other than CO_2 complicates the challenge of mitigation.

weight of the aircraft, and, 3) increased engine efficiency, both in thermodynamics and propulsion. Past reductions in the energy intensity of air travel by all these means and by increased load factors (number of passengers per plane) have been truly impressive: energy use per passenger mile today is less than one-third of what it was in 1970 (Davis, S.W., & Boundy, 2010, table 2.14). However, there is evidence that the rate of efficiency improvement in new aircraft has slowed over the past two decades (ICCT, 2009).

Researchers at the Massachusetts Institute of Technology (MIT) estimate that the specific fuel consumption (fuel combustion per unit of thrust)[47] of new aircraft can be reduced 15 to 25 percent by about 2025 (Schafer, Heywood, Jacoby, & Waitz, 2009). They estimate the potential for aerodynamic improvements to conventional tube and wing aircraft frames at 10 percent by approximately 2025, but that more radical, future concepts like the blended wing body with laminar flow control could reduce fuel use by more than 50 percent. The same study estimates the potential for weight reduction is more limited, concluding that a 0 to 10 percent reduction in the ratio of empty weight to maximum takeoff weight is possible. The realistic potential for operational improvements (such as improved air traffic control and energy-efficient flight paths) to reduce fuel use by 2025 was estimated to be 5 to 10 percent.

The European Commission's Advisory Council on Aeronautics Research in Europe set a goal of reducing the fuel consumption per passenger kilometer for new aircraft by 50 percent by 2020 (IATA, 2009a, p. 14). Of

47. Thrust is the forward force generated by the mass of air ejected rearward by a jet engine. It is the reaction force described by Newton's second and third laws. In modern jet engines thrust is produced both by the exhaust from the turbine engine and by air passed around the engine which is accelerated by fan blades.

that, 15 to 20 percent comes via engine improvements, 20 to 25 percent via airframe improvements, and 6 to 10 percent via operational improvements to the air traffic management system (ATM). The U.S. National Science and Technology Council's Aeronautics Science and Technology Subcommittee established similar goals (NSTC, 2007, p. 47): a 33 percent reduction in fuel consumption within 5 years, a 40 percent reduction within 10 years, and a 70 percent reduction within 25 years.

2.3.2 Engines and Airframes

The International Air Transport Association (IATA) identified 17 airframe and engine technologies that could be retrofitted to existing aircraft, potentially achieving a combined reduction in CO_2 emissions of 10 percent (IATA, 2009a, table 3-3). Retrofitting new wing tip designs could bring a 3 to 5 percent reduction, while engine retrofits (including advanced heat-resistant materials, better turbine and fan blade designs, and more efficient energy management) could provide a 1 to 2 percent reduction. In response to the high fuel prices of 2008, many aircraft are already equipped with raked or blended wingtips.[48]

Airlines consider other near-term technologies to be too complex for retrofit, but implementable on updated versions of current production aircraft. These options include the use of composite primary structures to reduce structural wing weight by 20 percent, increased use of advanced lightweight alloys, and active load alleviation.[49] While the IATA provides no estimate of the combined effectiveness of these technologies, their benefit should be at least as great as the benefits of the retrofit technologies (IATA, 2009a, table 3-4).

Other technologies are likely to be available for inclusion in the next generation of short-range (i.e., regional) aircraft. Short-range aircraft may be able to employ technologies such as the open rotor or unducted turbofan that may not be practical for long-range aircraft because of the latter's need for greater speed than can be achieved with open rotor aircraft. But the overall list contains enough potential technological advances for all airplanes to justify the NSTC goal of a 40 percent reduction in the fuel consumption rates of new aircraft by 2020.

The IATA made a rough estimate of the potential to reduce CO_2 emissions by combining selected compatible technologies from the lists (IATA, 2009a, table 3-7). They found a potential for retrofit technologies to reduce the emissions from existing aircraft by between 7 and 13 percent. Feasible modifications to current generation new aircraft could decrease their CO_2 emissions by 7 to 18 percent. The potential of advanced technologies applied to the next generation of new aircraft before 2020 was estimated to be a reduction of 25 to

48. Blended wingtips, or winglets, are a smooth extension of the terminus of a wing in the vertical direction intended to reduce drag by reducing turbulence at the wingtip. Raked wingtips accomplish the same purpose by extending the wingtip towards the aft of the plane at a greater angle than that of the main body of the wing.
49. Load alleviation is a method of controlling the aircraft to respond to buffeting by crosswinds and such, so as to reduce the stress on the airframe.

35 percent. New designs introduced after 2020 were judged to have the potential to lower emissions by 25 to 50 percent via energy efficiency improvements (all relative to the base aircraft).

2.3.3 Operational Efficiency Improvement

Today's air traffic control systems are not optimized for fuel efficiency (IEA, 2009a, p. 327). Routes are frequently longer than necessary due to fragmentation in control of the airspace and outdated technology. It also has been estimated that if the current method of step-down descent could be replaced by a system of continuous descent,[50] up to 500 gallons of fuel per flight could be saved (IATA, 2009a, p. 30).[51] A planned, continuous descent path allows maximum substitution of an aircraft's potential energy for fuel. The NextGen air traffic management system in the United States and the Single European Sky Air Traffic Management Research initiatives both aim to replace the current ground-based control system with a satellite-supported, globally integrated control system. The goal is to accommodate high-density traffic and all-weather operations while greatly reducing circuity, delays, and inefficient flight profiles.

The International Civil Aviation Organization (ICAO) has estimated that air traffic management improvements should be able to reduce fuel use and GHG emissions by 5 percent by 2015 (IEA, 2009a, p. 327). In the longer run, savings of 5 to 10 percent should be achievable (Schafer, Heywood, Jacoby, & Waitz, 2009). These goals are intended to be achievable despite continued increases in air travel. IATA established the following goals for operational improvements: energy intensity reduction of 3 to 5 percent from 2006 levels within 5 to 10 years and a further 6 to 10 percent beyond 10 years (IATA, 2009a, p. 15).

2.3.4 Alternative Fuels

Aircraft require a high energy density[52] fuel that can be burned efficiently, reliably, and cleanly in turbine engines. Commercial kerosene jet fuel (jet-A) has among the highest energy densities of petroleum fuels. In the near term, alternative fuel use by jet aircraft will be limited to "drop-in" biomass-derived substitutes for kerosene jet fuel. The most promising of these are biomass-to-liquid (BTL) jet fuel produced by gasifying biomass and

50. Under current practice, aircraft are required to descend for landing in a series of discrete steps. This imposes a requirement to maintain a fixed altitude at each step. Maintaining altitude at each step uses more fuel than if the aircraft were allowed to descend smoothly, or continuously along a path of descent designed to minimize fuel use.

51. The Boeing 767 has a fuel capacity of almost 24,000 gallons while the Boeing 787 capacity ranges from 12,800 to over 33,000 gallons (The Boeing Company, 2010).

52. Energy density measures energy content per unit of volume or of weight. Both are important for aircraft, but energy per unit of weight may be more important. Jet fuel, which is a middle distillate (commercial jets burn kerosene) has among the highest energy densities per unit of volume of any liquid fuel (35.7 megajoules per liter). By comparison, liquid hydrogen has only about one-fourth the energy per liter (8.5 MJ) as kerosene but more than three times the energy per kilogram.

synthesizing kerosene, and hydroprocessed renewable jet fuel (HRJ) produced by hydrotreating bio-derived oils to remove oxygen atoms and reacting with hydrogen to convert olefins to paraffins (IATA, 2009b, p. 39).

The feasibility of using biofuel to power jet aircraft was established on international flights by commercial jets in 2008 and 2009, and was used on the first commercial passenger flight from London to Doha on October 12, 2009. The fuel used on that flight was a 50 percent blend of standard jet-A and synthetic kerosene produced from biomass via the Fischer-Tropsch process.[53] The ability to blend biomass-derived jet fuel with conventional kerosene makes it possible to use large quantities of biofuel in commercial aircraft without significant changes to vehicles or infrastructure.

The climate change impacts of biofuels depend not only on the lifecycle emissions and indirect land use effects,[54] but also on the effects of high-altitude emissions, as described in **Box 2**. Even zero net carbon fuels will produce water vapor and are therefore likely to form contrails and induce cirrus cloud formation. However, it may be possible to exploit different properties of alternative fuels to reduce emissions of nitrogen oxides, particulates, and sulfur dioxide. Hydrogen, for example, would produce no particulates or sulfur dioxide emissions and very little nitrogen oxide. Fuels produced via Fischer-Tropsch synthesis are inherently low in contaminants such as sulfur due to the purity of the synthesis gas from which they are made, and biofuels are also low in sulfur.

Like other transportation modes, aviation is depending on the development of second and third generation biofuels to achieve low GHG impacts at low costs. A recent assessment of alternative biofuel options for aircraft concluded that Fischer-Tropsch synthesis of kerosene from biomass yields the most fuel energy per energy input and is likely to be the most economical alternative fuel, although it is too soon to rule out other processes. The IATA set an ambitious goal of 10 percent alternative fuel use in aviation by 2017. But in its latest update (IATA, 2009b), the IATA concluded that the hurdles faced by advanced biofuels have made the 10 percent target unlikely by 2017 without relying on higher GHG-emitting coal-to-liquids or gas-to-liquids fuels (IATA, 2009b, p. 46).

In the long run, aviation could conceivably be powered entirely by biofuels. One study estimated that replacing all jet kerosene by 2050 would require 90 million new acres devoted to oil crops, such as jatropha, algae or camelina, and 480 million acres for energy crops (for BTL), equal to 16 percent of the land currently under cultivation worldwide (IATA, 2009b, p. 47). There are an estimated 950 million acres of marginal agricultural land in the world that would

53. The Fischer-Tropsch process is a method of producing liquid hydrocarbon fuels from syngas, which is a mixture of hydrogen and carbon monoxide.
54. If land is converted to another agricultural use to produce biofuel, this will tend to raise the price of the agricultural commodity displaced. The higher price will encourage land somewhere in the world to be converted to agricultural use. If the land is cleared, carbon sequestered in the biomass and in the soil will be released to the atmosphere. The release of sequestered carbon will offset some of the potential GHG benefit of biofuel use.

probably be suitable for these crops. Whether the necessary economics of production can be achieved, and whether air transportation could outbid other potential users of biomass feedstocks, remain open questions.

Until recently, hydrogen was not considered a viable replacement for jet fuel. The energy density by volume of even liquid hydrogen is quite low, only 24 percent of that of kerosene jet fuel, so aircraft would have to carry four times the volume of fuel compared to kerosene. On the other hand, the energy density of liquid hydrogen per unit of mass is 2.7 times than that of kerosene, so storing the same amount of energy as liquid hydrogen would mean carrying only 37 percent of the weight. The gross take-off weight of a 120 passenger aircraft is about 60,000 kilogram (kg), of which almost one third is fuel. On-board storage of hydrogen would require pressurized, cryogenic tanks that would add about 10 percent to the weight of the aircraft (IEA, 2009a) but substituting lighter liquid hydrogen for kerosene would reduce gross total take-off weight by about 20 percent, improving overall energy efficiency. That net reduction in take-off weight might be worth the effort (Janic, 2008). But entirely new engine designs would be required to use hydrogen effectively, and a hydrogen supply infrastructure would also have to be created. So it is not likely that hydrogen aircraft could be a significant factor before 2040.

Table 6 defines the assumptions for air transportation. While use of hydrogen as a fuel for aviation is a possibility in the future, this report did not consider it in the report scenarios.

Table 6

Percent Change in Energy Intensity (gallons per seat-mile), Fuel Carbon Intensity (gCO_2e per megajoule), and Vehicle Travel for Air Transportation Used in the Low, Mid, and High Mitigation Scenarios Compared to the Reference Case

	2035			2050		
Report Scenario Assumptions for Air Transportation	Low	Mid	High	Low	Mid	High
Engines & Airframes (% change in energy intensity)	–10%	–25%	–40%	–40%	–50%	–70%
Operational Efficiency Improvement (% change in energy intensity)	–3%	–5%	–10%	–3%	–7.5%	–10%
Advanced Biofuel (% change in fuel carbon intensity)	0%	–10%	–15%	–10%	–15%	–37.5%
Vehicle Travel (% change in VMT)	–3%	–5%	–10%	–3%	–5%	–10%

2.4 Rail, Water, and Pipeline

Though they play critical roles in the nation's transportation system, the rail, water, and pipeline modes are relatively minor sources of GHG emissions.

Rail transportation plays a much greater role in freight movements in the United States than in other developed economies, where trucks account for a greater share of freight activity. When measured in ton-miles, rail moves 40 percent of all commodity shipments in the United States and only 17 percent in Europe. Because of rail's energy efficiency, however, rail freight accounts for only about 2 percent of transportation energy use and GHG emissions (Davis, Diegel, & Boundy, 2009, table 2.6 and 11.7; Noreland, 2008).[55] Rail passenger travel is an even smaller component of transportation energy use and GHG emissions, accounting for only 0.3 percent of transportation energy use (and 0.7 percent of passenger miles), of which rail transit and commuter rail systems are 0.2 percent, and intercity passenger rail is 0.1 percent.

The energy intensity of rail freight transportation has improved steadily over the past four decades. Rail freight energy intensity today is 305 Btu per ton-mile, less than half of what it was in the 1970s (Davis, S.W., & Boundy, 2010, table 2.16). Increased load factors (ton-miles per car-mile), greater locomotive energy efficiencies, and improved logistics have all played a role (BTS, 1996). Further improvements are possible, however. More energy-efficient locomotive engines can improve fuel efficiency by about 15 percent (IEA, 2009a, p. 299; DOT, 2010b, pp. 3-89). Switching from direct current (DC) to alternating current (AC) would reduce electrical losses and allow use of fewer locomotives and lower total horsepower. Regenerative braking, reducing the empty weight of rolling stock, and improving operations can all contribute to further efficiency gains. By 2030, rail fuel consumption and GHG emissions could be reduced by 15 to 19 percent by a combination of aerodynamic improvements, mass reduction in rail cars and wheel and rail lubrication systems; by 2050 reductions of 18 to 24 percent are possible (DOT, 2010b, pp. 3-90). Hybrid locomotives, with claimed efficiency gains of up to 50 percent are already in use in switching yard operations while research on hybrid long-haul locomotives is underway; General Electric intends to complete trials of a long-distance hybrid in 2010 (ICF International, 2009, pp. 22-23). A 2002 study by Argonne National Laboratory estimated that when utilizing a full range of technological and operational measures, rail fuel efficiency could be improved by 25 percent by 2010 and 50 percent by 2020 (Stodolsky, 2002). The actual improvement in fuel efficiency from 2000 to 2007 was 10 percent (Davis, Diegel, & Boundy, 2009, table 2.16).

55. In 2008, U.S. railroads averaged over 400 ton-miles per gallon of diesel fuel (Davis, S.W., & Boundy, 2010, table 2.16).

Locomotives can operate on a variety of alternative fuels including biodiesel, liquefied natural gas, and electricity (Danigelis, 2009). Rail electrification can increase energy efficiency by 15 percent and allow substitution of an increasingly low-carbon energy source as the electric utility sector decarbonizes. The cost of infrastructure to expand electrification of the rail system and its maintenance remain the key barrier to expanded electrification.

Globally, water-based transportation accounts for 9 percent of transportation energy use. But more than four-fifths of that is international transportation, which nations exclude from national GHG inventories because of existing agreements (IEA, 2009a, p. 339). In the United States, domestic commercial shipping produces 1 percent of national GHG emissions (recreational boating produces 0.9 percent). When international bunker fuels are included, all water transportation accounts for 5.1 percent (McCollum, Gould, & Greene, 2009, table 1).

Water transportation GHG emissions can be reduced by improving engine and propulsion efficiency, (e.g., improved propeller designs), reducing hydrodynamic drag and wave resistance, and by replacing conventional heavy oil and diesel with low-carbon biofuels or even solar and wind power (DOT, 2010b, pp. 3-97).[56] The IEA estimates that CO_2 emissions from the fleet of marine vessels could be reduced by up to 30 percent by improved new vessel designs and propulsion systems, up to 20 percent by retrofit and maintenance of existing vessels, and as much as 40 percent by operational improvements including speed reduction (IEA, 2009a, pp. 359-360). Combining these measures, they estimate that it would be feasible to reduce CO_2 emissions by up to 40 percent per ton-kilometer by 2030 and 60 percent by 2050.

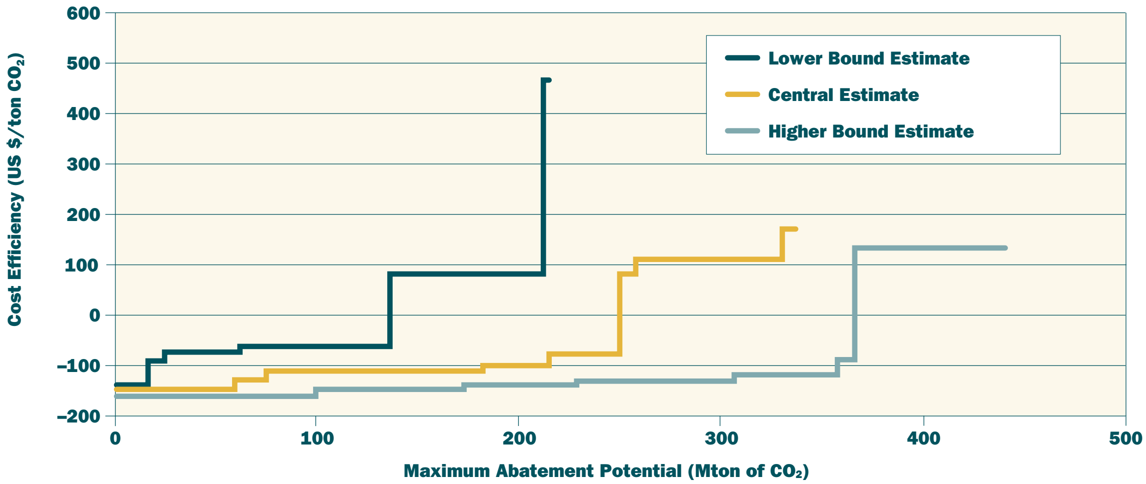
The International Maritime Organization (IMO) estimates that many measures could be taken at negative net cost and that almost all would cost less than $100 per ton of CO_2 taking fuel savings into account (IMO, 2009, p. 263). The IMO estimates the abatement potential for the year 2020 to be 210 to 440 megatonnes of CO_2 or about 15 to 30 percent of the total global emissions from ships projected under business-as-usual conditions (**Figure 10**).

Pipelines account for about 3 percent of transportation's energy use and nearly all of transportation's non-petroleum energy. Natural gas pipelines use natural gas to power their pumps while petroleum and petroleum product pipelines use electricity. Pipelines account for 77 percent of U.S. transportation's electricity use and 97 percent of natural gas use (Davis, Diegel, & Boundy, 2009, table 2.5). Based on energy use per ton-mile, pipelines are one of the most efficient transportation modes. As the electricity sector decarbonizes, emissions due

56. Engine efficiency measures the ratio of energy input to useful work at the engine crankshaft. Propulsion efficiency includes the efficiency with which the crankshaft work is converted to the work of moving the vessel. This is mainly a function of the efficiency of the propeller(s).

Figure 10

IMO Estimated Marginal CO_2 Abatement Cost Curves for Marine Transportation in 2020



Source: IMO, 2009

to petroleum pipelines will be reduced proportionately. The key issue for natural gas pipelines is to reduce methane leakage, which currently stands at about 1.4 percent of the gas transported (Lelieveld, et al., 2005). The scenarios used in this report did not consider emissions from pipelines.

Table 7

Percent Change in Fuel Economy for Freight Trucks Used in the Low, Mid, and High Mitigation Scenarios Compared to the Reference Case

Report Scenario Assumptions for Rail and Water Transportation	2035			2050		
	Low	Mid	High	Low	Mid	High
Rail	–10%	–15%	–20%	–25%	–30%	–40%
Water	–15%	–22.5%	–30%	–20%	–40%	–50%

2.5 System Efficiency

Improving the operating efficiency of the transportation system could reduce transportation's GHG emissions by several percent. Estimating future GHG reductions from system efficiency improvements, however, is difficult. First, system efficiency improvements are continuously being made and it is usually not clear to what extent such improvements are already included in baseline projections. Second, many system efficiency improvements are more readily reversible than technology-based efficiency gains. Behaviors like more efficient driving, ridesharing, and choice of transportation mode can be abandoned as quickly as they can be adopted. Nonetheless, system efficiency improvements can reduce GHG emissions significantly and generally produce valuable co-benefits such as reduced traffic congestion, improved air quality, and lower costs.

Governments can play a major role in improving the efficiency of transportation systems via the investments they make in infrastructure for highways, transit systems, and airports. Government agencies also manage traffic and enforce laws and regulations.

System efficiency improvements for air, rail, and marine travel were described above in the sections dealing with those modes. This section will deal exclusively with improving highway system efficiency in five areas:

- Traffic flows
- Vehicle occupancy rates
- Route and trip-making efficiency
- Efficient driving behavior
- Freight logistics

2.5.1 Improving Traffic Flow

If congestion reduces the average speed on freeways below 45 mph, CO_2 emissions increase (Davis, S.W., & Boundy, 2010, table 4.26; West, McGill, & Sluder, 1999). In part, this is because vehicles achieve lower fuel economy at slower speeds.[57] Increasing vehicle speeds to the range of 45 to 60 mph typically reduces GHG emissions per mile. Smoothing out stop-and-go traffic so that vehicles can travel at a relatively constant speed will also reduce CO_2 emissions. However, increasing traffic speeds beyond 60 mph will generally increase CO_2 emissions per mile. For every 5 miles per hour above 60 mph, fuel consumption increases by about 8 percent (DOE, 2010c).

Researchers at the University of California at Riverside have used detailed traffic flow data to estimate that each of the following three strategies could reduce CO_2 emissions on Los Angeles freeways by 7 to 12 percent, and in combination by as much as 30 percent (Barth & Boriboonsomsin, 2009; AASHTO, 2009).

- Congestion mitigation: ramp metering, incident management including real-time traveler information, and congestion pricing
- Speed management: speed limit enforcement, intelligent speed adaptation[58]
- Traffic smoothing: variable speed limits, dynamic intelligent speed adaptation, and congestion pricing

57. This is chiefly because they operate in lower gears. In lower gears, there are more engine revolutions, meaning more combustion events and thus more fuel use per mile. Congestion also results in more braking and accelerating, which lowers fuel economy.
58. Adjusting speed limits to traffic conditions.

