solutions

Reducing **Greenhouse Gas** Emissions From **U.S. Transportation**

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Pew Center on Global Climate Change

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Prepared for the Pew Center on Global Climate Change

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

Transportation accounts for nearly a third of our nation's greenhouse gas (GHG) emissions, and its emissions are growing rapidly. In this report, authors David Greene and Andreas Schafer find that numerous opportunities are available now and in the future to reduce the transportation sector's impact on climate. Many of these same actions would also address other national priorities, including reducing U.S. dependence on oil imports.

This latest Pew Center report is the first building block in our effort to examine key sectors, technologies, and policy options to construct the "10-50 Solution" to climate change. The idea is that we need to tackle climate change over the next fifty years, one decade at a time. This report points to the following key elements of the 10-50 Solution to transportation.

- *We can start now, and we must start now.* Fuel economy for cars and trucks could be increased by 25 to 33 percent over the next 10 to 15 years using market-ready technology at a net savings, if fuel savings are taken into account. Increasing efficiency of vehicles (aircraft, car, trucks and trains) takes time because fleet turnover typically takes 15 years or more.

- *We will need a sustained effort over many decades.* Technologies on the horizon are likely to enable fuel economy improvements in cars and light trucks of 50 to 100 percent by 2030. Transforming land-use patterns to enable more efficient travel, or transitioning to a hydrogen based transportation system, will require decades of incremental change.

- *R&D and voluntary efforts are necessary but not sufficient; mandatory policies are essential.* Since fuel economy is undervalued in the marketplace, policies such as mandatory GHG standards and public information are needed to pull technological improvements into the market. Fuel economy has gotten worse recently not because of lack of technology, but because of lack of policy. Hydrogen holds out the tantalizing promise of near-zero greenhouse gas emissions, but government must provide clear policy direction to drive massive private investment by the fuel and vehicle industries.

- *We need a mix of policies, and there are many to choose from.* Opportunities for significant emission reductions include implementing a carbon constraint, raising efficiency standards for automobiles, blending low-carbon fuels with gasoline, and changing land-use patterns through urban design and planning. Each of these measures could contribute to reducing GHG emissions, but none is sufficient alone. The authors estimate that a combination of reasonable measures would reduce carbon emissions by about 20 percent by 2015, and almost 50 percent by 2030, compared to "business as usual."

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Executive Summary

Since the introduction of motorized transportation systems, economic growth and advancing technology have allowed people and goods to travel farther and faster, steadily increasing the use of energy for transportation. Modern transportation systems are overwhelmingly powered by internal combustion engines fueled by petroleum. Emissions of carbon dioxide (CO_2), the principal greenhouse gas (GHG) produced by the transportation sector, have steadily increased along with travel, energy use, and oil imports. In the absence of any constraint or effective countermeasures, transportation energy use and GHG emissions will continue to increase.

In the U.S. economy, transportation is second only to electricity generation in terms of the volume and rate of growth of GHG emissions. In terms of carbon dioxide, which accounts for 95 percent of transportation's GHG emissions, transportation is the largest and fastest growing end-use sector.[1] Today, the U.S. transportation sector accounts for one-third of all U.S. end-use sector CO_2 emissions, and if projections hold, this share will rise to 36 percent by 2020. U.S. transportation is also a major emitter on a global scale. Each year it produces more CO_2 emissions than any other nation's entire economy, except China. Given its size and rate of growth, any serious GHG mitigation strategy must include the transportation sector.

This report evaluates potential CO_2 emission reductions from transportation in the United States. Measures considered include energy efficiency improvements, low-carbon alternative fuels, increasing the operating efficiency of the transportation system, and reducing travel. Highway vehicles should be the primary focus of policies to control GHG emissions, since they account for 72 percent of total transportation emissions. Passenger cars and light trucks together account for more than half of total sectoral emissions.

Energy Efficiency

By 2015, the fuel economy of new passenger cars and light trucks can be increased up to one-third by the adoption of proven technologies, at a cost below the value of the fuel that would be saved and without reducing the size or performance of vehicles. Before 2030, advanced diesel engines, gasoline or diesel hybrid vehicles, and hydrogen-powered fuel cell vehicles will likely permit new car and light truck fuel economy to be increased by at least 50 to 100 percent, while satisfying current and future emission standards. Efficiency gains of 25 to 50 percent for new heavy trucks will likely also be possible over the next 15 to 30 years. For new aircraft, fuel economy increases of 15 to 25 percent seem feasible by 2015, reaching 25 to 40 percent by 2030.

Because the energy efficiency of new vehicles will rise gradually, and because it takes time to turn over the entire fleet of vehicles in use, by 2015 the increase in energy efficiency achieved by all transportation vehicles in use will be only about half that achieved by new vehicles. With policies to ensure the use of cost-effective technologies to increase fuel economy, by 2015 it should be possible to boost the average efficiency of vehicles in use by 10 to 15 percent, reducing GHG emissions by about 11 percent. By 2030 GHG emissions reductions on the order of 25 percent should be achievable. These estimates take into account the tendency for slight increases in travel when fuel costs are lowered by efficiency gains.

Alternative Fuels

Despite 25 years of effort, alternatives to petroleum have not displaced more than a few percent of petroleum fuels. Petroleum fuels are supported by an extensive and well-functioning infrastructure. They also have high energy density, low cost, and a demonstrated ability to adapt to environmental challenges. In the near term, lower-carbon alternative fuels such as natural gas and liquefied petroleum gases will continue to be viable in niche markets. Lower-carbon replacement fuels, such as alcohols or ethers produced from biomass, can be blended with gasoline to displace several percent of petroleum use. If methods of producing ethanol from cellulose can be commercialized and if current tax subsidies are continued, renewable liquid fuels blended with petroleum fuels could reduce transportation's CO_2 emissions by 2 percent by 2015 and 7 percent by 2030.

Technological advances in fuel cells, hydrogen production, and hydrogen storage are needed to accomplish a transition to a largely hydrogen-powered transportation system. Such a transition will also require intensive planning, major commitments by government, industry, and the public, and supportive public policies. If achieved, however, a transition to hydrogen produced from renewable or nuclear energy or from fossil resources with carbon sequestration, could eliminate most of transportation's GHG emissions sometime after 2030.

System Efficiency

While changing behavior has the potential to reduce transportation fuel use and GHG emissions, large and sustainable reductions have never been achieved in this manner in the United States. Increasing wealth and vehicle ownership combined with decreasing household size and population densities has led to steadily declining vehicle occupancy rates. The same trends have historically contributed to declining market shares for mass transit, although mass transit ridership has been growing over the past few years. On the freight side, shippers increasingly value speed and reliability, favoring truck and airfreight, the most energy-intensive modes. Still, GHG emission reductions of a few percent can be achieved with concerted effort, and much might be possible if innovative strategies could be found to increase vehicle occupancy rates without diminishing service or convenience.

Reducing Transportation Activity

Mobility gives people access to opportunities and enhances the efficiency of the economy. Reducing transportation activity *per se* is not a desirable goal. Where there are environmental damages (such as GHG emissions) unaccounted for in private transportation decisions, increasing the cost of travel to reflect these impacts is beneficial from both an economic and environmental perspective. In particular, internalizing the externality of climate change through carbon cap-and-trade systems or direct pricing of the carbon content of motor fuels is an especially attractive option. An even greater impact can be achieved by redistributing certain fixed costs of motor vehicle travel so that they fall on carbon fuels. One example is collecting a portion of vehicle insurance fees as a surcharge on motor fuel. This could reduce GHG emissions from motor vehicles by 8 to 12 percent and could improve the overall economic efficiency of highway transportation.

The patterns of land use and development that have evolved over many decades are inefficient from a transportation perspective. If the geography of cities can be transformed to provide equal or greater accessibility with less travel, both the environment and the economy would benefit. Experimentation and modeling analyses indicate that travel reductions of 10 percent may be achievable in the long run, without loss of accessibility. The ability to consistently achieve and sustain such reductions has not been demonstrated in the United States, and much remains to be learned about planning and realizing more transportation-efficient patterns of land use.

Policy Options

There are plenty of practical and effective policies for reducing transportation's GHG emissions. The policies described in this report are not the only policies that can be effective; rather, they are representative of the kinds of policies a comprehensive strategy would include. A reasonable combination of policy measures should be able to reduce U.S. transportation sector CO_2 emissions by 20 to 25 percent by 2015 and by 45 to 50 percent by 2030 in comparison to a transportation future without any efforts to control carbon emissions. If the demand for transportation energy use continues to grow at 2 percent per year through 2030, achieving these reductions will result in CO_2 emissions in 2030 that are about the same as the current level.

These estimates of GHG reductions achievable by 2015 are based on: (1) proven energy efficiency technologies and low-carbon replacement fuels, (2) levels of efficiency improvement at which the value of the fuel saved is greater than or equal to the cost of technology, (3) no change in vehicle size or performance, (4) pricing and other policies that do not increase the overall cost of transportation and, (5) a carbon cap-and-trade system equivalent to approximately $50 per ton of carbon. Greenhouse gas reductions estimated to be achievable by 2030 are based on: (1) efficiency improvements that depend on technological progress judged highly likely by 2020 with a focused R&D effort, and (2) continuation or moderate extensions of pricing and behavioral policies adopted for 2015. GHG emissions would be lower if growth in demand for transportation fuel is slower, or with more stringent energy efficiency standards, a tighter carbon emissions cap, or if technological innovation is more rapid than assumed here.

Fuel efficiency improvements, especially of cars and light trucks, offer the largest potential for reducing CO_2 emissions from transportation over the next 30 years. Several policies can contribute to realizing this potential, including fuel economy standards. Fossil fuel or carbon pricing policies would encourage fuel economy improvements while simultaneously discouraging transportation demand. Pricing measures alone, however, would probably not be sufficient to achieve the above indicated emission reductions. A price of $100 per ton of carbon, which translates into $0.25 per gallon of gasoline, might increase fuel economy by about 5 to 10 percent and reduce light-duty vehicle travel by about 1 to 3 percent, far below the estimated potential of a comprehensive strategy.

The long lead times required to turn over the entire fleet of vehicles and the supporting infrastructure mean that policies must be implemented now to create the impetus for change in order to achieve the reduction levels indicated in this report. Within the next 15 years, energy efficiency improvements, various pricing policies, and low-carbon replacement fuels are the key components of a comprehensive effort to reduce GHG emissions. Over the longer term a large-scale transition away from petroleum fuel toward low-carbon alternative fuels should be considered. Among the most promising low-carbon fuels for the longer term is hydrogen, which has many desirable fuel characteristics and can be produced from a variety of zero-carbon feedstocks or from fossil fuels with subsequent carbon sequestration. Obstacles, however, remain in areas such as hydrogen storage and the cost of hydrogen fuel cell vehicles. A transition to hydrogen will require an entirely new infrastructure for producing, transporting, distributing, storing, and retailing hydrogen, and possibly for sequestering CO_2 emissions generated during its production.

Many of the policy measures discussed in this report do much more than reduce CO_2 emissions. For example, improving fuel efficiency of the U.S. transportation system reduces dependence on foreign oil imports and increases the global competitiveness of the U.S. vehicle industry. Similarly, more efficient land-use patterns not only increase the ridership potential of public transportation modes but also relieve traffic congestion. Taking these multiple benefits into account spreads the costs of controlling CO_2 emissions and adds incentives for taking action.

The size and rate of growth of transportation's GHG emissions make them impossible to ignore. The interconnectedness of transportation to nearly every aspect of human activity, the provision of most transportation infrastructure as public goods, the important external costs associated with transportation activity and energy use, and other market imperfections mean that no single policy is likely to achieve the needed reductions in transportation GHG emissions. A suite of policies will be necessary. Devising and implementing an effective, comprehensive strategy will be a difficult and complex task, but it can be done.

I. Introduction

The U.S. transportation system provides Americans with the greatest mobility of any society on earth. It is fundamental to the health of the U.S. economy and to its continued growth. But transportation is also the economy's largest source of CO_2 emissions, produced by burning petroleum fuels in internal combustion engines. In the coming decades, the transportation system faces important energy challenges. Sometime in the next 10 to 30 years, the world is likely to begin a transition away from petroleum products made from conventional oil. One option is to continue to use oil, but to produce it from either coal or unconventional fossil fuels, such as tar sands and shale oil. Another possibility is to shift to an entirely different energy carrier, such as hydrogen produced from either renewable energy sources or from fossil fuels with carbon sequestration. If the necessary technologies can be developed and effective policies put in place, a cleaner, more economically efficient energy future that is no longer dependent on oil will be possible. In the meantime, much can be accomplished that will be beneficial in its own right and will buy time to advance technology and make a smooth transition.

A. The World's Largest Transportation System

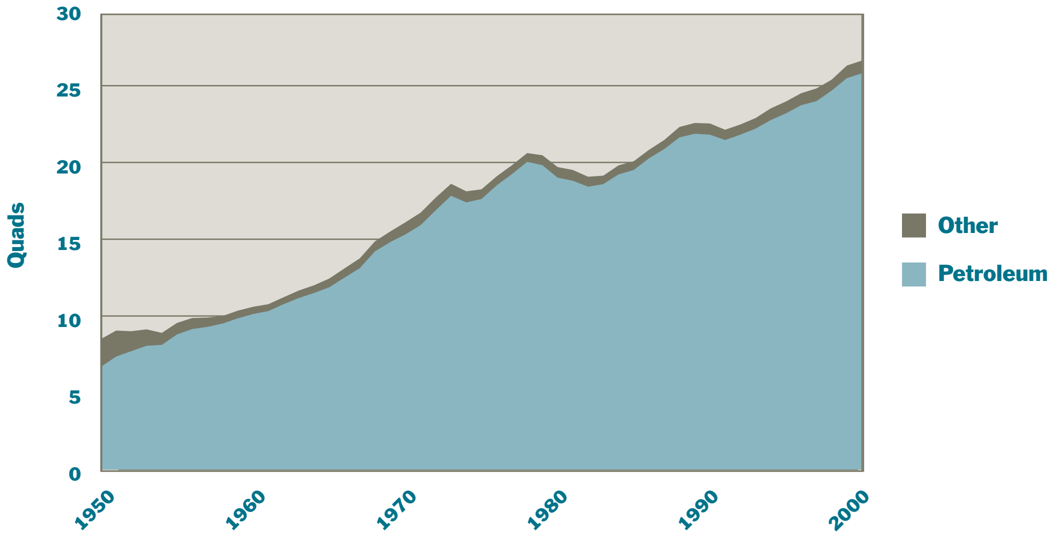
The U.S. transportation system is the largest in the world. It is not only a major source of global greenhouse gas (GHG) emissions, but it is also almost entirely responsible for U.S. oil dependence. Transportation is woven into nearly every aspect of life, and the amounts and kinds of transportation Americans use are strongly linked to long-lived investments in housing, commercial buildings, roads, and airports—indeed, the entire geography of the nation. Reducing GHG emissions from transportation presents special challenges. Yet the vast amount and continued growth of GHG emissions produced by the U.S. transportation system mean that the transportation sector must be a part of any meaningful GHG mitigation strategy.

Mobility of people and commodities is essential to modern societies. Each year Americans travel a total of 4.8 trillion person-miles, an amount nearly equivalent to a trip around the world for each and every person in the country, every year. The United States also has the most mobile economy in the world. In 2001 3.7 trillion ton-miles of freight were moved to facilitate production and consumption in the world's largest economy.

Transportation on such a massive scale requires enormous amounts of energy. As illustrated in Figure 1, energy use by the U.S. transportation system had increased to 27.1 quadrillion Btu (quads) by 2001. Only two nations, China (36.7 quads) and Russia (28.0 quads), use more energy than this in their entire economies.[2] All but 1 percent of the energy that powers transportation in the United States is obtained by burning fossil fuels, and all but 3 percent of it is derived from petroleum.

Figure 1

U.S. Transportation Energy Use 1950-2000



Source: U.S. DOE/EIA Annual Energy Review 2000, Table 2.1a.

The vast scale of transportation in America and its reliance on oil make it the second largest U.S. source of GHG emissions (Figure 2) and a major source globally. In 2000, GHG emissions from U.S. transportation amounted to 515 million metric tons of carbon equivalent, more than a quarter of total U.S. GHG emissions. Carbon dioxide is the most important greenhouse gas produced by the transportation sector, accounting for 95 percent of the warming effect of transportation's GHG emissions (Figure 3). The U.S. transportation system emits more CO_2 than any other nation's total CO_2 emissions, except China.

Within the transportation sector, highway transportation dominates both energy use and GHG emissions.[3] Highway vehicles account for 72 percent of transportation energy use and carbon emissions. Air transport comes in a distant second with 10 percent, followed by marine, rail, and pipelines (see

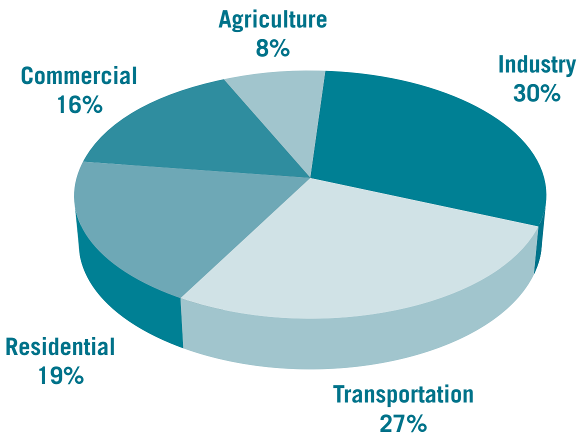
Figure 4). Within the highway mode, light-duty vehicles (passenger cars and light trucks) account for 75 percent of highway energy use. Carbon dioxide emissions from U.S. light-duty vehicles alone are comparable to the total carbon emissions of major industrialized countries like Germany and Japan.

Since 1980, CO_2 emissions from transportation have increased more rapidly than from any other energy-using sector (Figure 5). In 1998 carbon emissions from transportation surpassed those from the industrial sector.[4]

Transportation's CO_2 emissions and U.S. oil dependence are closely linked. Transportation consumes seven of every ten barrels of oil the nation uses. Today, imports supply more than half of U.S. oil needs (56 percent in 2001).[5] Dependence on oil has cost the economy trillions of dollars over the past thirty years and continues to create strategic and military risks (see Box 1, "Oil Dependence"). The U.S. Department of Energy projects that import dependence will continue to increase in coming decades as transportation-driven demand grows and domestic supply continues to decline.[6]

Figure 2

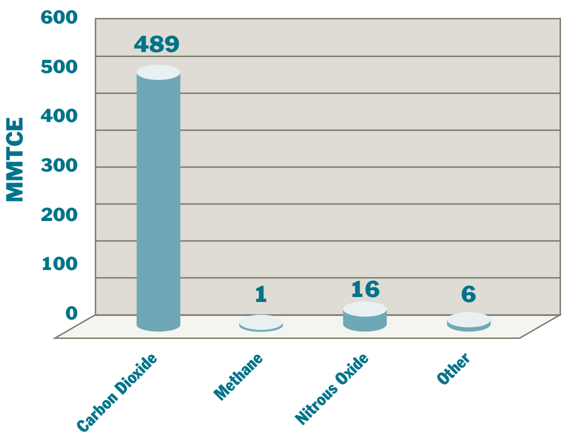
Transportation Share of U.S. Greenhouse Gas Emissions, 2000



Source: U.S. EPA, 2002, ES-5.

Figure 3

Transportation GHG Emissions by Gas, 2000

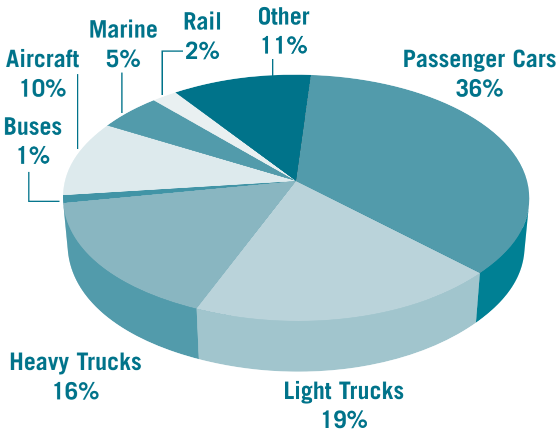


MMTCE = million metric tons of carbon-equivalent

Source: U.S. EPA, 2002.

Figure 4

Transportation GHG Emissions by Mode, 2000



Source: U.S. EPA, 2002, Table 1-14.

Figure 5

Carbon Dioxide Emissions by Energy-Using Sector

Source: U.S. DOE/EIA Annual Review 2001, Table 12.2.

B. A Global Energy Transition

If global mobility is to continue to expand, especially in the developing world, a transition to other sources of energy to power transportation must begin soon. The energy sources chosen will have important consequences for the global climate. Decisions made in the next several years could determine whether the world's transportation systems follow a path of continued reliance on high-carbon fossil fuels, or take an alternative path toward more diverse, low-carbon energy sources. Estimates of total world oil resources are uncertain and often controversial, yet there is a growing consensus that somewhere between one-fourth[7] and one-half[8] of all the recoverable resources of conventional[9] oil that exist on earth have already been consumed and that the halfway point will likely be reached sometime in the next 5 to 25 years.[10]

A transition to unconventional[11] oil resources could allow the world's economies to power their transportation sys-

Box 1

Oil Dependence

The international effort to curb GHG emissions offers the United States an opportunity to solve its thirty-year-old problem of oil dependence. Dependence on oil is a source of major economic, political, and strategic problems for the United States.[12] Significant efforts by every large economy to reduce CO_2 emissions, especially from transportation, could lead to major worldwide reductions in petroleum demand. That, in turn, would undermine the market power of the OPEC oil producers and could break their hold over world oil markets.

