

Future U.S. Highway Energy Use: A Fifty Year Perspective

DRAFT

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The Oil Issue

Awash in Oil

"There's plenty of cheap oil, says the U.S. Geological Survey"

Eric Niiler
Scientific American, September 2000

The End of Cheap Oil

"Global production of conventional oil will begin to decline sooner than most people think, probably within 10 years"

Colin J. Campbell and Jean H. Laherrère
Scientific American, March 1998

So is there plenty of oil or are we running out? The appropriate answer to *both* questions is "Yes." In this study, estimates of crude oil reserves and resources have been reviewed. The latest U.S Geological Survey does increase by 20% its earlier estimate of worldwide crude oil reserves. But that simply pushes back by about ten years the estimates of when half of the reserves of crude oil will have been consumed and world crude oil production will begin an inevitable decline. We are indeed *Awash in Oil*, but we are also *Awash in the Demand for Oil*.

Petroleum products have physical and chemical properties that make them very desirable as transportation fuels. Also, intensive exploitation has made petroleum a very affordable, and thus far abundant, fuel. This combination of attractive properties and affordability has resulted in more than 95% of the world's transportation system being fueled by petroleum. And, as might be expected, the demand for petroleum is rising rapidly – up 28% since 1973. Perhaps the situation could be summarized as:

With all the conventional oil we have discovered, and all we think awaits discovery, this source of virtually all of the world's transportation fuels will be forced to relinquish its solo role within perhaps 10 to 40 years as oil demand continues to grow. We simply cannot continue to rely exclusively on conventional oil, especially in transportation, the way we have in the past.

If the gap between the world's remaining oil and the demand for transportation energy is to be filled, then vast amounts of new fuels will be needed. Other hydrocarbon resources, including liquid fuels made from natural gas, coal, or tar sands, could fill this gap. Or part, or perhaps even all, of that gap could be filled with more efficient vehicles and the use of alternative fuels such as natural gas, renewables (e.g. ethanol or biodiesel), or hydrogen derived from a combination of feedstocks. The alternatives have a range of energy, environmental (e.g. greenhouse gas emissions), and economic consequences. This paper explores what the U.S. highway transportation energy situation might look like over the next fifty years and summarizes the impacts of a number of efficiency and alternative fuel use strategies.

Executive Summary

Whether we are awash in oil or nearing the end of cheap oil, the acceptance of authoritative estimates of conventional petroleum resources and projected demand for transportation fuels implies that ***the world's transportation systems must make a transition from conventional petroleum to other sources of energy within the next fifty years.*** Combining the range of US Geological Survey (USGS) estimates of remaining conventional oil resources with the Energy Information Administration's (EIA) economic growth cases for world oil demand implies that 50 percent of the world's total endowment of conventional oil will be used up before 2040 at the latest, or by 2010 at the earliest. The world's economies cannot and will not blindly consume conventional oil to the very last drop and only then begin to look for substitutes. That would be a recipe for economic disaster that market dynamics will preclude from happening. ***Long before 50 percent exhaustion is reached, a transition to alternative energy sources must begin.***

Without advanced vehicle and fuel technologies and strong public policies, the most likely transition would be from conventional oil to synthetic fuels (liquid fuels similar to gasoline and diesel derived from natural gas, coal, and unconventional oil resources, such as tar sands, oil shale, and heavy oil). The world's endowment of unconventional fossil energy sources is enormous. With more intensive refining and at greater cost, conventional petroleum products can be made from unconventional resources. The vast infrastructure already in place to support a petroleum based transportation system will tend to "lock-in" the world's economies to fossil energy alternatives.

Following the path of least resistance to reliance on liquids from unconventional fossil fuels could result in very high environmental and economic costs. Burning ever-greater quantities of ever more carbon-intensive fossil fuels will exacerbate the rate and extent of global climate change unless new technologies are developed to sequester carbon emissions. Accelerating worldwide production and use of unconventional fossil fuels will intensify problems of air and water pollution, as well as conflicts between fossil energy extraction and fragile habitats, unless new technologies for energy production and emissions control are developed. Leading up to the energy transition, continued reliance on petroleum as OPEC's share of the world oil market grows is almost certain to cost the U.S. economy trillions of dollars as a result of price shocks and monopolistic oil pricing, unless we can develop and implement major advances in fuel economy technologies and alternative fuels.