About 25 percent of U.S. VMT are on urban interstates and other urban freeways, of which a significant fraction occur under congested conditions (FHWA, 2010, table VM-202).

Traffic congestion in Los Angeles alone is responsible for an estimated 3.4 megatonnes of CO_2 per year, out of six megatonnes of CO_2 per year due to traffic congestion throughout the state of California (UCLA School of Public Affairs, 2009). This is approximately 3.5 percent of the 170 megatonnes of CO_2 emitted by California motor vehicles each year (CARB, 2010). It is not reasonable to expect that all traffic congestion in California could be eliminated, but if it could be cut in half by a variety of system improvements, a GHG emissions reduction of approximately 1.75 percent of the 170 megatonnes could be achieved. Traffic congestion in the rest of the United States is generally less severe; an estimated 2.8 billion gallons of fuel were wasted due to congestion nationwide in 2007, out of a total fuel consumption of 176.2 billion gallons (Schrank & Lomax, 2009). This amounts to approximately 25 megatonnes of CO_2 per year out of 1,550, or 1.6 percent.

It is not likely that traffic congestion could be reduced to zero. On the other hand, congestion has generally been increasing at a faster rate than vehicle travel; thus, in the future its impact on GHG emissions can be expected to increase. Further, since reducing traffic congestion saves time, which is a larger component of travel costs than fuel costs, vehicle travel is sure to increase somewhat when traffic congestion is reduced. The overall GHG reduction from reduced congestion is therefore likely to be considerably less than 1.6 percent, and probably closer to 0.5 to 1 percent of highway vehicle emissions (Cambridge Systematics, Inc., 2009).

2.5.2 Ridesharing and Carsharing

It has been said that the greatest oil reservoir in the world is the empty seats in American cars. The average occupancy rates for household vehicles in the United States are 1.1 for work trips and 1.6 overall (Davis, Diegel, & Boundy, 2009, Figure 8.2), implying that passenger vehicles in the United States produce on the order of 10 trillion empty seat miles each year (Greene & Schafer, 2003). Since the first oil price shocks in the 1970s, there have been numerous efforts to increase occupancy rates including carpool-matching programs, employer-organized carpooling, and high-occupancy vehicle (HOV) lanes. These efforts have mostly focused on the work trip, since increasing vehicle occupancy rates during peak travel period would also help reduce traffic congestion. About 10 percent of U.S. commuters carpool to work, but in some cities, the share exceeds 20 percent (Dorinson, Gay, Minnett, & Shaheen, 2009). However, work trips account for only 28 percent of household vehicle miles of travel and an even smaller share of total travel (Davis, S.W., & Boundy, 2010, table 8.8). In addition, carpooling has generally been declining in the United States: according to the 1980 Census, 20 percent of Americans carpooled to work but in the 2000 Census, only 11 percent did (Davis, S.W., & Boundy, 2010, table 8.15).

A 2007 survey of 94 metropolitan areas by the U.S. Department of Transportation (DOT) found that 52 agencies in 39 of the metropolitan areas were providing carpool-matching services (RITA, 2010). The survey found that 15 percent of the metropolitan areas had HOV lanes, which accounted for 4 percent of their freeway miles. Although notable successes in increasing rates of carpooling have been documented for specific projects, success seems to require continued effort, and the key to reaching the full potential has yet to be found (Dorinson, Gay, Minnett, & Shaheen, 2009). An analysis for MIT found that although only 8 percent of its employees and students currently carpooled, the maximum potential was between 50 and 77 percent (Amey, 2009). The reduction in VMT possible by achieving the maximum potential was much smaller, 9 to 27 percent, because commuting is only a fraction of daily miles. This can be compared with an estimate for the entire United States of a 0.4 to 2.0 percent reduction in GHG emissions from a package of employer-based ridesharing strategies, of which ridesharing accounts for about 0.4 percent (Cambridge Systematics, Inc., 2009; Amey, 2009). The U.S. DOT estimated GHG reduction potentials of 0.2 to 0.6 percent for nationwide commuter trip reduction programs by 2030 (DOT, 2010a, pp. 3-20).

The existence of HOV lanes and toll exemptions for multi-passenger vehicles has spawned spontaneous, flexible carpooling in several cities in which potential riders line up at known points and are picked up by single-occupant vehicle (SOV) drivers. The SOV drivers thus gain access to the HOV lane. There are approximately 3,500 flexible carpools each day in San Francisco, an equal number in Washington, DC, and about 1,000 in Houston (Dorinson, Gay, Minnett, & Shaheen, 2009). Energy savings have been estimated at 350 gallons per rider per year, three-fourths of which is attributed to improved traffic flow in the non-HOV lanes. The potential market for flexible carpooling has apparently not been estimated nor is much known about how it might be encouraged (Dorinson, Gay, Minnett, & Shaheen, 2009).

Carsharing is an arrangement in which a group of drivers agree to share a pool of vehicles. Because most privately owned vehicles are idle most of the time, carsharing can reduce the cost of access to a motor vehicle significantly while providing nearly the same level of service to the driver. It has been estimated that one vehicle that is shared replaces five privately owned vehicles (Millard-Ball, Murray, Schure, Fox, & J., 2005). Studies of carsharing arrangements in the United States and the European Union indicate that participants who formerly owned their own vehicles reduce their annual VMT by 30 to 40 percent (IEA, 2009a, p. 249). Because some participants did not own a vehicle previously, their vehicle travel increased. Nonetheless, the overall effect appears to be a reduction in VMT of about 30 percent. Because car sharing requires that individuals have convenient walking, biking, or public transit access to the shared vehicles, almost all carsharing programs are located in central cities. The IEA estimated that the cost of reducing GHG emissions by carsharing would be negative, saving approximately $250 per ton of CO_2 (Shaheen, 2004).[59] An extrapolation of carsharing trends by the IEA suggests that approximately 1 percent of the world's population might participate in carsharing programs by 2050. Assuming that 1 percent of U.S. drivers might reduce their annual VMT by 30 percent produces an estimated total reduction in U.S. GHG emissions of about 0.3 percent by 2050.

2.5.3 Route and Trip-Making Efficiency

Using GPS and in-vehicle navigation tools together with real-time traffic information should allow both travel time and distance to be reduced.

Nissan claims that systems combining efficient routing with eco-driving can reduce GHG emissions by 18 percent while cutting travel time by 20 percent. Using a rigorous experimental design, one recent study found that drivers given directions to an arbitrary route from a portable navigation system traveled 7 percent less distance in urban environments and 2 percent less distance in rural environments than drivers navigating with a paper map (Lee & Cheng, 2007). But it is not known what real benefits these systems could provide under average driving conditions (Lee & Cheng, 2007).

2.5.4 Efficient Driving Behavior

How vehicles are driven can strongly influence their fuel economy. Sensible, safe driving for improved fuel economy, sometimes referred to as eco-driving, includes anticipating traffic situations and maintaining adequate spacing between vehicles to avoid unnecessary braking and acceleration, staying within legal speed limits, using cruise control on the highway, avoiding aggressive driving, minimizing idling, and using overdrive gears (DOE, 2010a). Much of the available evidence on the impacts of fuel-efficient driving is anecdotal, or cautiously phrased (e.g., "The following eco-driving tips can increase fuel economy by up to 25 percent," [Ford Motor Company, Inc., 2006]). Empirical evidence indicates that it should be possible to improve fuel economy by 5 to 20 percent, or approximately 10 percent for the average driver (Greene, 1986; Gense, 2000; Govaerts & Verlaak, 2003; ECMT/IEA, 2005; SMMT, 2006; Ponticel, 2010).

Proper vehicle maintenance can also contribute to fuel economy. Keeping tires properly inflated provides fuel economy benefits of 1 to 3 percent, depending on the degree of underinflation. Proper inflation is also important for safe handling and substantially reduces tire wear. A random sample survey by the U.S. DOT (Thiriez

59. This estimate is based on the monetary cost savings to the carsharing participant and does not attempt to estimate any change in consumers' surplus that might result from potentially diminished or increased access to a motor vehicle.

& N., 2001) found that most tires were underinflated, and that only 1 in 4 drivers knew how to determine their vehicle's proper tire inflation pressure. Twenty five percent were underinflated by more than 4 pounds per square inch (psi). Fuel economy decreases by about 0.3 percent for every 1 psi drop in all four tires. Proper inflation of the 25 percent of tires underinflated by 4 psi could improve total on-road fuel economy by 0.3 percent.

2.5.5 Freight Logistics

In 2007, transportation accounted for about 28 percent of U.S. GHG emissions and freight movements account for about 28 percent of emissions from transportation, making freight's share of total emission about 8 percent. A background paper on freight logistics commissioned in support of this study (Southworth, 2010) concluded that GHG emissions from U.S. freight activity could be reduced between 5 percent and 10 percent by 2030 via the following strategies:

- Shifts to more energy efficient and less polluting modes of transportation (i.e., away from trucks and aircraft to rail and water modes)
- More fuel-efficient utilization of vehicle fleets through reduced ton-miles notably through the use of larger capacity vehicles and vessels, coupled with better vehicle-to-load matching, better vehicle route and schedule planning, and better locating of idle vehicles
- More efficient organization of supply-chain networks, including optimal location of trans-shipment points and freight consolidation and distribution centers

The potential for modal shifts is estimated to be up to 5 percent, leaving 2 to 5 percent mitigation potentially from freight logistics. Quantitative estimates for three categories of logistics improvements considered feasible by 2030 for trucking are shown in **Table 8.** Since trucking accounts for three-fourths of freight GHG emissions, this amounts to a 1.7 percent reduction in freight emissions.

Table 8

Examples of CO_2 reductions from Selected Trucking Logistics Improvements by 2030

	Fuel Savings (million gallons)	Percent of Total Fuel consumed in 2008	CO_2 Reductions (million metric tons)
Reduction in empty truck miles	367	1.0%	3.7
Reduction in idling due to better routing and scheduling	100	0.3%	1.0
Speed Reductions	375	1.0%	3.7
Total Savings	842	2.3%	8.4

Source: Southworth, 2010.

The U.S. DOT estimated that improvements to trucking operations, such as idling reduction, increased size and weight limits, and urban freight consolidations centers could reduce heavy-duty truck GHG emissions by about 0.5 to 1.3 percent by 2030 (DOT, 2010a, table 3.5).

Most of the potential benefits of improvements in freight logistics will be achieved by private sector initiatives, but governments can help with automated in-motion collection of tolls, verification of weight limits, policing speed limits, investments in intermodal facilities, and expansion of infrastructure capacity (Southworth, 2010, table 4).

2.5.6 Shifting Traffic to More Energy-Efficient Modes

U.S. transportation of passengers and freight is dominated by its less fuel-efficient modes—passenger travel by personal vehicles and freight transportation by large trucks (Davis, Diegel, & Boundy, 2009). One potential means of reducing energy use and GHG emissions is shifting traffic to more fuel-efficient modes.

Reducing energy use and emissions by shifting passenger travel from personal vehicles to public transportation will be extremely difficult in the United States, however. First, travelers often prefer to use personal vehicles due to their flexibility, door-to-door service, and privacy. Second, on average, public transportation modes are only slightly more efficient than personal vehicles. The most efficient modes—the three rail types—are only about one-third less energy-intensive than the LDV fleet even though LDV occupancy is only a little over one passenger per vehicle (see **Figure 11**).[60] Of course, measures that increase transit ridership without significantly increasing service levels (by rationalizing routes, increasing patronage by providing improved

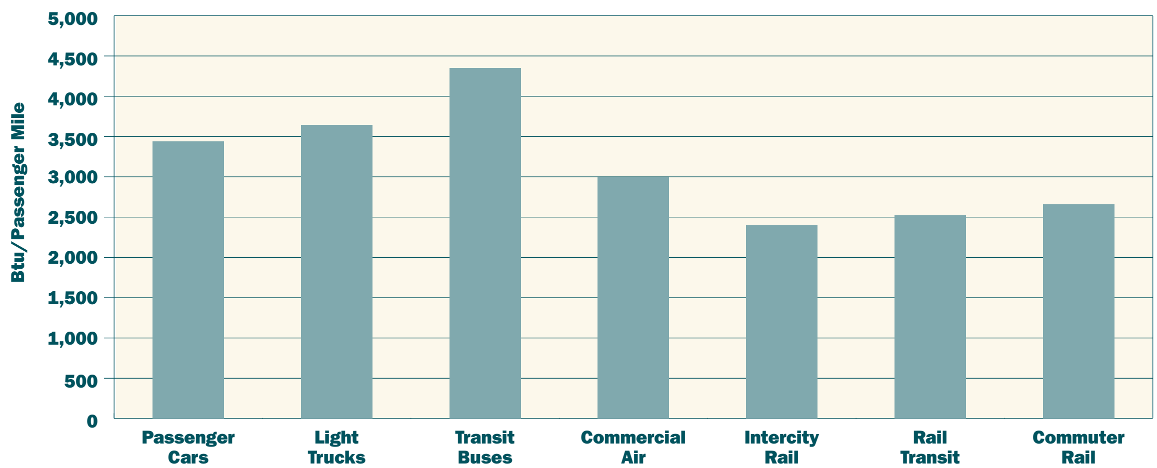
60. The table shows that public transportation is slightly more efficient than private vehicles *on average*. The values do not compare the same types of trips (a higher percentage of trips on public transportation than in private vehicles are work trips), and they do not cover the same geographic area (most trips on public transportation are in urban and close-in suburban areas, and a large fraction of the nation's transit trips occur in New York City). Also, they do not address the question of what types of travelers would be attracted to new or more efficient or cheaper public transportation services. Finally, the values in the figure do not appear to agree with the values for GHG emissions per passenger-mile in Figure 2.11 of DOT, 2010a, which shows buses to be the lowest-emitting source.

scheduling and route information, and so forth) will reduce GHG emissions from private vehicles without adding to transportation emissions.

Third, any shift from personal vehicles to public transit will start from an extremely low base. Currently, public transit supplies only about 1 percent of the total passenger miles of travel in the United States (Davis, Diegel, & Boundy, 2009), so a doubling of transit's travel share, an ambitious goal, would yield considerably less than a 1 percent reduction in transportation energy use and GHG emissions.

Figure 11

Energy Intensity of Alternate Passenger Travel Modes in the United States, 2007



Source: Davis, Diegel, & Boundy, 2009.

Increasing transit share is likely to allow at best a few percentage points reduction in U.S. GHG emissions, and then only if it is an integral part of a shift to more compact development (Section 2.5.7).

The average values in **Figure 11** also hide a wide range of energy intensities. For example, although U.S. light rail systems average 7,600 Btu per passenger mile, considerably worse than personal vehicles, the most efficient systems located in Salt Lake City, Portland, Oregon and San Diego have energy intensities of 2,500 Btu per passenger mile or better (Davis, Diegel, & Boundy, 2009, Figure 2.2). Similarly, heavy rail systems range in energy intensity from under 2,000 Btu per passenger mile in Atlanta and New York City to nearly 6,000 Btu per passenger mile in Miami and Cleveland (Davis, Diegel, & Boundy, 2009, Figure 2.3). As a result, strategies to reduce GHG emissions must focus on improving the efficiency of current systems and promoting systems that offer the highest efficiency.

Obtaining large reductions in energy use and GHG emissions by shifting freight truck and air traffic to other modes will also be difficult. Significant reductions in energy use and GHG emissions are possible if large volumes of freight can be shifted to rail and water (Facanha & Ang-Olson, 2008; IEA, 2008).[61] But obstacles include the growing demand for just-in-time delivery, which favors the faster modes; the small share of fuel cost in total freight costs (often less than 8 percent); the high costs of transferring cargo between modes, often necessary in using rail and shipping; and the great scheduling flexibility of trucking and its ability to cost-effectively handle small shipments and short shipment distances (Southworth, 2010). In fact, trends have gone in the opposite direction, moving from the more fuel-efficient to the less fuel-efficient modes. Between 1985 and 2004, about one quarter of the increase in U.S. freight energy consumption has come from mode shifts from rail and water to air and truck freight (DOE, 2008). The U.S. DOT (2010a, table 3.5) estimated that by improving rail infrastructure to avoid further diversion of rail traffic to trucks, up to a 0.8 percent reduction in GHG could be realized by 2030.

The best opportunities to shift freight traffic to rail and ship involve improving intermodal transfers and improving the logistics of these energy-efficient modes, to make them more attractive. Although trucks may be the clear choice for local pickup and final delivery, rail and water may be better for longer shipments, especially if the freight is containerized. Intermodal shipment becomes especially competitive at shipping distances over 1000 miles (Southworth, 2010). EPA's SmartWay freight program reports several cost-saving advances for truck-to-rail transfers, and there have been recent advances in rail-to-ship and truck-to-ship transfers, e.g. use of roll-on, roll-off[62] vessels carrying truck trailers and rail cars (Southworth, 2010).

For the scenarios in this report, any transportation modal shift is embedded within other assumptions for changes with respect to system efficiency (see **Table 9**).

2.5.7 Moving Towards Compact Development

Rapidly rising U.S. transportation demand has been fed in part by the growth pattern of American cities, which have spread out faster than they have gained population. There is substantial evidence that promoting compact, mixed-use development would yield reductions in the growth rate of travel along with other benefits. Higher residential and employment densities would bring trip origins and destinations closer together, making walking, bicycling, and public transit more feasible. More multi-family dwellings would bring additional energy savings from reduced heating and cooling needs,[63] and more efficient provision of services such as water and sewer systems.

61. Comparisons among modes can be difficult, however, because the types of freight carried by different modes often differ considerably, and care must be taken to account for the required transport at each end of the trip.
62. "Roll-on, roll-off" vessels can load and unload their cargo by rolling it directly on and off the vessel without using cranes.
63. Household energy use in multifamily dwellings is less than half that in single-family houses; however, this appears to be due primarily to the smaller size of multi-family dwellings, rather than to lower energy use per square foot (Diamond, 1995; Brown & Wolfe, 2007).

The National Research Council recently examined the ties between compact development and travel (NRC, 2009b). Assuming a doubling of residential density, it concluded that there is substantial evidence that creating compact development in combination with "higher employment concentrations, significant public transit measures, mixed uses, and other supportive demand management measures" might reduce household travel by 5 to 12 percent, and perhaps by as much as 25 percent. Most studies reviewed by the Council focused solely on increasing residential density (after controlling for the appropriate variables), and found reductions in travel of 5 percent or less.

It is highly uncertain how much change in land use patterns can be expected over the next several decades, but a clue is that demand for new housing may add up to 57 million new units (representing 54 percent of the current housing stock) by 2030 and between 62 and 105 million units (59 to 100 percent of the current housing stock) by 2050 (NRC, 2009b). If 25 percent of the new and replacement housing units were built in more compact development patterns, along with accompanying transit and other measures, and residents of those units drove 5 to 12 percent less as a result, personal travel could be reduced by 0.4 to 1.0 percent by 2030 and 0.5 to 1.7 percent by 2050 (NRC, 2009b).

The NRC also examined a scenario that assumed that 75 percent of new and replacement housing was steered into compact development. If coupled with the assumption that residents of these developments would drive 25 percent less than they would otherwise have driven—an assumption based on a single, but carefully done study (Bento, A.M. et al., 2005)—this scenario yields reductions in personal travel from the baseline of 7 to 8 percent by 2030 and 8 to 11 percent by 2050. However, this scenario is extreme, and the NRC Committee members disagreed about the feasibility of such a shift.

A study by the Urban Land Institute revealed that bundling land-use planning with policies to encourage modal shift away from single-occupancy trips could lead to GHG emission reductions from 6 to 10 percent below the study's baseline by 2030 and 9 to 15 percent below the baseline by 2050. There are two important factors to consider in interpreting these results. First, the policies that accompanied the land-use planning (e.g., public transit, multimodal freight strategies, and pricing) had a greater effect on the overall results than land-use planning alone. Second, for the maximum deployment case, 90 percent of all new development must be compact to reach the goal. (Cambridge Systematics, Inc., 2009).

Promotion of compact development faces important obstacles. Land use regulation is under local control, and local concerns about congestion, taxes, and home values may conflict with priorities such as energy security and climate change. Homeowners living in low-density communities may be opposed to higher density zoning in or near their neighborhoods. The NRC notes that state and citywide policies for promoting compact development are quite limited, and they speculate that strong political resistance explains the scarcity of such efforts (NRC, 2009b). The biggest opportunities for compact development appear to be in new housing construction and replacement units where higher density development is already occurring, such as near transit stops or areas where infill development is occurring.

This report's three scenarios were developed for a combined movement towards more compact and mixed land use and increased investment and other support for public transit, walking, and bicycling (**Table 9**). The primary GHG benefit comes from reduced VMT rather than actual mode shifts. Note that even in the high scenario, it is assumed that compact development does not encompass all new development, but attains a share of about 50 to 60 percent.

Table 9

Percent Change in Fuel Economy and VMT for LDVs and Freight Trucks Attributable to Particular Actions in the Low, Mid, and High Mitigation Scenarios Compared to the Reference Case

	2035			2050		
Report Scenario Assumptions for System Efficiency	Low	Mid	High	Low	Mid	High
Improving Traffic Flow (% change in mpg)	0%	1%	2%	0%	1%	2%
Ridesharing (% change in LDV VMT)	0%	–0.7%	–1.4%	0%	–1%	–2%
Route and Trip-Making Efficiency (% change in LDV VMT)	0%	–2%	–4%	0%	–5%	–10%
Efficient Driver Behavior (% change in LDV mpg)	2.5%	5%	10%	2.5%	5%	10%
Freight Logistics (% change in freight truck VMT)	0%	–2.3%	–5%	0%	–2.3%	–5%
Compact and Mixed Land Use (% change in LDV VMT)	–0.5%	–1%	–2%	–1.5%	–3%	–5%

2.6 Moving Away from Petroleum-Based Fuels

2.6.1 Difficulties of a Transition

As discussed in Section 2.1, improving the efficiency of gasoline- and diesel-fueled vehicles can greatly reduce oil use and GHG emissions—by up to 29 percent per vehicle for the LDV stock fleet from business-as-usual levels by 2035, and 44 percent by 2050. However, additional measures will be required to attain a large absolute reduction in transportation's GHG emissions. A primary option is the use of low-carbon fuels to displace petroleum-based fuels. From a climate change perspective, the lifecycle GHG emissions from a fuel must be considered;

such analyses must incorporate emissions from production, distribution, and vehicle operation including overall engine efficiency.[64]

Several attempts have been made in the United States to promote alternatives to petroleum-based fuels, including California's promotion of methanol and electric-drive vehicles, promotions of natural gas vehicles, and the Synthetic Fuels Corporation under the Carter Administration.