Oil price shocks and oil market manipulations by OPEC have cost America's economy trillions of dollars. For the past thirty years every major oil price shock has been followed by a recession in the United States, and every recession has been preceded by an oil price shock. Each year, tens of billions of dollars of excess oil profits help support regimes inimical to the United States. Concern over possible disruption of oil supplies influences U.S. foreign policy and military actions.

Two-thirds of the world's oil reserves are concentrated in a few countries that joined together in the late 1960s to form the OPEC cartel. When the Arab members of OPEC declared an oil boycott against the United States in 1973, world oil prices doubled. Prices tripled in 1979-80 when the Iran-Iraq war disrupted the flow of oil from the Persian Gulf. For the next five years, OPEC members, especially Saudi Arabia, maintained the higher price of oil by cutting production until in 1986 they had sacrificed so much market share that they were no longer able to effectively control the oil market. World oil prices collapsed. In 1990, the United States and its allies went to war in the Persian Gulf to prevent Iraq from overwhelming Kuwait and threatening the world's largest oil producer, Saudi Arabia. The Persian Gulf war produced another, shorter-lived oil price shock and another recession in the U.S. economy.

America and the world responded effectively to OPEC's supply shocks and higher prices but failed to sustain their efforts when oil prices crashed in 1986. U.S. petroleum consumption had been increasing every year from 1950 to 1973, at an average annual rate of over 4 percent. From 1973 to 1985, higher prices and energy policies caused U.S. petroleum consumption to decrease from 17.3 to 15.7 mmbd (million barrels per day). At the same time U.S. net imports fell from 6.0 mmbd to 4.3 mmbd. A combination of increasing fuel economy, other energy efficiency improvements and the substitution of other fuels for petroleum outside the transportation sector reversed the growth of U.S. petroleum demand. Other countries took similar actions, and non-OPEC oil suppliers significantly increased oil production. These actions effectively broke OPEC's control over world oil markets from 1986 to 1999.

The continued growth of world oil demand after 1986 and the concentration of oil resources in OPEC countries enabled OPEC to regain most of the oil market share it gave up during the 1980s. World oil prices remained low throughout the 1990s, until in 2000 OPEC members agreed on a new round of production cuts that once again doubled world oil prices. If oil-importing countries' policies are not changed, the U.S. Department of Energy projects that over the next twenty years U.S. imports will grow to over 60 percent of consumption, and OPEC's share of the world oil market will increase to 50 percent.

The actions oil-consuming nations took that produced the oil price collapse of 1986 proved that it is possible to dramatically reduce oil dependence. A renewed effort to increase transportation's energy efficiency and encourage the use of renewable energy by the transportation sector would produce multiple benefits: it would curb greenhouse gases, reduce price volatility, and strengthen U.S. energy security.[13] It is unquestionably true that higher oil prices encourage energy efficiency and fuel switching, yet oil prices can be maintained at higher levels by means of domestic policies that would have the added advantage of keeping the revenues generated within the U.S. economy, rather than exporting them to oil producers.

tems with high-carbon liquid fuels from fossil energy for the entire 21st century. The earth's crust contains vast reserves of high-carbon, unconventional oil in the form of heavy oil, oil and tar sands, and shale oil.[14] Unconventional oil resources are distinguished from conventional oil by their much higher viscosities, which make them far more difficult to extract and refine. But with advances in technology, it is likely that liquid fuels from unconventional oil will be available at prices not drastically higher than the price of oil today. Already today, Canadian oil sands and Venezuelan heavy oil are beginning to be produced and converted to conventional liquid fuels at competitive prices. In a sense, the transition to unconventional fossil resources for transportation has already begun.

The move from conventional to unconventional oil is likely because it would be compatible with the existing infrastructure for distributing and retailing transportation fuels, as well as with conventional vehicle technology. Still, it would require huge investments in the production, processing, and upgrading of unconventional energy resources, investments that once made would be difficult to change. A global transition to producing conventional liquid fuels from unconventional fossil resources would also significantly increase GHG emissions.[15]

Other energy futures for transportation are possible, but will probably require greater effort and depend on significant advances in technology. For example, unconventional fossil fuels could be utilized without harm to the climate if they were used to produce hydrogen and their carbon sequestered.[16] This would require an entirely new energy infrastructure for transportation, as well as technological breakthroughs for hydrogen use by transportation vehicles. Because of this, the transition to a low-carbon, hydrogen-based energy future for transportation will almost certainly take decades.

Greatly increasing the energy efficiency of transportation can extend the life of conventional oil resources and buy time to develop the technology for low-carbon alternatives. Increased use of renewable and other non-fossil energy would also help.

C. Trends in Transportation Activity, Energy Use, and Efficiency

Transportation energy use and greenhouse gas emissions are increasing because the growth of transportation activity exceeds the rate of improvement in energy efficiency and because little low-carbon fuel is used. Since 1970, passenger car and light truck travel has more than doubled, increasing at an average rate of 3 percent per year.[17] U.S. air travel grew faster still, increasing five-fold from 1970 to 2000, at an average annual rate of 5.4 percent. Travel by all modes of public transit, which had not grown from 1985 to 1995, increased by 20 percent from 1995 to 2000 but still accounts for only about 1 percent of total U.S. passenger miles.[18]

Ton-miles of freight transported also more than doubled over the past thirty years, and there has been a substantial shift in traffic from the less energy-intensive rail, water, and pipeline modes to more energy-intensive trucking and air transport. In 1970, trucks carried 18 percent of intercity freight ton-miles; by 1998, trucking's share had increased to 28 percent.[19]

Transportation's energy use and GHG emissions since 1970 have increased more slowly than transportation activity because of significant improvements in energy efficiency by nearly all modes of transport. From 1975 to 1988, new passenger car miles per gallon increased from 15.8 to 28.6, and new light truck miles per gallon grew from 13.7 to 21.2. Since 1988, the fuel economy of new cars and light

Box 2

Changing Transportation Energy Use Takes Time

Like other energy-consuming sectors, transportation's energy use is linked to long-lived transportation equipment. A typical passenger car or light truck can be expected to last about 15 years.[20] Commercial aircraft sold today are likely to be around 20 to 35 years from now.[21] Marine vessels last even longer, although their power plants are often rebuilt or replaced.

It also takes time for transportation equipment manufacturers to adopt new technologies and incorporate them into their products. Today, each passenger car and light truck model undergoes a complete redesign approximately every eight years, but product plans are "locked in" two to three years in advance. Thus, if the decision to completely redesign vehicles were made today, it would take about ten years to fully implement it in new vehicles. Replacing all the existing vehicles on the road would take even longer.

Nearly complete replacement can be accomplished sooner than the sum of vehicle lifetime and the total product redesign cycle. This is because new equipment is used more intensively. In its first year a typical new passenger car will be driven over 15,000 miles. Vehicles ten years old or older are driven on average only 9,000 miles. As a rule, after 15 years approximately 90 percent of vehicle miles will be traveled in cars with the newer, more efficient technology. Similarly, it takes about 10 to 15 years for the U.S. fleet of commercial aircraft to achieve the same fuel efficiency as newly designed aircraft (Lee, et al., 2001, p. 184).

Replacing the petroleum-based transportation energy system with new technology that requires an entirely new energy infrastructure, such as hydrogen-powered fuel cell vehicles, will take much longer. Storing adequate amounts of hydrogen on-board a vehicle remains a technical challenge, and fuel cell costs must be further reduced by an order of magnitude to compete with conventional internal combustion engines. Even if these challenges are quickly solved, hydrogen fuel cell vehicles would not be ready for widespread marketing before 2010 at the earliest, and more likely not before 2015.[22] Widespread marketing is dependent not only on technological readiness, but also on the creation of a completely new infrastructure for producing, distributing, storing, and retailing hydrogen fuel.

Policies that affect the level of transportation demand, such as fuel taxes, can have an immediate impact, but significant changes in transportation vehicles and energy sources cannot be accomplished quickly. Major energy efficiency improvements will require about 15 years to affect the vast majority of vehicles in use, and a complete transition to a new energy source for transportation will take at least three decades. Policies that affect land use and transportation infrastructure may require even longer to achieve their full impact.

trucks has not increased. In fact, because light trucks meet lower standards, the increased popularity of light trucks has caused the combined fuel economy of new light-duty vehicles to decline from 25.9 miles per gallon (mpg) in 1988 to 24.0 mpg for vehicles sold in 2002.[23]

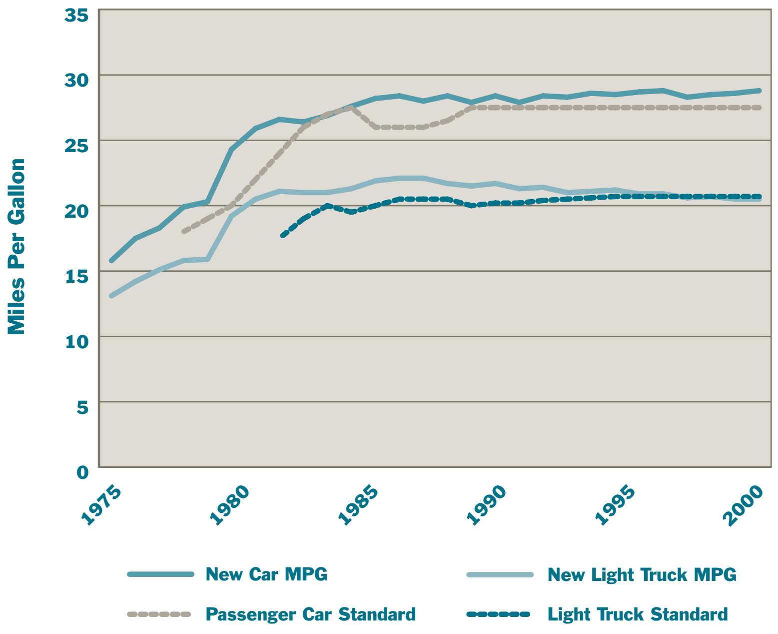
Passenger-miles per gallon for commercial air travel has increased by 150 percent since 1975, partly due to an increase in occupancy rates, but mostly due to a near doubling of aircraft energy efficiency.[24] The energy required to move a ton of freight by rail was also cut in half.[25] Truck and waterborne freight transport do not appear to have done as well, though the data for these modes is weaker. During the past 30 years, energy use per ton-mile for domestic waterborne commerce and truck freight appears to have fallen by less than 10 percent. The miles per gallon for an average tractor-trailer in the United States appears to be about the same today as it was twenty years ago,[26] although the size of tractor-trailers has increased.

The causes of energy efficiency improvements differed from mode to mode. Efficiency improvements in air travel were largely driven by market forces responding to higher oil prices in the 1970s and 1980s, in combination with continued technological advances in aircraft and propulsion, increasing average aircraft size, and higher seat occupancy rates.[27] With the exception of the federal government's significant investments in aerospace technology research through the Department of Defense and the National Aeronautics and Space Administration, government policies had little to do with the increasing energy efficiency of air travel. The dramatic reduction in rail energy use per ton-mile was achieved by a combination of increased car loadings and improved technology and operations. The increased tons per rail car was partly a result of the loss of higher value and lower weight freight to trucking and partly a result of greater operational efficiency.

Federal fuel economy standards, on the other hand, played a major role in increasing light-duty vehicle fuel economy. The federal Corporate Average Fuel Economy (CAFE) standards established in 1975 required new passenger car fuel economy to increase from 18.0 mpg in 1978 to 27.5 mpg in 1985, where the standard remains to this day (Figure 6). Less was required of light trucks; standards set by the U.S. Department of Transportation increased to 20.5 mpg in 1987 and stand at 20.7 mpg today.[28] The actual fuel economy of new passenger cars and light trucks has closely followed the standards, indicating the significant influence they have had on light-duty vehicle fuel economy.

Figure 6

U.S. Passenger Car and Light Truck **Fuel Economy Standards**



Source: Davis, S.C. and S. Diegel (2002), Table 7.19.

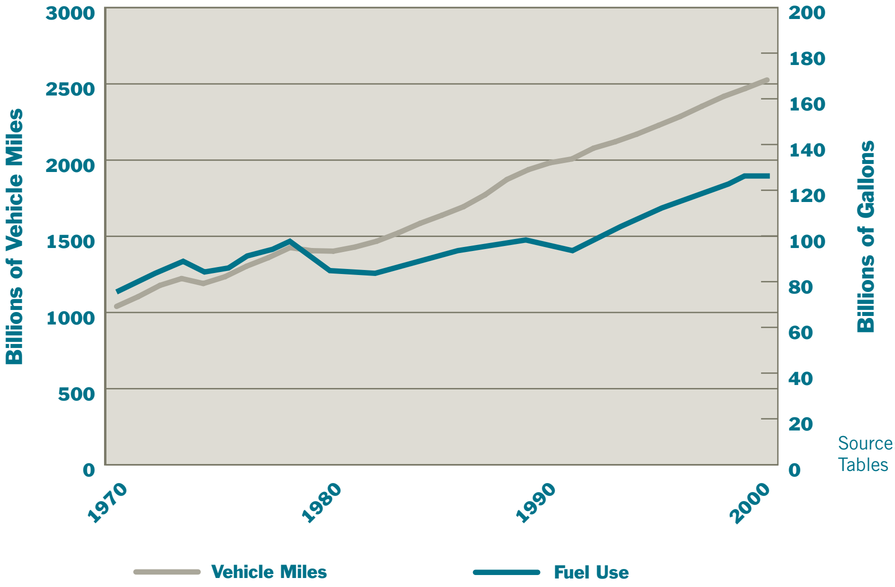
Past fuel economy gains have had a major impact on petroleum consumption. The National Research Council[29] estimated that if the fuel economy of light-duty vehicles had not improved since 1975, U.S. gasoline consumption would be about 2.8 mmbd (30 percent) higher today (Figure 7). This represents approximately 100 million metric tons of carbon emissions avoided annually, roughly equal to the total annual carbon emissions of France or Mexico.

Over the past decade, however, improvements in transportation energy efficiency have been modest to non-existent. The fuel economy of new passenger cars and light trucks has not increased since 1988. Today's new passenger cars and light trucks get fewer miles per gallon than the vehicles sold fifteen years ago. Because it takes 15 years or more for changes in new vehicle fuel economy to fully transform the on-road vehicle fleet, the average fuel economy of all passenger cars and light trucks on the road continued to inch upward from 19.6 mpg in 1991 to 20.1 mpg in 2000. Stagnant fuel economy and increased travel has greatly increased petroleum use and CO_2 emissions. Since 1985, U.S. net oil imports have grown from 4.3 mmbd to 10.1 mmbd.

Without changes in U.S. energy policies, the U.S. Department of Energy foresees continued growth in transportation petroleum use, oil imports, and GHG emissions. By 2020, transportation petroleum use is

Figure 7

Passenger Car and Light Truck **Travel and Fuel Use**



Source: Davis, S.C. and S. Diegel (2002), Tables 7.1 and 7.2.

expected to expand from 13.7 to 19.9 mmbd, accounting for 90 percent of the total increase in U.S. petroleum use over that period.[30] Light trucks alone are expected to account for 40 percent of the growth in transportation oil use over the next 20 years. Transportation's carbon emissions are forecast to increase by almost 50 percent from 517 mmtC to 753 mmtC, at a faster rate than any other sector of the economy. If this prediction holds, transportation will be responsible for 36 percent of U.S. carbon emissions in 2020.

D. Options for Reducing Greenhouse Gas Emissions from Transportation

There are four fundamental ways to reduce carbon emissions from the transportation sector: (1) increase the energy efficiency of transportation vehicles, (2) substitute energy sources that are low in carbon for carbon-intensive sources,(3) increase the efficiency with which transportation systems provide mobility, and (4) reduce transportation activity. Various options are available to achieve these goals.

Technology exists today that has the potential to substantially increase the energy efficiency of transportation vehicles. The greatest potential lies in personal highway vehicles. It is possible to increase the fuel economy of new passenger cars and light trucks by 25 to 33 percent by 2015, and increases of 50 to 100 percent will likely be feasible by 2030.

Significantly reducing the carbon intensity of transportation energy will require use of alternatives to petroleum, such as natural gas, bio-fuels, or hydrogen. When produced from renewable energy sources or nuclear energy, the use of hydrogen can result in nearly zero carbon emissions. Producing hydrogen from fossil fuels (the most economical method today) would generate substantial GHG emissions unless the carbon were captured and sequestered. Effectively reducing carbon emissions by substituting alternative fuels for petroleum requires a consideration of GHG emissions over the full fuel cycle (see Box 8, "Life-Cycle Analysis: From Well to Wheels").

The transportation system's energy efficiency can be increased by operating vehicles more efficiently or by shifting activity from more energy-intensive to less energy-intensive modes of transportation. Decreasing transportation activity generally implies a loss of mobility. In some cases, a reduction in travel can be accomplished without losing convenient access to people and places. For example, using more direct routes from origins to destinations, increasing vehicle occupancy rates, or designing more geographically efficient communities can result in less motorized transport without compromising accessibility.

The role of governments is especially critical in controlling transportation's environmental impacts. Consumers and businesses acting according to self-interest will not fully consider the need to reduce GHG emissions when they purchase vehicles and fuels and decide how much to travel. Economists call this a public good externality, because the costs and benefits of controlling it are external to market decision-making. If the market does not fully value reducing GHG emissions, firms will under-invest in research and development (R&D) to create new, less polluting technologies. Without collective action to curb public good externalities, market economies will produce excessive amounts of environmental pollution.

A wide variety of policies and measures are available to governments to correct this problem.[31] Governments can directly invest in R&D or can partner with industry to accelerate technological progress. Market forces can be harnessed through emission cap-and-trade programs or by using fiscal policies (taxes, subsidies, and incentives) to "internalize" the value of reducing carbon emissions. Regulations, such as fuel economy standards, can be used to increase the efficiency of energy use or to change the properties of transportation fuels. Public information and education programs can help markets function more effectively and may lead to significant voluntary efforts to curb emissions.

Deciding on the best policy is often controversial. Opposition to specific policies by interest groups or by voters can block the adoption of potentially effective policies. Poorly designed or poorly implemented policies can produce unintended negative consequences. It is not the purpose of this report to recommend specific policies and measures for reducing transportation's GHG emissions. Rather, this report attempts to identify practical options and opportunities to curb GHG emissions, both today and in the future. There will be several alternatives that can achieve the same greenhouse gas target. In the end, a comprehensive strategy to reduce emissions from the U.S. transportation system will require a combination of different types of policies.

II. Energy Efficiency

Significant reductions in greenhouse gas emissions from U.S. transportation can be achieved by increasing the energy efficiency of transportation equipment. This strategy requires only incremental changes to conventional technologies and fuels, and so preserves both the characteristics of modern conventional vehicles that consumers desire and the enormous investment in the infrastructure for producing, distributing, and retailing conventional petroleum fuels. However, increasing energy efficiency of the transportation system takes time, typically 15 years or more between efficiency gains in new equipment and comparable efficiency gains for the entire fleet of transportation vehicles (see Box 2, "Changing Transportation Energy Use Takes Time").

A. Passenger Cars and Light Trucks[27]

By 2015, the fuel economy of light-duty vehicles[32] (passenger cars, vans, minivans, sport-utility vehicles, and pick-up trucks) can be increased by about one-fourth to one-third with existing technology at a cost less than the value of the fuel saved. By 2030, it is likely that fuel economy can be increased to significantly higher levels (50 percent to 100 percent), at possibly greater cost, depending on the progress of technology. Vehicle fuel efficiency can be increased by improving the energy efficiency of the drive train (engine and transmission) and by reducing the amount of energy necessary to move the vehicle (by reducing weight, aerodynamic drag, and rolling resistance). While the single largest contribution to improved fuel efficiency is expected to come from the drive train, the largest total increase in fuel economy can be achieved through a combination of these technologies, which allows a compounding of individual energy efficiency improvement potentials.

Only rarely is the full power of a vehicle's engine needed. For example, a typical passenger car requires less than 20 horsepower to cruise on a level highway, meaning that the typical model year 2000 passenger car has more than eight times the power it needs for cruising. Several technologies are now available that can improve engine efficiency when operating under "low load" conditions. An appropriate combination of these technologies could increase engine efficiency by up to 25 percent.[33] Transmissions also offer a significant energy efficiency improvement potential of several percent.[34] Reductions in aerodynamic drag of at least 10 percent (lowering fuel consumption by about 2 percent) are readily achievable, and the rolling resistance of tires can be lowered (leading to fuel consumption reductions of 1 to 1.5 percent) without compromising handling, comfort, or braking. There are also opportunities to reduce vehicle weight by greater use of advanced lightweight, high-strength steels, aluminum, and composite materials. For example, the steel industry has shown how the weight of the structural components of a typical passenger car can be reduced by about 25 percent (approximately 100 lbs.) with no loss of crashworthiness or performance.[35] Vehicles made from aluminum can achieve a 40 percent reduction in the weight of structural components, with improved crashworthiness.[36] Additional emerging vehicle technologies that could improve efficiency are the 42-volt electrical system, which permits electrification of many accessories that are now mechanically operated, and the integrated starter/alternator (ISA), which allows the engine to be shut down during idling or deceleration and restarted instantly when needed. Depending on the amount of battery storage, the ISA system can also permit a certain amount of regenerative braking, recapturing energy normally wasted in braking for later use.

By combining such proven and near-term technologies (excluding weight reduction), a recent study of automotive fuel economy by the National Research Council (NRC) concluded, “Technologies exist that, if applied to passenger cars and light trucks, would significantly reduce fuel consumption within 15 years.”[37] Based on their assessment, the NRC Committee found that passenger car fuel economy could most likely be increased by 12 (for subcompacts) to 27 percent (for large cars) and light truck fuel economy by 25 (small SUVs) to 42 percent (large SUVs), using technologies that would not change the size, weight, or performance of vehicles. While many of these technologies would increase the vehicle’s price, they could more than pay back their cost over the life of the vehicle.[38] The NRC study, however, also cited reasons to believe that when choosing a car, the typical car buyer considers only the first three years of fuel savings, not the fuel savings over the life of the car. If this is so, it represents a significant market barrier to fuel economy improvements (see Box, “Markets and Fuel Economy”).