Although there is considerable uncertainty, the strategies examined here indicate that the U.S. should start transportation's energy transition immediately, since the time to fully implement a new vehicle technology in all vehicles on the road is 30 years or more, and the time to fully implement a new fuel would take even longer. This analysis presents a Base Case of continued reliance on conventional and unconventional fossil fuels, and several strategies of alternative transportation energy futures that lead away from greater consumption of unconventional fossil energy. It is not the intention in presenting these strategies either to predict the future or prescribe it. Nor is an attempt made to estimate the costs of alternative paths and pick winners. Insights into which paths may be most desirable can be gained, we believe, through further analysis. Our point is to demonstrate that *plausible alternatives exist, although achieving them will require continued advances in the technologies of vehicles and fuels, as well as effective public policies*. While our methodology relies on assumptions concerning technological advances and their market success, it reflects normal rates of capital stock turnover and usage. Therefore, we believe that our conclusions about the urgency of developing advanced technology and beginning the energy transition are reliable, despite the fact that we are not yet able to identify the "best" transition path.

The Base Case yields slightly more than a doubling of oil use and carbon emissions over the next 50 years because of continued growth in travel and continued stagnation of fuel economy levels in the fleet. The strategies span a range from incremental improvements in fleet fuel economy, yielding an eventual 50% fuel economy increase by 2050 but continuing strong growth in oil use and carbon emissions, to radical changes in both vehicle technology and fuels that, within the same time frame, could eliminate most oil use in the light-duty fleet and reduce its carbon emissions to 40% below today's levels and 29% below 1990 levels. Intermediate cases assuming more modest penetration of new fuels and technology can still achieve substantial reductions in oil use and carbon emissions from projected levels.

Achieving extreme reductions from the projected Base Case carbon emissions will require both the widespread use of new technologies, e.g. hybrid and fuel cell technologies, and shifts to renewable fuels, e.g. ethanol. Liquid fuels from natural gas, such as Fischer-Tropsch diesel, and electricity can provide significant decreases in oil use but offer less progress in reducing carbon emissions. In all cases, *it takes several decades for the effects of the new technologies and fuels to be fully effective, implying that early action is critical*.

Introduction

The U.S. transportation system as a whole and the highway mode in particular will be much different in the year 2050 compared to today. The type and number of vehicles in use and the fuels employed to power them are unknown. Yet planning for the future requires acting on the information at hand: assessing the implications of the current path and the potential benefit of alternative futures. This paper puts transportation energy issues into a long-run perspective so that informed planning can begin early enough to make a decisive difference.

This paper examines the global oil supply and demand over the next 50 years to show that a transition away from conventional oil will begin. The analysis reviews the energy, economic, and environmental implications of the alternatives that are available to meet some of the anticipated gap between world conventional oil production and the liquid fuels required to support a growing world economy. This paper then describes several U.S. transportation technology strategies with a range of efficiency improvements and fuel substitutions, and calculates their first order effects on energy use, petroleum consumption, and carbon emissions over a 50-year time horizon.

These strategies are intended to be plausible options rather than predictions. Since no attempt has yet been made to quantify the costs of these alternatives, this paper does not claim that the strategies are cost effective or efficient market solutions -- it does not select winners. Rather, it illustrates that alternative avenues exist in which efficient technologies and alternative energy sources can contribute to a desirable energy future for transportation. These strategies have been structured with feasible times for product introductions and realistic representations of capital stock turnover. Therefore, they do indicate the time-scale that will be required to accomplish such transitions.