These efforts either failed or attained modest success at best, because of the entrenchment of an elaborate infrastructure for petroleum-based fuels, improvements in the already-excellent characteristics of gasoline and diesel fuels,[65] oil price volatility (which increases the economic risk to alternative fuel developers), and technical and cost barriers.

In the future, successful penetration of large numbers of alternative fuel vehicles, and substitution of significant quantities of gasoline and diesel fuels, will depend on several factors:

- Most importantly, cost-competitive vehicles and fuels
- A sustained and robust RDD&D program
- Avoidance of major mistakes (e.g. vehicle breakdowns and safety problems, and toxic emissions from fuel production) on the part of both vehicle designers and fuel providers
- A major commitment from government and/or industry to subsidize elements of the new fuel system including early development of refueling infrastructure
- Sustained high oil prices or government's willingness to use taxes or other pricing policies to keep petroleum-based fuel prices higher than the alternatives

Another factor that should be considered in developing programs to replace petroleum fuels with alternatives is the overall robustness of any new fuel system. Since gasoline and diesel fuel are energy dense and easily transported, petroleum-based systems tend to be quite robust in the face of local emergencies. In contrast, some alternative fuel sources, such as electricity and hydrogen, are vulnerable to local emergencies such as damage

64. See **Figure 9** for a breakdown of the expected range in miles per gasoline-equivalent gallon for a variety of vehicle types. The lifecycle GHG emissions from hydrogen, biofuels, electricity, and others all depend on how each fuel is produced and distributed, and how the performance of these vehicles evolve over time. How the lifecycle emissions of an alternative fuel compares to gasoline or diesel also depends on how the performance of conventional gasoline and diesel engines evolve over time, and whether, for example, the United States begins using higher-carbon feedstocks for fossil fuels. Lifecycle emission estimates vary widely because estimating these emissions, both now and in the future, requires making a number of critical assumptions.

65. Gasoline and diesel fuel are liquid fuels that are easily stored (without pressurization) and transported, high in specific energy (energy/weight) and energy density (energy/volume), and currently being manufactured with low sulfur content and other characteristics that allow stringent emission controls. Competing liquid fuels such as ethanol have lower energy density requiring larger fuel tanks; gaseous fuels such as methane and hydrogen require heavy, highly pressurized fuel tanks for equivalent range; and batteries for electricity storage have specific energies 100 or more times smaller than either gasoline or diesel.

to the electricity grid or the rupture of pipelines from earthquakes or other causes and significant resupply may be difficult because of these fuels' low energy density.

The current major candidates for significant displacement of gasoline and other petroleum-based fuels are hydrogen in fuel cell vehicles; liquid fuels from biomass (with corn-based ethanol already available in significant quantities); electricity; compressed and liquefied natural gas; and liquid fuels from coal and natural gas. For liquid fuels from coal or natural gas, carbon capture and storage (CCS)[66] will be required to avoid increases in GHG emissions. Liquefied petroleum gas (LPG) is also a viable substitute for petroleum fuels, but its supply is quite limited.

There have been numerous analyses of the prospects for these alternative fuels, including some studies that use complex market models. For example, Plotkin and Singh (2009) used a version of the National Energy Modeling System to examine prospects for advanced conventional vehicles, PHEVs and FCVs in the U.S. LDV market, and Greene, Leiby, and Bowman (2007) evaluated a transition to FCVs using an optimization model (HYTRANS) that incorporated the behavior of fuel suppliers, vehicle manufacturers, and consumers. Both of these analyses concluded that substantial quantities of fuel cell and other advanced vehicles could enter the U.S. market, but would require significant government subsidies to do so. It is also unclear how consumers are likely to react to these new vehicles and fuels.

2.6.2 Hydrogen

Hydrogen had, until quite recently, been considered the leading candidate for accomplishing large displacements of gasoline from the light-duty fleet. Hydrogen's attractiveness as a vehicle fuel stems from the high energy efficiency of fuel cell drivetrains,[67] the ability to produce hydrogen from a wide variety of feedstocks, the ability to rapidly refill the fuel tank (in contrast to battery recharging), and the lack of any harmful emissions from hydrogen fuel cell vehicles.

Concerns about the viability of hydrogen stem from the need to build an entirely new production, distribution, and refueling infrastructure to support a hydrogen-fueled fleet; hydrogen's low volumetric energy density, creating on-board fuel storage challenges; and the current high cost of fuel cells and fuel cell vehicles. Until recently, the use of hydrogen in fuel cell vehicles had been the DOE's primary focus in its long-term research

66. Carbon capture and storage generally involves removing CO_2 from an exhaust stream where it has been concentrated and transporting it to an underground storage site, possibly an exhausted natural gas or oil reservoir or deep saline formation.
67. A fuel cell drivetrain consists of a fuel cell system, hydrogen storage, an electric motor and controller, and a battery for hybrid vehicles. Fuel cell drivetrains have an energy efficiency of 50 percent versus approximately 20 percent for current spark-ignition conventional drivetrains.

program on transportation fuel options,[68] and the program had substantial success in bringing down the costs of fuel cells and other major components of a hydrogen-based system. However, the DOE's proposed FY2010 budget dramatically slashed hydrogen RDD&D funds in order to focus on nearer-term options, and the DOE's research emphasis appears to have shifted to plug-in hybrid electric vehicles (PHEV)[69] and other options.

Although hydrogen fuel cell vehicles emit no CO_2 or other GHGs, there are emissions from hydrogen production depending primarily on the feedstocks and conversion processes used, and fuel distribution can also add to GHG emissions.[70] Most hydrogen produced today is obtained from natural gas using a process called Steam Methane Reforming (SMR). Although natural gas is likely to provide much of the hydrogen initially used in fuel cell vehicles, other feedstocks including biomass and coal may eventually dominate, and electricity may play a role in some markets.[71] Bandivadekar (2008) projects that a 2035 fuel cell car fueled with hydrogen from natural gas would have lifecycle GHG emissions slightly higher than a 2035 HEV (192 grams per mile versus 175 grams per mile) at an additional cost of $1,800. This balance would change dramatically if the natural gas conversion included CCS, which would drop the lifecycle emissions of the FCV to very low levels.

With many of the components of a hydrogen fleet and its refueling infrastructure at an early stage of development, it is not surprising that competing analyses offer quite different views of the future prospects for hydrogen as a vehicle fuel. For example, Greene, Leiby, and Bowman (2007) examined three scenarios in which government support coupled with strong technological progress (attainment of DOE targets) helped bring 2 to 10 million FCVs into the LDV market by 2025 and determined that the transition to hydrogen could be sustained past that date. Depending on the scenario chosen, policies enacted, and degree of industry cost sharing, the estimated cost to the government of the transition was $8 to $45 billion. Plotkin and Singh (2009) found that with expected future costs for FCVs, attaining significant penetration of hydrogen into the LDV market could be obtained only by offering $7,500 per vehicle subsidies for FCVs until at least 2050. Those subsidies yielded a 64 percent FCV share of the new vehicle fleet by 2050.

Another scenario examined the impacts of breakthroughs in fuel cell costs, where optimistic DOE cost goals were fully met. In this case, FCVs attained a 25 percent share of the LDV new vehicle market by 2050 without vehicle subsidies but with a jump-start of hydrogen fuel stations; without the jump-start support, FCV share was only 7 percent in 2050.

68. To the degree that the NRC, in its annual review of the Hydrogen Program, urged the DOE to evaluate other fuels that could attain the same national goals as the Hydrogen Program, National Research Council, 2004.
69. PHEVs are hybrids with larger batteries that can be recharged by the grid and thus can "electrify" a portion of a vehicle's daily travel.
70. Through energy required to transport and compress the hydrogen.
71. Obtaining hydrogen from electrolysis currently is more expensive than producing it from fossil fuels, but electrolysis may make economic sense in isolated locations, and technology changes may shift the relative economics of the competing production processes.

Probably the greatest challenge facing hydrogen is that significant penetration of fuel cell vehicles will almost certainly require a large government commitment of financial support before many of the projected reductions in costs (from learning-by-doing and mass production) and improvements in performance can occur. Financing a refueling infrastructure is a major challenge for hydrogen.

2.6.3 Biomass Liquid Fuels

Using biomass as a feedstock for liquid fuels is another promising alternative to petroleum-based fuels. Potential biomass fuels include ethanol made by converting sugar and starch crops or cellulosic material, biobutanol from the same processes,[72] biodiesel from oil crops or from pyrolysis of cellulosic feedstocks, and multiple liquids from Fischer-Tropsch conversion of biomass. Ethanol from corn, used primarily as a blending agent in gasoline, is currently the most successful alternative transportation fuel,[73] with U.S. production of 10.6 billion gallons (about 7 billion gallons gasoline-equivalent) in 2009 (Renewable Fuels Association, 2010). Brazilian production of ethanol from sugar cane is close behind, with about 7 billion gallons of ethanol in 2009 (RenewableEnergyWorld.com, 2009). That compares to the consumption target of 15 billion gallons of ethanol (mostly corn) by 2015 in the 2007 Energy Independence and Security Act (EISA).[74]

Because regrowing biomass harvested for fuel production absorbs much of the CO_2 emitted by vehicles burning the fuel, biomass fuels have been viewed as a key source of large reductions in GHG emissions. However, obtaining such reductions depends on minimizing GHG emissions from growing and harvesting the biomass (e.g., from fertilizer and pesticide production and use or fossil fuels used in harvesting) and converting it to useable fuels, and avoiding potential negative impacts from land use changes that may arise either directly or indirectly from harvesting biomass.[75]

The magnitude of GHG emissions from land use changes caused by biomass fuels is controversial. Some analysts have claimed that indirect land use changes from corn-based ethanol and even cellulosic ethanol will substantially *increase* GHG emissions compared to using gasoline (Searchinger, 2008). Others, including the U.S. EPA, have argued that both corn-based and cellulosic ethanol can be grown without large adverse secondary land use impacts, thus with substantial lifecycle GHG emission reductions compared to gasoline (Tyner, 2010;

72. Biobutanol is more compatible with the current gasoline infrastructure than ethanol is, because biobutanol can be mixed with gasoline at the refinery and shipped in pipelines, whereas ethanol absorbs water, causing pipeline corrosion, and must be mixed with gasoline at terminals close to markets.
73. Wood and wood waste products are another very successful biomass fuel used to generate over 2 trillion Btus of electricity and heat per year, primarily in the forest products industry (EIA, 2009d).
74. The overall biomass fuels target is 36 billion gallons by 2022; after 2015, increases are to come from advanced biofuels with a greater than 50 percent GHG reduction compared to gasoline.
75. An example of a direct land-use effect is the clearing of forests to grow biomass for fuel; an indirect effect is the clearing of forests to grow crops that were displaced elsewhere by their cropland being converted to a biomass plantation.

EPA, 2010c). Avoidance of indirect land use impacts depends on continued increases in yields of corn and other biomass as well as increases in conversion efficiency of ethanol production. It also requires optimum use of ethanol byproducts to replace corn proteins in cattle feed,[76] and careful selection of lands for biomass plantations to avoid cropland conversion. Finally, it depends on how farmers in developing nations respond to higher crop prices, i.e., whether they farm more intensively or put more land into production. It therefore is prudent to continue to study the issue of indirect land use impacts.

Looking at just the direct impacts, it is clear that net lifecycle GHG emissions from corn ethanol have declined. The reasons include increasing crop yields, increasing distillery efficiency, and a shift in distillery fuel from coal to natural gas. EPA has concluded that corn-based ethanol produced in a natural gas-fired (or biomass or biogas-fired) facility using "advanced efficient technologies" (technologies EPA considers typical of new production facilities) will have lifecycle GHG emissions at least 20 percent below 2005 gasoline levels taking international land use changes into account (EPA, 2010a).

Obtaining further GHG reductions from biomass fuels requires that biomass feedstocks be restricted to residuals from forestry and farming operations, municipal solid waste, and crops grown on marginal lands that are not used for food and feed production. The National Academy of Sciences estimates that about 400 million dry tons per year of biomass feedstocks are available in the United States without significant impacts on food prices or the environment (NRC, 2009c). This much biomass could provide enough liquid fuel to displace about 22 billion gallons of gasoline (about 16 percent of current U.S. consumption). Over time, the available feedstock could grow to 550 million dry tons of biomass by 2020, capable of providing enough liquid fuel to displace 29 billion gallons of gasoline (NRC, 2009c). However, NAS estimates that in 2020, ethanol produced from this biomass would be cost-competitive with gasoline without a price on carbon only if oil prices exceeded $100 per barrel. Other fuels that might be more compatible with the current infrastructure have even higher costs.

2.6.4 Electricity

The combination of major improvements in electric drivetrains (both improved performance and reduced costs) stimulated partly by the production and sale of millions of gasoline-electric hybrids, and growing interest in PHEVs has revived interest in electricity as a transportation fuel. Despite major improvements in batteries, pure electric vehicles remain extremely range-limited.[77] PHEVs overcome the range limitation by allowing normal

76. A byproduct of ethanol production is either wet or dry distillers grains, which are high protein feeds for cattle and a substitute for proteins from soybean and corn meal.

77. The weight of the batteries needed to allow an EV to attain ranges much above 100 miles begins to escalate sharply with higher range, because the high battery weight degrades vehicle efficiency—which in turn requires higher battery power and energy storage, and more weight, leading to a vicious spiral.

operation using liquid fuels after the battery has been depleted, and allow the use of smaller, and therefore less expensive batteries compared to pure electric vehicles (EVs)—though with added costs for the engine-based drivetrain. Because most LDVs are driven for relatively short distances on most days, a PHEV with 40 miles of electric range (PHEV40) can electrify about 60 percent of vehicle miles driven.[78] Even cheaper PHEVs with a 10-mile electric range (PHEV10) should be able to electrify about 20 percent of miles driven.

There is considerable disagreement about likely costs, however. The NAS recently concluded that current PHEV battery packs would cost well over $1000 per kilowatt-hour (kWh),[79] dropping over the next 10 years to about $400 per kilowatt-hour (kWh) (NRC, 2010a). Nelson et al. (2009) estimate that, in mass production of 100,000 battery packs per year, PHEV20 battery packs would cost $255 per kWh and PHEV40 battery packs would cost $210 per kWh. A key difference in battery cost estimates seems to be disagreement about the level of maturity of automotive-scale Lithium-ion batteries and thus the potential for further improvements and cost reductions. However, at least four new Lithium-ion chemistries are currently being developed for near-term PHEVs (Santini, 2010) with the potential for lower cost and higher available specific energy.[80] Further, the NAS assumes that only 50 percent of the energy stored in PHEV batteries will be accessible, to assure the needed battery longevity. Although first generation PHEVs appear to be adopting this limitation on battery availability, this is almost certainly a conservative approach and it seems likely that the NAS estimates will prove to be overly pessimistic.

The NAS assessment developed two scenarios for PHEV deployment—a maximum practical scenario yielding 40 million PHEVs on the road by 2030 out of a total fleet of 300 million, rising to nearly 250 million PHEVs by 2050, and a more probable case yielding 13 million PHEVs by 2030 and about 100 million by 2050 (NRC, 2010a).[81] Both of these scenarios appear to be quite optimistic, conditioned at a minimum on substantial cost reductions in PHEV batteries, strong incentives to potential purchasers, and major infrastructure investments in charging stations and electricity distribution networks.

The GHG emission reduction potential of PHEVs depends on the source of the electricity used for recharging. *On the Road in 2035* (Bandivadekar, A. et al., 2008) estimates that in 2035, PHEV30s would emit

78. Operating either all electrically for the first 40 miles of each day (assuming a fully charged battery), or in "blended mode" (where the engine is used when high power is required) for somewhat more than 40 miles to reach the battery's minimum charge level. The 60 percent electrification assumes that the PHEV driver is an "average" driver. Presumably, vehicle purchasers will select PHEV ranges that maximize their electricity usage, because travel on electricity generally will be considerably much less expensive than travel using gasoline, at least in terms of fuel cost. (The fuel cost of a 300 Wh per mile EV using $0.10 per kWh electricity would be $0.03 per mile. With $3.00 per gallon gasoline, even a 50 mpg car would use $0.06 of gasoline per mile.)

79. The Chevrolet Volt, designed to go between 25 and 50 miles on battery energy before shifting to engine power, has a battery pack capacity of 16 kWh (General Motors, 2010).

80. A battery's specific energy is the amount of electricity it can store with each unit of weight, e.g. watt-hours per kilogram; its specific power is the amount of power it can produce with each unit of weight, e.g. watts per kilogram.

81. Both scenarios envisioned combinations of PHEV10s and PHEV40s.

about the same GHG emissions as hybrids without plug-in capability if the electricity used in recharging was identical to current U.S. average generation. Obtaining substantial reductions past this level would require, therefore, considerable progress decarbonizing the U.S. electrical grid, as illustrated, for example, in **Figure 5**.

Pure battery electric vehicles seem unlikely to significantly replace internal combustion engine-based vehicles in the near future because of high costs and energy storage challenges. Recent analyses have found that vehicles with ranges of 200 miles and above will be significantly heavier than competing vehicles, reducing overall efficiency. *On the Road in 2035* (Bandivadekar, A. et al., 2008) assumes that, in 2035, the Lithium-ion batteries in an EV with 200-mile range would have a specific energy of 150 watt-hours (Wh) of useable energy per kg. A midsize EV passenger car would weigh nearly 3600 pounds compared to about 2800 for a comparable 2035 car with a gasoline engine.[82] The EV would cost $14,400 more than the competing 2035 gasoline fueled car, and $11,900 more than a 2035 gasoline fueled HEV. The EV's lifecycle GHG emissions would be higher than those of a gasoline fueled HEV (230 grams per mile assuming average U.S. electricity versus 175 grams per mile) unless the carbon intensity of the power sector is reduced.

An additional concern about EVs is charging time, estimated to be 7 to 30 hours for a 200-mile range vehicle depending on whether 240V current or regular 120V household current is used.

A more optimistic view of EVs' future exists, but it will take heroic progress in battery development to achieve much higher specific energy and much lower cost—and even then EVs with high mileage range would likely still be heavy and expensive.[83] EVs could, however, play a role as limited-range urban and niche vehicles. Nissan has introduced the Leaf, a subcompact EV with a 100 mile announced range, with an initial price of $32,800 (less a $7,500 Federal tax credit); other EVs with similar range (e.g., Ford Focus EV) will follow. These vehicles enjoy the benefits of being able to recharge at home and cheaper fuel. However, the potential market for these vehicles is highly uncertain at this time.

2.6.5 Coal-to-Liquid Fuels

Coal is also a viable source of liquid fuels, and the NAS estimates that such fuels could compete with gasoline at oil prices as low as $60 per barrel (NRC, 2009c). However, such fuels would provide few or no GHG benefits with CCS used in their production—and would cause large increases in CO_2 emissions if CCS were not used (EPA, 2007; Wang, 2007; DOT, 2010a).

82. A similar analysis by Thomas (2009) estimated vehicle weight at about 3,700 pounds with the same specific energy assumption and over 6,000 pounds for a 300-mile range vehicle.
83. For example, a 300-mile range EV would require about 75 kWh of useable energy for a small to midsize car. Even at an optimistic 300 Wh of useable energy per kg and $200 per kWh, the battery would weigh 550 pounds and cost $15,000.

2.6.6 Natural Gas

As with coal, natural gas can be transformed into liquid fuels using Fischer-Tropsch technology, but with only modest GHG benefits if CCS is used in making the fuels (Wang, 2007). However, vehicles fueled directly by compressed or liquefied natural gas (NGVs) do offer reductions in GHG emissions compared to gasoline and diesel-fueled vehicles. DOE estimates that a dedicated compressed natural gas (CNG) vehicle will obtain about the same fuel economy, on a gasoline-equivalent basis, as an otherwise-identical gasoline-fueled vehicle (DOE, 2010d). Using Argonne National Laboratory's GREET model to estimate lifecycle GHG emissions, this implies that the CNG vehicle has 15 percent lower lifecycle GHG emissions than a similar gasoline-fueled vehicle.

New engine designs may allow bi-fuel engines (primarily natural gas and gasoline) to obtain substantial CO_2 reductions burning natural gas while providing fueling flexibility to overcome natural gas's refueling infrastructure issues. For example, Volkswagen's Passat Ecofuel sedan uses both a supercharger and a turbocharger to get maximum performance and efficiency when operating either on gasoline or natural gas, with 23 percent lower GHG emissions operating on CNG than on gasoline (Volkswagen AG, 2009).

Worldwide, there are more than 9.5 million NGVs on the road, and their numbers have been growing by 30 percent annually since 2000 (IANGV, 2010). While there are only a little over 100,000 NGVs deployed in the U.S. (Yborra, 2008), about one-fifth of full-size transit buses are fueled by natural gas, and there are thousands of natural-gas fueled airport shuttles, delivery vans, trash haulers, and other vehicles.

NGVs could be part of a U.S. strategy to reduce GHG emissions and increase energy security. Given recent shale gas discoveries, they could be fueled by domestic gas.[84] They also provide significant reductions in emissions of particulate matter, NO_X, and hydrocarbons. However, use of natural gas to replace coal in the electricity sector would provide a bigger GHG benefit (on the order of a 50 percent reduction) than using natural gas in vehicles.

2.6.7 Report Scenarios for Alternative Fuels

The three scenarios in this report all include biomass fuels and PHEVs. In the Low and Mid Mitigation Scenarios, reductions in the carbon intensity of LDV fuels are achieved by greater use of these and other technologies. Hydrogen fuel cell vehicles or battery electric vehicles and advanced biofuels from algae and other sources enable even greater decarbonization in the High Mitigation Scenario in 2050.

Each scenario has a mix of PHEV ranges, from 10 to 40 miles, with the more aggressive scenarios tending more toward the longer ranges (see **Table 10**). As a result, in the Low Mitigation Scenario electricity powers about

84. There remain some environmental concerns with accessing shale gas, including concerns about contamination of freshwater aquifers from the hydraulic fracturing used in gas recovery.

Table 10

Assumptions for Alternative Fuel Use in LDVs, Freight Trucks, and Air Transportation in the Low, Mid, and High Mitigation Scenarios.