Box 3

Markets and Fuel Economy

If consumers do not fully value the lifetime fuel savings of increased fuel economy, manufacturers will not produce vehicles with economically efficient fuel economy levels, and fuel price increases will not induce appropriate mpg increases. A recent report of the National Research Council on fuel economy standards suggested that consumers might value only the first three years of fuel savings produced by increased fuel economy. Honda Motor Company has stated that typical consumers value only the first 50,000 miles of fuel savings. Recent survey evidence from the U.S. Department of Energy supports these views, indicating that consumers expect on average a 2.8-year payback for an investment in higher fuel economy. There is also evidence that trucking companies base their purchasing decisions on similarly low amortization periods of about 3 years.[49]

The figures below illustrate how important the consequences of such a “market failure” could be for fuel economy and GHG emissions. The present value of fuel savings for a typical passenger car (shown in Figure A below) increases to $1,000 at 34 mpg and $2,000 at 44 mpg. This assumes a 14-year vehicle life, 15,600 miles per year of travel when new, decreasing by 4.5 percent per year with age, gasoline at $1.50 per gallon, and an annual rate of return on investment of 12 percent. Also shown in Figure A is the cost of increased fuel economy, based on the NRC study mentioned above. The net value to the consumer (fuel savings minus vehicle price increase) is relatively modest, increasing to a maximum of about $200 at 33 mpg and decreasing to zero at 39 mpg.

Figure A

Price and Value of Increased Fuel Economy to Passenger Car Buyer, Using NRC Avg. Price Curves and Valuing Fuel Savings Over 14-year Vehicle Life

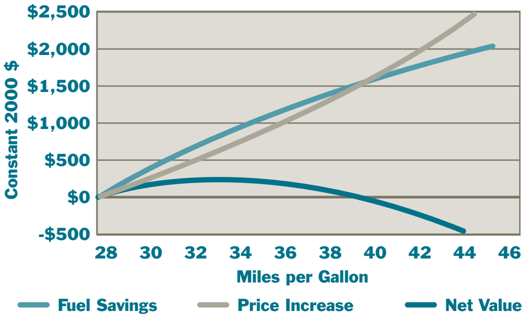
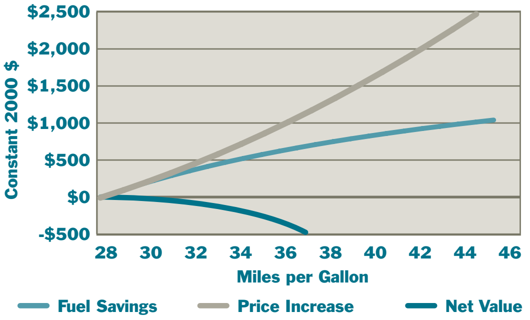


Figure A may help explain why consumers appear to be relatively uninterested in higher fuel economy. Over a range from 28 to 42 mpg, the change in net value is only plus or minus $200, or less than 1 percent of the price of a typical car. From the manufacturer’s perspective, achieving a 10 mpg increase in fuel economy across all product lines would require complete redesigns and billions of dollars of investments in retooling for new engines, transmissions, and body designs. In effect, it would amount to risking the entire company to achieve something in which customers are barely interested. The clear implication is that the market for passenger car fuel economy may not function efficiently if manufacturers are even slightly averse to risk.

But if consumers do not fully value fuel savings over the life of a vehicle, the situation is even worse. Figure B shows the same curves, but calculates fuel savings as an undiscounted sum over the first three years of a vehicle’s life. In this case, no net savings are available from increasing fuel economy. If this is truly the way consumers value fuel economy, or even if manufacturers believe that consumers value fuel economy in this way, it should be no surprise that car manufacturers see little point in producing more efficient vehicles. Governmental policies, including market based and mandatory mechanisms, can help overcome such barriers and bring more fuel-efficient technologies into the market (see Section VI, Policy Options).

Figure B

Price and Value of Increased Fuel Economy to Passenger Car Buyer, Using NRC Avg. Price Curves With a 3-Year Simple Payback



Note: Figures A and B assume cars driven 15,600 miles per year when new, decreasing at 4.5% per year, 12% discount rate, 14 year vehicle life, $1.50 per gallon gasoline, 15% shortfall between EPA test and on-road fuel economy.

Taking a longer look ahead, a team of researchers at MIT's Energy Laboratory concluded that much greater increases in fuel economy could be achieved with new technologies likely to be ready for use by 2020. They found that by 2020 it should be possible to increase the fuel economy of passenger cars by 50 percent using evolved conventional technologies and to more than double miles per gallon using advanced technologies that could be developed and commercialized by 2020; the associated increase in retail price would amount to 5 percent and 20 percent, respectively.[39] New technologies will expand the envelope of technical feasibility well beyond the limits of current technologies considered by the 2002 NRC study.

Table 1 summarizes key characteristics of selected vehicles from the MIT study. The "evolved" 2020 gasoline vehicle represents what may be achievable through the continued improvement of conventional technologies, such as those considered in the 2002 NRC report. The advanced conventional vehicle adds more efficient lean-burn[40] engine technology and substitution of lighter-weight materials without compromising crashworthiness.

Several of the 2020 advanced vehicles include a compression-ignition diesel engine, where fuel is injected into highly compressed hot air and auto-ignites. While diesel engines introduced in passenger cars and light trucks in the United States in the 1980s did not compete well against gasoline engines, significant advances in diesel technology have been made over the past decade (see Box 4, "Diesel Vehicles: Promise and Problems"). In Europe, where fuel prices are about three times higher than in the United States, modern diesels comprise 40 percent of the new automobile market. The key questions they face in the United States are whether consumers will pay a price premium of $1,000 to $2,000 for a more powerful, more durable engine with 40 to 50 percent better fuel economy and whether even modern diesels can meet the more stringent levels of U.S. emissions standards. There are reasons to believe diesels will meet U.S. emission standards and will find success in certain markets.

Two of the advanced vehicles considered by MIT are hybrids, in which the internal combustion engine is complemented by an electric motor. Various hybrid designs and operating strategies are possible, but generally a downsized internal combustion engine operates more of the time near its maximum efficiency point.[41] The electric motor supplies peak power for acceleration and allows the internal combustion engine to be shut down instead of operating in inefficient regimes, such as idling or deceleration. High power-density batteries are added to permit energy captured during regenerative braking to be stored for use by the electric motor and to provide power supply for accessories when the engine is shut off. By

Table 1

Fuel Economy Potential of Advanced Vehicle Technologies in 2020

	1996 Baseline Gasoline	2020 Evolved Gasoline	2020 Advanced Gasoline	2020 Advanced Diesel	2020 Gasoline Hybrid	2020 Diesel Hybrid
Fuel Economy (MPG)	28.0	43.0	49.0	56.0	71.0	82.5
Percent Increase over Baseline	--	54	75	100	154	195
Carbon Emissions (gC/mi)	116	76	67	60	48	43
Percent Reduction over Baseline	--	34	42	48	59	63
Weight (lbs.)	3,179	2,717	2,497	2,618	2,541	2,618
Price (1997 $)	17,200	18,000	19,400	20,500	21,200	22,200
Life Cycle Cost ($/mi)	0.50	0.49	0.52	0.53	0.55	0.56

Source: Weiss, et al., 2000, Tables 5.3 and 5.4.

Note: Life cycle costs per mile shown in Table 1 include amortized capital costs, fuel costs, maintenance, insurance, and license and registration fees. The advanced vehicles include significant measures for reducing driving resistance (including an aluminum vehicle body).

making the most effective use of both power sources, the advanced hybrid design in combination with a continuously variable transmission can improve fuel economy by 40 to 50 percent.

Already in 2002, three hybrid vehicles were commercially available: the Toyota Prius, Honda Insight, and the hybrid version of the Honda Civic. Over the next few years, more hybrids are expected to enter the U.S. market. Hybrids today have 30 to 40 percent higher fuel economy than comparable conventional vehicles but cost $3,000 to $4,000 more. Manufacturers are likely to find creative ways to use hybrid technology to add value for consumers, such as providing electrical outlets capable of running any household appliance or power tool, allowing the vehicle to be used as an emergency generator, or offering on-demand 4-wheel drive. These and other special features could make hybrids attractive to customers even at a price premium. With special value-added features and a wider availability of vehicle types, hybrids could become a major technology for raising fuel economy and reducing GHG emissions.

The above-referenced and numerous other assessments of the technological potential to increase light-duty vehicle fuel economy indicate that fuel economy can probably be increased cost-effectively by 25 to 33 percent over the next 10 to 15 years using market-ready technologies.[42] As used here, the term "cost-effective" is defined as the fuel economy level at which the last dollar spent to improve fuel economy produces exactly one dollar in present value, lifetime fuel savings. By 2030, fuel economy can be increased by 50 to 100 percent using advanced technologies that are likely to be available by that time. The higher range of increase, however, may increase the retail price of vehicles beyond what can be recovered by consumers over the life of the vehicle, if U.S. gasoline prices are approximately $1.50 per gallon or less.

Box 4

Diesel Vehicles: Promise and Problems

In the past, American motorists associated diesel engines with poor driving performance, noise, soot, and an unpleasant odor. However, their higher compression ratio[73] and higher air-fuel ratios made them more energy-efficient in both urban and highway driving compared to their gasoline engine counterparts, and their heavier construction made them more durable. As a result, they were primarily used in freight transportation, a sector that traditionally operates on a tight budget. But over the past decade, significant progress in diesel engine technology (including electronic controls, high-pressure fuel injection, variable injection timing, improved combustion chamber design, and turbo-charging[45]) has improved the performance of diesels, further increased their energy efficiency, and reduced their emissions.

Modern diesel engines are about 33 percent more energy-efficient than a gasoline vehicle of comparable size and power. As a gallon of diesel fuel contains 12 percent more energy than a gallon of gasoline, 33 percent higher energy efficiency translates into nearly 50 percent more miles per gallon. In Europe, the diesel's significant fuel economy advantage, combined with much higher fuel prices, has produced soaring diesel vehicle sales. Within the European Union, diesel vehicles currently account for 40 percent of all newly registered light-duty vehicles and have even penetrated into the luxury car segment. By contrast, diesel vehicles account for less than one percent of U.S. light-duty vehicle sales.

The fundamental problem of diesel engines has been their higher emissions of uncontrolled nitrogen oxide and fine particulates. Fine particulates are considered a significant health threat because of their ability to penetrate into lung tissue. However, recent progress in emission control technology is very promising. Particulate filters are capable of reducing fine (nano-sized) particle emissions by two orders of magnitude. Various types of nitrogen oxide reduction catalysts exist that can reduce nitrogen oxide emissions by more than 50 percent,[43] but some are poisoned by the sulfur in diesel fuel. Diesel emissions control will be greatly assisted when new requirements for low-sulfur fuel are implemented in mid-2006. Regular diesel fuel contains a maximum of 500 parts per million of sulfur; soon to be introduced low-sulfur fuel will have a maximum sulfur content of 15 parts per million. Still, it remains to be seen whether even considerably cleaner diesel technology will be able to satisfy future, increasingly tight emission standards.

Clearly, predicting technological progress is uncertain. Advanced technologies may be available sooner or later than expected, and possibly never. The diesel engine is one example. Unless its emissions of nitrogen oxides and particulates can be reduced to meet current and future government standards, its proven fuel economy benefits will not be available to manufacturers. In addition, there may be market barriers to the use of advanced fuel economy technologies. If consumers do not fully value lifetime fuel savings, manufacturers will be understandably reluctant to make major engineering and design changes to raise fuel economy. And if market trends continue to favor ever heavier and more powerful vehicles, technologies that could be used to increase fuel economy will instead be needed just to hold it constant.

B. Heavy-Duty Vehicles

Heavy-duty vehicle fuel efficiency can be improved by about 25 percent (in long-distance transport) to 50 percent (in short distance stop-and-go transport).

Heavy-duty vehicles operate in both long-distance and local transport, with the total fuel use being roughly equally split.[44] After driver compensation, fuel costs are typically the second largest expenditure item for heavy-duty vehicle operators. As a result, virtually every large new truck and bus in the United States is already equipped with a turbo-charged,[45] direct-injection diesel engine, the most energy-efficient internal combustion engine available. State-of-the-art turbo-charged diesel engines achieve 46 to 47 percent peak thermal efficiency, versus only 25 percent for spark-ignited gasoline engines. Thus, there is less potential for improving fuel efficiency in heavy-duty than light-duty vehicles.

For heavy-duty vehicles operating in long-distance traffic, it may be possible to raise diesel engine peak thermal efficiency to 55 percent by a combination of various technologies.[46] Some of the required technologies face significant hurdles, however, in reducing pollutant emissions and in their cost-effectiveness. A greater potential for reducing the fuel consumption of trucks in line-haul operations can be achieved by reducing their driving resistances. At the high speeds typical of long-distance traffic, aerodynamic drag can dominate vehicle power needs. Aerodynamic drag for trucks is greater than for cars,[47] and reductions of 20 percent or more are possible.[48]

A significant amount of fuel combustion can also be avoided by reducing truck idling. According to a study by Argonne National Laboratory,[49] the average tractor-trailer spends 6 hours idling each day, primarily to generate electricity for its auxiliary systems, such as air conditioning and heating, while it is parked at rest stops. Auxiliary power units are an emerging technology that can eliminate up to 80 percent of idling by tractor-trailers. At this rate, the potential annual fuel savings amount to over 1,200 gallons per truck (or about 10 percent of its fuel use). The GHG emissions impacts, however, will depend on how the auxiliary power itself is produced.

Because they can recover braking energy and shut off the engine during idling, hybrid drive trains are a promising technology for heavy-duty vehicles that operate locally, in stop-and-go mode.[50] For hybrid buses operating in urban transport, fuel efficiency improvements of up to 50 percent have been reported. Estimates suggest that hybrid systems have the potential to improve fuel economy by 25 to 70 percent in comparison with a diesel engine mechanical drive train.[51]

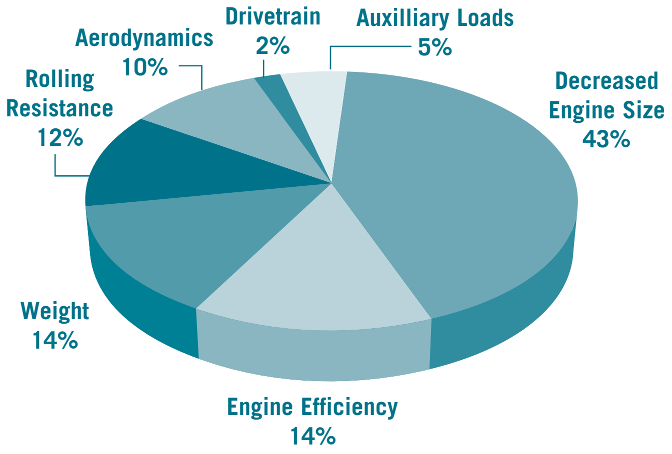
The U.S. Department of Energy, in collaboration with other federal agencies and truck manufacturers and suppliers, established the 21st Century Truck program in 2000 to dramatically improve the fuel economy of trucks in the United States. Based on a technical analysis of fuel economy potential, the program set ambitious goals for light trucks and three classes of heavy trucks. With a combination of engine, aerodynamic, rolling resistance, and materials technologies, the plan called for a 50 to 75 percent improvement in fuel economy for light trucks, a 140 percent improvement for medium-sized trucks, a 60 percent improvement for over-the-road tractor trailers, and a 160 percent fuel economy increase for transit buses. Figure 8 breaks down a potential 70 percent fuel economy increase for line haul trucks. These goals were believed to be achievable with "aggressive development and implementation of technologies currently being considered but not yet commercially viable,"[52] although it is unclear at what cost.

C. Commercial Aircraft

In the near term, the fuel efficiency of new commercial aircraft can be improved by about 20 percent; over the long term, fuel efficiency improvements of up to 50 percent appear feasible. From 1971 to 1998, a combination of technological and operational efficiency improvements achieved a 60 percent reduction in the energy intensity of commercial air travel in the United States, an average rate of decrease of 3.3 percent per year.[53] At the same time, air travel increased at 5.5 percent per year, with the result that energy use by the air mode continued to increase by 2.2 percent per year. Recent assessments foresee slower rates of change for both energy intensity and air traffic, with the growth of travel still exceeding the rate of efficiency improvement by about 2 percent per year.

Figure 8

Components of a Potential 70 Percent Increase in Truck Fuel Economy (Line-haul Tractor-trailers)



Source: U.S. DOE/OSTI, 2000, Table 4.1.

Aircraft fuel efficiency depends on engine-specific fuel consumption, aerodynamic efficiency, structural efficiency (operating empty weight divided by maximum take-off weight), and operational factors, such as occupancy rates, the ratio of flying time to ground time, and the length of the actual route flown, including diversions, relative to the most direct route. Of the approximately 60 percent reduction in energy use per passenger mile achieved since 1970, 57 percent can be attributed to improvements in the efficiency of aircraft engines, 22 percent to aerodynamic improvements, 17 percent to increased seat occupancy rates, and the remaining 4 percent to a variety of factors, especially increased aircraft size.[54]

Opportunities for further improvements remain in all areas, with the largest contributions expected from improved engines and aerodynamics.[55] Considering all the technological options and taking into account the time required for implementation and stock turnover, several assessments have concluded that a 25 to 45 percent reduction in aircraft energy intensity is possible by 2025, and 40 to 50 percent by 2050.[56] Interpolating these potential reductions in energy intensity results in a range of 15 to 25 percent by 2015 and 25 to 40 percent by 2030.

In the year 2000, the National Aeronautics and Space Administration (NASA) set more ambitious R&D goals of developing technologies to reduce the CO_2 emissions of future aircraft by 25 percent by 2010 and 50 percent by 2025.[57] According to NASA's blueprint for revolutionizing aircraft technology, "Today's aircraft weigh twice as much, use 75 percent more fuel, and create four times the noise than the technologically possible, 'to be' aircraft."[58] The most recent progress report of NASA's Ultra-Efficient Engine Technology program projects that engine technologies currently under development will be able to reduce fuel use by 27 percent for large commercial aircraft and by 19 to 24 percent for small to medium sized commercial aircraft.[59]

D. Rail, Water, and Pipeline

The highway and air modes receive the most attention because they produce more than four-fifths of transportation's carbon emissions and will likely account for an even greater share in the future. In addition, moving freight by rail, water, and pipeline is already so energy efficient in terms of energy use per ton-mile that less attention has been paid to increasing the energy efficiency of these modes. Nonetheless, there is room for improvement. Increases of 5 to 10 percent in the thermal efficiency of diesel engines, such as envisioned for heavy trucks, would also benefit locomotives, nearly all of which are powered by diesel-electric generators, and some marine vessels, as well.[60] Aerodynamic improvements and weight reductions in trains are still possible, and railroads continue to make efforts to reduce rolling resistance between steel wheels and tracks, and in axle units. Improving the shapes and smoothness of ship hulls could reduce ship fuel consumption by 5 to 20 percent and improved propellers could increase ships' power plant efficiency by 5 to 10 percentage points.[61] Fueling ships with liquefied natural gas can reduce CO_2 emissions by 38 percent.[62] It has also been suggested that ships could be powered by molten carbonate fuel cells, with efficiencies between 54 and 64 percent, which is comparable to the thermal efficiency of current low-speed marine diesel engines. Greater use of computer controls for piloting ships might add another few percent to efficiency gains.[63] Although pipelines have been largely ignored in assessments of energy efficiency potential, there can be little doubt that greater efficiencies in pumps and motors are possible.

E. The Next 15 Years and Beyond

Only about half of the potential to increase new vehicle energy efficiency can be realized in vehicle fleets by 2015. This is because U.S. vehicle manufacturers are not currently implementing significant reductions in GHG emissions, and because of the time lag between any efficiency changes in new vehicles and efficiency changes in the vehicle fleet as a whole (see Box 2, "Changing Transportation Energy Use Takes Time"). Taking this into account, the potential for increasing vehicle fuel efficiency by 2015 appears to be about 10 to 15 percent. A 12.5 percent efficiency improvement would translate into an 11 percent decrease in CO_2 emissions and fuel consumption.[64]

However, beyond 2015, the fuel efficiency of new transportation equipment can be increased by 25 to 100 percent, depending on the mode of transport. The largest fuel efficiency improvement potential exists for passenger cars and light trucks; several assessments suggest possible improvements of up to a factor of two with no loss of performance at an increase in vehicle retail price of only a few percent. This could translate into approximately a 38 percent reduction in GHG emissions.[65] The fuel efficiency improvement potential is 25 to 50 percent for new heavy-duty vehicles (depending on whether they operate in intercity or urban traffic) and up to 50 percent for new commercial aircraft. These translate into 24 percent and 27 percent reductions in CO_2 emissions.

There is no guarantee that the potential energy efficiency gains of advanced technologies will be realized in the absence of strong policy initiatives. As recent history has shown, the same technologies that can be used to reduce energy use and GHG emissions can instead be used to increase the power and speed of transportation vehicles. While free markets allow consumers to express their preferences for vehicle performance, speed, size and amenities, they take no account of the impacts of greenhouse gases on the global climate. The apparent undervaluing of future fuel savings by car buyers may compound this market failure (see Box 3, "Markets and Fuel Economy"). Continued growth in travel and freight demand would result in continued strong growth of GHG emissions from transportation. Thus, the authors' estimated potentials for reducing GHG emissions should be considered achievable only if backed by a carefully designed set of policies to insure they are realized. Examples of such policies are discussed in Section VI of this report.