	2035			2050		
Report Scenario Assumptions for Alternative Fuels	Low	Mid	High	Low	Mid	High
PHEV LDVs** (million vehicles)	1	3	*	10	20	*
Total Biofuel Production (billion gallons)	35	45	*	50	60	*
Corn Ethanol Production (billion gallons)	15	15	*	15	15	*
Algae-based Liquid Fuel Production*** (billion gallons)	0	0	*	0	0	*
Alternative Fuels for LDVs**** (% change in fuel carbon intensity compared to reference case)	–5%	–10%	–15%	–5%	–10%	–47.2%
Advanced biofuels for freight trucks**** (% change in fuel carbon intensity compared to reference case)	–2%	–10%	–15%	–10%	–15%	–37.5%
Advanced biofuels for air transportation (% change in fuel carbon intensity compared to reference case)	0%	–10%	–15%	–10%	–15%	–37.5%

**There are many ways to achieve the fuel carbon intensity reductions defined here. While PHEVs and advanced biofuels will likely play a role (as will hydrogen fuel cell vehicles), this report does not specify specific targets for each to emphasize that there are multiple pathways that could achieve the GHG emission reduction goals and that it is unclear at present which path might be taken.*
*** In each scenario, the PHEVs are assumed to displace grid-independent hybrids; they are not additive to the substantial number of hybrids assumed to be in the fleet.*
**** These fuels are assumed to achieve an 80 percent reduction in GHG emissions compared to conventional diesel.*
***** Also includes impact from a low carbon fuel standard and renewable fuel standard.*

30 percent of PHEVs' VMT and 40 percent in the Mid Mitigation Scenario. The fuel economy and carbon intensity objectives of the High Mitigation Scenario can be achieved by a variety of mixes of advanced technology vehicles, as discussed in Section 2.1.2. Because all three scenarios include reductions in the carbon intensity of the electric sector, the PHEVs attain GHG emissions significantly lower than competing vehicles.

2.7 Potential Breakthrough Technologies for the Long Term

2.7.1 Speculative Technologies

The following three (among many) technologies appear to be capable of fundamentally altering the prospects for major reductions in GHG emissions from transportation—assuming that RDD&D challenges can be met. Two—algae-based liquid fuels and automated highways—have been incorporated into the High Mitigation Scenario of future U.S. transportation.

2.7.2 Lithium Air Batteries

Obtaining higher energy densities in batteries is crucial to developing electric vehicles with longer ranges. Gasoline's energy density is about 13,000 Watt-hour (Wh) per kg compared to current Lithium-ion batteries' 100 to 200 Wh per kg, nickel metal hydrides' 60 to 120 Wh per kg, and lead acid's 25 to 40 Wh per kg.

A number of research organizations are trying to develop practical lithium metal-air batteries. The anode (the negative electrode) is made of lithium metal, while the surrounding air acts as a cathode (or positive electrode). Potential energy densities are 5,000 Wh per kg and higher, enough to allow EVs to attain ranges equal to those of internal combustion engine (ICE) vehicles. These batteries could also be used to store electricity for the power grid, improving penetration of intermittent electricity sources such as wind and solar.

2.7.3 Third Generation Biofuels

Current biofuel efforts are focused on relatively conventional crops ranging from corn to fast growing grasses. All are limited by large acreage requirements; fuel yields per acre per year range from 50 gallons of biodiesel from soybeans to about 440 gallons of ethanol from corn (ExxonMobil, 2010; Argonne National Laboratory, 2010). So-called third generation biofuels offer much larger yields. Obtaining oils from algae grown in open ponds or in closed-system bioreactors offers yields at least an order of magnitude larger than conventional crops, with yield estimates well over 5,000 gallons per acre per year.

Algae has the advantage of producing oils that can be converted into diesel, biogasoline, or jet fuel, and carbohydrates that can be fermented into bioethanol and biobutanol; there also is the potential for algae to directly produce hydrogen. Production also does not require fertile land or high quality water, avoiding conflicts with food and feed production. And algae grow quickly, especially if fed with concentrated CO_2, such as exhaust streams of fossil power plants.

The challenges to algae-based fuel production include finding strains that have both high oil content and resistance to viral infection, and reducing the costs of growing, harvesting, and fuel processing.

2.7.4 Automated Highways

By 2050 it is conceivable that portions of the nation's highway system could operate in an automated mode, allowing vehicles to "drive themselves" in coordination with other vehicles and interacting with the highway system (Shladover, 2000). The potential benefits include reduced accidents, increased capacity, and 10 to 20 percent reductions in GHG emissions. Fully automated highways face social and institutional as well as technical hurdles, the most important of which is demonstrating reliability.

Table 11

Percent Change in Fuel Economy for LDVs and Freight Trucks from Breakthrough Technologies Used in the Low, Mid, and High Mitigation Scenarios Compared to the Reference Case

	2035			2050		
Report Scenario Assumptions for Breakthrough Technologies	Low	Mid	High	Low	Mid	High
Automated Highways for LDVs (% change in mpg)	0%	0%	0%	0%	0%	5%
Automated Highways for freight trucks (% change in mpg)	0%	0%	0%	0%	5%	10%

This section has reviewed a range of options to reduce transportation GHG emissions. The next section will review policy options for realizing these potential reductions.

3. Policies to Promote Mitigation

3.1 Introduction

Reducing GHG emissions from transportation requires public policies to implement or induce the mitigation strategies described in the previous section. As with other forms of air pollution, climate- altering GHG emissions are what economists call a "public good externality." In the absence of appropriate public polices, markets fail to adequately control environmental externalities, resulting in excessive pollution. Transportation vehicles emitting CO_2 in the United States are changing the climates of all the world's nations. But in deciding what kinds of vehicles to buy, how much to travel, and how much freight to move, individuals do not appropriately consider these global impacts. Motorists pay for vehicles, for the gasoline they use, and (through gasoline and other taxes) most of the cost of building and maintaining the roads they drive on, but they do not pay for polluting the global atmosphere. When polluting the atmosphere is free, protecting the environment requires public policy action. However, as mentioned in Section 1.2.3, pricing GHG emissions alone will not get the job done for transportation.

In determining what public policies are needed, it is important to understand behaviors of the private market in the current environment.

First, land use control is a local government function, but state and federal policies can have an effect. Land markets will respond to carbon prices, but given the important role of government regulation, there is little reason to expect the responses to be economically efficient (NRC, 2009b, p. 79).

In addition, motor vehicle fuel economy is subject to what energy economists have called the "energy efficiency paradox." Markets fail to adopt energy-efficient technologies that are cost-effective when considering the full value of fuel savings over the life of a vehicle. The energy paradox is found in many markets for energy-using equipment, from refrigerators and home insulation to compact fluorescent light bulbs. The new field of behavioral economics provides an explanation for the paradox in the theory of loss aversion. Loss aversion, perhaps the most well established principle of behavioral economics, states that when faced with a risky bet, consumers typically exaggerate the probability of losing money and overvalue potential losses relative to potential gains by approximately a factor of two (DellaVigna, 2009). Paying more up front for fuel economy appears to be a risky bet because many factors are uncertain: future fuel prices, real-world fuel economy, useful life, and actual miles of use. As a result, manufacturers and consumers may pass up substantial opportunities to improve fuel economy, options that would easily pay for themselves based on the *expected* value[85] of future fuel savings (Greene, German, & Delucchi, 2009; Greene, 2010c). Addressing the energy efficiency paradox can have a much greater impact on CO_2 emissions than carbon prices in the range of $25 to $50 per ton of CO_2 (Allcott & Wozny, 2009).

It is also critical to highlight that GHG mitigation policies for transportation provide additional public benefits. Reducing GHG emissions will also reduce dependence on petroleum and improve energy security (CFR, 2006). By promoting energy efficiency and increasing the use of renewable energy, it may also contribute to the creation of a sustainable energy system. When such co-benefits are taken into account, much stronger mitigation actions become cost effective.

Finally, reductions of 50 percent or more from 2005 levels by 2050 will require the use of technologies unproven today. It is widely recognized that firms are not able to capture the full benefits of technological innovation and, as a result, markets tend to systematically under-invest in RDD&D especially for public goods (Jones & Williams, 1998; Margolis, R.M., Kammen, D.M., 1999) . The energy efficiency paradox only makes this underinvestment worse. Consequently, public RDD&D policy must be a key component of a comprehensive policy strategy.

3.2 Fuel Economy and GHG Standards

3.2.1 Fuel Economy and GHG Standards for Light-Duty Vehicles

Fuel economy and GHG standards have become a universally accepted method of reducing oil use and GHG emissions from LDVs. **Figure 12** shows the range of standards currently in force worldwide.[86]

The desirability of fuel economy regulations has been especially controversial in the United States. The arguments against standards focus on their claimed economic inefficiency and the higher air pollution, congestion, and traffic injuries and fatalities caused by any increase in driving associated with reduced fuel consumption (and costs) per mile, the "rebound effect" (Plotkin & Singh, 2009).[87] Arguments for standards focus on fuel savings and reductions in GHG emissions having higher value to society than to individual consumers and evidence that vehicle purchasers do not really weigh the tradeoff between fuel economy and increased purchase costs when they make

85. Statistically, the expected value is the mean of a probability distribution. In this case, when economists or engineers calculate the value of fuel savings from increasing fuel economy, they pick average or consensus values for variables that are uncertain, such as the price of fuel or vehicle lifetime. This results in a single value for future fuel savings, analogous to the statistical expected value.

86. The values shown in the figure have been normalized to adjust for differences in the test procedures used to measure either fuel consumption or GHG emissions.

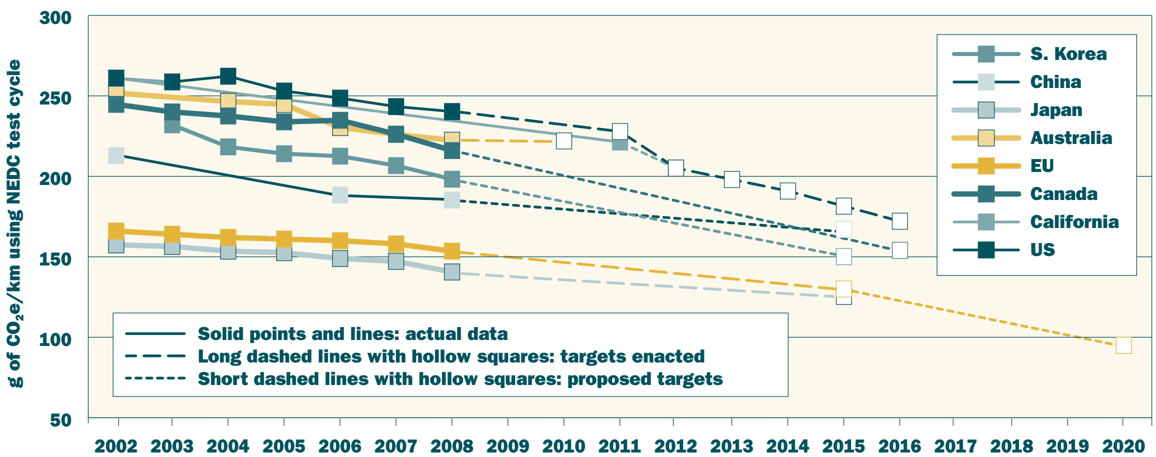
87. Recent analyses put the driving rebound in the United States at about a 10 percent increase in driving from a 100 percent increase in fuel economy, with the effect trending downwards with increasing income (Small & Van Dender, 2004).

buying decisions (Turrentine & Kurani, 2007). Proponents cite studies showing that the fuel economy rebound effect is small and could be compensated for by modestly higher fuel taxes or other VMT policies (Small & Van Dender, 2007; Greene, 2010b).

Vehicle safety issues have also been a source of vigorous arguments between supporters and opponents of new standards in the United States. The fact that the new U.S. fuel economy and emission standards are indexed to vehicle size addresses safety concerns by removing incentives for manufacturers to downsize vehicles in order to meet the standards.[88]

Figure 12

GHG Emission Targets in Different Areas, Adjusted to Take Account of Differences in Driving Cycle



The EPA, the National Highway Traffic Safety Administration (NHTSA), and the State of California are evaluating standards for the post-2016 period, and the White House recently issued a Presidential Memorandum that called for EPA and NHTSA to jointly develop new GHG and fuel economy standards for the 2017 to 2025 period that are harmonized with California and other state standards (White House, 2010).

Decisions about new standards will have to deal with the structure of the standards and their stringency. The current standards are attribute standards rather than being uniform. They tie fuel economy or GHG targets to vehicle attributes such as weight, engine displacement, or size. The current U.S. structure ties variable fuel economy targets to vehicle footprint—wheelbase multiplied by track width (in other words, the larger the vehicle footprint, the lower the fuel economy target).

88. The footprint-based targets do not encourage downsizing and may encourage some increases in track width and wheelbase (since such increases would yield a less stringent fuel economy and GHG emissions target). Any increase in track width should discourage rollovers; wheelbase increases should improve directional stability and may allow more crush space for occupant protection.

Uniform standards are easy to explain and, on one level, seem fair, but imply different levels of stringency depending strongly on the types of vehicles each manufacturer produces (makers of primarily small vehicles will find it much easier to meet such a standard than will makers of a wide mix of vehicles). Such standards provide a strong incentive towards smaller vehicles.[89]

Attribute-based standards will tend to narrow the differences among vehicle manufacturers in the "degree of difficulty" of the targets. A criticism of attribute-based standards, however, is that they do not guarantee reaching a fuel economy (or GHG) target, since fleet attributes can change—thus changing the numerical target. And the choice of attributes matters—a weight-based standard may remove incentives for weight reduction, a valuable fuel-saving option.[90] The footprint-based standard in the new U.S. system may offer some safety benefits because it brings a positive incentive to lengthen the wheelbase and widen track width (which may enhance vehicle stability).

Another crucial aspect of a standard's structure is the degree of trading of fuel economy or GHG credits allowed. The new U.S. standards are aimed at manufacturers' fleet averages, not individual vehicles or groups of vehicles, and allow manufacturers to "bank" and "borrow" credits (save credits earned in one year to use in a future year, or borrow from expected future credits), average across cars and light-duty trucks, and trade credits across manufacturers. The European system will allow manufacturers to form pools that can meet targets as one unit, but does not establish a formal market for tradable credits. The Japanese and Chinese systems are much less flexible. The more flexible systems help reduce the costs of compliance and may also allow higher targets to be set.

The current U.S. standards set fleet targets for 2016 of 37.8 mpg for passenger cars and 28.8 mpg for light-duty trucks.[91] Since the current standards now use 2016 as a target date, new standards might focus on 2025 to 2030, perhaps with intermediate targets (as noted, EPA and NHTSA are now working on new targets for the post-2016 timeframe). A key consideration for this timeframe will be the extent to which new standards assume that targets should reflect significant contributions from hybrids, PHEVs, EVs, fuel cell vehicles, and other advanced drivetrains.[92]

89. The question of whether such incentives are appropriate is controversial, and some countries have focused more on them than others.
90. Some incentive may be retained by deliberately allowing stringency to vary along the weight curve, giving less difficult targets favoring lighter, smaller vehicles.
91. Assuming no significant change in the fleet's average track width and wheelbase values (Federal Register, May 7, 2010, page 25330).
92. Through 2016, EPA and NHTSA used a tank-to-tailpipe standard, which treated electric vehicles as zero emission vehicles (ZEV). For 2016–2025 standards, a well-to-wheels standard may be considered which could impact the credits generated by EVs, PHEVs, and other alternative-fueled vehicles.

3.2.2 Heavy-Duty Vehicle Fuel Economy Standards

Heavy-duty vehicles—large freight trucks, buses, and specialized vehicles such as urban garbage trucks—account for 18 percent of the U.S. transportation sector's oil use and CO_2 emissions, and their oil use and CO_2 emissions are growing rapidly (EIA, 2010a).

Both Japan and the European Union have taken steps to regulate efficiency of these vehicles. Japan instituted fuel consumption regulations for heavy-duty trucks in 2006, with target consumption levels for 2015. The European Union has the goal of promulgating a CO_2 emission standard for heavy-duty trucks by 2013–2014. Unlike the Japanese standard, which regulates engines only, the EU plans to regulate vehicle fuel consumption and emissions, and they plan to structure the regulation to control emissions on a unit-of-work basis.[93]

The U.S. EPA has initiated a voluntary program for heavy-duty trucks and other vehicles, called SmartWay. SmartWay certified tractors must have aerodynamic improvements like roof fairings or cab side extenders, idle reduction and low rolling resistance tires, and a 2007 or newer engine; trailers must have low rolling resistance tires and aerodynamic measures such as a rounded tail (EPA, 2010d).

Using the SmartWay program as a guide, the State of California has moved to regulate heavy-duty truck fuel consumption. Starting with model year 2011, California will require all sleeper-cab tractors designed to haul 53-foot and longer trailers, as well as the trailers themselves, to be EPA SmartWay certified. Further, older trailers will be required to begin retrofitting SmartWay technologies, over a phase-in period. Other states may "opt in" to California's standards or comply with national standards set by the EPA.

U.S. development of fuel economy or CO_2 emission standards for heavy-duty vehicles could reduce the projected growth in these vehicles' oil consumption and CO_2 emissions. Regulators should be able to use the experience gained by the Japanese and Europeans to help build a regulatory structure. With an industry with multiple small and moderate-sized manufacturers and generally separate tractor and trailer manufacturers, as well as a large array of vehicle types and duty cycles, regulators will have to choose an appropriate regulatory design carefully, including the choice of where to place the compliance obligation. The Administration has now asked the EPA and DOT to develop new standards for medium- and heavy-duty trucks by July 30, 2011, with projected standards to go into effect for the 2014 model year (White House, 2010).[94]

93. In the EU, emissions will be measured as grams per ton-kilometer, grams per cubic meter-kilometer, or grams per passenger-kilometer, depending on the type of vehicles being regulated, rather than grams per kilometer, the standard measure for LDVs (NRC, 2010b).

94. As with LDVs, the EPA will define a standard for GHG emissions and the DOT will define a fuel efficiency standard for medium- and heavy-duty trucks.

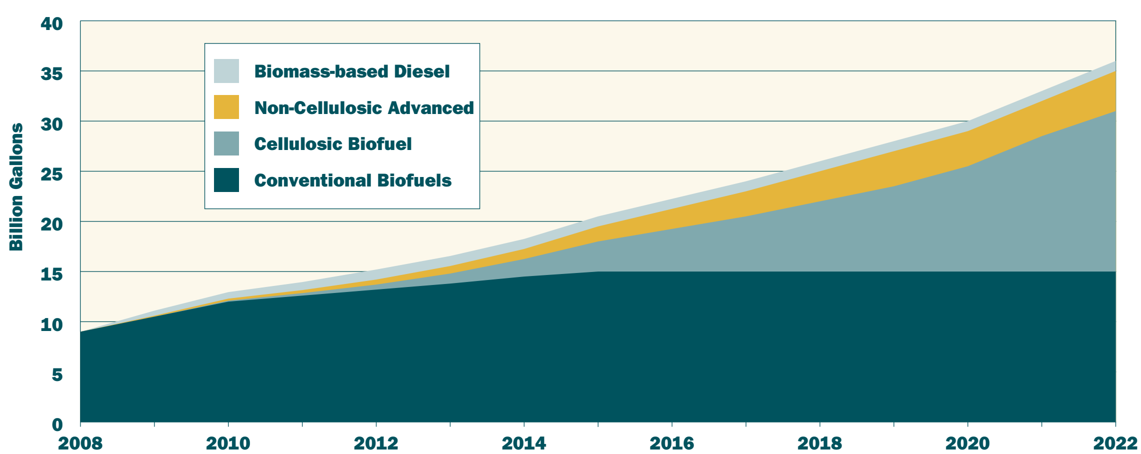
3.2.3 Renewable and Low-Carbon Fuel Standards

Renewable and low-carbon fuel standards guarantee an outcome but not the cost. Renewable fuel standards (RFS) specify that the fuel must be derived from renewable energy resources. Low-carbon fuel standards (LCFS) require a reduction in the carbon content of fuels on a lifecycle basis—from "well to wheels." They are performance standards so they do not give preference to any particular energy resource and thus allow greater flexibility and scope for innovation. They also bring with them the full set of regulatory issues, including how to measure, certify, and enforce the carbon content of fuels. A critical issue is ensuring reductions for the full lifecycle GHG emissions of each fuel. The current U.S. RFS has some attributes of an LCFS in that it requires the renewable fuels to be low-carbon.

The EPA's rulemaking establishing the new Renewable Fuel Standard (RFS2) under the Energy Independence and Security Act of 2007 calls for 36 billion gallons of renewable fuels to be sold for use by highway vehicles by 2022 (EPA, 2009a). Of this total, 15 billion gallons may be ethanol produced from food feedstocks (e.g., corn) and the remainder must be either "advanced" or cellulosic biofuel (**Figure 13**). Advanced biofuels must reduce lifecycle GHG emissions by 50 percent relative to gasoline while cellulosic biofuel must achieve a 60 percent emissions reduction.[95] To qualify under the standard, a renewable fuel must achieve at least a 20 percent reduction in GHG emissions, a target that U.S. corn-based ethanol just meets according to the EPA's assessment. The EPA reduced the requirement for 2010 from 100 million gallons of cellulosic biofuel to just 6.5 million gallons because it was clear that capacity did not exist to produce 100 million gallons.

Figure 13

EPA **Renewable Fuels** Volume Requirements



95. Here, lifecycle GHG emissions include indirect land use change.

California's LCFS requires the carbon content of all fuel sold for transportation use in California (except for jet fuel and fuels for certain watercraft) to be reduced by 10 percent by 2020 (CARB, 2010) on a lifecycle basis. The LCFS takes into account carbon emissions from indirect land use changes that occur outside of the United States. According to the California Air Resource Board, corn-based ethanol from the U.S. Midwest has on average about 4 percent higher lifecycle emissions than gasoline, although corn-based ethanol can reduce emissions by 19 percent or increase them by 10 percent depending on the process (CARB, 2010).[96]

In contrast to the RFS, which only includes biofuels, the LCFS is designed to be a performance-based standard. Any fuel that meets the lifecycle carbon emissions requirement (and other transportation fuel regulations) can be used to meet the standard, thus inducing innovation in the fuels sector and achieving more cost-effective reductions in GHGs than policies that focus on a specific fuel (Farrell & Sperling, 2007). Critics argue that the policy would increase "leakage," an increase in carbon intensity outside of California as suppliers preferentially send low-carbon stocks to California. Proponents expect California's actions to demonstrate the feasibility of the LCFS as a national policy, and are hopeful that it will be adopted nationwide, reducing the potential for leakage.

3.2.4 Report Scenarios for Fuel Economy and GHG Standards

This report used the policies described above in each scenario in combination with other mitigation options described in Section 2 and pricing options described in Section 3.2.4. The fuel economy targets for both LDVs and freight trucks are designed to achieve the levels cited in **Table 2** and **Table 5**. For LDVs, the 2035 targets (in EPA test mpg) for the Low, Mid, and High Mitigation Scenarios are about 60 mpg, 70 mpg, and 80 mpg for cars, and 39, 46, and 52 mpg for light trucks, respectively. The values for freight trucks seek to raise fuel economy from current levels by 30, 40, and 55 percent by 2035 for the three scenarios.

3.3 Pricing

3.3.1 Introduction

The importance of prices in a market economy can hardly be overstated. Prices send a powerful signal to consumers and suppliers about how much and what kinds of energy to produce and use; they stimulate innovation and can change behavior. Using prices to encourage GHG mitigation in transportation should be a basic element of any comprehensive mitigation strategy. Because GHG emissions are an externality, in theory, the ideal solution would be to put a price on GHG emissions equal to the marginal damage they do to the global climate. Indeed, this is the goal of carbon cap-and-trade or carbon tax policies. As this report has argued in

96. For RFS2, the U.S. EPA only released an estimate for one lifecycle analysis of 20 percent lower GHG emissions than gasoline for corn ethanol.

Section 1.3.2, transportation markets are likely to respond inefficiently to a carbon externality price: nevertheless, there will be a response that will contribute to the total GHG mitigation needed from the transportation sector.

There also are opportunities to change the ways in which transportation is paid for without increasing its total cost, achieving GHG mitigation as a co-benefit. Examples include the funding mechanisms for highway construction and maintenance, vehicle liability insurance, and parking. Addressing other externalities, like traffic congestion or air pollution, can also contribute to GHG mitigation. Pricing policies can also be used to address the market's tendency to undervalue fuel economy improvements.

This section will make extensive use of the concept of elasticities. Elasticities are a measure of the percent change in the quantity demanded of some good caused by a 1 percent change in its price. If, for example, a 1 percent increase in the price of automobiles causes a 1 percent decrease in new car sales, the price elasticity of automobile demand would be said to be –0.01/(+0.01) = –1.[97]

3.3.2 Carbon Pricing

By increasing the cost of fossil-based fuels, a carbon price would affect the quantity of vehicle travel, the efficiency of vehicles, and the carbon content of transportation fuels. The sensitivities of vehicle travel and fuel economy to the price of fuel have been extensively researched and reasonably well quantified. The sensitivity of the carbon content of fuels to the price of carbon is less well understood.

Increasing the price of fuel causes a small reduction in the amount of vehicle travel. Studies based on data from 1960 through 1990 generally concluded that the long-run elasticity of vehicle travel with respect to fuel cost per mile was approximately –0.2 (Greene, Kahn, & Gibson, 1999; Greene, 1992). More recent studies, however, have indicated that the responsiveness of vehicle miles of travelled (VMT) to the price of fuel has been decreasing due to increasing vehicle efficiencies and increasing incomes. The sensitivity of VMT to the price of fuel is now closer to –0.1 (Small & Van Dender, 2007; Greene, 2010b).

At the beginning of March 2010, the average retail price of gasoline in the U.S. was $2.70 per gallon (EIA, 2010a). A carbon price of $25 per ton would raise the price of gasoline about 8 percent. Applying an elasticity of –0.1, the reduction in vehicle travel would be 0.8 percent.

Raising the price of motor fuel by pricing carbon would also encourage manufacturers to design more fuel-efficient vehicles and consumers to buy them. It has proven difficult to estimate the manufacturers' response to

97. Price elasticities can be either short-run (e.g., the period in which in which the stock of vehicles and their fuel economy were fixed—a matter of months or a few years) or long-run (which would include the redesign of vehicles by manufacturers and the complete turnover of the stock of vehicles, and would likely require 15 to 20 years to be fully realized).

higher fuel prices, in large part because it is difficult to control for the effect of fuel economy standards in effect since 1978. Econometric studies of consumers' responses to fuel prices indicate that the short-run elasticity of new vehicle fuel economy with respect to the price of gasoline is about +0.1 to +0.2 (Klier & Linn, 2008; Austin & Dinan, 2005; Dahl, 1995).[98] This effect takes place entirely via changes in the mix of vehicles sold, assuming the fuel economy of each vehicle remains constant. Given enough time (5 to 10 years), manufacturers can redesign all their vehicles, improving fuel economy, as well. Analytical estimates of this long-run response indicate an elasticity of approximately +0.2 (Austin & Dinan, 2005; Greene & DeCicco, 2000; Greene, 1992). A total fuel economy elasticity of +0.4 would imply that carbon prices of $25 or $50 per ton of CO_2 on top of current fuel prices would reduce motor vehicle GHG emissions by 3.2 percent and 6.4 percent, respectively.

The total long-run price elasticity of gasoline demand should be approximately the elasticity of vehicle travel minus the elasticity of fuel economy (the sum of the short-run sales mix and longer-run technology and design effects), or –0.1 – (+0.3 to +0.4) = –0.4 to –0.5. These estimates are of the same general magnitude as empirical estimates (e.g., Haughton & Sarkar, 1996: –0.3 and Dahl, 1995: –0.4 to –0.5; Espey, 1996: –0.5). Combining the vehicle travel and fuel economy effects would produce long-run GHG reductions of approximately 4 percent and 8 percent. While this will contribute meaningfully to GHG mitigation, it is small relative to what is needed.

3.3.3 Innovative Approaches to Paying for Vehicle Travel

Noting the erosion of motor fuel tax revenues due to improvements in fuel economy, increase in the use of ethanol, diversion of revenues to non-highway uses and inflation, the Committee for the Study of the Long-term Viability of Fuel Taxes for Transportation Finance proposed that vehicle mileage be taxed instead. The Committee argued that "the public would benefit greatly from a transition to a fee structure that more directly charged vehicle operators for their actual use of roads (TRB, 2006, pp. 3-4)."

A VMT tax would signal motorists to reduce vehicle travel but would not encourage them to select more energy-efficient vehicles (see Section 3.3.4), nor would it encourage manufacturers to design more efficient vehicles. But it is possible to design a VMT fee that varies in proportion to a vehicle's fuel economy, so that it could have the same benefits as the energy user fee described in Section 3.3.4.

98. Klier and Linn use an econometric estimation. Austin and Dinan use an analysis using a model they constructed. Dahl is a survey of the literature. The short-run price elasticity of new vehicle fuel economy reflects sales mix shifts within a single year, before manufacturers have had time to change the design and technology content of vehicles. When gasoline prices rise, some new car buyers opt for the more efficient makes and models within a size class, others choose a smaller vehicle or a smaller engine, or fewer energy consuming options.

Another pricing idea for reducing VMT is pay-as-you-drive (PAYD) insurance, in which insurance costs rise with miles driven. A better alternative from the perspective of GHG mitigation would be pay-at-the-pump (PATP) insurance levied via an additional surcharge on all forms of energy purchased for vehicle use.

The cost transferred to fuel or miles by these policies is substantial. According to the U.S. Census Bureau, the average insurance expenditure per insured vehicle was $817 in 2006. If minimal liability insurance comprises one third, PATP insurance would amount to $0.68 per gallon for a vehicle consuming 400 gallons of gasoline per year. That is approximately a 25 percent increase in the cost of fuel, which would reduce fuel consumption and GHG emissions by about 5 to 10 percent.

3.3.4 Motor Fuel Taxes and Highway User Fees

Raising highway motor fuel taxes would have a similar effect on vehicle use and fuel economy as carbon prices. But U.S. motor fuel taxes differ in an important way. They are user fees that fund approximately half of the costs of building and maintaining road infrastructure. As a result, there is an opportunity to use fuel taxes to reduce GHG emissions, rather than turning to fees for VMT, which would have a lesser effect. Motor fuel taxes for gasoline are comprised of an excise tax of $0.184 per gallon at the federal level and an average of $0.205 at the state level for a total of $0.39 per gallon. For diesel, the taxes are somewhat higher: $0.244 federal and $0.208 average state taxes for a total of about $0.45 per gallon. A critical problem with motor fuel taxes in the past has been the erosion of revenue due to three principal factors: 1) inflation, 2) increasing fuel economy and 3) subsidies to alternative fuels (Greene, 2010b). Fuel economy standards now in place will further erode motor fuel tax revenues in the future. Substitution of low-carbon energy sources for petroleum fuels will further reduce revenues from taxes on gasoline and diesel fuel.

Currently, the motor fuel tax has three main advantages: 1) it is relatively easy and inexpensive to collect, 2) demand for motor fuel is relatively inelastic making revenues relatively reliable and, 3) nearly all users of the highway system must pay it, since very few vehicles run on fuels other than gasoline and diesel.

The laws of physics suggest that transportation cannot be accomplished without energy, so a straightforward solution to the problem of ensuring a stable level of financing roads that would also contribute to GHG mitigation would be to charge highway users according to their energy use. The fact that energy efficiency will change over time can be managed by indexing the user fee to the average level of energy efficiency of highway vehicles. As energy efficiency improves, the fee increases but total revenues per unit of transportation remain the same. The problem of inflation can likewise be addressed by indexing to inflation, using general indices or a highway construction and maintenance cost index. The problem caused by substitution of alternative energy sources is solved by requiring all energy users to pay the fee. While this means the user fee will not necessarily favor low-carbon fuels, it will uniformly promote energy efficiency.

The impact of the energy-based user fee on GHG emissions would be three to four times the impact of a fee based on vehicle miles. The current combined motor fuel state and federal tax is approximately $0.40 per gallon and the average fuel economy of all highway travel in 2008 was 17.4 miles per gallon (FHWA, 2010, table VM-1), or $0.023 per mile. If the same amount of revenue were raised by the VMT tax as the motor fuel tax, there would be no change in the cost per mile of driving; fuel cost would drop by $0.023 per mile but this would be exactly offset by a VMT tax of $0.023 per mile. With gasoline at $2.70 per gallon, fuel cost per mile is $0.155. Using the elasticity estimate of -0.1, the VMT tax would reduce vehicle miles and thus GHG emissions by approximately (0.023/0.155)(-0.1) = .015 or 1.5 percent. But the VMT tax provides no incentive to improve energy efficiency. In fact, by replacing the motor fuel tax it reduces the price of fuel by about 15 percent. Using the elasticity of fuel economy with respect to the price of fuel of -0.3, this would mean a decrease in fuel economy of 4.5 percent and an increase in GHG emissions of about 4 percent.[99] The energy tax, on the other hand, would reduce vehicle travel by about 1.5 percent and increase fuel economy by about 4.5 percent, for a net reduction in GHG emissions of about 5.5 percent, more than three times the impact of the VMT tax.

By making energy more expensive, the energy user fee would make it easier for manufacturers to sell high mpg vehicles and reduce the tendency of the market to switch from passenger cars to lower mpg light-duty trucks. In brief, the indexed energy user fee provides the same incentive to reduce vehicle travel as the VMT fee while additionally providing an incentive to improve energy efficiency.[100]

3.3.5 Other Externality Taxes

GHG emissions are not the only external cost of motor vehicle energy use and travel. Others include energy security problems, emissions of particulates and smog-forming gases, as well as traffic congestion and certain aspects of highway safety (Parry & Small, 2005).[101] The marginal economic costs of oil import dependence, for instance, translate into an externality tax of approximately $0.30 per gallon of motor fuel, roughly the same

99. The elasticity of -0.3 excludes the effect of fuel price on manufacturers' decisions to reduce GHG emissions through technology and design changes to vehicles. This assumes that strict emissions standards requiring such actions are already in effect.
100. The energy user fee would not directly address the problem of traffic congestion nor the greater responsibility of heavy-duty vehicles for infrastructure damage. However, congestion must be addressed specifically in any case. Larger, heavier vehicles would need to be targeted with special taxes, as they are today.
101. The market failure at the heart of the problem of oil dependence is monopoly power exercised by the OPEC cartel rather than an externality (Greene & Hopson, 2009). On the other hand, some of the costs borne by oil importers as a consequence of this monopoly power can be appropriately characterized as external costs (Leiby, 2008).

magnitude as a carbon price of $30 per ton or as the current highway user fees. Internalizing external costs of petroleum fuels and of vehicle use would yield significant GHG reductions.

3.3.6 Low-Carbon Fuel Subsidies

Pricing carbon will give low-carbon fuels an inherent cost advantage, although some non-petroleum fuels have been subsidized since at least 1983 via a reduction in the federal motor fuel tax (FHWA, 2010, table FE-101A). For instance, gasohol, a blend of 10 percent ethanol and 90 percent gasoline, now receives a 4.5 cents per gallon reduction in the federal motor fuel excise tax, which works out to 45 cents per gallon of ethanol. New energy sources will also require subsidies—at least during the transition period to new fuels.

3.3.7 Vehicle Incentives

U.S. policy has provided a variety of incentives for alternative fuel and advanced technology vehicles. Hybrid electric vehicles and light-duty diesel vehicles have been eligible for up to a $4,000 tax credit, for instance (DOE, 2010b)—although only the first 60,000 qualifying vehicles (hybrids plus clean diesels) sold by a manufacturer were eligible for the full credit. EVs and PHEVs now are eligible for up to a $7,500 tax credit, while other dedicated alternative fuel vehicles (e.g., not flexible fuel vehicles) may qualify for up to a $4,000 tax credit per vehicle.

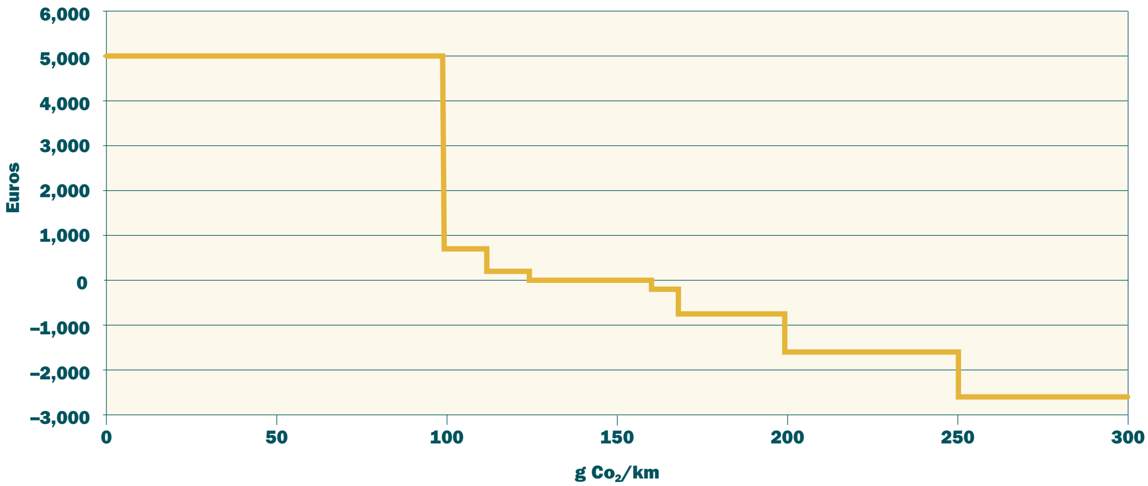
All of the incentives come with restrictions and expiration dates. This is because, with annual LDV sales of around 15 million units per year, meaningful subsidies can become an expensive drain on the treasury. Subsidizing 250,000 hybrid vehicles at $4,000 each would cost $1 billion. Still, subsidies have an important role to play in breaking down the barriers to novel technologies.

3.3.8 Feebates

Feebates are a promising policy mechanism that is unfamiliar to most Americans. Feebates are graduated fees on high-emission vehicles combined with graduated rebates to low-emission vehicles. They can be revenue neutral, making them more economically feasible than tax credits. They can also be designed to correct the consumers' tendency to undervalue future fuel savings. At least 14 OECD countries have implemented taxes based on vehicles' CO_2 emissions. Some are taxes at the time of purchase or first registration; others are circulation taxes paid annually. The best-known CO_2-related purchase tax is France's Bonus/Malus feebate, which levies a fee on vehicles whose emissions exceed 160 grams of CO_2 per kilometer and provides rebates for vehicles with emissions of less than 130 grams of CO_2 per kilometer. Fees for the highest-emitting vehicles were € 2,600 (about $3,500), while the lowest emission vehicles received a € 1,000 (approx. $1,350) rebate (**Figure 14**).

Figure 14

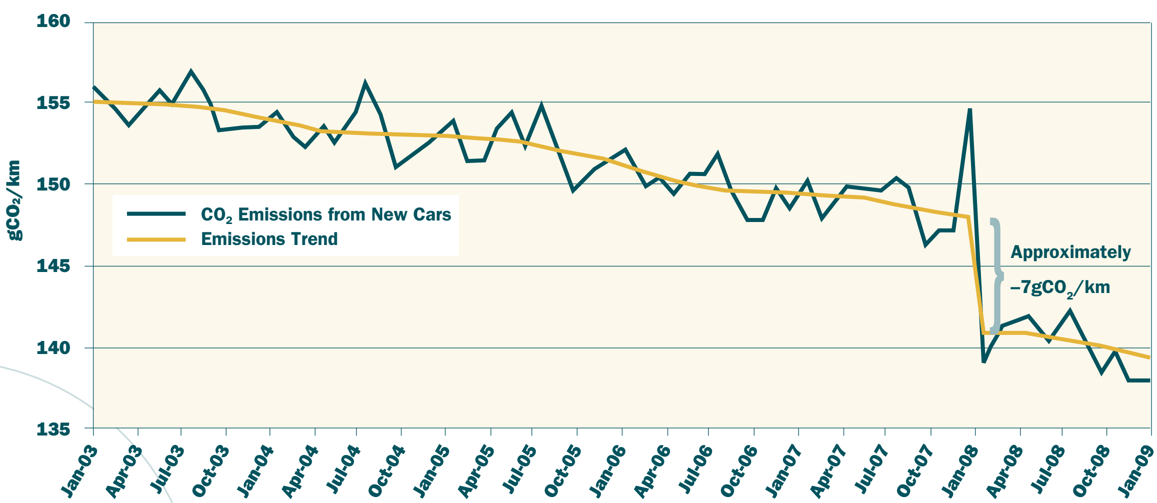
Fee and Rebate Schedule of France's Bonus/Malus Feebate System



The Bonus/Malus caused an immediate 7 grams of CO_2 per kilometer (approximately 5 percent) drop in the average emissions of passenger vehicles sold in France in January 2008 that persisted afterwards (**Figure 15**). The impact is due to a substantial change in the mix of vehicles sold. Vehicles qualifying for the Bonus claimed a market share of 43 percent in 2008 compared to 30 percent the year before. Vehicles incurring the Malus saw their market share drop to 15 percent from 25 percent in 2007. Since the effect was larger than anticipated, the Bonus-Malus program cost the government about 300 million Euros in 2008. Other countries with graduated CO_2 taxes have seen similar impacts (CARB, 2010).

Figure 15

Impact of **France's Bonus/Malus Feebates** on CO_2 Emissions of New Cars



France already had a strict vehicle emissions standard, showing that feebates can achieve additional cost-effective CO_2 reductions even when other incentives are in place. A recent analysis by the University of California at Davis for the California Air Resources Board estimated that if a revenue-neutral feebate system of $20 per gram of CO_2 per mile were implemented in California, new vehicle emissions would drop by about 10 grams of CO_2 per mile, with a negative net mitigation cost of –$100 (i.e., a large cost savings) per ton of CO_2 (Bunch & Greene, 2010). The negative cost is a consequence of the undervaluation of fuel savings in the market for new cars. Using the same model, Liu et al. (2011) estimated that a national feebate system, given that national vehicle GHG emissions standards were in effect, would further reduce GHG emissions rates by about 10 percent. Both studies assumed that feebates would be indexed to the sizes of vehicles, in the same way as fuel economy and GHG emissions standards. The new U.S. fuel economy and emission standards are indexed to vehicle size in part to address safety concerns by removing incentives for manufacturers to downsize vehicles in order to meet the standards.[102]

3.3.9 Pricing Congestion and Parking

Other options for mitigating GHG emissions by changing the way vehicle use is paid for include congestion pricing and pricing parking. Both strategies are under the control of state, local, or regional governments. Traffic congestion has long been recognized as an externality. Each driver entering the highway under congested conditions slows down every other driver just a little bit, but considers only the negligible impact his entry has on his own speed. Thus too many drivers enter a roadway at one time, leading to inefficient delays.

Congestion pricing would only apply during congested driving conditions. Schrank and Lomax (2009), however, estimate that the average U.S. driver wasted about 20 hours due to traffic congestion in 2009.[103] A congestion pricing fee of $0.50 per mile is estimated to increase total per mile costs by 33 percent. With a total cost elasticity of –1, this would reduce travel under congested conditions by 33 percent (about 3 percent of total vehicle miles).[104] Congestion pricing is an example of a policy primarily justified by benefits other than GHG reduction, and which would have a relatively small impact at the national scale but a much larger impact in those areas where traffic congestion is frequent and severe.

Free parking is a different kind of issue. Parking spaces take up large quantities of real estate and so are not really free. The idea that users of free parking should pay the real cost therefore has appeal. On the other hand,

102 The footprint-based targets do not encourage downsizing and may encourage some increases in track width and wheelbase (since such increases would yield a less stringent fuel economy and GHG emissions target). Any increase in track width should discourage rollovers; wheelbase increases should improve directional stability and may allow more crush space for occupant protection.

103. The rough estimate of 20 hours per year is based on Schrank and Lomax's (2009) estimate of 4.17 billion total hours of delay and 210 million licensed drivers.

104. The possible rebound effect of increasing travel speeds during previously uncongested conditions is ignored here but would tend to reduce the mitigating impact of congestion pricing to some degree.

there are good reasons why business would want to offer free parking to attract customers or to provide an untaxed benefit to employees.

Pricing currently free parking can reduce single occupant vehicle (SOV) commuting (Vaca & Kuzmyak, 2005). The most effective strategies seem to be area-wide pricing increases (including on-street parking) and "parking cash-out" policies in which employers eliminate free parking but make a compensating cash payment to employees. Nationwide, only 5 percent of employees pay for parking at work (DOT, 2010b, pp. 5-71). If that number were doubled, one study estimated that total U.S. vehicle miles of travel would be reduced by about 0.3 percent (EEA, 2008).

3.3.10 Report Scenarios for Pricing

This report incorporated a number of pricing policies from above into the Low, Mid, and High Mitigation Scenarios described in Section 4. **Table 12** summarizes these policies. The pricing policies included in this report target cars and trucks. They are intended to affect fuel economy, VMT, and fuel carbon intensity. **Table 13** defines their impacts on these targets.