Box 5

Energy Efficiency and the "Rebound Effect"

When the energy efficiency of a car, truck or other vehicle is increased, GHG emissions are reduced because it takes less fossil fuel to move the vehicle. But if the price of fuel remains constant, the cost per mile of travel also decreases. Any decrease in the cost of travel will encourage additional travel, and the additional travel will produce additional GHG emissions. This increase in travel as a result of a technical improvement in energy efficiency has been called the "rebound effect."[66]

Fortunately, it turns out that vehicle travel is relatively insensitive to energy efficiency improvements. Based on past responses to both fuel economy increases and fuel price changes, there is strong evidence that a 10 percent increase in fuel economy would lead to a 1 to 2 percent increase in vehicle travel. Thus, fuel use and emissions would be reduced, on net, by 8 to 9 percent. Increasing energy efficiency, even without an increase in the price of energy, appears to be an effective way to reduce emissions.

The rebound effect in transportation is relatively small, because fuel costs are generally a relatively small share (10 to 20 percent) of the total cost of vehicle travel. This is not only true for passenger cars, but also for trucks and even commercial aircraft.[67] The cost of the vehicle, the value of the traveler's time and other costs, such as maintenance and insurance, predominate. For most types of transportation, a one percent decrease in cost (excluding the value of the traveler's time) will result, very approximately, in a one percent increase in demand. A 10 percent increase in energy efficiency would reduce fuel costs by 10 percent, but reduce total cost by only 1 to 2 percent, and that would cause an increase in travel of only 1 to 2 percent. Unless fuel costs become a much larger component of total travel cost or travel itself becomes much more sensitive to cost, transportation rebound effects will remain small.

III. Alternative Fuels

Alternative fuels could significantly reduce greenhouse gas emissions, but they face major challenges. Alternative fuels offer reductions in GHG emissions from 10 to 100 percent over the full fuel cycle, but often suffer from higher costs, limited driving range, and a lack of fuel supply and refueling infrastructure. Largely unaffected by these constraints, replacement fuels (fuels that can be blended with petroleum fuels) can reduce GHG emissions by up to 20 percent. The extent to which alternative fuels reduce GHG emissions depends on how they are produced as well as used (see Box 8, "Life Cycle Analyses—From Well-to-Wheels"). Obtaining the full fuel-cycle GHG benefits of alternative fuels requires specifically designed engines and in many cases dedicated catalysts, which are especially designed to reduce specific exhaust components.

A. Light-Duty Vehicles

A variety of alternative and replacement fuels could be used in light-duty vehicles. Greenhouse gas emission reductions available from alternative fuel use in passenger cars and light trucks range from 10 to 20 percent for alternative liquid hydrocarbons to 30 to 100 percent for fuels with a low or zero carbon-to-hydrogen ratio.[68]

Liquefied Petroleum Gas

Compared to a gasoline vehicle, vehicles dedicated to liquefied petroleum gas (LPG) can reduce GHG emissions by almost 20 percent. Although LPG is the most widely used alternative transportation fuel in the United States,[69] its potential as a large-scale transportation fuel is limited. LPG consists of mainly propane and traces of additional light hydrocarbons that are gaseous at atmospheric pressure and temperature. LPG occurs naturally in crude oil and natural gas production fields and is a by-product of natural gas processing and crude oil refining. The quantity of LPG produced is small relative to petroleum and natural gas production. In 1999, world production of oil and gas amounted to a combined total of 228 quads; only 9 quads of the by-product LPG were produced. Because LPG reserves are so much smaller than those of crude oil and natural gas, it can never be a large-scale transportation fuel.

Due to its higher octane number[70] (comparable to that of alcohol fuel), vehicles with engines dedicated to LPG offer a 10 percent reduction in energy use compared to a lean-burn gasoline engine producing the same amount of power.[71] Because of its lower carbon-to-hydrogen ratio, CO_2 emissions are reduced by almost 20 percent. LPG also produces somewhat less smog-forming pollution.

LPG's disadvantages are modest. While a pressurized LPG tank is nearly 30 percent larger compared to a gasoline tank storing the same amount of energy, recent advances in lightweight LPG tank technology result in only a minor weight increase relative to gasoline. LPG vehicles tend to cost a few hundred dollars more than a gasoline vehicle, due to the more expensive pressurized fuel tank.

Low Carbon-to-Hydrogen Fuels

Fuels with low carbon-to-hydrogen ratios include compressed natural gas (CNG) and alcohol fuels (ethanol and methanol). Alcohol fuels can be produced from fossil fuels, waste, or biomass. Due to the limited land area available for growing biofuel feedstocks and the dependence of biofuel economics on co-production of other products (see Box 7, "Biomass Production Potential and Fuel Costs"), these fuels can only play a limited or intermediate role in fueling transportation systems. Gasoline infrastructure can be converted for handling alcohol fuels, at a cost, and hundreds of thousands of flexible-fuel vehicles, capable of running on any blend of gasoline and up to 85 percent ethanol, are already on the road in the United States as a result of incentives offered to U.S. manufacturers under federal fuel economy regulations. The existence of a nearly ubiquitous natural gas supply infrastructure is an advantage for CNG, although a complete network of refueling stations capable of delivering compressed gas into vehicles is still lacking. In addition, worldwide experience with alcohol and CNG vehicles is extensive, with major CNG demonstration programs having been conducted in Canada and New Zealand, and a massive alcohol fuel program in Brazil.

Internal combustion engines designed for one of these fuels can take advantage of their higher octane number by increasing the engine's compression ratio,[72] a key determinant of engine efficiency. Compared to a lean-burn gasoline engine producing the same power, engines designed specifically for alcohol fuels or CNG offer 10 percent higher energy efficiency. In combination with the lower fuel carbon content, these engines can reduce CO_2 emissions by about 30 percent using CNG and up to 100 percent using alcohols produced from cellulosic biomass.

Control of emissions from CNG vehicles is especially important[73] because their unburned exhaust consists mainly of methane, a greenhouse gas with global warming potential 21 times greater than that of CO_2.[74] For a CNG vehicle with a fuel efficiency of 30 miles per gallon of gasoline equivalent, the 30 percent reduction in CO_2 emissions compared to a gasoline fueled vehicle would be offset at an emission level of 4.9 grams of methane per mile.[75] This compares to actual emissions of 1.3 to 2.7 grams of methane per mile from CNG vehicles without a dedicated catalyst, depending on engine operation (stoichiometric[76] or lean-burn).[77] Effective methane catalysts reduce about 80 percent of the methane in the exhaust. In combination with typical methane leakage rates of 0.5 to 1 percent that may occur in CNG vehicle applications, use of an effective methane catalyst would affect the original 30 percent reduction in CO_2 emissions only marginally.

Due to their lower volumetric energy content, alcohol and CNG-fueled vehicles require larger and heavier fuel tanks to store the same amount of energy as a gasoline vehicle. As shown in Table 3, this increase is especially large for CNG, even if stored in a lightweight advanced tank at a pressure of 3,600 pounds per square inch (psi). The more complex, larger fuel tanks also make dedicated CNG vehicles more costly than gasoline vehicles.

Hydrogen and Electricity

Hydrogen and electricity can be produced from a variety of feedstocks, including fuels that do not contain any carbon. Greenhouse gas emissions from producing hydrogen and electricity from fossil fuels can be nearly eliminated if they are collected at the fuel processing plant and permanently sequestered. Studies examining the capture, separation, and storage or reuse of carbon emissions at electricity generation plants suggest energy penalties of 10 to 20 percent and an increase in levelized costs of 25 to 50 percent, depending on the fuel, plant design, and other factors. Similar changes in conversion efficiency and costs could be expected for the sequestration of carbon produced in the generation of hydrogen from fossil fuels (see Box 8, “Life-Cycle Analyses—From Well to Wheels”). While valuable experience with hydrogen vehicles has been accumulated through fleet tests, hydrogen vehicles will likely not be introduced commercially on a significant scale during the next 10 years, mainly because of the missing infrastructure and remaining technological hurdles, such as unsatisfactory on-board storage options.

Hydrogen can be burned in internal combustion (IC) engines or oxidized in fuel cells. Mainly because of their potential for extremely lean air-fuel mixtures, supercharged[78] hydrogen-fueled IC engines offer a roughly 15 percent reduction in energy use over lean-burn gasoline engines producing the same

Box 6

Box: Fuel Cell Technology and Hydrogen

Like a battery, a fuel cell is an electrochemical device in which the chemical energy of the fuel is converted directly into electricity. However, a fuel cell does not require recharging; it operates as long as the fuel (typically hydrogen) and an oxidizer (typically air) are supplied continuously from outside the cell. Due to the direct conversion of chemical energy into electricity, fuel cell systems (fuel cell reactor plus supporting technologies) operate at high efficiencies, often above 50 percent. Highest efficiencies are achieved at low power requirements, which corresponds to most driving.

Fuel cells can be distinguished according to various characteristics, including the type of fuel, oxidizer, electrolyte, and operating temperature. The favorite technology for light-duty vehicle applications is the low-temperature fuel cell, which offers favorable usage characteristics, but requires catalysts to enhance cell reactions, typically platinum—a relatively scarce and precious noble metal. The environmental performance of low-temperature fuel cells using hydrogen directly is outstanding, as emissions consist mainly of water. Within the family of low-temperature fuel cells, the proton-exchange membrane fuel cell offers comparatively high power per unit weight and volume, in addition to other advantages.

Low-temperature fuel cells using hydrocarbons directly still require a breakthrough in catalyst technology for technical applications, and wide availability of hydrogen would require new infrastructure. Thus much effort is currently underway in developing low-cost and energy-efficient gasoline-to-hydrogen fuel reformers. These chemical reactors offer the advantage of using the existing fuel infrastructure, but increase complexity, costs, vehicle weight, and emissions. As hydrogen needs to be produced either on-board or in stationary plants, a comparison with vehicles driven by other fuels needs to be based on the entire well-to-wheels life cycle (see Box, “Life-Cycle Analyses—From Well To Wheels”).

Fuel cells are still at an early stage of development and have exclusively been utilized in niche markets such as military applications and space flights. Fuel cell system costs are on the order of several thousand dollars per kW today. To compete with internal combustion engine hybrid vehicles, fuel cell system costs need to achieve a cost target of about $50 per kW. Whether this goal will be achieved at all depends on a number of factors, including the degree of platinum reduction.

power. The potential for a two-fold efficiency increase makes fuel cells a more promising long-term option for use of hydrogen. Fuel cells require pure hydrogen fuel, and although hydrogen can be produced on-board the vehicle from a variety of liquid fuels (including gasoline), compressed hydrogen is the ideal fuel for low-temperature fuel cells (see Box, “Fuel Cell Technology and Hydrogen”). Emissions of hydrogen-propelled vehicles mainly consist of water vapor, even without the use of any exhaust gas control—a consequence of the extremely lean-burn combustion conditions in hydrogen engines and the low operating temperature of the automotive fuel cell.

Because electrical energy can be transformed into useable work without thermodynamic loss, electric vehicles consume significantly less final energy per mile than internal combustion engine vehicles. An even lower rate of final energy use can be achieved through regenerative braking, using the electric motor as a generator, and by completely shutting off the motor during vehicle stops. Thus, electric vehicles offer the highest end-use energy efficiencies of all mobile power plants, approximately 0.2 kWh per mile (based on the U.S. combined driving cycle), and zero emissions at the place of operation. Depending on the type of fuel used to generate electricity, electric vehicles can substantially reduce or increase GHG emissions over the full fuel cycle (see Box 8, "Life-Cycle Analyses—From Well to Wheels").

Hydrogen and electric vehicles have higher costs due primarily to the greater difficulty of energy storage, which is also one of the largest obstacles to commercializing these technologies. As shown in Table 3, current compressed hydrogen tanks storing the same amount of energy as gasoline are more than ten times larger and nearly four times heavier. Since such an enormous tank volume is hardly feasible in conventional vehicle designs, hydrogen vehicles are likely to have limited driving range, unless they are highly fuel-efficient. The significantly heavier tank also offsets some of the fuel efficiency gain from the inherently more energy-efficient engine dedicated to hydrogen fuel.

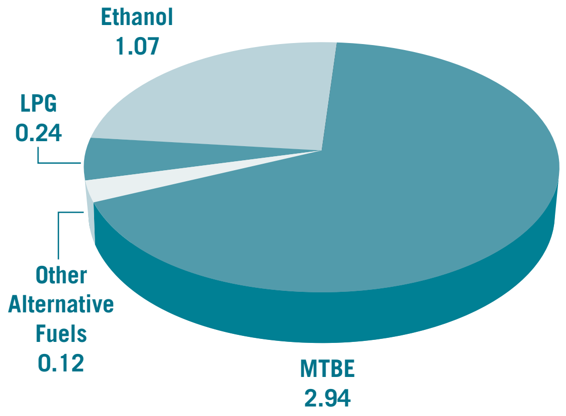
On-board energy storage is an even greater problem for electric vehicles. Current batteries are bulky and heavy, reducing vehicle range to below 150 miles before the batteries need to be recharged. An additional potential constraint for many battery designs is their heavy metal content and the associated emissions from battery recycling. It was estimated that over the lifetime of a vehicle, electric vehicles equipped with lead-acid batteries would emit 60 times more lead per kilometer than a comparable car fueled with leaded gasoline.[79] Due to their toxicity, some of the advanced battery technologies such as nickel metal hydride may not offer any real improvement.

Table 3 summarizes the major characteristics of alternative fuels and vehicle storage systems. These comparisons are based on constant fuel efficiency across vehicles. Improved efficiency is especially important to alternative fuel vehicles because it offsets the generally higher costs of alternative fuels, as well as the extra weight of tank and fuel.

Figure 9

Alternative and Replacement Fuel Use

2001, in Billion Gallons of Gasoline-Equivalent



Source: U.S. DOE, EIA (2002). Alternatives to Traditional Transportation Fuels, Table 10.

Table 3

Characteristics of Alternative Transportation Fuels and Vehicle Storage Systems

	Carbon/Hydrogen Ratio	Tank System containing 15 GGE of fuel		Approximate Fuel Costs, Delivered to Vehicle (Current) US$/GGE
		Fuel Volume (gal)	Total Mass (lbs.)	
Diesel	0.55	13.6	115	1.5
Gasoline	0.50	15.0	115	1.5
Liquefied Petroleum Gas	0.38	20.7	115	1.5
Ethanol	0.33	22.7	179	1.5-3.0
Methanol	0.25	31.0	240	2.7-3.5
Compressed Natural Gas (3600 psi)	0.25	46.3	268	1.5
Compressed Hydrogen (5000 psi)	0.00	175.1	408	3-4
Liquid Hydrogen	0.00	56.9	298	5-6
Electricity	N/A	450-1,000	5,600-14,000	3.4

Notes:

Ethanol. Lower range in fuel costs reflects current prices with corn as feedstock, which include a $0.55/gal (ethanol) tax subsidy. Higher range based on projected ethanol from cellulose biomass with plant gate costs of $ 1.40/gal (ethanol), $0.40/gal (ethanol) for transportation, distribution, storage, plus $0.20/gal (ethanol) subsidy. Multiplying by the ratio of volume specific energy content of 1.5 leads to $3/GGE.

Methanol. Range in projected costs dependent on cellulosic biomass-to-methanol technology.

Compressed and liquid hydrogen. Lower cost range: hydrogen from natural gas. Higher cost range, hydrogen from renewable electricity.

Electricity. Range in tank volume and mass based upon U.S. Advanced Battery Consortium mid-term and long-term targets; fuel costs correspond to an electricity price of 10¢/kWhel. Due to the three to four times higher end-use energy efficiency of electric vehicles, the actual battery mass to achieve a driving range of up to 150 miles is significantly below the indicated range.

Costs of all alternative fuels include taxes of 30¢/GGE.

GGE: gallon of gasoline equivalent

Replacement Fuels

While all alternative fuels described above experience severe difficulties when competing against the gasoline infrastructure, some of them, most notably alcohols, can be blended with petroleum fuels as “replacement fuels.” Replacement fuels are compatible with conventional vehicles; thus, no infrastructure change is necessary. The most widely used replacement fuels are ethers and alcohols blended with gasoline to produce “gasohol.” Because replacement fuel blends are compatible with the ubiquitous existing fuel distribution and retailing systems, they could relatively quickly displace some petroleum in transportation without having to overcome the transitional barriers faced by alternative fuels.

Driven partly by tax subsidies and fuel quality requirements for oxygen in gasoline, replacement fuels displaced four billion gallons (or about 3 percent) of gasoline in 2001 (Figure 9).[80] This is more than ten times the impact of all types of alternative transportation fuels combined, including natural gas, pure alcohol fuels, electricity, and liquefied petroleum gas. While methyl tertiary butyl ether (MTBE) accounts for nearly 75 percent of today’s replacement fuels, concerns about groundwater contamination from leaking fuel storage facilities will almost certainly result in the phase-out of MTBE, which is very likely to be replaced by ethanol.[81]

As with alternative fuels, the extent to which replacement fuels can reduce GHG emissions depends on how they are produced. MTBE is largely derived from natural gas.[82] Because of energy losses in converting natural gas, and the carbon content of MTBE itself, use of MTBE does not reduce GHG emissions in comparison with gasoline. By contrast, ethanol produced from corn in the United States

Box 7

Biomass Production Potential and Fuel Costs

In the United States, 1.76 billion gallons of ethanol were produced in 2001, with 95 percent made by fermentation of corn.[83] Using corn as a feedstock generates high-value by-products for the food and animal feed industries. However, as the market for these by-products becomes saturated, any increase in corn-based ethanol production is likely to result in strongly rising ethanol costs. The corn-to-ethanol process also heavily relies on fossil fuel inputs; given current corn yields, production methods, and modern fermentation and distillation methods, corn-based ethanol reduces full fuel cycle GHG emissions by slightly more than 30 percent in comparison with gasoline.[84] By contrast, future ethanol production may come mainly from dedicated cellulosic feedstocks such as switch grass, hardwoods and softwoods, or from agricultural residues and municipal refuse. Production of ethanol from cellulose requires much less energy and much less fertilizer than production from corn. Current estimates indicate that net GHG emissions of ethanol produced from cellulose can be close to zero, assuming excess electricity from cellulosic conversion is used to replace fossil-fuel based electricity in the grid.[85]

Owing to the low efficiency of storing solar energy in plant matter (the photosynthesis process), large land areas would be needed to provide a major share of transportation energy from biofuels. Current annual biomass yields typically vary between 2 tons per hectare (ha) in arid regions and 20 tons per ha in good rainfall areas,[86] but it is likely that energy crops would be grown on less-productive lands. It is this requirement for large land areas that raises the food-vs.-fuel debate. In the industrial world stabilizing population and rising agricultural productivity have reduced land requirements for food production. Further decline in agricultural land through a continuous increase in productivity and phase-out of agricultural subsidies could provide idled cropland of 52 Mha for the United States by the 2030s.[87] Covering that area with biomass plantations would yield an energy equivalent of 10 billion gallons of gasoline. However, at current efficiency levels, fueling the entire U.S. light-duty vehicle fleet with ethanol would require a land area of 300 to 500 Mha, or 17 to 28 percent of the entire land area of the lower 48 states.[88] Thus, unless the vehicle fleet consists of highly fuel-efficient automobiles and light trucks, biomass fuels cannot become the primary transportation fuel. The greater the efficiency of the fleet, the greater the relative contribution biofuels could make.

Due to the various inputs into biofuel production, current and projected ethanol costs are higher than current gasoline prices. Estimates for the United States suggest that cellulosic biomass-based ethanol costs would be about $1.20 to $1.40 per gal at the plant gate before taxes. Taking into account its lower energy content compared to gasoline and costs for distributing the fuel, ethanol would sell for $2.70 per gallon of gasoline equivalent[89] at gas stations, before taxes.[90] Other studies like that of the U.S. Department of Energy's research program have set a goal of producing ethanol at only $0.75 per gallon by 2015.[91] While even this would not make ethanol cost-competitive with gasoline as an alternative fuel, it could make it economical as a replacement fuel blended with gasoline. These and many other estimates are speculative, however, since no commercial-scale cellulosic biomass-to-ethanol plants exist yet.

reduces full fuel cycle GHG emissions by 30 percent compared to gasoline and by 1 to 4 percent if blended with gasoline in proportions of 5 to 20 percent. Ethanol could deliver even greater GHG emission reductions in the future if net GHG emissions of ethanol produced from low-cost cellulosic feedstocks are close to zero (see Box, "Biomass Production Potential and Fuel Costs").

Greenhouse gas emission reductions of up to 15 percent compared to gasoline might be possible by blending gasoline with ethyl tertiary butyl ether (ETBE) from cellulosic ethanol (up to 17 percent ethanol, by volume). Such blends can be used in conventional vehicles with no performance problems, meeting all requirements for clean gasoline under the Clean Air Act. It has been estimated that by 2010, ethanol from cellulosic sources converted to ETBE could reduce GHG emissions from gasoline combustion by 7 percent, while meeting all fuel requirements.[92] At blending levels of 5 to 20 percent, cellulosic ethanol and gasoline blends can reduce GHG emissions by 3 to 14 percent. At present, such goals appear very ambitious because no commercial-scale plants for producing ethanol from cellulose have been built.

B. Heavy-Duty Vehicles

Among all fuel options for heavy vehicles, only carbon-free fuels generate fewer GHG emissions than diesel fuels. Due to their high engine efficiency and robustness, compression-ignition engines running on diesel fuel are used by nearly all heavy-duty vehicles, and this is not likely to change in the next few decades. As was pointed out in Section II, the importance of low fuel expenditures has driven nearly all heavy-duty vehicle owners to choose highly efficient diesel engines. Other fuels cannot match diesel's energy efficiency. In addition, the higher space requirements for storing alternative fuels can result in the loss of valuable payload and cargo space (see Table 3). As with light-duty diesels, heavy-duty vehicle exhaust emissions are a growing concern. However, heavy-duty diesels differ from their smaller counterparts in that state-of-the art emission controls can already meet current and expected particulate emissions standards.