Table 12

Mitigation Pricing Policies

	Pricing Mechanism	Targeted Consumer Response	GHG Impact Compared to BAU	Used in Report Scenarios
Carbon Pricing	Carbon-based Fuel Charge	Consume less carbon-based fuels	Decrease	Yes
VMT Fee	Distance Charge	Reduce VMT (e.g., drive less, reduce SOV trips)	Increase	No
PAYD Insurance	Distance Charge	Reduce VMT	Decrease	No
PATP Insurance	Fuel Charge	Consume less motor fuel	Decrease	Yes
Motor fuel tax	Fuel Charge	Consume less motor fuel	No Change*	No
Road user tax on energy	Fuel Charge	Consume less motor fuel; purchase more fuel-efficient vehicle	Decrease	Yes
Energy security tax	Fuel Charge	Consume less petroleum	Decrease	No
Low-carbon fuel subsidy	Fuel Subsidy	Purchase more low-carbon fuel	Decrease	No
Vehicle tax credits	Vehicle Purchase Subsidy	Purchase low-emission vehicle	Decrease	No
Feebates	Vehicle Purchase Subsidy/Charge	Purchase low-emission vehicle	Decrease	Yes
Congestion pricing	Location Fee	Drive less during peak travel; Reduce SOV trips	Decrease	No
Parking pricing	Location Fee	Drive less; Reduce VMT	Decrease	No

**Note that business-as-usual (BAU) assumes existing motor fuel tax continues.*

Table 13

Percent Change in Fuel Economy and VMT for LDVs and Freight Trucks from Pricing Mechanisms Used in the Low, Mid, and High Mitigation Scenarios Compared to the Reference Case.

	2035			2050		
Report Scenario Assumptions for Pricing Mechanisms	Low	Mid	High	Low	Mid	High
Carbon price for LDVs (% change in mpg)	2.44%	2.44%	2.44%	3.57%	3.57%	3.57%
Carbon price for freight trucks (% change in mpg)	1.21%	1.21%	1.21%	1.77%	1.77%	1.77%
Carbon price for LDVs and freight trucks (% change in VMT)	–1.2%	–1.2%	–1.2%	–1.74%	–1.74%	–1.74%
Road user tax on energy for LDVs (% change in mpg)	0.94%	1.55%	1.88%	2.23%	2.23%	2.23%
Road user tax on energy for LDVs (% change in VMT)	–0.19%	–0.49%	–0.64%	–0.39%	–0.77%	–1.03%
Road user tax on energy for freight trucks (% change in mpg)	0.9%	1.49%	1.8%	2.14%	2.14%	2.14%
Road user tax on energy for freight trucks (% change in VMT)	–0.29%	–0.52%	–0.62%	–0.49%	–0.76%	–0.89%
PATP insurance for LDVs and freight trucks (% change in mpg)	0%	4.37%	4.37%	0%	5.2%	5.2%
PATP insurance for LDVs (% change in VMT)	0%	–0.97%	–0.97%	0%	–0.97%	–0.97%
PATP insurance for freight trucks (% change in VMT)	0%	–1.97%	–2.16%	0%	–3.03%	–3.32%
Feebates for LDVs (% change in mpg)	0%	10%	10%	0%	10%	10%

3.4 Policy Strategy for Transportation GHG Mitigation

Achieving the full potential to reduce transportation's GHG emissions will require a comprehensive strategy comprised of many policies. The core policies that will produce the individually greatest impacts are vehicle efficiency improvement, pricing carbon, and reducing the carbon intensity of transportation fuels. Two of these, efficiency improvement and carbon intensity reduction, will depend on the progress of technology over time, progress that cannot be accurately predicted far in advance. Thus, these policies must be adaptable.

But these three major policies will not be enough. An array of other policies and measures, some based on technology, others on price signals, still others on changing institutional or individual behavior, need to be implemented in innovative ways at various levels of government and with the participation of individuals and organizations. Many of these policies will not be justifiable on the basis of their GHG mitigation benefits alone; they will depend on other benefits such as reducing traffic congestion, improving system efficiencies, reducing petroleum dependence or enhancing safety. Finally, based on the analysis in this report, it makes sense to begin what will ultimately become a full-scale transition from a carbon-intensive transportation system to one based on sustainable low-carbon energy, requiring policies that account for the potential long-term social benefits of the transition.

3.4.1 A Comprehensive Strategy is Needed

A comprehensive policy for transportation should promote energy-efficient vehicles, encourage low-carbon fuels, restructure the pricing of transportation to contribute to GHG mitigation, and promote system efficiency in day-to-day operations and, in the long term, geography and infrastructure.

Support for RDD&D is critical to all four policy areas. Still, a great deal can be done now, and in several areas, current policies are on the right track and making appropriate progress.

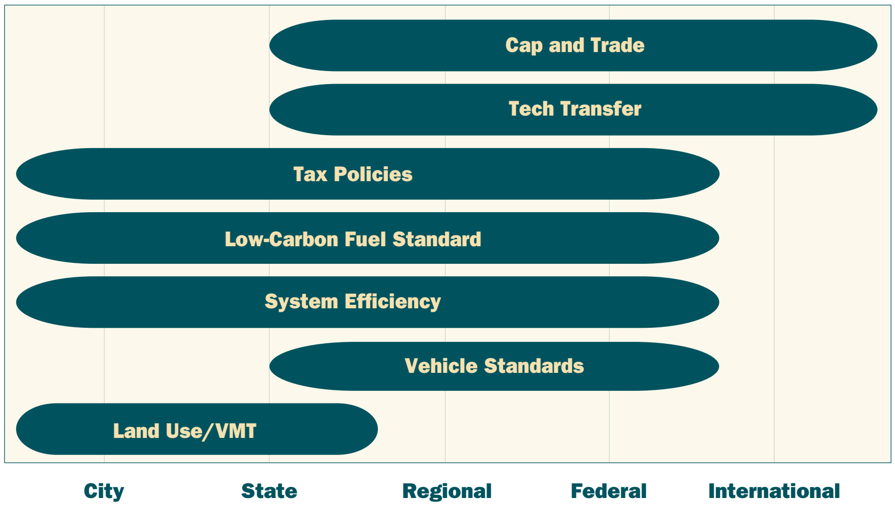
3.4.2 The Roles of Each Level of Government

All levels of government, as well as businesses and private individuals, have responsibilities for mitigating transportation's GHG emissions (see **Figure 16**).

The federal government's role includes an international commitment to reduce GHG emissions throughout the economy, setting vehicle emissions standards, establishing regulations to reduce the carbon intensity of energy used in transportation, and supporting RDD&D. There is also much the federal government can do to enable, encourage, and support actions by states, local governments, individuals and businesses, and to inform the public.

Figure 16

Policies to Mitigate GHG Emissions from Transportation Across All Levels of Government Including Agreements at the International Level



States and local governments manage traffic flow, control speeds, and train drivers, all of which present opportunities for GHG mitigation. States and local governments can influence land use planning and design to reduce dependence on motor vehicle travel. In addition, California and other states "opting in" to California's environmental standards can continue to be a testing ground for innovative policies and a catalyst for progress at the national level.

3.4.3 Transitioning to Sustainable Transportation Energy

In the long run, the transition to an alternative energy basis for motor vehicle transportation will have to begin before it is clear which technology and energy form will succeed. It takes two to three decades, at least, to fundamentally change the energy basis for transportation. Consider that the first mass-market hybrid vehicles were introduced in the United States in 2000 and by 2010 hybrid vehicles comprised only 2 to 3 percent of new LDV sales. A nearly complete transition to electricity or hydrogen or both will require an absolute minimum of two decades. A more realistic estimate is 30 or 40 years.

Given the importance of an energy transition to reaching a 2050 GHG mitigation goal of at least a 50 percent reduction below current levels, the United States needs to begin before it is certain of the outcome. A rational, sustainable policy framework for achieving the transition efficiently and expeditiously is needed.

Alternative energy technologies face five major economic barriers to market acceptance:

1. Reducing costs by achieving scale economies
2. Establishing a diverse product line to satisfy consumers' preferences
3. Reducing costs and improving performance through learning-by-doing
4. Overcoming consumers' aversion to the risk of novel products
5. Overcoming the "chicken or egg" dilemma of fuel and vehicle availability

These natural economic barriers imply that a novel energy technology must not only be as good as the incumbent technology, but it must be sufficiently better to overcome them. The combination of technology lock-in and the time constants for change in the motor vehicle market imply that vehicle manufacturers would have to endure one to two decades of annual losses in the billions of dollars to accomplish a transition to hydrogen or electric vehicles without government assistance. Unless entirely unforeseen breakthroughs make electric or fuel cell vehicles far superior to conventional technology, government policy will be essential to the transition. The challenge for government policy is daunting.

RDD&D of advanced technologies is the first step. Today, electric vehicles are hindered by inadequate on-board energy storage, high costs for batteries, and the need for supporting infrastructure. Hydrogen fuel cell vehicles are handicapped by inadequate on-board energy storage, high costs for fuel cells, and the need to develop an entirely new hydrogen infrastructure. Advanced biofuels face high costs, as well as the need to insure low GHG emissions and to manage potential conflicts with food production that could limit supply.

The second step is to determine whether, if each technology is successful, the potential benefits to society will outweigh the costs. A recent NRC (2009a) study, for example, estimated that a scenario of increased energy efficiency and transition to hydrogen fuel cell vehicles would reduce U.S. GHG emissions by 10 gigatons and petroleum consumption by about 25 billion barrels, cumulatively through 2050. Valuing emission reductions at roughly $50 per ton and the social benefit of petroleum demand reduction at $20 per barrel would yield an undiscounted value of $1 trillion.[105] The same NRC study estimated the excess costs of the transition at $40 billion to $100 billion. In this example, even though costs and benefits have not been discounted to a common year's values, it is clear that the value of the benefits of making the transition exceed the costs of doing so.

105. These numbers are not intended to be precise and are for illustrative purposes only. They are based on Table 6.9 and Figures 6.15 and 6.16 of NRC 2008.

Determining government's role in supporting a transition to sustainable transportation requires balancing the costs of upfront subsidies against the prospect of much larger but uncertain future benefits. See Appendix C for an introduction to the theory behind this calculation. Some level of government support for buying down the cost of advanced technologies and overcoming natural market barriers to a transition is reasonable; the question is how much. The challenge is to find the right balance on the one hand between setting performance standards that provide a level playing field for all technologies to compete and on the other hand ensuring that promising technologies are developed sufficiently for consumers and society to make judgments about their costs and benefits. The only way to do this responsibly is to periodically reevaluate technological progress and market acceptance in the light of new information and experience, and to make adjustments.

4. Mitigation Potential

Reducing GHG emissions from the U.S. transportation sector by 50 percent or more by 2050 will require a comprehensive policy strategy comprised of many of the policies described in Section 3. To estimate the combined impact of the numerous policies described in this report requires a method that accounts for the most important interactions among them.

In estimating cumulative impact, two kinds of important policy interactions must be accounted for. First, when two or more policies address the same factor, their combined impact is likely to be smaller than the sum of their individual impacts. The second type of interaction effect is the rebound effect. Policies that increase energy efficiency reduce the cost of energy services, such as vehicle travel, and the reduced price leads to increased consumption that partially offsets the benefit of increased efficiency (Sorrell, 2007). Recent evidence finds that the rebound effect has been decreasing over time with increasing income, and that it now stands at about 10 percent (a 10 percent increase in efficiency produces a 1 percent increase in vehicle travel) (Small & Van Dender, 2007; Sorrell & Dimitropoulos, 2007; Greene, 2010b).

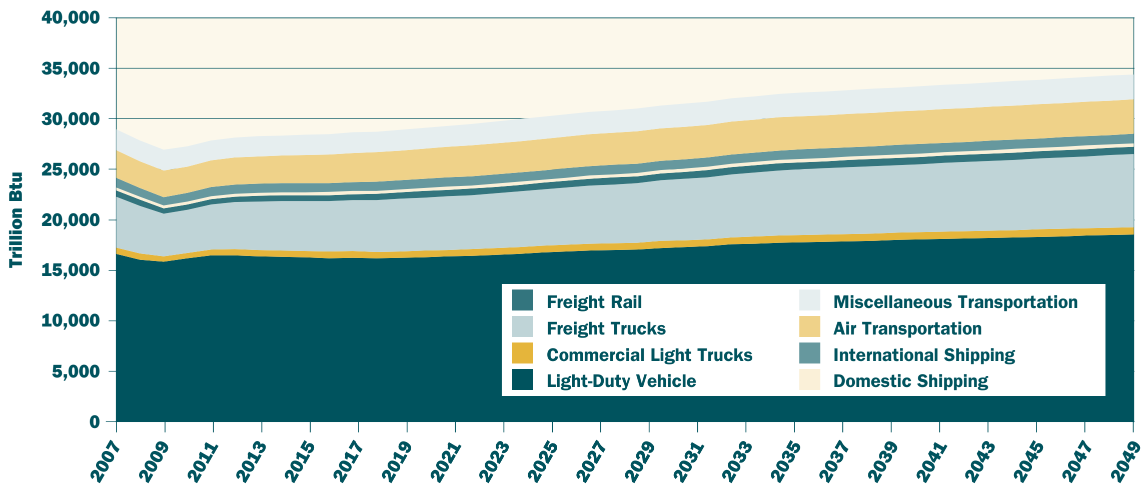
The method of estimating impacts begins with a Base Case forecast of transportation energy use and the resulting CO_2 emissions.[106] The projection chosen is the EIA's *Annual Energy Outlook 2010* Reference Case. Impacts are estimated using the Kaya identity (McCollum & Yang, 2009). The Kaya identity states that total GHG emissions are the product of (1) the level of activity (e.g., vehicle miles of travel), (2) the share of activity for each mode, vehicle, and fuel type, (3) the energy intensity of the mode and vehicle type (e.g., energy use per vehicle mile), and (4) the carbon intensity of the fuel type (see Appendix B for further details).

The Base Case is the EIA's 2010 AEO Reference Case projection (EIA, 2010a), extrapolated from 2035 to 2050. The Base Case contains a short decline in transportation energy use due to the economic recession of 2008 to 2009. Energy use in all modes then recovers, growing at a relatively consistent rate through 2035; the growth pattern is retained in the authors' extrapolation to 2050 (**Figure 17**). Transportation energy use increases from 25.6 quads in 2010 to 34.2 quads in 2050 and CO_2 emissions grow from 1.83 gigatons in 2010 to 2.41 gigatons in 2050. LDVs, freight trucks, and air account for 90 percent of CO_2 emissions over the forecast period.

106. In transportation, it is appropriate to use CO_2 as a proxy for all GHG emissions. Over 95 percent of GHG emissions from transportation are CO_2 and nearly all the remaining emissions are a byproduct of fuel combustion.

Figure 17

Base Case Transportation Energy Use by Mode



In the Base Case, new LDV fuel economy increases from 28.6 miles per gallon in 2010 to 40.0 in 2035. The fuel economy of the on-road light-duty fleet increases from 21.0 miles per gallon in 2010 to 29.4 in 2035. The increases are primarily driven by federal fuel economy and emission standards but also reflect gasoline prices which reach $3.90 per gallon in 2035. Biofuel use, in the form of ethanol, increases dramatically in the Base Case. Renewable fuel use beyond 10 percent ethanol blending with gasoline[107] increases from less than 0.1 billion gallons in 2010 to 21 billion gallons in 2035 and 40 billion gallons in 2050. In the Reference Case, alcohol fuels begin at 90 percent of the lifecycle carbon emissions of gasoline in 2010 but their lifecycle carbon emissions decline by 27 percent by 2022 and remain at that level through 2050.

The estimated impacts of policies (**Table 14**) are incremental to improvements in energy efficiency and reductions in carbon intensity already contained in the Base Case. The changes in efficiency, activity levels, and carbon intensity in the Base Case through 2035 are shown in the first column of numbers in **Table 14**. LDV fuel economy increases by 39 percent by 2035 (a 28 percent reduction in energy intensity). The fuel economy of heavy-duty vehicles is up 16 percent, while aircraft fuel economy improves by 12 percent. The remaining columns show the incremental changes due to policies, measures, and technologies in the Low, Mid, and High Mitigation Scenarios. For example, in the High Mitigation Scenario in 2035, LDV fuel economy increases 40 percent over the expected level that year as a result of fuel economy standards and 10 percent due to improved vehicle operation.

107. Current fuel may only contain a maximum of 10 percent ethanol for vehicles manufactured before 2007 because of fears that higher blends may damage auto components; in October of 2010, EPA increased the maximum ethanol blend percentage with gasoline to 15 for 2007 and later model years.

Table 14

Policy and Mitigation Option Assumptions Used for the Low, Mid, and High Mitigation Scenarios

For each item, the value indicates the percent change in energy efficiency, vehicle miles traveled, fuel carbon intensity, or energy intensity relative to the AEO 2010 reference case as a result of implementing the item. For instance, improving traffic flow will increase energy efficiency of LDVs by 1 percentage point beyond the 39 percent improvement in the Mid Mitigation Scenario in 2035.

For each mode, the changes contained in the reference case (AEO 2010) are shown in italics in the first column indicating the business-as-usual percent change from 2010 to 2035. The AEO 2010 Reference Case provides projections to 2035 only. GHG emissions for 2050 were obtained by extrapolation of the AEO's projections in 2035.

POLICY/MITIGATION OPTION	AEO 2010 (2010–2035)	2035			2050		
		Low	Mid	High	Low	Mid	High
LIGHT-DUTY VEHICLES							
Change in Energy Efficiency for Total Stock (miles per gallon)	*39%*						
Fuel Economy/Emissions Standards		15.00%	30.00%	40.00%	35.00%	60.00%	80.00%
Driver Behavior & Maintenance		2.50%	5.00%	10.00%	2.50%	5.00%	10.00%
Improved Traffic Flow		0.00%	1.00%	2.00%	0.00%	1.00%	2.00%
Pricing Policies							
Carbon Price		2.44%	2.44%	2.44%	3.57%	3.57%	3.57%
Road User Tax on Energy		0.94%	1.55%	1.88%	2.23%	2.23%	2.23%
Pay at the Pump Insurance		0.00%	4.37%	4.37%	0.00%	5.20%	5.20%
Feebates		0.00%	10.00%	10.00%	0.00%	10.00%	10.00%
Automated Highways		0.00%	0.00%	1.00%	0.00%	0.00%	5.00%
Change in Vehicle Miles Traveled (billion vehicle miles traveled)	*54%*						
Road User Tax on Energy		–0.19%	–0.49%	–0.64%	–0.39%	–0.77%	–1.03%
Carbon Price		–1.20%	–1.20%	–1.20%	–1.74%	–1.74%	–1.74%
Pay at the Pump Insurance		0.00%	–0.97%	–0.97%	0.00%	–0.97%	–0.97%
Trip Planning & Route Efficiency		0.00%	–2.00%	–4.00%	0.00%	–5.00%	–10.00%
Ridesharing		0.00%	–0.70%	–1.40%	0.00%	–1.00%	–2.00%
Land Use & Infrastructure Development		0.50%	–1.00%	–2.00%	–1.50%	–3.00%	–5.00%
Change in Fuel Carbon Intensity for Total Stock (gCO_2e/MJ)	*–7%*						
LCFS: 2035 / Increased Hydrogen & Electricity: 2050		–5.00%	–10.00%	–15.00%	–5.00%	–10.00%	–47.22%

POLICY/MITIGATION OPTION	AEO 2010 (2010–2035)	2035 Low	2035 Mid	2035 High	2050 Low	2050 Mid	2050 High
FREIGHT TRUCKS							
Change in Energy Efficiency for Total Stock (miles per gallon)	*16%*						
Fuel Economy/Emissions Stds. Long-haul		15.00%	25.00%	30.00%	25.00%	35.00%	40.00%
Fuel Economy/Emissions Stds. Local		15.00%	25.00%	30.00%	25.00%	35.00%	40.00%
Carbon Price		1.21%	1.21%	1.21%	1.77%	1.77%	1.77%
Road User Tax on Energy		0.90%	1.49%	1.80%	2.14%	2.14%	2.14%
Pay-at-the-Pump Insurance		0.00%	4.37%	4.37%	0.00%	5.20%	5.20%
Traffic Flow Improvement		0.00%	1.00%	2.00%	0.00%	1.00%	2.00%
Automated Highways		0.00%	0.00%	0.00%	0.00%	5.00%	10.00%
Change in Vehicle Miles Traveled (billion vehicle miles traveled)	*77%*						
Freight Logistics		0.00%	–2.30%	–5.00%	0.00%	–2.30%	–5.00%
Carbon Price		–1.20%	–1.20%	–1.20%	–1.74%	–1.74%	–1.74%
Pay-at-the-Pump Insurance		0.00%	–1.97%	–2.16%	0.00%	–3.03%	–3.32%
Road User Tax on Energy		–0.29%	–0.52%	–0.62%	–0.49%	–0.76%	–0.89%
Change in Fuel Carbon Intensity for Total Stock (gCO_2e/MJ)	*–1%*						
Advanced Biofuel		–2.00%	–10.00%	–15.00%	–10.00%	–15.00%	–37.50%
AIRCRAFT							
Change Energy Intensity for Total Stock (gallons per seat mile)	*–11%*						
Propulsion/Weight/Drag Improvements		–10.00%	–25.00%	–40.00%	–40.00%	–50.00%	–70.00%
Operational Improvements		–3.00%	–5.00%	–10.00%	–3.00%	–7.50%	–10.00%
Change in Fuel Carbon Intensity for Total Stock (gCO_2e per MJ)	*0%*						
Advanced Biofuel		0.00%	–10.00%	–15.00%	–10.00%	–15.00%	–37.50%
Hydrogen		0.00%	0.00%	0.00%	0.00%	0.00%	–10.38%
Change in Vehicle Miles Traveled (billion seat miles available)	*38%*						
Routing & Flight Paths		–3.00%	–5.00%	–10.00%	–3.00%	–5.00%	–10.00%
RAIL							
Change in Energy Intensity for all Trains (thousand Btus per ton-mile)	*–2%*						
Advanced Technology		–10.00%	–15.00%	–20.00%	–25.00%	–30.00%	–40.00%
SHIPPING							
Change in Energy Intensity for all Ships (thousand Btus per ton-mile)	*–5%*						
Advanced Technology		–15.00%	–22.50%	–30.00%	–20.00%	–40.00%	–50.00%

The three mitigation scenarios include differing assumptions about public attitudes about climate change, technological progress, and mixes of policies. These are described below.

4.1 Scenarios of Public Attitude Towards Climate Change

Low Mitigation Scenario: A majority of U.S. citizens considers climate change to be a serious issue; however, they are unwilling to change their own behavior and will support only modest policies to address it.

Mid Mitigation Scenario: 60 to 75 percent of the public considers addressing climate change to be a high priority. The public is willing to shift some of their preferences (for example, for lower-emitting vehicles) and to support somewhat more aggressive policies.

High Mitigation Scenario: The public is very concerned about climate change, considering it a very serious threat. Not only are stronger policies acceptable, but some degree of behavioral change, as well. Consumers change habits and preferences, including driving behavior, to reflect their concern for the global climate.

4.2 Scenarios of Public Policy Context

Low Mitigation Scenario: The federal government implements a carbon tax or an economy-wide carbon cap and trade system beginning in 2035. By 2050, GHG emissions per kWh are 50 percent below current levels as a consequence of electric utilities' response to these policies. Subsidies for biofuels continue, as do renewable fuel standards. Post-2016 fuel economy standards increase by 2 percent per year and standards are set for heavy-duty vehicles.

Mid Mitigation Scenario: In addition to the policies in the Low Mitigation Scenario, federal policy is designed to significantly reduce CO_2 emissions from energy use to about 50 percent below 2005 levels by 2050 as an average across all sectors. By 2030, the electricity sector has already reached the 50 percent reduction goal. By 2050 it is 80 percent decarbonized. Most state governments use their authorities to enact ambitious GHG reduction policies that complement federal action. Only a few state governments do not consider such reductions to be necessary. However, the public is reluctant to change its travel behavior.

High Mitigation Scenario: The federal government is committed by treaty to an aggressive goal for reducing economy-wide GHG emissions, such as 80 percent below 2005 levels by 2050. Nearly all state and local governments enact reduction policies that complement federal action. By 2030, GHG emissions from electricity generation are 50 percent below current levels and by 2050 electricity generation is nearly GHG-free because of electric utilities' response to these policies. RDD&D investments are greatly increased. Fuel economy standards for highway vehicles are aggressive, and standards are set for commercial aircraft. Feebates, congestion pricing, greater control of land use, and similar policies are enacted.

4.3 Scenarios for Rate of Technological Progress

Low Mitigation Scenario: Levels of expenditure on RDD&D typical of the past decade are continued. To a large extent, the United States depends on technological progress being made in Europe and Asia. Batteries and fuel cells remain relatively expensive in comparison to internal combustion engines.

Mid Mitigation Scenario: More rapid progress in energy-efficient technologies and low-carbon fuels is made both in the United States and around the world. Expenditures by the public and private sector on energy technology RDD&D are doubled. Costs of hybrids, PHEVs, EVs, fuel cell vehicles, and second generation biofuels are significantly reduced. Carbon capture and sequestration (CCS) of powerplant or industrial emissions for enhanced oil recovery are prevalent.

High Mitigation Scenario: Technological progress is consistent with the NRC's optimistic scenarios for fuel cell and battery electric vehicles. CCS is widely implemented in the electric power sector and in production of biofuels via gasification and synthesis, and zero-carbon sources such as renewables and nuclear power are widely used for electricity generation. Advances in operational systems and vehicle controls allow maximum efficiency for air, marine, and ground transportation. A substantial degree of automation is achieved on highways by 2050. Breakthroughs in biofuels allow greater use in air transportation and trucking.

4.4 Scenarios of Energy Prices

All three scenarios use the EIA's *Annual Energy Outlook 2010* Reference Case Projection as a starting point. In the Reference Case, oil prices rise from approximately $70 per barrel in 2010 to $120 per barrel in 2020 and $200 per barrel in 2035. In the authors' view, these prices are not likely to be sustained continuously at such high levels over such a long period of time. These same price assumptions are maintained in all three of this report's scenarios.

4.5 Policy Impacts

The inputs to the Kaya equation analysis are shown in **Table 14** for the Low, Mid, and High Mitigation Scenarios. Under "Energy Efficiency," the percentages represent percent changes in fuel economy (e.g., miles per gallon) assumed to be produced by the policies listed, compared to the reference case. Cumulative impacts of fuel economy improvements are summed to obtain the total impact.[108] Under "Vehicle Travel," the percentages represent percent changes in vehicle miles of travel.[109] Under "Fuel Carbon Intensity," the percentages represent changes in the average carbon content of energy used. For some modes, "Energy Intensity" is a more commonly used measure. Percentage reductions in energy use per unit of activity are combined multiplicatively to avoid overestimating their combined impact. The values used in **Table 14** have been derived from the section of the report that addresses each policy.

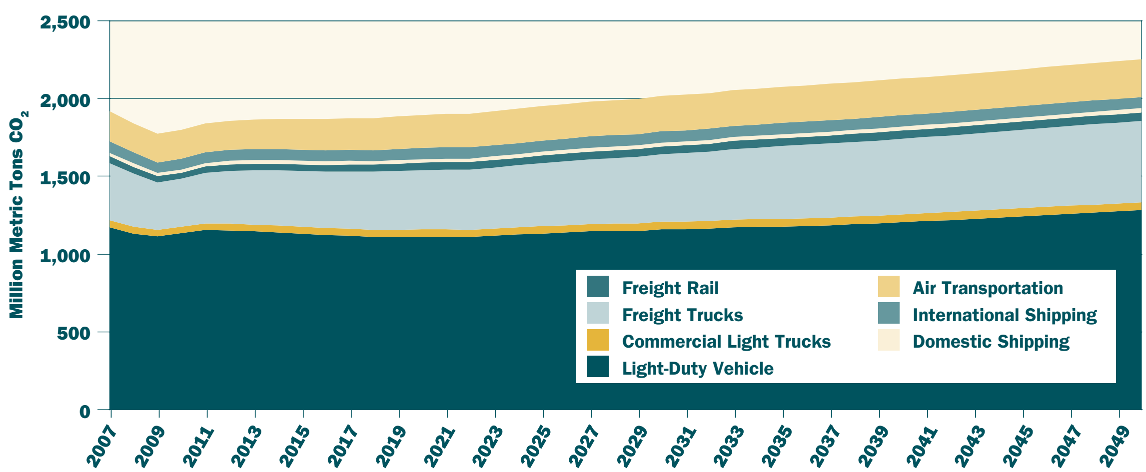
108. For example, three policies producing a 5, 10, and a 15 percent impact, would together achieve a 30 percent increase in fuel economy (a 23 percent reduction in fuel consumption) rather than a 33 percent (1.05 x 1.1 x 1.15 = 1.33) increase in fuel economy (25 percent reduction in fuel consumption).

109. These impacts are accumulated multiplicatively. Thus, a -2, -1, -4 and -5 percent reduction in fuel economy produce an overall (1-0.2)x(1-0.01) x (1–0.4) x (1–0.5) = 0.885, a –11.5 percent reduction in VMT rather than a –2%–1%–4%–5% = –12 percent reduction in VMT.

In the Base Case, CO_2 emissions from LDVs remain the dominant source of GHGs through 2050, but growth is restrained by fuel economy improvements and relatively high petroleum prices (**Figure 18**). The largest increase in CO_2 emissions comes from freight trucks, whose share increases from 16 percent in 2010 to 22 percent in 2035 and 23 percent in 2050. According to the EIA, emissions from air travel also increase, although the increase is modest. Total transportation sector CO_2 emissions increase from 1.8 billion metric tons in 2010 to 2.3 billion in 2050.

Figure 18

Transportation CO_2 Emissions from Energy Use: Base Case Scenario

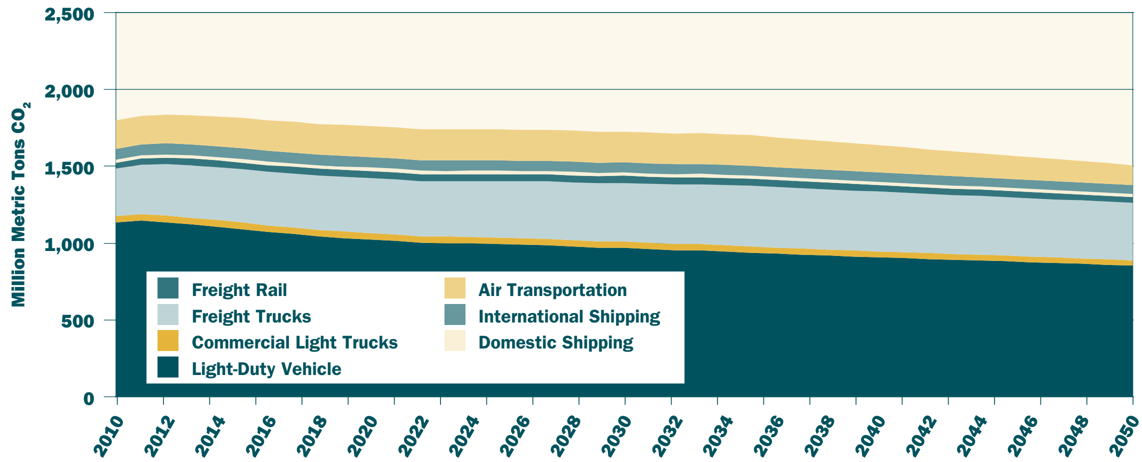


In the Low Mitigation Scenario, total transportation CO_2 emissions decline slowly from 1.80 gigatons in 2010 to 1.49 gigatons in 2050 (**Figure 22**), a 35 percent reduction from the Base Case in 2050 but only a 17 percent reduction from the 2010 level.

Most of the GHG reductions come from LDVs and aircraft. Freight truck emissions continue to grow (**Figure 19**). In the Low Mitigation Scenario, there is no fuel switching beyond the introduction of advanced biofuels in accordance with the RFS. However, greater use of low-carbon advanced biofuels due to technological progress reduces the overall carbon intensity of LDV energy use by 5 percent by 2050.

Figure 19

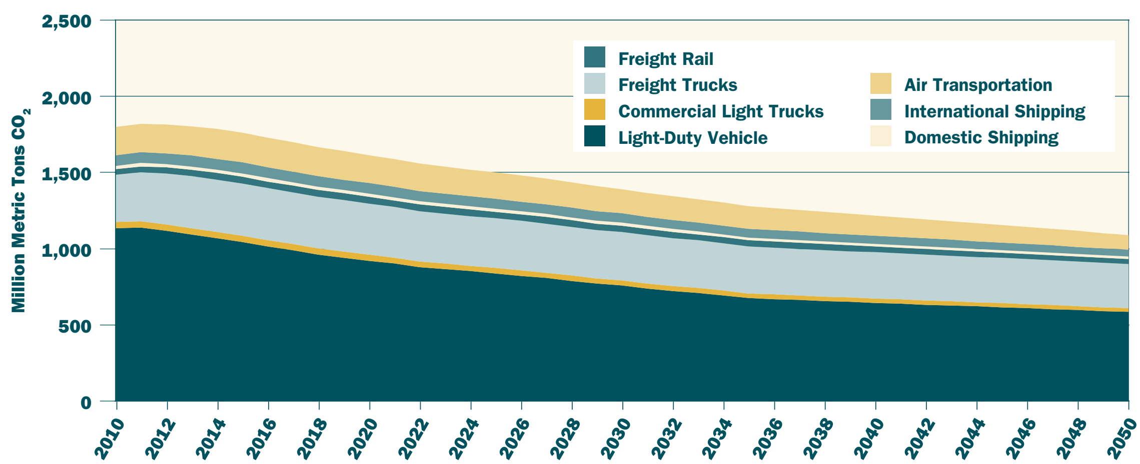
Transportation CO_2 Emissions Projections by Mode: Low Mitigation Case



The Mid Mitigation Scenario cuts CO_2 emissions in 2050 by 40 percent relative to 2010 (**Figure 22**). Pricing policies, such as feebates and PATP insurance reinforce greater improvements in fuel economy technology, encouraging motorists not only to drive somewhat less but also to opt for the more efficient vehicle offerings. Greater gains in decarbonization and energy efficiency are achieved in all modes **(Figure 20**).

Figure 20

Transportation CO_2 Emissions to 2050 by Mode: Mid Mitigation Case



In the High Mitigation Scenario, GHG emissions are reduced by 65 percent in 2050 compared to their 2010 level **(Figure 22**). That case not only includes much greater increases in fuel economy but major changes in transportation's energy sources, as well. A substantial shift of LDVs to a combination of electricity and/or hydrogen occurs. Hydrogen and electricity are produced with low-carbon energy sources. Novel development of biofuels, e.g., from algae, enables greater use of biofuels by all vehicles including heavy-duty trucks and aircraft.

In the High Mitigation Scenario, freight trucks account for 31 percent of CO_2 emissions in 2050, nearly double their share in 2010 (**Figure 21**). LDVs' share of total CO_2 emissions declines from 59 percent in 2010 to 49 percent in 2050, while the share due to air travel decreases from 10 to 7 percent. All modes make major reductions relative to the Base Case: LDVs -76 percent; Freight trucks -63 percent; Air -83 percent; Shipping -51 percent; and Rail -61 percent.

Figure 21

Transportation CO_2 Emissions to 2050 by Mode: High Mitigation Case

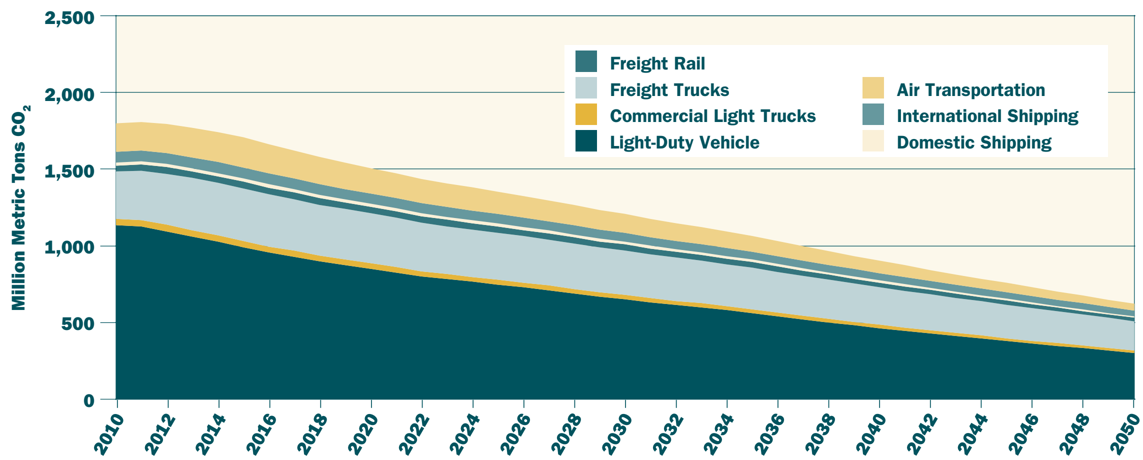
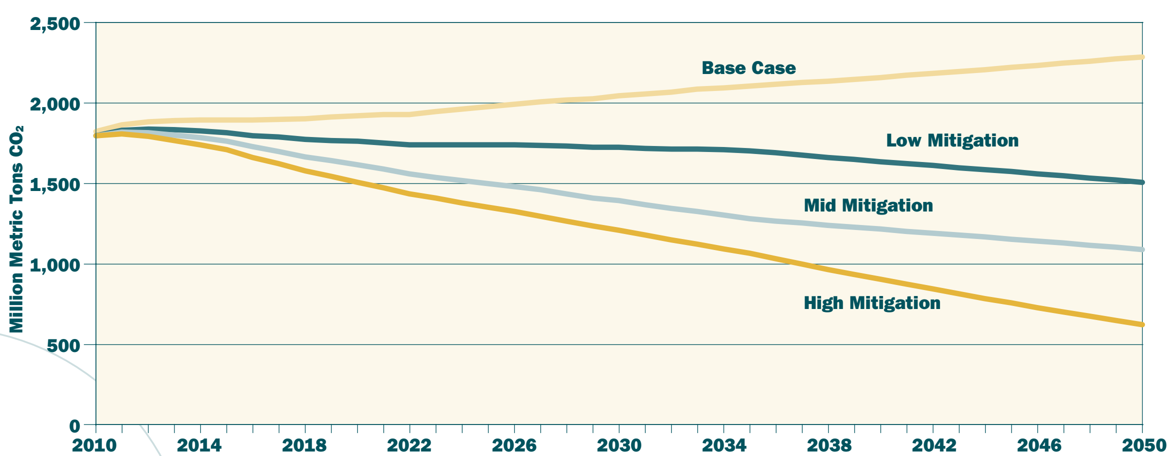


Figure 22

U.S. Transportation CO_2 Emissions in the **Three Mitigation Scenarios**



No single strategy is able to make the reductions in transportation's GHG emissions that are likely to be necessary to avoid dangerous climate change, as **Table 15** shows. In addition, all scenarios—especially the Mid and High Mitigation Scenarios—assume technological progress in energy efficiency, low-carbon fuels, and system operations. Although it is certain that technological progress will occur, no one can predict how much will be accomplished or how quickly, so policies that encourage and accelerate innovation are of paramount importance. The progress of technology also must be monitored and policies adapted to make effective use of technological progress, as it occurs.

Table 15

2050 Incremental Impacts of Efficiency Improvements, Low-Carbon Fuels, and Other Mitigation Options for Reducing GHG Emissions

	Low Scenario	Mid Scenario	High Scenario
Technological Improvements to Vehicle Efficiency Only			
Reduction versus 2010	–4%	–16%	–25%
Versus Base Case 2050	–25%	–34%	–41%
Technological Vehicle Efficiency Plus Low-Carbon Fuels			
Reduction versus 2010	–10%	–25%	–54%
Versus Base Case 2050	–29%	–41%	–64%
All Strategies and Policies			
Reduction versus 2010	–16%	–39%	–65%
Versus Base Case 2050	–34%	–52%	–73%
Annual Oil Savings below BAU (mmb)*	1,700	2,600	3,700

**Estimates of oil savings are approximate.*

5. Conclusion

The U.S. transportation sector is a major source of global GHG emissions. Each year it emits more CO_2 than any other nation's entire economy, with the sole exception of China. In 2008, transportation accounted for 27 percent of total U.S. GHG emissions. Essentially all of transportation's CO_2 emissions are due to its energy use, and CO_2 is the predominant GHG produced by transportation, accounting for 95 percent of its total emissions. Highway vehicles are responsible for 78 percent of the sector's GHG emissions. In order to limit the damage due to climate change, developed countries like the United States will have to reduce their GHG emissions by a significant amount. This report uses an economy-wide target of at least 50 percent below current levels by 2050. To achieve such dramatic, economy-wide GHG reductions, transportation will have to play a major role.

It is likely that the U.S. transportation sector will be able to make reductions in GHG emissions on the order of 50 percent or more by 2050 cost-effectively, provided that strong policy measures are implemented and that substantial progress is made in advanced vehicle technologies and low-carbon energy sources.

Just as no one technology can achieve the emission reductions that appear to be necessary, no single policy can bring them about. Those policies include pricing carbon, setting stricter fuel economy or emissions standards, converting the current motor fuel tax to a comprehensive energy user fee (indexed to the average energy efficiency of motor vehicles), instituting feebates tied to new vehicle emission rates, and converting part of motor vehicle insurance to PATP or PAYD insurance. State and local governments and metropolitan planning organizations around the United States have also shown that there are ways to reduce demand for motor vehicle travel while preserving or enhancing accessibility to homes, businesses, and leisure activities. Finally, there are ways to meaningfully improve the operating efficiency of transportation systems via advanced air traffic management and flight planning, training in eco-driving for motorists, intelligent vehicles and traffic controls, and ultimately, automated highways for heavy- and light-duty vehicles.

Energy efficiency improvements must play a major role in GHG mitigation. A reasonable fuel efficiency target for 2050 is on-road fleet average emission rates of 195 to 150 grams per mile for all petroleum-fueled LDVs (about 45 to 60 miles per gallon). For heavy-duty vehicles, existing technologies and measures can cost-effectively improve the fuel economy of new vehicles by 30 to 50 percent, reducing GHG emission rates by up to one third. For new aircraft, reductions in CO_2 emissions of 25 to 35 percent should be achievable over the next decade or two. Rail energy intensity could be reduced by 15 to 30 percent over the next two decades and by 20 to 40 percent by 2050. Comparable improvements are possible for shipping.

Increased use of biofuels with low lifecycle GHG emissions is another important option for reducing transportation's GHG emissions. The future potential of biofuels is substantial; they could displace up to 15 percent of transportation fuel use in 2035 and 35 percent or more in 2050. However, at this time it is unclear which feedstocks, conversion processes, and final uses of bioenergy in transportation are the most advantageous. Research and learning-by-doing are needed to comprehensively assess the costs and benefits of alternative biofuel uses, from ethanol in passenger cars to distillate biofuel in jet aircraft.

Deep reductions in GHG emissions from LDVs by 2050 will very likely require a transition to hydrogen, electricity, or a combination of the two as the principal source of energy. Both have shortcomings at the present time, but if the technologies can be successfully developed, the excess financial costs of a transition should be manageable.

Mitigating GHG emissions by designing communities that are conducive to shorter vehicle trips and non-motorized travel could achieve a 1 to 2 percent reduction in nationwide vehicle travel by 2035 and a 1.5 to 5 percent reduction by 2050. Further, individual communities with a commitment to creating a travel-efficient environment could do substantially more.

Pricing can be a very powerful tool for increasing energy efficiency, promoting low-carbon fuels, and encouraging environmentally beneficial travel choices. The American public, however, has historically resisted policies for transportation that use prices to influence environmental decisions. For this reason, this report has focused on pricing policies that change the incidence of transportation costs without increasing overall costs. Notable exceptions are pricing carbon and pricing congestion.

This report uses three scenarios to illustrate a range of GHG mitigation potential for the U.S. transportation sector. The emission reductions below 2010 levels achieved in 2050 by these scenarios range from 17 percent in the Low Mitigation Scenario to 65 percent in the High Mitigation Scenario. Technological improvements to vehicle energy efficiency, low-carbon energy sources, and all other strategies make roughly comparable contributions to GHG mitigation in the High Mitigation Scenario.

No single technology, no single policy, and no single mode is able to accomplish a 65 percent reduction in transportation's GHG emissions. Achieving reductions of that magnitude requires a comprehensive strategy, with strong public support, sustained by rapid technological progress. Transportation will remain a cornerstone of the U.S. economy and a fundamental contributor to Americans' quality of life to 2050 and beyond. The enormous value to society of the mobility of people and commodities must be preserved. Because rates of technological progress and future energy prices are uncertain, the GHG mitigation strategy for transportation must be adaptable.