C. Non-Highway Modes

Owing to their high energy density in terms of both volume and weight, petroleum products are the ideal fuel for air transportation and also meet the requirements of railways and marine diesels. Because of space and weight constraints, aircraft impose the most rigorous requirements on transportation fuels. Liquid hydrocarbons offer the highest energy content per unit weight and volume of any fuel. The only viable alternatives to jet fuel for air travel are liquid hydrogen and liquefied natural gas. According to various studies projecting future characteristics of hydrogen aircraft, the major difference in total aircraft operating costs would result from the significantly higher costs of hydrogen fuel. Liquid hydrogen produced on a renewable basis would quadruple today's (untaxed) jet fuel prices. As fuel costs of aircraft account for about 25 percent of total direct operating costs today, a shift toward hydrogen fuel would increase total costs by 75 percent and increase the share of fuel costs to more than half of total operating costs, all other factors being equal. Although hydrogen aircraft offer fuel efficiency benefits that are difficult to achieve with hydrocarbon-based technology, direct operating costs would likely remain substantially higher compared to conventional jet fuel aircraft.

Railroad and marine two-stroke diesel engines are even more fuel-efficient than heavy-duty truck diesels. Given the current U.S. fuel mix for generating electricity, shifting rail locomotives from diesel to electricity could increase GHG emissions, unless the CO_2 associated with generating the electricity were captured and sequestered. Perhaps the most promising longer-term options for marine and rail transport are high-temperature fuel cells, with conversion efficiencies of 60 percent and above. Of course, this too would require an infrastructure for supplying hydrogen.

D. The Next 15 Years and Beyond

During the next 15 years, replacement fuels offer the greatest promise for reducing transportation sector GHG emissions; their contribution to emission reduction may be significantly complemented by hydrogen after 2015. Among the alternative fuels discussed above, only hydrogen and electricity can be produced on a sufficiently large scale to satisfy transportation sector fuel needs with zero net carbon emissions. However, infrastructure, on-board fuel storage, and cost constraints make hydrogen a long-term alternative. In the interim, liquefied petroleum gas, conventional natural gas, and biofuels can make small contributions to reducing GHG emissions. Although these fuels could play a transition role, it is questionable whether the associated high investments and limited GHG emission reduction potential would justify large-scale shifts to any of these fuels. A more promising alternative for the next 15 years and beyond are replacement fuels, which only require marginal changes to the existing transportation infrastructure and offer GHG emission reduction potentials of up to 14 percent for mixtures of gasoline and renewable biomass fuels.

Box 8

Life-Cycle Analyses—From Well-to-Wheels

A shift from gasoline to alternative fuels with lower carbon-to-hydrogen ratios is generally seen as a promising way to cut carbon emissions. However, as many of these fuels can be produced from a variety of feedstocks and processes, their comparative performance (including GHG emissions) needs to be evaluated over the entire fuel cycle, ranging from fuel extraction at the well through useful energy at the wheels.

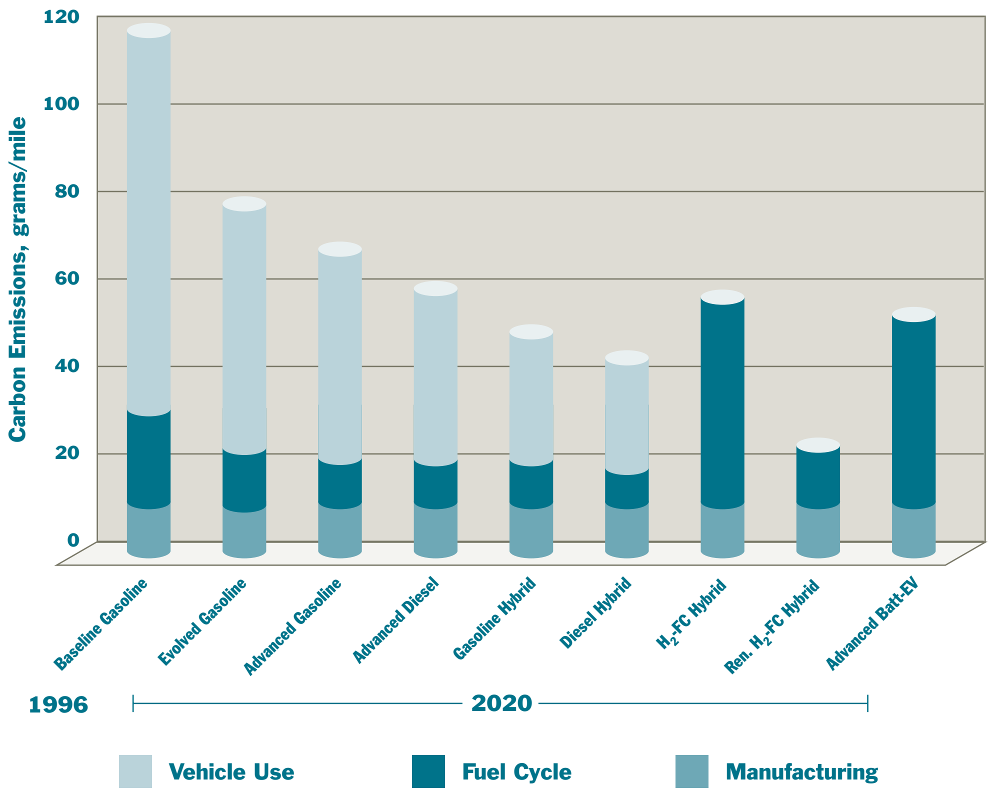
For example, carbon-free hydrogen fuel can be produced from splitting water molecules (H_2O) into hydrogen (H_2) and oxygen (O_2) via electrolysis, using electricity from solar or nuclear power. Following this route, hydrogen would be produced in a completely carbon-free manner. However, about half of the hydrogen produced worldwide today is derived from splitting natural gas, mainly consisting of methane (CH_4), into the carbon (C) and hydrogen (H) atoms, by a process called steam reforming. Following that route, switching from gasoline to hydrogen would not cause any appreciable reduction of carbon dioxide emissions, as the resulting emissions of nearly 20 pounds of CO_2 per gallon of gasoline equivalent of hydrogen are nearly identical to those when burning one gallon of gasoline directly. In part due to their higher carbon-to-hydrogen ratios, the use of oil or coal as a hydrogen feedstock would increase carbon dioxide emissions compared to the direct use of gasoline, unless carbon capture and sequestration technology were developed. This example illustrates that examining the entire path for producing and using a fuel is critical when comparing alternative vehicle and fuel options.

Well-to-wheel analyses suggest that energy requirements for the production of alternative fuels are typically 25 to 50 percent of the energy contained in the feedstock, depending on the alternative fuel to be produced, the feedstock, and the conversion process. This extra energy input can generally not be offset by the only slightly higher vehicle fuel efficiencies that result from burning an alternative fuel. Thus, a shift toward low-carbon synthetic transportation fuels typically results in higher primary energy use, which offsets at least some of the gain in GHG emission reduction unless carbon-free fuels are employed or the fuel carbon is extracted and disposed of after fuel production from fossil fuels.

Figure 10 on the next page illustrates well-to-wheel carbon emissions of the vehicles from Table 1. In addition, three automobile-fuel systems were added: a hydrogen fuel cell vehicle, where hydrogen is produced from natural gas; the same fuel cell vehicle, where hydrogen is produced with renewable power (but still compressed using grid electricity); and an advanced battery-electric vehicle, where electricity is produced according to the 2020 U.S. fuel mix projected by the Energy Information Administration.[93] Carbon emissions are grouped into vehicle manufacturing and recycling (including the transport and processing of materials), fuel cycle (processing, transmission/distribution, and if applicable, compression of fuels), and vehicle use (emissions while driving). Figure 10 illustrates two important points. First, about 75 percent of all well-to-wheel carbon emissions occur during vehicle operation, unless zero-carbon fuels are used. Second, while the fuel cell hybrid and battery-electric vehicle have no emissions during vehicle use, the production of hydrogen and electricity can cause fuel-cycle carbon emissions to be several times higher compared to all other vehicles, resulting in higher total carbon emissions compared to their hybrid gasoline and diesel internal combustion engine counterparts. Carbon emissions resulting from fuel production, however, can be reduced to practically zero if renewable or net carbon-free sources are used—for example, by sequestering carbon.

Figure 10

Well-to-Wheel Carbon Emissions of Various Vehicle-Fuel Combinations



Notes: For the H_2-FC Hybrid, the hydrogen fuel is produced from natural gas. For the Ren. H_2-FC Hybrid, the hydrogen is produced from electrolysis using renewable power, but is compressed using a mix of power sources from the grid.

Source: Weiss, M., et al. (2000).

IV. System Efficiency

Transportation greenhouse gas emissions could be reduced by several percent via various behavioral changes that can be implemented quickly but require determined and sustained effort. Achieving such impacts would require more comprehensive and effective efforts than have been seen to date in the United States. Even if the technology of transportation equipment were fixed and alternative fuels were not available, it would still be possible to reduce GHG emissions without loss of accessibility using the following approaches: (1) taking more direct routes from origins to destinations, (2) increasing vehicle occupancy rates, (3) shifting traffic from modes with high emission rates to modes with low emission rates, and (4) improving the in-use efficiency of vehicles through better maintenance and driving behavior. In addition, Chapter 5 will discuss restructuring the built environment to maintain accessibility with less vehicle travel through more efficient land use and urban design.

Governments play a major role in the efficiency of the transportation system through the investments they make in infrastructure and operations, particularly for highways, transit systems and airports. In the year 2000, governments at all levels in the United States spent $130 billion dollars providing and maintaining highways for public use.[94] Nearly all of the money is spent by state and local governments, but $33 billion is collected by the federal government and distributed mostly to states. Highway user fees of all kinds amounted to $99 billion in 2000, but more than $20 billion of those fees was spent on nonhighway purposes, with $8 billion going to mass transportation. Other major sources of funds for highways are general fund appropriations by state and local governments, property taxes, and other taxes and fees, mostly collected by local governments. Governments spent $21 billion on airports in 2000, slightly less than the amount collected from users of air transport.[95] The Airport and Airway Trust Fund is the single largest revenue source, with $10.5 billion in 2000. Governments spent $32 billion on transit systems in 2000, $8 billion on water transport systems, and less than $1 billion on all rail projects.

A. Reducing the Circuity of Travel

Travel routes rarely follow the shortest distance between two points. It has been estimated that oceangoing ships might cut their energy use and CO_2 emissions by 4 to 7 percent through more intelligent weather routing and adaptive autopilot control systems, which are already in use in commercial aircraft.[96] In principle, it should be possible to reduce aircraft energy use by minimizing their time idling on the ground and by better managing airspace to allow more direct routing. Flight distance efficiency, however, has historically remained roughly constant at about 90 percent of the maximum possible. In the face of growing air traffic it may be enough of a challenge just to hold operational efficiency at this level.[97] In trucking, computers and global positioning satellites are already being used to more efficiently route long-haul trucks. Application of information technology to highways and transit systems will soon allow auto and transit users to save time and energy by finding the most efficient routes under prevailing traffic conditions.

B. Increasing Vehicle Occupancy Rates

It has been said that the empty seats in America's highway vehicles are the greatest oil reserve in the world.[98] Given that the average number of occupants per vehicle in the United States is 1.6 for all trips and 1.1 for the journey to work,[99] some 10 trillion empty seat miles are produced by U.S. highway vehicles each year. In theory, increasing vehicle occupancy rates by ridesharing could have an enormous impact on energy use and emissions. Past efforts to promote ridesharing via ride-matching services, vanpools, high-occupancy vehicle lanes, free parking, and subsidies have had only limited success in the United States.[100] Despite these efforts, highway vehicle occupancy rates have been declining, not increasing (from 2.2 persons per vehicle in 1969 to 1.6 in 1995). With a steady decline in the average household size (from 3.2 persons per household in 1969 to 2.6 in 1995) and a continuous growth in the number of vehicles per household (from 1.2 to 1.8 during the same time period), both the opportunity and the need for sharing a vehicle have declined.

Perhaps the single largest experiment to increase vehicle occupancy was Southern California's comprehensive Regulation XV program. The program required employers to design programs to increase average vehicle ridership (AVR), defined as the ratio of the number of employees arriving between 6 am and 9 am to the number of motor vehicles used by those employees. After two years, a survey of employers at 1,110 sites showed that ridesharing was up 40 percent from a very low initial level, but average vehicle occupancy had increased only from 1.22 to 1.25. The fraction of drivers driving alone decreased from 76.2 percent to only 71.4 percent. Also, while ridesharing increased, transit use declined as passengers were drawn from transit vehicles into ridesharing.[101] The California legislature eventually ended this unpopular program.

Despite decades of efforts, no one has found the key to unlock the massive potential of carpooling. Success has been achieved in specific areas under special conditions (High-Occupancy-Vehicle requirements, parking restrictions) or for limited periods of time. Increased occupancy rates have made a sustained contribution to the energy efficiency of air travel, but how to raise automobile occupancy rates nationwide remains a mystery. Until a workable approach is found, the practical potential for reducing GHG emissions by increasing vehicle occupancy is small, despite the 10 trillion empty seat miles Americans produce each year.

C. Shifting Traffic to More Energy-Efficient Modes

Achieving large-scale shifts in transportation activity to favor more efficient modes has proven difficult. For example, although there are very large differences in the energy intensities of freight modes, little effort has been expended trying to shift freight traffic from truck to rail or rail to water in order to reduce energy use and GHG emissions. Attempts to do so would run counter to the increasing requirements for speed and reliability of an increasingly service-oriented economy. In addition, because different modes offer different services in terms of cost, speed, and performance, the differences in energy intensity are greatly reduced when one compares modes based on equivalent levels of service.[102]

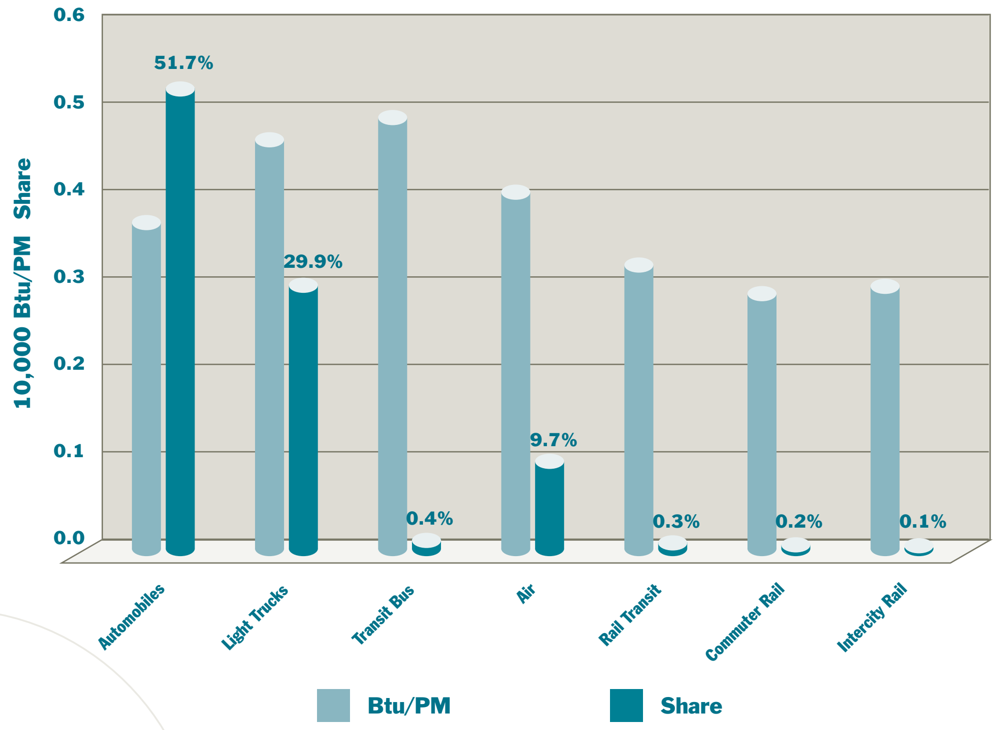
The greatest opportunity for improving the operating efficiency of freight transport may lie in ensuring that the infrastructure exists to allow freight to be transferred quickly and efficiently among modes. If intermodal transfers can be made fast, reliable and inexpensive, the best features of each mode can be combined to achieve greater energy efficiency than a single high-speed mode. For example, with efficient intermodal transfers, containerized cargo arriving at U.S. ports can be transferred to rail for the greatest part of its overland transport, then transferred to a truck for local delivery. If transfers are expensive and time consuming, the same container might be put immediately on a truck for more energy intensive point-to-point delivery. Intermodal freight is second only to air freight in value-to-weight and rate of growth.[103]

At the national level, passenger transportation modes are surprisingly similar in their energy use per passenger mile (Figure 11). Carbon intensity mirrors energy intensity because all the modes except rail transit use petroleum fuels with similar carbon contents. The national average figures to some extent obscure differences from place to place. While the national average energy use per passenger-mile for rail transit is 3,100 Btu, heavy rail systems in Brooklyn and Atlanta and light rail systems in Newark and Salt Lake City average around 2,000 Btu.[104] Moreover, where electricity is generated from hydropower, nuclear power, or natural gas rather than coal, GHG emissions will be reduced by electric rail systems even if energy intensities are high. Transit efficiencies could be much higher relative to passenger cars if transit occupancy rates could be greatly increased, but this has proven to be no easier in the United States than increasing automobile occupancy rates.

Significantly reducing national GHG emissions via increased use of transit would require momentous efforts. All modes of transit (bus and rail) account for only 1 percent of passenger-miles traveled in the United States today.[105] Doubling national transit use would affect only 1 percent of total passenger travel. This suggests that even innovative solutions, such as Bus Rapid Transit (BRT), which seeks to

Figure 11

Average **Energy Intensities and Modal Shares** of Passenger Travel in the United States, 2000



Source: Davis and Diegel, 2002. BTS 2002, Table 1-31.

Note: PM means passenger-miles

Box 9

Human Factors: Speed and Energy Use

For a given vehicle (technology, weight, and design held constant) the most important determinants of energy use and carbon dioxide emissions are acceleration and speed.[106] Aerodynamic drag increases with the square of speed, and rolling resistance increases in direct proportion to speed, while internal engine friction and the energy required to run mechanical accessories, such as oil and water pumps, increase with engine speed. In stop-and-go driving, average speed is also correlated with the number of stops and starts, and with the amount of time spent idling. As a result, fuel economy generally increases as average speed increases, up to about 40 miles per hour. On the highway, faster driving costs fuel but saves time. Increasing speed from 60 to 70 miles per hour would decrease the fuel economy of an average car from about 30 mpg to 25 mpg. Consider a 60-mile trip traveled at 70 versus 60 miles per hour. By going 10 mph faster, the traveler saves 8.6 minutes, but consumes 0.4 more gallons of fuel. Assuming gasoline cost $1.50 per gallon, it cost $0.60 to save 8.6 minutes, equivalent to $4.20 per hour. Few drivers would value their time at less than that.

In January 1974, Congress passed a law limiting the national speed limit to 55 mph. Since most roads had posted limits at or below 55, this affected only traffic on interstates and other major freeways. The National Research Council[107] estimated that the “double nickel” speed limit reduced national highway fuel consumption by about 2 percent, and that it also probably saved 2,000 to 4,000 lives per year, due to lower fatality rates in highway crashes. The 55 mph speed limit was restricted to apply only to urban highways in 1987 and finally repealed in 1995.

combine the speed, reliability and comfort of rail transit with the flexibility of buses, can have only a very limited impact on GHG emissions at the national scale.[108]

D. Vehicle Maintenance and Driver Behavior

Driver behavior affects fuel economy. Minimizing unnecessary braking (for instance, by not tailgating), observing the speed limit, anticipating the actions of other drivers, and avoiding excessively rapid acceleration can increase miles per gallon by a few percent over normal driving behavior. It is possible to increase fuel economy by another few percent via optimal vehicle maintenance. Studies of programs to promote these behaviors, however, have found that it is difficult to sustain the gains without regular driver retraining.[109]

V. Reducing Transportation Activity

One way to reduce the GHG emissions of transportation is to reduce transportation activity, or travel, itself. This can often be accomplished without compromising accessibility. One approach to reducing transportation activity is to change land use to decrease the need to travel or enable alternatives to driving. Another approach is to use pricing mechanisms, which can redistribute or increase the cost of travel.

A. Changing Land Use to Substitute Accessibility for Travel

The geographic distribution of people and places, especially the density of development, strongly influences the demand for transportation. In addition, the way settlements are built—whether neighborhoods have sidewalks or bike paths, whether homes are within walking distance of shops or transit stops—influences both the amount and kinds of transportation. While the relationships between land use, accessibility, and travel are understood at a very general level, much more needs to be known about practical means of improving development patterns to reduce vehicle travel while enhancing accessibility and the quality of life in metropolitan areas.[110]

For over 50 years automobile-centered cities and towns have been built in the United States. To date, existing tools such as land-use planning, zoning, and transportation infrastructure investments have been primarily used to enhance the mobility provided by motor vehicles, rather than to trade off car travel and accessibility. However, if such tools are used to reduce vehicle travel, their potential can be significant, at least over the longer term. Studies of large-scale metropolitan planning strategies for reducing travel while maintaining accessibility suggest that a combination of land use and transit policies might succeed in reducing vehicle miles traveled in urban areas by about 5 to 7 percent over a period of thirty years, and perhaps 9 to 10 percent if combined with policies to charge for parking and for use of congested roads.[111] Modeling and simulation analyses of travel at the neighborhood level suggest that vehicle travel might be reduced 10 to 25 percent by changing the design of subdivision development to more closely resemble the grid street layouts and mixed land uses of pre-WWII communities.[112]

A synthesis of recent studies finds that travel is relatively insensitive to changes in the built environment alone,[113] estimating that doubling local densities of population and employment could be expected to reduce vehicle miles traveled by only about 5 percent. Improving regional accessibility (defined by the distances to regional centers) could have a much larger impact. The implication is that major changes in the geography of American cities would be needed, combined with additional pricing policies, to achieve reductions in travel of more than 10 percent.

In addition, there are significant barriers to changing U.S. geographic patterns, and major changes will take decades to effect. The possibility of reducing the need for vehicular travel on the order of 10 percent or more without loss of accessibility justifies continuing efforts to develop a better understanding of and better practical tools for influencing transportation via land use.

B. Pricing Transportation

Transportation costs and their composition are strong determinants of the demand for travel. Changing the costs and their structure can be an effective tool for controlling GHG emissions. Two areas deserve special attention: (1) "internalizing" some of the external costs of transportation, such as air pollution, GHG emissions, and traffic congestion and (2) transferring some of the components of transportation costs now paid as fixed costs, such as automobile insurance, to be paid per mile or per gallon of fuel consumed, while keeping total costs level.

Shifting the Incidence of Costs to Reduce Greenhouse Gas Emissions

According to recent estimates, the unintended consequences of transportation, including traffic congestion, environmental impacts, uncompensated traffic accident damages, and oil dependence impose very substantial costs on society.[114] The full cost of transportation consists of five components: (1) the cost of a vehicle, including its maintenance and insurance, (2) variable costs, such as fuel and tolls, (3) the time of the vehicle operator and traveler, (4) the cost of infrastructure, such as roads, airports, and terminals, and (5) external costs imposed on others, but not directly borne by the traveler or carrier. External costs include air pollution, traffic congestion, GHG emissions, impacts of infrastructure on habitats, and noise. In general, travelers and carriers fully and directly pay the cost of the first three components, directly pay half or more of the cost of infrastructure through user fees such as motor fuel taxes, and pay none of the external costs.[115]

To effectively internalize the external costs of transportation, it is not enough to simply calculate all the unintended costs of transportation and add them up into a per-mile price for vehicle travel or per-gallon price for motor fuel. To improve on the current system, economic theory requires that pricing be directly related to the damage done. This implies, for example, that a price for pollutant emissions must distinguish between cleaner and dirtier cars. Pricing must recognize that emissions increase during heavy acceleration and when the car's air conditioning is running, that the impact on air quality depends on the ambient temperature and other atmospheric conditions, and that the ultimate health damage depends on how many people are exposed. Given the potential complexity of such a pricing system, it is no surprise that most of the external costs of transportation are already partly addressed by non-price policies, such as motor vehicle emissions standards, traffic controls, and automotive fuel economy standards. Despite all of this, there is still some role for externality taxes on vehicle travel or motor fuel, and they could have a significant impact.[116]

In the United States, highway infrastructure is generally provided as a free public good and paid for by a variety of taxes, including motor fuel, real estate, and sales taxes. Some analysts have argued that free access to highways results in over-consumption of highway transportation.[117] It was in part this claim that led the Intermodal Surface Transportation Equity Act (ISTEA) of 1991 to permit greater flexibility in the use of highway trust funds to address mobility issues at the state and local level. Through the Congestion Mitigation and Air Quality (CMAQ) provisions of the ISTEA, for example, the act allows funds previously dedicated to highway construction, maintenance, and operation to be used to mitigate some of the external costs of transportation. This new strategy was continued under the Transportation Equity Act for the 21st Century (TEA-21). These acts were not meant to address all the unintended consequences of transportation for society and the environment.

Transportation researchers and planners have long sought an efficient way to price congestion. Congestion leads to excessive engine idling, which wastes fuel and increases GHG emissions. There have been some promising experiments, and advances in telecommunications have greatly reduced the costs of toll collection. Simulation of economically efficient congestion tolls in a large metropolitan area indicated that vehicle miles would decline by about 20 percent on expressways and less than 10 percent on other roads.[118] These estimates apply only to relatively large metropolitan areas and only during congested peak travel conditions. The effect on total vehicle travel would be much smaller. Moreover, a 1 percent reduction in the time cost of travel (a 1 percent increase in average speed) would induce about a 1 percent increase in travel, leaving the travel time budget unchanged. This is an important consideration for congestion mitigation or congestion pricing measures, since relieving congestion increases average speeds, engendering a rebound effect. Other problems include public unwillingness to pay for the use of formerly free roads and potentially regressive income distribution effects. As Americans have become accustomed to free access to highways, significant changes to the structure of transportation costs would undoubtedly meet with opposition. In fact, congestion pricing tends to make all travelers worse off until the funds collected are redistributed.

While efficient pricing policies for controlling traffic congestion and urban air pollution require sophisticated implementation, pricing the carbon content of motor fuel is perhaps the only case in which a simple motor fuel tax would effectively internalize the relevant environmental damage. Essentially all of the carbon in fossil fuels is emitted as carbon dioxide, and no matter where or when the carbon is emitted, the effect on the climate is the same. Thus, charging for the carbon in the fuel is equivalent to charging for harm to the climate. But three factors cloud the issue. First, it is not clear what dollar value should be assigned to the damage done to the climate by a ton of carbon emissions. Charges on the order of $50 to $100 per ton of carbon would translate into $0.12 to $0.25 per gallon of gasoline, a significant amount, but nowhere near enough to stimulate a significant reduction in vehicle miles traveled (VMT) or major improvements in fuel economy. This underlines the importance of developing new technologies, using alternative fuels, and implementing government policies to reduce transportation's GHG emissions. Second, there is reason to believe that the private vehicle market does not respond effectively to price signals when it comes to fuel economy (see Box 3, "Markets and Fuel Economy"). Third, current motor fuel taxes are a surrogate for a highway user tax. Because the tax falls on motor fuel rather than miles traveled, it discourages travel to some extent through the cost of fuel per mile, and it also encourages higher fuel economy. Thus, it could be argued that the current motor fuel tax, at approximately $0.45 per gallon, is already internalizing some of the environmental impacts of motor fuel use.

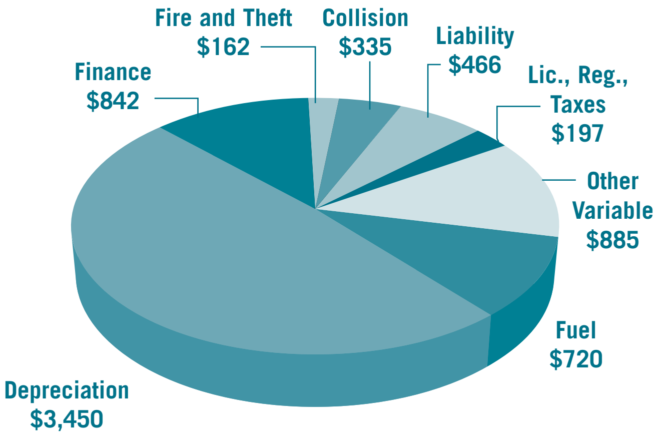
Transferring Fixed Costs to Per Gallon Costs

Many fixed expenses are large relative to fuel costs. There is potential to strongly affect vehicle travel or fuel consumption by transferring fixed to per gallon costs without changing the total costs of travel.

It is possible to shift the cost of owning and operating a motor vehicle onto motor fuel without increasing the total cost. Fuel is a minor component of overall travel cost. Insurance costs plus licensing, registration fees, and other taxes exceed fuel costs by 60 percent. Some of these costs, such as liability insurance, might more logically be associated with miles traveled than charged as a fixed fee. Transferring any significant fraction of insurance and licensing, registration fees, and other vehicle taxes to be collected as a tax on motor fuel would substantially increase the price of fuel without increasing the overall cost of vehicle travel. As motor fuel taxes, they would encourage increased fuel economy and decreased driving, thereby significantly reducing GHG emissions.

Figure 12

Annual Costs for a Model Year 2001 Automobile



Source: Davis and Diegel, 2002, Transportation Energy Data Book, Ed. 22, Tables 5.12 and 5.13.

Impacts of Pricing Policies

Because fuel accounts for a minority of the monetary costs of travel (the share varied from 10 percent to 20 percent for U.S. automobiles between 1985 and 2001[119]), the impacts of fuel and carbon taxes on total vehicle travel will be proportionately smaller, about a 1 percent to 2 percent VMT decrease for a 10 percent increase in the price of fuel (see Box 5, "Energy Efficiency and the 'Rebound Effect'"). But fuel prices also influence the types of vehicles people buy and their demand for fuel economy. This in turn encourages car manufacturers to design vehicles with higher fuel economy. The economics literature indicates that a 10 percent increase in the price of fuel would lead ultimately to about a 5 percent to 6 percent increase in new car fuel economy.[120] A literature survey done for the U.S. Department of Energy that gave greater weight to the effects of the U.S. automotive fuel economy standards concluded that a 10 percent fuel price increase would produce only a 2 percent increase in miles per gallon.[121] Engineering-economic analyses of the technological potential for fuel economy improvement also support a 2 percent fuel economy increase for a 10 percent increase in fuel price.[122] These studies explicitly exclude the effects of car buyers choosing more fuel-efficient makes and models, so the full impact would be larger than 2 percent. The authors use a 4 percent increase in fuel economy for a 10 percent increase in fuel price to estimate policy impacts in Section VI. Combining the effects of fuel price on travel and fuel economy (and taking into account the rebound effect of fuel economy on travel), a 10 percent fuel price increase should reduce fuel consumption and emissions by 5 to 6 percent in the long run, once the fuel economy improvement has penetrated the in-use vehicle stock. Of this total impact, the 1 to 2 percent reduction via the impact on vehicle travel will occur immediately.

C. Travel Reduction Measures—A Summary

A historical review of non-pricing measures to reduce travel, such as ridesharing, transit improvements, HOV lanes, bicycle and pedestrian facilities, flexible work hours, telecommuting, and land-use planning, found that the most effective programs reduced vehicle travel by less than 6 percent.[123] Frequently, the impacts were fractions of a percent reduction (Table 5). Obviously, historical achievements do not necessarily predict the performance of future programs. Furthermore, it could well be that the combined effect of an integrated suite of programs could reduce vehicle travel by 10 percent, or more. However, realizing significant improvements at a national scale in the United States would be an enormous challenge.

Table 5

Vehicle Travel Impacts of Transportation Controls

Transportation Control Measure	Percent Reduction in Vehicle Miles
Employer trip reduction	0.2% to 3.3%
Area-wide ridesharing	0.1 to 2.0
Transit improvements	0.0 to 2.6
HOV lanes	0.2 to 1.4
Park-and-ride lots	0.1 to 0.5
Bicycle/pedestrian facilities	< 0.1
Parking pricing	
Work	0.5 to 4.0
Non-work	3.1 to 4.2
Congestion pricing	0.2 to 5.7
Compressed work week	0.0 to 0.6
Telecommuting	0.0 to 3.4
Land-use planning	0.0 to 5.2
Signal timing	< 0.1
Incident management	0.0 to a 0.1 increase
Emissions/VMT tax	0.2 to 0.6
Buy-backs of older cars	> 0.0

Source: Greene, 1996, Table 7.3.[124]

VI. Policy Options

Because energy markets on their own cannot be expected to adequately limit GHG emissions, government action is critically important. Several strategies are available to governments. Direct investment in research and development or partnerships with industry can accelerate progress in energy efficiency and low-carbon energy technologies. Regulatory standards can direct markets to increase energy efficiency in the absence of adequate price signals. Fiscal and market-based policies can work through market mechanisms to mitigate emissions. Coordinated land-use planning and infrastructure investments can increase accessibility of homes, workplaces, and other destinations while simultaneously reducing the need for vehicle travel. Public education has the potential not only to change consumers' behavior, but also to improve the efficiency of markets by creating better-informed producers, consumers, and citizens. A comprehensive and balanced policy to mitigate transportation's carbon emissions should combine elements of all these approaches.

A. Research, Development, and Demonstration

Advancing technology is critical to achieving major greenhouse gas emissions reductions from transportation. An expanded publicly funded research, development, and demonstration program should be a key element of any comprehensive GHG strategy for transportation. It is clear that improving climate-friendly technologies (for instance, reducing the cost of fuel cells, developing improved emissions controls for diesel engines, and decreasing the cost of producing ethanol from cellulose) is the key to cost-effectively solving the problem of transportation GHG emissions. Private markets cannot be relied on to make adequate investments in research and development to find solutions to environmental problems.[125] Governments can rectify this shortcoming by supporting R&D in the public's interest.

There are many ways that governments can foster research, through contracts and grants to universities, partnerships with industry, and funding of private or governmental research institutions. Research can also be stimulated by other policies, such as efficiency standards or fiscal incentives.

A comprehensive strategy would include research programs aimed at increasing the energy efficiency of each transportation mode and reducing the carbon content of fuels. It would also address cross-cutting, fundamental technologies that can benefit many transportation modes. In the past, the Partnership for a New Generation of Vehicles (PNGV) combined government and industry efforts to develop technology necessary for an up to three-times more energy-efficient automobile.[126] The FreedomCAR program, which is focused on developing hydrogen fuel cell vehicles, will also continue research on the advanced internal combustion engine and vehicle system technologies pursued under the PNGV. Recognizing the importance of developing the infrastructure to support a hydrogen-powered transportation system, the U.S. Department of Energy has established a research program focused on infrastructure technology and begun investigating a transition from petroleum to hydrogen.[127]

It is equally important that other transportation modes be addressed. The federal government's 21st Century Truck Program set appropriately ambitious goals for a partnership of government and industry participants. A strong aircraft energy efficiency program is also essential, as are meaningful efficiency efforts for rail, marine, and pipeline. Supply of low-carbon energy sources for transportation also requires research and development. Cheaper and more efficient means of producing biomass fuels and producing hydrogen renewably or from fossil fuels with sequestration of carbon are promising possibilities.

B. Energy Efficiency Standards

More than half of transportation's GHG emissions could be addressed by a single policy: increased fuel economy standards for automobiles and light trucks. Better still would be GHG emissions standards, in grams per mile, such as adopted by the European Union and more recently under development by the state of California, since they provide increased flexibility in achieving GHG reductions and an additional incentive to reduce the carbon content of fuels. There is little doubt that higher mile per gallon targets would be effective in raising light-duty vehicle fuel economy and reducing carbon dioxide emissions. In 2003, the National Highway Traffic Safety Administration (NHTSA) proposed a rule to increase light truck fuel economy standards by 1.5 mpg over the next four years. While this is a welcome beginning, it is very important that NHTSA set more ambitious standards with longer lead times to allow adequate opportunity for manufacturers to implement fuel economy innovations in all their product lines (see Box 2, "Changing Transportation Energy Use Takes Time"). Targets for the year 2015 might be able to achieve CO_2 emissions reductions of

20 to 25 percent from new vehicles. In the longer term, reductions of 33 to 50 percent over what would occur at constant fuel economy may be possible. Regulatory standards are less appropriate for heavy trucks, aircraft, rail, or pipeline modes, principally because these modes have strong financial incentives to reduce fuel costs by increasing fuel economy.

Mandatory efficiency standards are not the only option available for raising fuel economy levels. Voluntary standards have been adopted by the European Union and European car manufacturers (most of whom also manufacture and sell cars in the United States). To date, European manufacturers are making satisfactory progress toward meeting the voluntary goals. Canada's fuel economy standards are also the result of a voluntary agreement. The historically adversarial relationship between the U.S. government and the automobile industry in the area of environmental protection argues against the possibility of voluntary standards in this country. The motor vehicle industry, however, might consider them preferable to mandatory standards. Voluntary standards could also be developed for other modes of transport, thereby ensuring continuing energy-efficiency progress in trucks, aircraft, locomotives, ships, and even pipelines.

By failing to meaningfully address GHG emissions from transportation vehicles, U.S. manufacturers risk conceding global leadership in automotive technology. The European voluntary fuel economy agreement calls for reducing the CO_2 emissions of the average new 2006 light-duty vehicle to 193 grams of CO_2 per mile, which translates into a vehicle fuel efficiency of 39 mpg. The Japanese mandatory fuel economy standards for each weight class set a similar goal. Achieving that level of fuel efficiency will be quite a technological challenge, one that will keep foreign manufacturers on the cutting edge of technology.

C. Alternative Fuels

Alternative fuels can only be successfully introduced with strong government involvement. Shifting a large fraction of total transportation energy use to an alternative fuel will require very large investments for both the fuel and vehicle industries. Government must play a central role in mitigating the associated risks by providing clear policy direction. Consider the cost of replacing the U.S. gasoline infrastructure with hydrogen. Perhaps the least expensive means of producing hydrogen is via steam reforming of natural gas. Building up a natural gas-to-hydrogen infrastructure would require capital investments of several hundred billion dollars,[128] although this would be spread over many years. Also the vehicle industry would need to invest heavily in several models of hydrogen fuel cell vehicles, with a typical production run of 100,000 to 300,000 vehicles per model per year. Without a ubiquitous network of refueling stations, consumers will be reluctant to buy alternative fuel vehicles. Without a substantial population of vehicles on the road, fuel suppliers will be reluctant to invest in an extensive fuel delivery network. Overcoming this problem will almost certainly require a sustained government commitment with both incentives and regulatory support.[129]

D. Pricing Policies

The U.S. highway system is funded through a federal tax on motor fuels, but other energy or carbon taxes have thus far not found acceptance in the United States. Targeted subsidies and incentives, however, are widely used. For example, exemption from a large fraction of the federal motor fuel tax created the ethanol fuel market. The gas-guzzler tax (a graduated tax on new passenger cars getting less than 22.5 mpg, starting at $1,000 and increasing to $7,700 at under 12.5 mpg) discourages the sale of passenger cars with low fuel economy. Surprisingly, there is no comparable tax on light trucks with low fuel economy. Numerous other tax incentives encourage alternative fuels, electric vehicles, hybrid vehicles, and use of ethanol.

A carbon cap-and-trade system, or even a carbon tax, would encourage a wide array of actions to reduce GHG emissions from transportation, but it is not a substitute for a comprehensive strategy. Achieving the necessary reductions requires addressing the need for new technologies, the market failures for light-duty vehicle fuel economy, as well as the synergistic effects of land use patterns, infrastructure supply, and transportation demand.

Creative pricing policies worth considering include “variabilizing” some of the fixed costs of vehicle travel by converting annual fees and charges into surcharges on motor fuel. One such idea is “pay-at-the-pump” automobile insurance, where a minimum required amount of insurance (basic liability) is paid for by all through a surcharge on gasoline or diesel fuel of about $0.35 per gallon. This strategy alone could produce a 10 to 12 percent reduction in GHG emissions by highway vehicles.[130] Motorists would still have to sign up with an insurance carrier and would have to pay additional insurance premiums for increased liability or collision, or if their risk pool required it. The plan eliminates the problem of uninsured motorists, ties at least some of the cost of insurance to the amount of vehicle travel, and does not increase the total costs of motor vehicle travel. On the other hand, it puts governments in the business of collecting and distributing large amounts of revenue to insurance companies, a prospect the industry is not likely to welcome.

Another promising policy option calls for replacing the current fuel economy regulations with a system of taxes (fees) and incentives (rebates) to discourage low-efficiency vehicles and promote high-efficiency vehicles.[131] In theory, these "feebates" should be able to achieve the same kinds of fuel economy increases as regulations, but harmonize the interests of car buyers and manufacturers. By levying a tax on low-mpg vehicles and subsidizing higher-mpg vehicles, feebates encourage manufacturers to use fuel economy technologies to avoid the taxes and acquire the rebates. At the same time they provide a price signal to car buyers to choose models with higher fuel economy. Feebates can be designed to be "revenue neutral" by dispensing as much in rebates as they collect in fees. An especially attractive feature of the feebate approach is that it provides a continuing financial incentive for manufacturers to improve fuel economy by developing and implementing advanced technologies.

E. Land-Use Planning and Infrastructure Investment

Land-use and transportation infrastructure policies will have little immediate impact on GHG emissions, but they could be among the most important policies in the long run. Developing a better understanding of and practical tools for influencing transportation through land use is critical to creating efficient transportation systems. There is clear evidence that mixed land uses and neighborhoods designed to accommodate walking and cycling reduce the need for motorized trips without loss of accessibility. Investments in transit infrastructure and land-use policies favoring transit-oriented development not only reduce automobile trips but also increase transit occupancy rates and increase the density of development. Moreover, there are other valid reasons for striving for more efficient land use, including reducing traffic congestion, protecting habitats, and improving air quality.

F. Public Information and Education

The present level of public understanding of climate change and greenhouse gas issues is a serious barrier to progress in reducing GHG emissions from transportation. It appears that the public is generally not aware of the relationship between the transportation choices they make and their consequences for climate change.[132] Better informing the public might not only change some behaviors (for example, by raising awareness of the value of fuel economy), but also make citizens more inclined to support public policies and measures to reduce GHG emissions.

G. The Right Mix

No single policy approach is either necessary or sufficient; the right mix will include a balanced combination of public education, technology research, development and demonstration, and fiscal and regulatory measures. Within each policy category, there will be more than one policy measure that can be effective. What is important is that all components be addressed by meaningful measures that are both cost-effective and successful in reducing emissions. Experience with higher oil prices and fuel economy standards has shown that it is possible to slow the growth of transportation petroleum use and GHG emissions; this report shows that options exist that can have a significant impact in the future.