This report demonstrates that with cost-effective policies and plausible technological progress and shifts in consumer behavior, the United States can reduce GHG emissions from transportation by 65 percent below 2010 levels by 2050. Greater or lesser reductions may turn out to be appropriate in the future. In any case, a great deal can be done with confidence today. It is imperative to get started right away, and to adjust as the future unfolds.

Appendices

Appendix A: Cost Estimates for Advanced Technologies and Fuels

Analyses that evaluate and compare advanced technologies and fuels for transportation use various measures of costs and cost-effectiveness. Users of these analyses should understand both the substantial uncertainties and the difficulties inherent in trying to compare alternative analyses.

Estimates of the costs of existing technologies often break down the technologies into their component parts and estimate the materials and manufacturing cost of each component and the assembly cost for the complete technology. Cost estimators also have a good understanding of the cost reductions obtained by mass production at larger scales known as economies of scale. Further, they have a substantial evidence base for the cost reductions obtained from learning-by-doing as manufacturers redesign their products and manufacturing processes to gain efficiencies.

Estimates of the costs of new technologies suffer from considerable uncertainties, however. In particular, substantial changes in design and materials can occur as technologies move from initial prototypes to mass-produced products. Air bags evolved from a single $1,000 to $2,000 driver-side airbag to standard dual front, side, and often additional bags even in economy cars, for instance. The Toyota Prius hybrid drivetrain underwent dramatic design changes, cost reductions, and performance improvements. The specific power (power/weight) of Prius's nickel-metal hydride batteries improved from 660 Watts per kilogram (W/kg) in 1998 to 1,250 W/kg in 2004 (Toyota, 2006). The 2001 Prius was a compact sedan that attained 41 (on-road) mpg according to U.S. EPA estimates, with a 0 to 60 mph acceleration time of 12.8 seconds; the 2004 Prius was larger (midsize), attained 46 mpg, and had a 0 to 60 mph acceleration time of 10.5 seconds. The 2010 Prius attained 50 mpg and a 0 to 60 mph acceleration time of 9.8 seconds (Toyota, 2009).

Cost estimators also must account for changes in the cost of critical materials and for changing environmental standards. They must consider the costs of integrating new technologies into the vehicle, and of mitigating durability, safety, and NVH (noise, vibration, and harshness) problems that the technology may cause;[110]

110. For example, Honda dealt with NVH problems associated with its engine cylinder deactivation system by adding computer-controlled mounts to counteract vibration, modifying the torque converter to smooth transitions between 3, 4, and 6 cylinder operation, and adding noise cancellation inside the passenger cabin, with costs rivaling the technology costs (personal communication with John German, International Council on Clean Transportation, formerly Manager of Environmental and Energy Analyses, American Honda Motor Company).

though these costs are hard to predict. In evaluating new fuels, estimators must account for improvements in conversion processes, changes in distribution methods (e.g., shifting from truck transportation to pipelines), along with changes in feedstock costs and crop yields.

Information about costs for key components of new technologies is often tightly held by developers, and the information sources may be biased to overestimate costs (if in search of subsidies) or underestimate them (if seeking financial support or regulatory approval).

Aside from the uncertainty inherent in cost estimates, technology evaluations often use measures of cost-effectiveness that introduce further uncertainty and complexity. Estimates of "net costs" (fuel savings minus front-end costs) or "years to break-even" introduce assumptions about future oil prices or petroleum product prices, discount rates, and reference technologies to which the new technologies are being compared. A study of multiple alternative drivetrain technologies for LDVs conducted by Argonne National Laboratory (Plotkin & Singh, 2009) illustrates the importance of these assumptions. **Figure 23** shows the net costs for midsize cars with 12 different 2030 drivetrain technologies, compared to a 2007 gasoline-fueled car. In this analysis, the drivetrain costs were estimated by using a literature review and interviews with industry sources. The figure shows that net cost estimates differ markedly as discount rates shift from low "societal" rates to the high rates that average vehicle purchasers appear to use. At a 4 percent discount rate, most of the technologies have fuel savings significantly higher than the initial costs of the technologies. At a 20 percent discount rate, the gasoline-fueled conventional drivetrain, hybrid, and plug-in hybrid with 10-mile range barely break even, with all other technologies having initial costs higher than any future fuel savings.

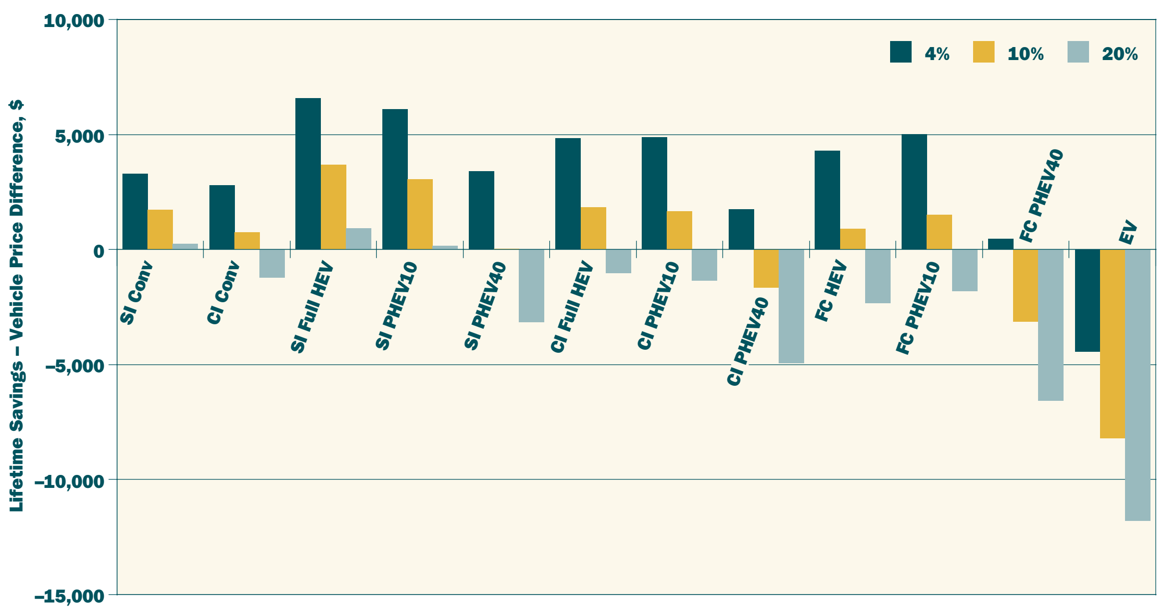
In **Figure 23**, the reference vehicle is a 2007 midsize car with a conventional gasoline-fueled drivetrain. Other analysts might speculate that, in 2030, the advanced hybrid drivetrain vehicle would likely be the first choice of vehicle purchasers against which vehicles with other drivetrain technologies would be compared; they might wish to see that 2030 hybrid vehicle used as the reference vehicle instead (**Figure 24**). The results are dramatically different with the change in reference vehicle—if net costs were the vehicle purchasers' only criterion, *none* of the other drivetrain choices appears attractive.

A drop in fuel prices undermines the cost-effectiveness of expensive new technologies.

Since cost estimates themselves are uncertain, it is also worthwhile to examine other estimates. **Figure 24** repeats the first figure using a set of more optimistic technology cost estimates based on U.S. DOE cost goals. Net costs are dramatically improved compared to **Figure 23**. Even using the SI full hybrid as the reference vehicle, all of the fuel cell vehicles would have positive net costs.

Figure 23

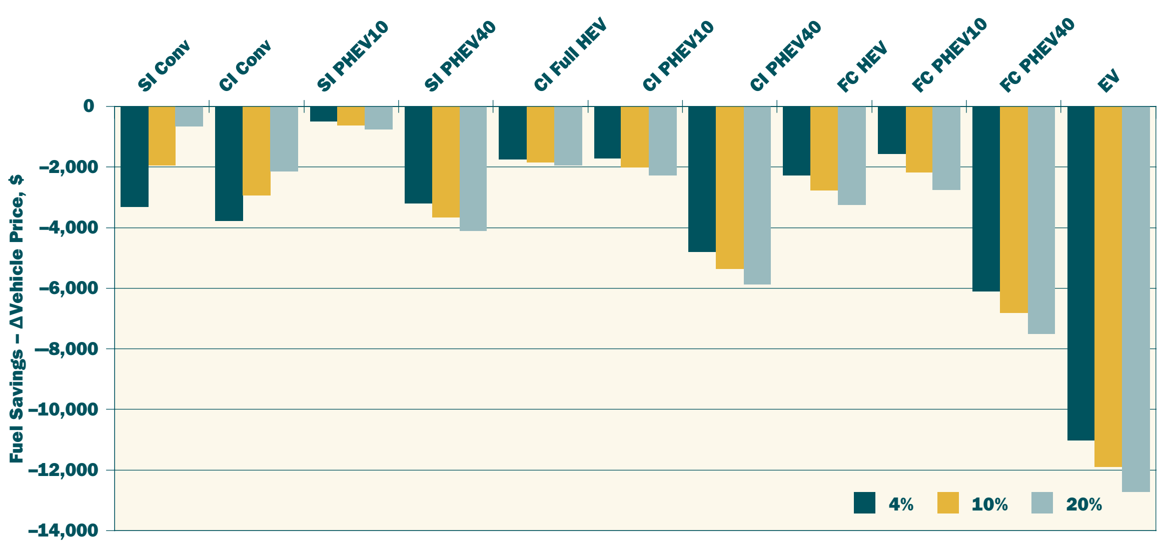
Lifetime Net Savings (or Costs) Using Different Discount Rates for Fuel Savings of 2030 Advanced Midsized Cars (Reference to 2007 SI Conventional Vehicle) Assuming $3.15 per Gallon Cost (Literature Review)



(SI Conv = spark ignition advanced conventional; CI = compression ignition/diesel; Full HEV = hybrid electric vehicle; PHEV = plug-in hybrid; FC = fuel cell; EV = electric vehicle)

Figure 24

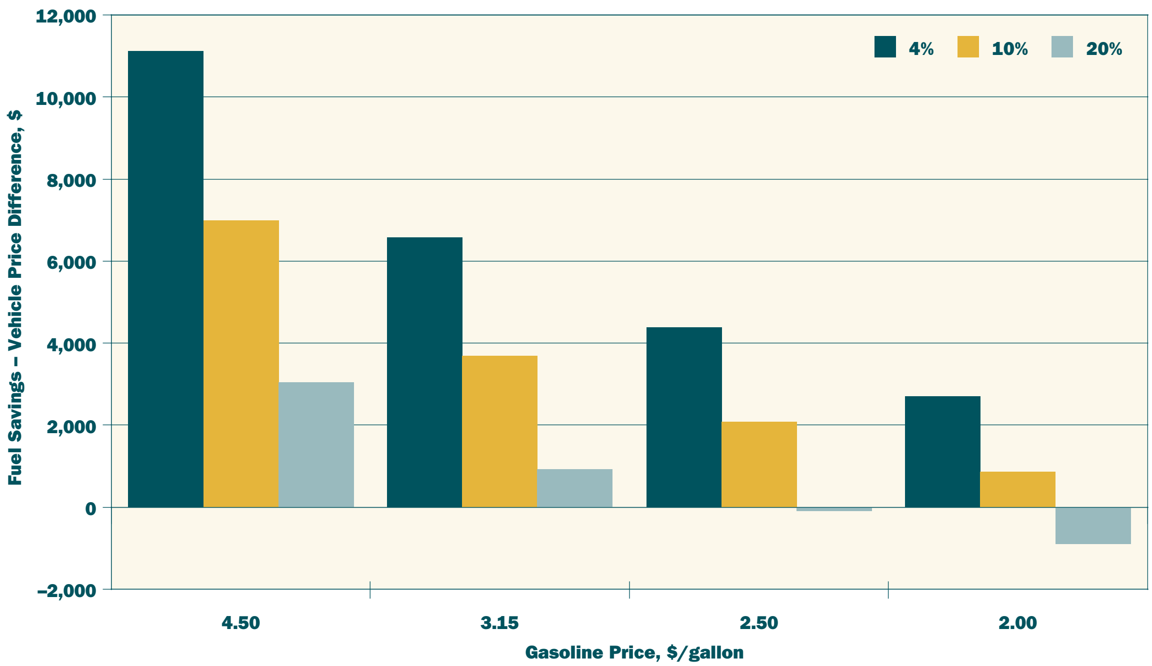
Lifetime Net Savings (or Costs) Using Different Discount Rates for Fuel Savings of 2030 Advanced Midsize Cars (Referenced to 2030 Hybrid Vehicle) Assuming $3.15 per Gallon Cost (Literature Review)



(SI Conv = spark ignition advanced conventional; CI = compression ignition/diesel; Full HEV = hybrid electric vehicle; PHEV = plug-in hybrid; FC = fuel cell; EV = electric vehicle)

Figure 25

Lifetime Net Savings (or Costs) Using Difference Discount Rates for Fuel Savings of 2030 Hybrid Midsize Car, at Different Fuel Prices Referenced to 2007 SI Midsize Car



The underlying lesson of these figures is that estimates of the cost-effectiveness of new technologies (and fuels) cannot be fully understood or compared to other estimates unless the assumptions underlying the estimates are exposed and understood, and the results of competing estimates "normalized" to the same set of assumptions. Another lesson is that, given the high uncertainty surrounding both the technology cost estimates themselves and the variables that will determine cost-effectiveness, estimates of future cost and cost-effectiveness should rarely be viewed as the sole or even primary forecaster of a technology's future viability.

A final point is that it is important to understand precisely what the estimates mean. Although technology "costs" generally refer to manufacturers' costs, some "cost estimates" do refer to expected retail prices. And different analysts may use different markups in translating manufacturing costs to retail prices. Further, some of the performance measures used as the denominators in cost estimates (e.g., $/kWh) need to be understood precisely. Kilowatt-hours can refer to a battery's full rated capacity, that is from 100 percent to 0 percent charge, or instead to usable capacity, the electricity that can be obtained on a regular basis without shortening battery life. The latter may refer to only 50 or 60 percent of the battery's full rated capacity, and may increase over time as battery designs improves.

Appendix B: The Kaya Method

Adding up the impacts of mitigation actions requires a quantitative representation of transportation's GHG emissions and their interrelationships. A simple yet rigorous model can be specified using the Kaya identity (McCollum & Yang, 2009). The Kaya identity estimates the GHG emissions from transportation for a future year by decomposing the contributing factors that determine emissions using the equation:

Transportation GHG emissions

= The sum over all transportation modes, vehicle types, and fuels of

{Energy Services Produced × Energy Intensity × Carbon Intensity}

For the equations below, each term listed above is defined as follows:

i – transportation mode

j – vehicle type

k – fuel type

t – year

M – number of transportation modes

V – number of vehicle types

N – number of fuel types

Q_t – the energy services produced

σ_{tij} – share of energy services in transportation mode *i* by vehicle type *j* in year *t*

s_{tijk} – the share of σtij produced by fuel type k

e_{tijk} – the energy intensity of vehicle *j* in mode *i* using fuel type *k* in year *t*

C_{tk} – the carbon intensity of fuel *k* in year *t*

E – energy use

The Kaya calculations have been implemented in an Excel™ spreadsheet, which is available from the authors on request.

Equation 1

$$GHG_t = Q_t \sum_{i=1}^{M} \sum_{j=1}^{V} \sum_{k=1}^{N} s_{tijk} \sigma_{tij} e_{tijk} C_{tk}$$

Energy services can be measured in a variety of ways. Transportation energy services are frequently measured in terms of passenger-miles or ton-miles. Ultimately, energy services are the utility consumers derive from mobility and the contribution of goods movements to productivity. The difficult problem of measuring energy services is avoided here by using the projected energy use in future years to represent the level of energy services provided. Because energy services (Q) equal energy use (E) divided by energy intensity (e), energy use in the future years can be substituted for energy services. The distribution of energy services by mode is then represented by the distribution of energy use by mode.

Equation 2

$$GHG_t = Q_t \sum_{i=1}^{M}\sum_{j=1}^{V}\sum_{k=1}^{N} s_{tijk}\sigma_{tij}e_{tijk}C_{tk} = \sum_{i=1}^{M}\sum_{j=1}^{V}\sum_{k=1}^{N}\left(s_{tijk}\sigma_{tij}Q_t e_{tijk}\right)C_{tk} = \sum_{i=1}^{M}\sum_{j=1}^{V}\sum_{k=1}^{N}\frac{e_{tijk}}{e_{tijk}}E_{tijk}C_{tk}$$

Impacts were estimated relative to a baseline projection for two future years, 2030 and 2050. Impacts of energy intensity improvements were estimated by introducing the ratio of energy intensity in the scenario to energy intensity in the baseline projection into Equation 2. Let the impact of measure x on energy intensity be δ_x, where δ_x is $-1 < \delta_x < 0$ if the measure reduced energy intensity and > 0 if energy intensity is increased. The relative energy intensity after the impact of measure x is then $1+ \delta_x$.

Equation 3

$$\frac{e^*_{ijk}}{e_{ijk}} = \frac{e_{ijk}\left(1+\delta_{ijkx}\right)}{e_{ijk}} = \left(1+\delta_{ijkx}\right)$$

Let Δ_{ky} be the impact of measure y on the carbon intensity of fuel *k*, and $-1 < \Delta_{ky} < 0$ indicates a reduction in carbon intensity. Since energy services have been replaced by energy use, shares can be eliminated by replacing E with E_{ijk}, and impacts of measure z on energy services shares or any change in the relative amount of activity (γ_{ijkz}) defined once again as changes relative to the baseline projection. Finally, rebound effects due to reductions in energy intensity can be represented by mode and vehicle type specific elasticities (β_{ij}). This leads to the following implementation of the Kaya identity.

$$GHG_t = \sum_{i=1}^{M}\sum_{j=1}^{V}\sum_{k=1}^{N} E_{ijk}\left[\prod_{x=1}^{X}\left(1+\delta_{ijkx}\right)\right]^{1+\beta_{ij}}\left[\prod_{z=1}^{Z}\left(1+\gamma_{ijkz}\right)\right]\left[C_k\prod_{y=1}^{Y}\left(1+\Delta_{ky}\right)\right]$$

The advantages of the Kaya method are transparency, repeatability, a rigorous accounting framework, and the ability to avoid double counting when accumulating impacts. For example, if substituting zero net carbon electricity for petroleum reduced petroleum consumption by 50 percent, then a 50 percent reduction in energy intensity can reduce GHG emissions by only an additional $0.5 \times 0.5 = 0.25$, or 25 percent. The chief limitations of the Kaya method are that it cannot estimate a general equilibrium outcome and that it accounts only for the first order interactions among interventions. For example, if improving the energy efficiency of heavy-duty trucks draws traffic from the rail system, the Kaya framework will not automatically make such an adjustment. The analyst must independently estimate the effect and alter the respective modal (energy) shares.

Appendix C: The Government's Role in Energy Transitions

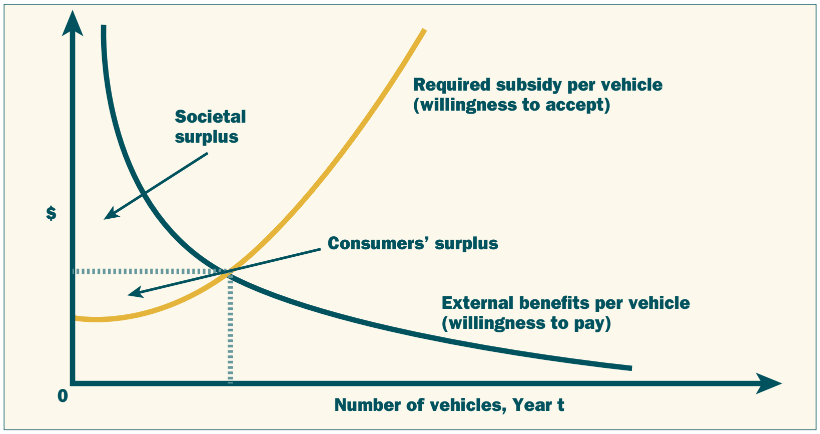
Assuming the energy transition appears likely to be beneficial, society has a willingness to pay to achieve the transition of less than or equal to the present value of total social benefits minus the excess transition costs. However, there is probably no need to pay anywhere near that amount. Given that society wants to make the transition, reducing any of the five market barriers listed in Section 3.4.3 can be thought of as an external benefit.[111] Society's willingness to pay an individual to purchase a fuel cell vehicle (or a battery electric vehicle) is the sum of the external benefits the additional vehicle produces. Similarly, each additional hydrogen fuel station (or electric vehicle recharging station) makes fuel cell vehicles more valuable to potential buyers. The purchase of another vehicle increases scale economies, adds to learning, decreases risk, and increases the chances that additional makes and models of fuel cell (or electric) vehicles will be offered. In any given year, society's willingness to pay would be a downward sloping function of the number of alternative vehicles sold. Society would be willing to pay more for the first, second, and third vehicles sold than for the 10,001st, 10,002nd, and 10,003rd, because the benefit per vehicle decreases.

On the other hand, each potential vehicle buyer (or potential station owner) has a willingness to accept the alternative energy vehicle, that is, a price at which they will choose the new technology over the conventional technology. The willingness to accept price would be lowest for early adopters who just happened to want the make and model first offered, and who happened to live close to a refueling outlet. At a particular time and for a given state of vehicle and fuel availability, additional buyers would require a greater subsidy to be willing to accept the new technology. Integrated over the population of potential buyers, consumers' willingness to accept would be an upward sloping function of the number of vehicles sold. Analogously to demand and supply curves, an optimal solution exists at the intersection of the two functions (illustrated in **Figure 26**). Each year the curves will shift as technology progresses, infrastructure is built up, and consumers' attitudes change.

111. Most of the benefits are pecuniary external benefits in technical economic terminology, because they are reflected in market prices. Scale economies and learning-by-doing are good examples of pecuniary external benefits. The benefits of increased diversity of choice appears to be a network benefit, while the benefit to potential alternative fuel vehicle buyers of making fuel more available is an indirect network benefit (as is the value to fuel providers of adding another alternative fuel vehicle to the stock). The value to more risk averse consumers produced by early adopters when they buy a novel product appears to be a simple external benefit.

Figure 26

Illustration of **Optimal Subsidy** and Quantity of Alternative Energy Vehicles



The framework presented above is incomplete because it does not include the dynamics of change over time and the dependence of future states on earlier actions.

In the real world, however, technological progress is uncertain. Thus, periodically, the likelihood of success and the size of the potential benefits must be re-evaluated to determine if the project should be continued or ended, either because it is already successful or is unlikely to ever succeed.

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