H. How Much Can Carbon Emissions Be Reduced?

Combining different types of policies can significantly reduce transportation's GHG emissions in the near term and achieve dramatic reductions in the longer term. In this section the combined impacts of a variety of measures on transportation GHG emissions are estimated in 2015 and 2030. Correctly estimating the GHG reduction potential of combinations of policies requires accounting for the potential interactions among them. For example, if the carbon content of gasoline is decreased by blending with renewable ethanol, the benefit of increasing fuel economy is diminished to that degree. Care has been taken to avoid possible double counting of benefits in such calculations.[133]

Table 6 summarizes the authors' estimates of the potential for reducing U.S. transportation sector CO_2 emissions by 2015 and 2030 based on the year 2000 emission levels. The first two columns of text identify the target emissions source and example policy options. The first column of data shows the year 2000 GHG emissions for the portion of the transportation sector to which the policy applies. The expected impacts (in percent reductions) for the relevant mode or fuel are shown in the second and third columns of data for the years 2015 and 2030. The impacts on total transportation GHG emissions (in percent reductions), weighted by year 2000 total transport sector CO_2 emissions, are reported in the last two columns.

The potential improvements from research, development, and demonstration are not counted directly as GHG reductions, but instead are "captured" by other policies such as efficiency standards or pricing policies. Advancing technology through RD&D helps enable GHG reductions but is not sufficient to achieve them, because without policies, markets cannot be relied on to reduce externalities like GHG emissions. The estimates shown are subject to considerable uncertainty, especially for the year 2030; however, the authors are confident that reductions of the general magnitudes shown are achievable.

Because nearly 90 percent of U.S. transportation CO_2 emissions are released by light-duty vehicles, heavy trucks, and aircraft, most of the indicated measures concentrate on these modes. The reduction in CO_2 emissions from the U.S. vehicle fleet that is achievable through fuel efficiency improvements without sacrificing mobility, performance, or safety is indicated in the first section of the table, "Research, Development, and Demonstration." As concluded in Section II, a realistic potential for reducing fuel consumption and CO_2 emissions from the light-duty vehicle fleet may be 11 percent by 2015 and 38 percent by 2030. Slightly smaller 2030 potentials exist for heavy-trucks and commercial aircraft. If, however, these potentials are obtained via fuel efficiency standards without an increase in the price of fuel, the rebound effect (incorporated in the estimates in Table 6) reduces these potentials slightly.

In addition to efficiency standards, alternative fuels can make an important contribution to reducing CO_2 emissions. Low-carbon replacement fuels in 10 percent blends with gasoline could reduce CO_2 emissions by about 2 percent (using ethanol made from corn) by 2015 and by up to 7 percent (using ethanol from cellulosic biomass) by 2030. The potential of hydrogen fuel to displace gasoline is less clear. If hydrogen fueled all government fleet vehicles by 2015 and could be exclusively produced from net zero-carbon fuels, the reduction in light-duty vehicle CO_2 emissions would be nearly 3 percent. From that perspective, a 1 percent reduction is perhaps optimistic. While the amount of hydrogen fuel will likely be small through 2015, it can become much more significant by 2030. As an optimistic case, the authors assume that every eighth light-duty vehicle, over 25 million vehicles, will be fueled with hydrogen by 2030. This fleet currently corresponds to the population of light-duty vehicles in California. If half of the hydrogen necessary to fuel that fleet is produced from natural gas and the other half from zero-carbon fuels, light-duty vehicle CO_2 emissions could be reduced by about 6 percent.[134]

The fiscal policies in the table include a subsidy for realizing the introduction of low-carbon replacement fuels, a carbon price increasing from $50 in 2015 to $100 per ton of carbon in 2030 (assuming a price elasticity of fuel efficiency of -0.4), and an increase in gasoline price of 35 cents per gallon in 2015 up to 55 cents per gallon in 2030, offset by equivalent reductions in the fixed costs of vehicle travel (assuming a price elasticity of fuel demand of -0.4). Finally, behavioral changes consist of alterations in land-use and infrastructure, improvements in systems efficiency, and climate change education.

Altogether, CO_2 emission reductions of about 20 percent by 2015 and almost 50 percent by 2030 appear to be feasible. These estimates are to be interpreted as relative to what emissions would otherwise have been rather than reductions from today's emissions levels. If the demand for transportation fuel continues to grow as in the past, the projected reduction potential will just be large enough to stabilize transportation sector CO_2 emissions at the year 2000 level by 2030.

The GHG reductions achievable by 2015 are based on: (1) proven energy efficiency technologies, (2) levels of efficiency improvement at which the value of fuel saved is greater than or equal to the cost of technology, (3) no change in vehicle size or performance, (4) pricing and other policies that do not increase the overall cost of transportation and, (5) a carbon cap-and-trade system equivalent to approximately $50 per ton of carbon. GHG reductions estimated to be achievable by 2030 are based on: (1) efficiency improvements that depend on technological progress judged highly likely by 2020 given a focused R&D effort, and (2) continuation or moderate extensions of pricing and behavioral policies adopted for 2015. GHG emissions would be lower if growth in demand for transportation fuel is slower, or with more stringent energy efficiency standards, a tighter carbon cap, or more rapid technological innovation than assumed here.

Table 6

Potential Impacts of **Transportation GHG Reduction Policies** to 2015, 2030* based on year 2000 emission levels.

			Reduction Potential per Mode/Fuel (%)		Transportation Sector Reduction Potential (%)	
Emissions Source	**Example Policies**	**Carbon Emission (mmt CO_2) 2000**	**2015**	**2030**	**2015**	**2030**
Research, Development & Demonstration						
Light-duty vehicles (LDV)	PNGV, FreedomCAR	1061	11**	38**	7**	23**
Heavy Trucks	21st Century Truck	294	11**	24**	2**	4**
Commercial Aircraft	NASA EEE. Aerospace Tech.	196	11**	27**	1**	3**
Efficiency Standards						
Light-duty vehicles	CAFE, Voluntary, Feebates	1061	9	31	6	18
Heavy Trucks	Voluntary Standards	294	9	20	2	3
Commercial Aircraft	Voluntary SMPG Standards	196	9	22	1	2
Replacement & Alternative Fuels						
Low-Carbon Replacement Fuels (~10% of LDV fuel)	Ethanol tax exemption	100	30	100	2	7
Hydrogen Fuel (All LDV fuel)	FreedomCAR, California Fuel Cell Partnership	1061	1	6	1	4
Pricing Policies						
Low-carbon fuel subsidy (~10% of LDV fuel)	Federal Tax exemption for bio-ethanol	100	30	100	2	6
Carbon pricing (All transportation fuel)	Carbon tax, carbon cap-and-trade system	1792	3	6	3	6
Variabilization (All highway vehicle fuel)	Pay at the pump insurance	1355	8	12	6	9
Behavioral						
Land Use & Infra-structure (2/3 of highway fuel)	Urban Design, Planning	903	5	10	3	5
System Efficiency (25% LDV fuel)	Rideshare, transit promotion	265	2	5	0	1
Climate Change Education (All transportation fuel)	Labeling	1792	1	2	1	2
Fuel Economy Information (All LDV fuel)	Driver training, www.fueleconomy.gov	1061	1	2	1	1
TOTAL		**1792**			**22**	**48**

Notes:
* Carbon emissions for the year 2000 are used to weight percent reductions for the respective emissions source and example policy category in calculating total percent reduction potential. The elasticity of vehicle travel with respect to fuel price is -0.15 for all modes. Price elasticity of energy efficiency with respect to fuel price is -0.4.

**R&D efficiency improvements have no direct effect on total. Their influence is seen through efficiency standards impacts.

Policies affecting the same target emissions, such as passenger car efficiency, low carbon fuels, and land use policies are multiplicative, to avoid double counting (e.g., (1-0.1)*(1-0.2) = 1-0.28, a 28 percent rather than a 30 percent reduction).

VII. Conclusions

By combining a variety of policies, U.S. transportation-related carbon emissions could be cut by 20 to 25 percent by 2015 and by 45 to 50 percent by 2030, in comparison to a continuation of current trends in energy efficiency, petroleum dependence, and traffic growth. Curbing the growth of transportation's GHG emissions will require a combination of meaningful policies and technological progress. A successful policy portfolio will involve all modes of transportation and will include a variety of measures, from fuel economy and fiscal policies to infrastructure investments. In the longer run, technological progress—and policies that promote it—must provide the means for continued efficiency improvements and ultimately for a transition to low-carbon energy sources for transportation. There are many specific forms of policies that can achieve the same objective.

Reducing transportation's GHG emissions will not be easy because demand for mobility of both people and goods will almost certainly continue to grow. Increasing transportation activity will result in growing energy use and GHG emissions, unless the energy efficiency of vehicles can be increased, alternative energy sources developed, and ways found to improve the ability of land use and transportation systems to provide accessibility with less motor vehicle travel.

The international effort to protect the global climate, especially efforts to reduce GHG emissions from transportation, provides a unique opportunity for the United States to work cooperatively with other countries to reduce worldwide demand for oil. Both near-term and longer-term actions to reduce GHG emissions from transportation will produce major benefits for U.S. energy security in the form of reduced oil imports and reduced economic losses from oil price shocks. Actions to reduce GHG emissions taken in concert with the other oil-consuming nations of the world will undermine the market power of the OPEC cartel, amplifying the United States' own efforts to increase energy security. By staying out of the global effort to reduce GHG emissions, the United States may be squandering its best chance to solve the oil dependence problem.

Harnessing market forces is a very useful but probably insufficient strategy for mitigating transportation's GHG emissions. Even a carbon cap-and-trade system, as beneficial as it would be, would be hindered by the tendency of households to undervalue fuel economy. It would be unlikely to bring about an appropriate level of investment in long-term transportation energy technologies and would not guide important investments in transportation infrastructure and the built environment. A combination of policies is needed to promote energy efficiency, stimulate investments in research and development, improve land use and infrastructure planning, and harness market forces.

For at least the next decade, the U.S. transportation system will continue to be powered primarily by conventional, petroleum-based liquid fuels. As a result, the most productive near-term options to reduce GHG emissions will be fossil fuel or carbon pricing policies, energy efficiency improvements, and the blending of low-carbon replacement fuels with petroleum liquids.

Over the next 15 to 30 years, new technologies will be introduced, and the stock of transportation vehicles will be turned over twice, making much larger increases in energy efficiency possible. The world is also likely to have begun an important transition from conventional petroleum to alternative energy sources. The path of least resistance would be a gradual transition to increased use of unconventional sources of liquid hydrocarbon fuels, yet promising technologies are emerging that could lead in a very different direction, toward major roles for hydrogen and electric motors. It is not too soon to begin planning for and developing the technologies for an energy transition for transportation. The use of unconventional fossil fuels entails higher costs and more severe environmental consequences. An alternative, cleaner, more economically efficient energy future for tranportation is possible, if the right technologies can be developed.

Increasing the efficiency of energy use now will buy more time for the transition and for the development of alternative technologies. Other decisions made over the next 10 years in R&D and also in infrastructure investments will influence the path taken. The paths that lead toward very low GHG emissions will require bold changes in technology and investments in infrastructure. At the same time, continued improvements in energy efficiency will be valuable whichever path is chosen. If the high-carbon fossil fuel path is chosen, continuing efficiency gains will be needed to hold carbon emissions in check. If the low-carbon path is chosen, higher efficiencies will help reduce the costs of clean technologies.

An attractive alternative to a petroleum-based transportation system is one based on hydrogen. Hydrogen can be produced from a variety of energy resources with minimal environmental impacts with the right technologies. Hydrogen, however, is not yet ready to compete with petroleum. Technological advances are needed in hydrogen storage, in the robustness and cost of fuel cells to produce power from hydrogen, and in economical and environmentally benign hydrogen production. The federal government's newly created FreedomCAR and hydrogen initiatives and California's Fuel Cell Partnership aim to create a transportation system powered by pollution-free hydrogen fuel cells. Even with the best efforts of these programs, it will be at least 15 to 20 years before hydrogen can achieve significant success in the marketplace.

The United States is the source of one-fourth of the world's GHG emissions. It is also the owner of the world's largest transportation system, the fastest growing source of CO_2 emissions in the U.S. economy. The U.S. transportation system is a key target for GHG emissions reduction. There are many responsible and cost-effective actions that can be taken to restrain the growth of GHG emissions from transportation. Action can begin today, and pathways exist to a low-carbon future for transportation. Formulating and implementing an effective, comprehensive strategy will not be easy, but it can be done.

Endnotes

1. The end use sectors are industry, residential, commercial, transportation and agriculture. Electric utility GHG emissions are apportioned to the sectors according to their electricity use.

2. U.S. Department of Energy, Energy Information Administration (USDOE/EIA), 2002a. *International Energy Annual,* 2000, DOE/EIA – 0219 (2000), Washington, DC.

3. U.S. Environmental Protection Agency (EPA), 2002. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000*, Office of Atmospheric Programs, Washington, D.C., April 15, 2002.

4. U.S. Department of Energy, Energy Information Administration, 2002d, Annual Energy Review 2001, Tables 12.1 and 12.2, Washington, D.C., November. Electricity generation produces more carbon emissions than any other activity in the U.S. economy, but it is considered an energy conversion activity not an end use. Carbon emissions from electricity generation are distributed among the four end use sectors according to their share of electricity consumption.

5. U.S. Department of Energy, Energy Information Administration (USDOE/EIA), 2002b. *Monthly Energy Review,* DOE/EIA – 0035 (2003/02), Washington, DC.

6. U.S. Department of Energy, Energy Information Administration (USDOE/EIA), 2002c. *Annual Energy Outlook,* 2002, DOE/EIA – 0219 (2002), Washington, DC.

7. U.S. Geological Survey (USGS), 2000. World Petroleum Assessment 2000 – Description and Results, U.S. Geological Survey Digital Data Series – DDS-60, U.S. Department of the Interior, Reston, Virginia, available on the internet at http://greenwood.cr.usgs.gov/WorldEnergy/DDS-60.

8. Laherrere, J., 2001. “Estimates of Oil Reserves”, presented at the EMF/IEA/IIASA meeting. Laxenburg, Austria, June 19, available at http://www.oilcrisis.com/laherrere/. Bentley, R.W., R.H. Booth, J.D. Burton, M.L. Coleman, B.W. Sellwood and G.R. Whitfield, 2000. “Perspectives on the Future of Oil.” *Energy Exploration and Exploitation*, vol. 18, nos. 1 and 2, pp. 147-206.

9. Conventional oil includes liquid hydrocarbons of light and medium gravity and viscosity, occurring in porous and permeable reservoirs. This definition typically includes natural gas liquids. Some analysts include oil producible by enhanced recovery methods as conventional while others do not.

10. Nakiçenoviç, N. A. Grübeer, and A. McDonald, 1998. *Global Energy Perspectives*, published for the International Institute of Applied Systems Analysis and the World Energy Council, Cambridge University Press, Cambridge, U.K. Johnson, L., 2001.

11. Unconventional oil comprises deposits of greater density than water (e.g., heavy oil), viscosities in excess of 10,000 cP (e.g., oil sands), or occurs in tight formations (e.g., shale oil).

12. Greene, D.L. and N. Tishchishyna, 2001. “The Costs of Oil Dependence: A 2000 Update.” *Transportation Quarterly,* vol. 55, no. 3, pp. 11-32.

13. Smith, D.W., R.R. Nordhaus, T.C. Roberts and M. Chupka, 2002. “Designing a climate-friendly energy policy: Options for the Near Term.” Pew Center on Global Climate Change, Arlington, VA, July.

14. World Energy Council (WEC), 1992. *Survey of Energy Resources*, 16th ed., World Energy Council, London. Rogner, H.H., 1997. “An Assessment of World Hydrocarbon Resources.” *Annual Review of Energy and Environment*, vol. 22, pp. 217-262.

15. Grubb, M., 2001. “Who’s Afraid of Atmospheric Stabilization? Making the Link Between Energy Resources and Climate Change”, *Energy Policy*, vol. 29, pp. 837-845.

16. Williams, R., 2002. “Toward Zero Emissions for Transportation Using Fossil Fuels,” Center for Energy and Environmental Studies, Princeton University, in VIII Biennial Asilomar Conference on Transportation, Energy and Environmental Policy: Managing Transitions,” K.S. Kurani and D. Sperling, eds., Transportation Research Board, Washington, D.C., forthcoming.

17. U.S. Department of Transportation, Federal Highway Administration, 2001. *Highway Statistics 2001*, Washington, D.C.

18. U.S. Department of Transportation, Bureau of Transportation Statistics, 2002. *Transportation Statistics*, op. cit., Table 1-31.

19. Ibid., Table 1-41.

20. Davis, S.C. and S. Diegel, 2002. Transportation Energy Data Book: Edition 22, ORNL – 6967, Oak Ridge National Library, Oak Ridge, Tennessee.

21. Lee, J.J., S.P. Lukachko, I.A. Waitz and A. Schafer, 2001. “Historical and Future Trends in Aircraft Performance, Cost and Emissions”, *Annual Review of Energy and the Environment,* vol. 26, pp. 167-200.

22. DeCicco, J.M., 2001. Fuel Cell Vehicles: Technology, Market, and Policy Issues, Society of Automotive Engineers, Inc., Warrandale, Pennsylvania.

23. Hellman, K.H. and R.M Heavenrich, 2002. “Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2002,” Advanced Technology Division, Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Ann Arbor, Michigan.

24. Davis, S.C. and S. Diegel, 2002. *Transportation Energy Data Book: Edition 22*, ORNL-6967, Oak Ridge National Laboratory, Oak Ridge, Tennessee, June, Tables 2.12 and 2.13.

25. Ibid., Table 2.15.

26. Davis, S.C. and S. Diegel, 2002. *Transportation Energy Data Book: Edition 22*, ORNL-6967, Oak Ridge National Laboratory, Oak Ridge, Tennessee, June, Table 8.2.

27. Greene, D.L., 1992. “Energy-Efficiency Improvement Potential of Commercial Aircraft,” *Annual Review of Energy and the Environment*, vol. 17, pp. 537-73.

28. A rulemaking by the Department of Transportation, in progress at time of writing, calls for the light truck standard to be raised to 22.2 mpg by 2008.

29. National Research Council, Committee on the Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, 2002. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*, National Academy Press, Washington, D.C.

30. U.S. Department of Energy, Energy Information Administration, 2001. *Annual Energy Outlook 2002*, DOE/EIA-0383(2002), Washington, D.C.

31. U.S. Department of Energy, Office of Policy and International Affairs, 1996. *Policies and Measures for Reducing Energy Related Greenhouse Gas Emissions: Lessons from Recent Literature*, DOE/PO-0047, Washington, D.C., July.

32. Light-duty vehicles include all passenger cars and light trucks (vans, minivans, SUVs and pick-ups) of less than 8,500 gross vehicle weight (GVW). Some definitions include light trucks of up to 10,000 GVW, but fuel economy and emissions regulations use the 8,500 lb. cut-off point.

33. The technologies include incremental reductions in engine friction and improvements in engine breathing, including valve-train technologies, variable valve lift and timing, and cylinder deactivation.

34. The *automatic shift/manual transmission* replaces the automatic transmission’s hydraulic torque converter and pump with electronically controlled mechanisms, thereby reducing the energy requirements to operate the transmission and increasing the precision with which it can be controlled. Other transmission strategies are aimed at operating the engine closer to its most energy-efficient state (low speeds and high loads) through increasing the number of gears in automatic transmissions from 4 to 5 or 6, or by means of *continuously variable transmissions* that allow gear ratios to be infinitely variable over a wide range.

35. UltraLight Steel Auto Body Consortium, 1998. *UltraLight Steel Auto Body*, Final Report, American Iron and Steel Institute, Washington, D.C., March.

36. See, e.g., http://www.autoaluminum.org/audi.htm

37. National Research Council, Committee on the Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, 2002. op. cit. p. 3. Almost all of the described technologies considered by the NRC study could be implemented in new vehicles within ten years. The 10-15 year time period was intended to allow manufacturers to implement advanced fuel economy technologies across their entire product lines, allowing for typical design cycles and the normal replacement of manufacturing equipment.

38. For example, for light trucks the Committee estimated that the (discounted) value of fuel savings, over the life of the vehicle, available by applying advanced technologies would exceed the increase in vehicle price by $500 (for small SUVs) to $1200 (for large SUVs). The NAS Committee acknowledged considerable uncertainty in their estimates of both technology cost and performance. On the pessimistic side, increases of only 1 to 15 percent for passenger car and 14 to 35 percent for light truck fuel economy might be all that could be expected at the cost-efficient fuel economy levels. On the optimistic side, gains of 21 to 37 percent might be achievable for cars and 35 to 49 percent for light trucks.

39. Weiss, M., J.B. Heywood, E.M. Drake, A. Schafer and F.F. AuYeung, 2000. *On the Road in 2020: A Life Cycle analysis of New Automobile Technologies*, Energy Laboratory, Massachusetts Institute of Technology, Cambridge, October.

40. Lean burn refers to a gasoline engine operating at high air-fuel ratios.

41. The point of highest engine efficiency is at lower speeds and higher loads, where friction and pumping losses are reduced.

42. E.g., see Greene, D.L, and J.DeCicco, 2000. “Engineering-Economic Analysis of Automotive Fuel Economy Potential in the United States.” *Annual Review of Energy and Environment*, vol. 25, pp. 477-535.

43. Lüders H., Stommel P., and Geckler S., 1999, Diesel Exhaust Treatment—New Approaches to Ultra Low Emission Diesel Vehicles, SAE paper 1999-01-0108.

44. U.S. Department of Energy (USDOE/OSTI), 2000. *Technology Roadmap for the 21st Century Truck Program*, 21CT-01, available at http://www.osti.gov/hvt/21stcenturytruck.pdf, Washington, DC, December.

45. In turbo-charging, the intake air is compressed with some of the exhaust gas energy, which would otherwise be wasted. Thus, more air can be taken in and more engine power can be produced from a given engine size.

46. These measures include increased peak pressure, insulation of the combustion chamber, friction reduction and recovery of waste heat.

47. The aerodynamic drag coefficients of heavy trucks are between 0.6 and 0.9 (compared to about 0.3 for passenger cars).

48. Greene, D.L. and S.E. Plotkin, 2001. “Energy futures for the U.S. transport sector,” *Energy Policy*, vol. 29, no. 14, pp. 1255-1270; Greene, D.L., 1996. *Transportation and Energy*, Eno Transportation Foundation, Washington, D.C., Table 5.5.

49. Stodolsky, F., 2002. “Analysis of Technology Options to Reduce Truck Idling,” Argonne National Laboratory, Argonne, Illinois, available at www.transportation.anl.gov.ttrdc/idling/html.

50. Shutting off the engine during vehicle stops requires larger batteries to supply continuously operating components with electricity during engine shut-off.

51. Greene and Plotkin, 2001, op.cit.; An F., Stodolsky F., Vyas A., Cuenca R., and Eberhardt J.J., Scenario Analysis of Hybrid Class 3-7 Heavy Vehicles, SAE paper 2000-01-0989

52. U.S. Department of Energy (USDOE/OSTI), 2000, op. cit., p. xvi.

53. Lee, J.J., S.P. Lukachko, I.A. Waitz and A. Schafer, 2001. “Historical and Future Trends in Aircraft Performance, Cost, and Emissions.” *Annual Review of Energy and the Environment*, vol. 26, pp. 167-200.

54. Lee, J.J., S.P. Lukachko, I.A. Waitz and A. Schafer, 2001. “Historical and Future Trends in Aircraft Performance, Cost, and Emissions.” *Annual Review of Energy and the Environment*, vol. 26, pp. 167-200.

55. Historically, significant gains in propulsion efficiency have been achieved by increasing the bypass ratio of turbo-fan engines (ratio of air passing through the fan to that passing through the combustion chamber of the engine itself). Further improvements of 5-10 percent appear to be possible (Greene, 1992). Improvements in the thermodynamic efficiency of turbine engines on the order of 15 to 20 percent might be achieved by increasing temperature and compression. Advanced aerodynamics could further reduce fuel consumption by 10 to 20 percent (Greene, 1992).

56. National Research Council, Aeronautics and Space Engineering Board, 1992. *Aeronautical Technologies for the Twenty-First Century*, National Academy Press, Washington, D.C.; Penner, J.E., D.H. Lister, D.J. Griggs, D.J. Dokken and M. McFarland, 1999. *Aviation and the Global Atmosphere*, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, p. 242; Greene, D.L., 1992. “Energy-Efficiency Improvement Potential of Commercial Aircraft,” *Annual Review of Energy and Environment*, vol. 17, pp. 537-73; Lee, et al., 2001. op. cit. Also cited (IPCC, 1999, p. 242).

57. National Aeronautics and Space Administration (NASA), 2000. “Aerospace Technology Enterprise: Strategic Plan.” available on the internet at www.aeronautics.nasa.gov.

58. National Aeronautics and Space Administration (NASA), 2002, NASA Aeronautics Blueprint, available on the internet at ww.aerospace.nasa.gov/aero_blueprint/toc.html.

59. National Aeronautics and Space Administration (NASA), 2001. “Ultra-Efficient Engine Technology Program.” Fiscal Year 2001 Performance Report, John H. Glenn Research Center at Lewis Field, Cleveland, Ohio.

60. Metz, B., O. Davidson, R. Swart and J. Pan, 2001. *Climate Change 2001: Mitigation*, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.p. 198.

61. MARINTEK, 2000. “Study of Greenhouse Gas Emissions from Ships.” Norwegian Marine Technology Research Institute, Trondheim, Norway.

62. Corbett, J.J., 2002. “Marine Transportation and Global Climate Change.” In *Global Climate Change and Transportation: Coming to Terms*, Eno Transportation Foundation, Washington, D.C.

63. Metz, B., O. Davidson, R. Swart and J. Pan, 2001. *Climate Change 2001: Mitigation*, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK., p. 198.

64. The 12.5 percent efficiency improvement is converted to fuel consumption and CO_2 emission reduction as follows: 100%/(1+0.125) = 89% of the 2000 level, or 11 percent below the original value.

65. When translating this potential new vehicle improvement into an improvement in the entire light-duty vehicle *fleet* in 2030, the authors assume that the entire 2015 potential of 25 percent and half the incremental potential between 2015 (25%) and 2030 (100%), i.e., 37.5% can be realized. Consequently, the new level of fuel consumption and CO_2 emissions of the light-duty vehicle fleet would result to 100%/(1+0.125 + 0.375) = 0.62 or 38% below the original year 2000 level.

66. Khazzoom, J.D., 1980. “Economic Implications of Mandated Efficiency in Standards for Household Appliances.” *The Energy Journal,* vol. 1, no. 4. pp. 21-40.

67. Lee, J.J., S.P. Lukachko, I.A. Waitz and A. Schafer, 2001. “Historical and Future Trends in Aircraft Performance, Cost and Emissions,” *Annual Review of Energy and the Environment,* vol. 26, pp. 167-200.

68. The lower the ratio of carbon to hydrogen, the less carbon dioxide is released when burning a fuel.

69. In the U.S., more than 350,000 LPG vehicles exist today and most operate in vehicle fleets; the vehicles are fueled by nearly 4,200 LPG fueling stations.

70. A fuel’s octane number indicates the resistance of a motor fuel to knock, i.e., igniting the fuel in an uncontrolled manner, which can harm the engine. Octane numbers are based on a scale between 0 (no resistance to knock) and 120 (highest resistance to knock), with regular gasoline having a number of about 92.

71. To make sure that these comparisons of alternative fuels and gasoline are consistent in terms of engine operation conditions and produced power, the authors assume a gasoline engine operating at high air-fuel ratios (lean-burn) and a given power output as the reference technology.

72. An engine’s compression ratio is defined as the ratio of the total volume of the cylinder at bottom-dead-center, divided by the volume above the piston at top-dead-center.

73. While carbon monoxide emissions are substantially reduced, the increase in compression ratio causes higher NO_X emissions that need to be controlled with a dedicated catalyst. In addition, depending on the fuel, further exhaust gas cleaning may be necessary (e.g. formaldehyde emissions in alcohol-fueled engines).

74. On a mass basis over a time period of 100 years.

75. A vehicle with a fuel efficiency of 30 mpg releases about 323 grams of CO_2 per mile. Shifting to natural gas reduces carbon emissions per unit energy by about 25 percent; and raises engine efficiency by 10 percent. Assuming that the gain in engine efficiency gets directly translated into vehicle fuel efficiency, the CNG vehicle emits 323 x 0.75/1.1 = 220 grams of CO_2 per mile. As methane is 21 times stronger GHG than CO_2 on a mass basis over a time period of 100 years, emitting (323-220)/21 = 4.9 grams of methane per mile would offset the entire reduction effort.

76. In stoichiometric combustion, there is just enough oxygen to convert all fuel carbon and hydrogen into carbon dioxide and water, respectively. In practice, however, even at a stoichiometric ratio complete combustion is not fully accomplished.

77. Karl H.Hellman, Gregory K. Piotrowski, and Ronald M. Schaefer, 1994, Evaluation of Specialized Methane Catalytic Converters on a CNG-Fueled Vehicle, SAE Technical Paper Series 940473; Mitsunori Ishii, Shizuo Ishizawa, Eiji Inada, Ryuichi Idoguchi, and Toru Sekiba, 1994, Experimental Studies on a Natural Gas Vehicle, SAE Technical Paper Series 942005; S. Hill, M.Sulatisky, J.Lychak, K.Nakamura, T.Matsui, G.Rideout, 1996, A Lean-Burn, Sub-Compact Natural Gas Vehicle, SAE Technical Paper Series 961676.

78. Because of the low volumetric energy density of hydrogen and the associated power loss, hydrogen-engines are typically supercharged to increase the amount of hydrogen and air in the cylinder.

79. Lester B. Lave, Chris T. Hendrickson, and Francis C. McMicheal, 1995, “Environmental Implications of Electric Cars,” *Science,* Vol. 268, 19 May 1995, pp. 993-995.

80. U.S. Department of Energy, Energy Information Administration (USDOE/EIA), 2002d. *Alternatives to Traditional Transportation Fuels*, Table 10, Estimated Consumption of Vehicle Fuels in the United States, 1992-2001, available on the Web at, http://www.eia.doe.gov/cneaf/alternate/page/datatables/table10.html, Washington, D.C.

81. Additional motivations for substituting ethanol for MBTE include ethanol’s partial exemption from the federal motor fuel tax (worth $0.54 per gallon of ethanol) and its ability to boost gasoline’s octane rating and thereby save some cost in gasoline refining. However, in the blending proportions typically used (5-20 percent) it also increases evaporative emissions.

82. U.S. Department of Transportation, Bureau of Transportation Statistics (USDOT/BTS), 1997. *Transportation Statistics Annual Report 1997*, BTS97-S-01, U.S. Government Printing Office, Washington, D.C., p. 92.

83. Davis and Diegal, op. cit., Table 2.10.

84. Shapouri, H., J.A. Duffield and M.Wang, 2002. *The Energy Balance of Corn Ethanol: An Update,* Agricultural Economic Report NO. 813, U.S. Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses, Washington, D.C.; Wang, M., C. Saricks, and D. Santine, 1999a. “Effects of Fuel Ethanol Use on Fuel-Cycle Energy and greenhouse Gas Emissions.” USDOE, Argonne National Laboratory, Argonne, Illinois. Also available at, Wang, M.S., GREET Web Site, 2002. http://www.transportation.anl.gov/ttrde/greet/, Argonne National Laboratory, Argonne, IL.

85. Wang, M.Q., 1999b. GREET 1.5 – *Transportation Fuel Cycle Model, Volume 1: Methodology, Development, Use and Results,* ANL/ESD-39, vol. 1, Argonne National Laboratory, Argonne, IL, August.

86. In some cases, annual yields as high as 100 tons per ha were reported for sugar cane in Brazil. The type of plant that be grown in a particular region and the amount of sunlight are crucial determinants and limit the yield in many countries, including the U.S.

87. David O. Hall, Frank Rosillo-Calle, Robert H. Williams, Jeremy Woods, 1993, “Biomass for Energy: Supply Prospects.” In Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, Robert H. Williams (eds.), *Renewable Energy—Sources for Fuels and Electricity,* Island Press, pp.593-692.

88. Lester B. Lave, W. Michael Griffin, Heather Maclean, 2001, “The Ethanol Answer to Carbon Emissions,” *Issues in Science and Technology,* Winter 2001, http://www.nap.edu/issues/18.2/lave.html

89. One gallon of ethanol contains only 66 percent of the energy contained in one gallon of gasoline. Thus, $2.70 per gal of gasoline equivalent corresponds to $1.80 per gallon of ethanol.

90. Pat Perez et al., Evaluation of Biomass-to-Ethanol Fuel Potential in California, California Energy Commission, August, 1999; Lester B. Lave, W. Michael Griffin, Heather Maclean, 2001, The Ethanol Answer to Carbon Emissions, Issues in Science and Technology, Winter 2001, http://www.nap.edu/issues/18.2/lave.html

91. National Research Council (NRC), 1999. Review of the Research Strategy for Biomass-Derived Transportation Fuels, National Academy Press, Washington, DC.

92. Singh, M. and G. Hadder, 1997. "Low Greenhouse Gas Fuels for Automobiles," presented at the Society of Automotive Engineers Government/Industry Meeting, May 6, 1997, Washington, D.C., the authors are with Argonne National Laboratory, Chicago, Illinois and Oak Ridge National Laboratory, Oak Ridge, Tennessee, respectively.

93. Weiss, M., J.B. Heywood, E.M. Drake, A. Schafer and F.F. An Yeung, 2000, *On the Road in 2020: A Life Cycle Analysis of New Automobile Technologies,* Energy Laboratory, Massachusetts Institute of Technology, Cambridge, MA, October.

94. Statistics on highway user revenues and their disposition are from the U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics*, table HF-10.

95. Revenue and expenditure estimates for non-highway modes are from the U.S. Department of Transportation, Bureau of Transportation Statistics, *Pocket Guide to Transportation 2003*, tables 26 and 27, available at www.bts.gov.

96. Penner, et al., op. cit., p. 198.

97. Lee, et al. op. cit, p. 195.

98. This idea is attributed to Professor Charles Lave, Univ. of California at Irvine.

99. Davis and Diegel, op. cit., fig. 11.2.

100. U.S. Congress, Office of Technology Assessment, 1994. *Saving Energy in U.S. Transportation*, OTA-ETI-589, U.S. Government Printing Office, Washington, D.C.

101. Greene, D.L., 1996, op. cit., p. 223.

102. Ibid, p. 68.

103. U.S. Department of Transportation, Bureau of Transportation Statistics, Transportation Statistics Annual Report 1999, BTS99-S-01, Washington, D.C.

104. U.S. Department of Transportation, Federal Transit Administration, 2000 National Transit Databases, Washington, D.C., available at www.fta.dot.gov/ntl.

105. U.S. Department of Transportation, Bureau of Transportation Statistics, 2002. *National Transportation Statistics 2002,* BTS 02-08. Tables 1-31 and 1-41.

106. Ross, M., 1994. Automobile Fuel Consumption and Emissions: Effects of Vehicle and Driving Characteristics, *Annual Review of Energy and the Environment,* vol. 19, pp. 75-112.

107. National Research Council, Transportation Research Board, 1984. 55: *A Decade of Experience,* Special Report 204, National Academy Press, Washington, D.C.

108. U.S. Department of Transportation, Federal Transit Administration, 2002. "Bus Rapid Transit," on the internet at www.fta.gov/brt.

109. Greene, D.L. 1986. "Driver Energy Conservation Awareness Training: Review and Recommendations for a National Program," ORNL/TM-9897, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

110. Surface Transportation Environmental Cooperative Research Program Advisory Board, 2002. *Surface Transportation Environmental Research*, Special Report 268, Transportation Research Board, National Research Council, Washington, D.C.

111. Rodier, C.J, R.A. Johnston and J.E. Abraham, 2002. "Heuristic policy analysis of regional land use, transit and travel pricing scenarios using two urban models," *Transportation Research D*, vol 7D, no. 4, pp. 243-254; Waterson, T., 1993. "Linked Simulation of Land-use and Transportation Systems: Developments and Experience in the Puget Sound Region," *Transportation Research*, vol. 27A, no. 3, pp. 193-206.

112. Ryan, S. and M.G. McNally, 1995. “Accessibility and Neotraditional Neighborhoods: A Review of Design Concepts, Policies and Recent Literature.” *Transportation Research*, vol. 29A, no. 2, pp. 87-105.

113. Ewing, R. and R. Cevero, 2001. “Travel and the Built Environment,” presented at the 21st Annual Meeting of the Transportation Research Board, National Research Council, Washington, D.C., January. The derived elasticities are based on considerable generalization, because devising relevant measures of the structure of cities is difficult (concepts such as “local design,” “local diversity of land use” and “regional accessibility” are obviously difficult to quantify and are usually measured in different ways by different analysts). Nevertheless, these numbers (percent reductions in travel demand per percent change in the built environment) convey some sense of what might be accomplished by a concerted effort to create transportation-efficient communities.

114. One recent estimate of the total additional costs of U.S. highway transport comes to more than $200 billion per year. Parry, W.H., 2002. “Is Gasoline UnderTaxed in the United States?” Parry, however, makes the mistake of assuming the problems could be corrected by a tax on gasoline, or a general tax on vehicle use.

115. This is not to say that transportation pays nothing to mitigate the external costs it produces. For example, emissions controls on motor vehicles, paid for by the motorist, reduce the air pollution produced by motor vehicles by a factor of ten or more, compared to what it would be if vehicle emissions were not controlled. The damage done by residual or unregulated emissions such as GHGs, however, is not paid for.

116. For example, the theoretical justification for a per-mile emissions tax given vehicular emissions standards has been explained by Freeman, A.M., 1997. “Externalities, Prices and Taxes: Second Best Issues in Transportation.” pp. 173-192 in Greene, Jones and Delucchi, op. cit.

117. Greene, D.L., M.A. Delucchi and D.W. Jones, 1999. *The Full Costs and Benefits of Transportation*, Elsevier, The Hague.

118. Anderson, D. and H. Mohring, 1997, “Congestion Costs and Congestion Pricing.” pp. 315-336 in Greene, D.L., D.W. Jones and M. Delucchi, *The Full Costs and Benefits of Transportation*, Springer, Heidelberg.

119. Davis, S.C. and S.W. Diegel, 2002. *Transportation Energy Data Book, Ed. 22*, Table 5.12, ORNL-6967, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

120. Extensive literature surveys can be found in Dahl, C.A., 1986, “Gasoline Demand Survey.” *The Energy Journal*, vol. 7. no. 1, pp. 67-82; Dahl, C., 1995. “Demand for Transportation Fuels: A Survey of Demand Elasticities and Their Components,” *Journal of Energy Literature*, vol. I, no. 2, pp. 3-27. The authors of this report believe that nearly all studies of the gasoline price elasticity of fuel economy overestimate the effect of price by failing to adequately account for the effect of the U.S. Automotive Fuel Economy Standards. For this reason the authors use the estimates provided by the U.S. Department of Energy, cited next.

121. Office of Policy and International Affairs, U.S. Department of Energy, 1996. *Policies and Measures for Reducing Energy Related Greenhouse Gas Emissions: Lessons From the Literature*, Chapter 5, DOE/PO-0047, Washington, D.C.

122. Greene, D.L. and J.DeCicco, 2000, op.cit.

123. Greene, D.L., 1996, Table 7.3.

124. Original sources for this table published in Greene, 1996 are Apogee Research, Inc., 1994. “Costs and Effectiveness of Transportation Control Measures (TCMs): A Review and Analysis of the Literature,” National Association of Regional Councils, Washington, D.C.; U.S. Congress Office of Technology Assessment, 1994. *Saving Energy in U.S. Transportation*, OTA-ETI-589, U.S. Gov’t Printing Office, Washington, D.C.; U.S. General Accounting Office, 1993. “Urban Transportation: Reducing Vehicle Emissions with Transportation Control Measures,” GAO-RCED-93-169, Washington, D.C.

125. National Research Council, Committee on Benefits of DOE R&D on Energy Efficiency and Fossil Energy, 2002. *Energy Research at DOE: Was it Worth It?* National Academy Press, Washington, D.C., p. 13.

126. National Research Council, Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles, 2001, *Review of the Research Program of the Partnership for a New Generation of Vehicles: Seventh Report*, National Academy Press, Washington, D.C.

127. For a critical assessment of these programs see, e.g., Sperling, D., 2002, "Updating Automotive Research," Issues in Science and Technology." Spring, 2002, pp. 85-89. The US DOE's "National Hydrogen Energy Roadmap." Nov. 2002, www.eren.doe.gov/hydrogen, makes a beginning toward planning the economy's possible transition to hydrogen.

128. In 2000, light-duty vehicles consumed nearly 132 billion gallons of gasoline, which corresponds to a power requirement of some 0.5 TW. Based on investment costs of $300-400/kW hydrogen for steam-reforming natural gas to hydrogen, total investments of hydrogen production alone would be $150-200 billion. Including transmission and distribution systems, storage facilities, and the retail station infrastructure, total investments can easily amount to $500 billion.

129. For example, the Canadian natural gas vehicle program has failed, largely due to the lack of sufficient CNG fueling stations. Investments in additional stations were not made, since the existing stations did not reach early profitability. Lack of profitability, in turn, reduced the sales of vehicles converted from gasoline to natural gas. Peter C. Flynn, 2002. "Commercializing an alternative vehicle fuel: lessons learned from natural gas vehicles," *Energy Policy* (30):613-619.

130. Interlaboratory Working Group, 2000, *Scenarios for a Clean Energy Future*, p. 6.22, Oak Ridge, TN, Oak Ridge National Laboratory, and Berkeley, CA, Lawrence Berkeley National Laboratory, ORNL/CON-476 and LBNL-44029, November.

131. Davis, W.B., M.D. Levine and K. Train, 1995. *Effects of Feebates on Vehicle Fuel Economy, Carbon Dioxide Emissions, and Consumer Surplus*, DOE/PO-0031, Office of Policy, U.S. Department of Energy, Washington, D.C., February.

132. Nye, K., J. Saulsbury, D. Green, and J. Hopson, 2003. "Providing Consumers with Web-Based Information on the Environmental Effects of Automobiles," ORNL/TM-2003, forthcoming, Environmental Studies Division, Oak Ridge National Laboratory, Oak Ridge, TN.

133. For example, the total carbon emissions of passenger cars and light trucks in 2000 were 1061 million metric tons of carbon dioxide (mmtCO_2). Assume that 10 percent of gasoline is replaced by net zero carbon ethanol produced from cellulose, and that a fuel economy increase of one third is achieved (implying a reduction in fuel consumption of 25 percent). The total reduction in GHG emissions from these two actions before accounting for the rebound effect would be:

$$1{,}061\ (1-((1-0.1)\ (1-0.25))) = 1{,}061\ (1-0.675) = 345.8$$

134. Compared to the life-cycle GHG emissions of a gasoline fueled vehicle, those of a comparable hydrogen vehicle are roughly of the same size, as the CO_2 emissions associated with the extra energy input for hydrogen production from natural gas are offset by the lower carbon content of natural gas. Thus, if only half of the hydrogen vehicle fleet (12.5 percent of the entire fleet) emits CO_2, the entire emission reduction results in 6.25 percent.

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This report discusses options for reducing greenhouse gas emissions from the U.S. transportation sector. The Pew Center on Global Climate Change was established by the Pew Charitable Trusts to bring a new cooperative approach and critical scientific, economic, and technological expertise to the global climate change debate. We intend to inform this debate through wide-ranging analyses that will add new facts and perspectives in four areas: policy (domestic and international), economics, environment, and solutions.

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