Situation Analysis

Energy Supply

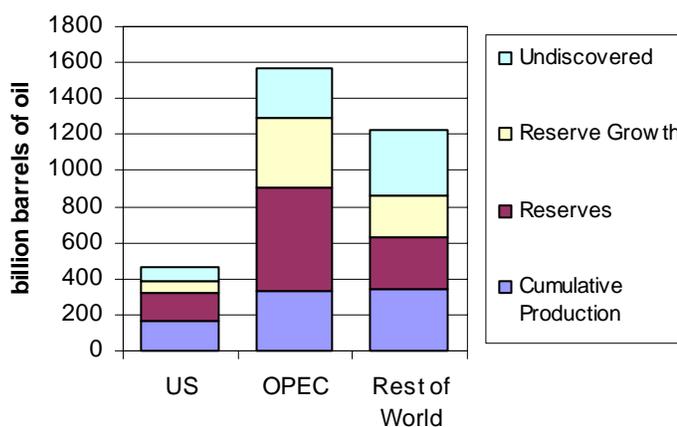
Petroleum

After the energy crises of the 1970s, the world took steps to bring new oil supplies to market and at the same time attempted to become less dependent on petroleum. In some nations, notably the U.S., there was particular concern about imported oil because of its implications for energy security. By the late 1970s, the Alaska pipeline was completed and substantial oil reserves were being exploited in Mexico and the North Sea. Higher oil prices also encouraged new oil exploration. New technology enhanced the process and lowered the cost of finding oil and extracting it. New oil discoveries have made significant short-term contributions to oil supplies, and fuel substitution has made large inroads in oil use -- although alternative fuels have made only a small contribution in the transportation sector. In addition, energy efficiency improvements have made important reductions in the rate of growth of oil demand. These actions, along with the increased oil production of 3 mbpd by Saudi Arabia in 1986 and a declining world economy, contributed to a period of relatively low oil prices and relatively stable supply from 1986 to 1999 (interrupted in 1990 by the Persian Gulf War).

The world is approaching the point at which half of the total resources of conventional oil believed to exist on earth will have been used up.

Before this point is reached, a transition to alternative sources of energy must be well underway to insure adequacy of world supplies of liquid fuels. The latest US Geological Survey (USGS) assessment, shown in Figure 1, placed the world's ultimate supplies of conventional oil at about 3 trillion barrels (mean estimate), with some 700 billion barrels as yet undiscovered.* Since the discovery of oil at Titusville, Pennsylvania in 1859, the world has recovered and used about 850 billion barrels of oil -- nearly half of the known petroleum resources and about one fourth of the estimated total conventional oil resources on earth. Geologists have observed that when oil fields and even regions reach the halfway point of depletion, oil production generally begins to decline. U.S. crude production peaked in 1970 when approximately half of the nation's oil resources had been produced, and has declined steadily since.

Figure 1: World Ultimate Conventional Oil Resource



Note: Calculations based on USGS 2000 World Assessment.

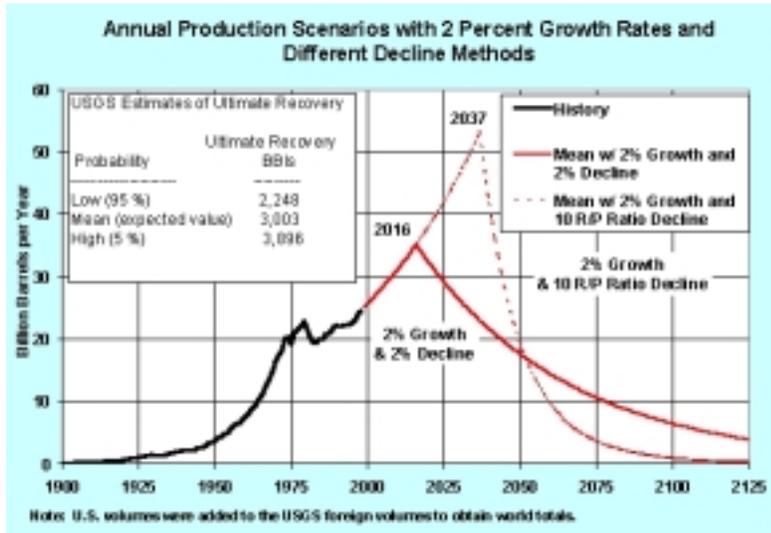
The World Conventional Oil Gap

World oil consumption has been increasing at a rate of 2.2% per year since 1993, and reached 75.6 million barrels per day in the first half of 2000. Although the U.S. currently accounts for one fourth of world consumption, growth in oil use has been lower in the U.S. than in the rest of the world for the last 40 years. The Energy Information Administration (EIA) projects that world oil demand will grow between 1.1% and 2.7% per year through 2020.¹ For midrange forecasts of demand growth of 1.9%, oil consumption in Asian countries will be equal to that in the U.S. by 2020. China, India, and South Korea will more than double their oil consumption over this period. Similarly, demand in Central and South America is expected to double, with Brazil accounting for much of that growth.

The date the world reaches the point of peak conventional oil production will depend on the ultimate resource quantity, demand growth rate, and the production decline rate. Using the most up-to-date USGS world resource estimates, the Energy Information Administration (EIA) developed a set of illustrative production curves for 2% demand growth and various decline assumptions. EIA's own methodology applies a maximum world reserve to production ratio (R/P) of 10. As shown in Figure 2, for a mean resource estimate, this results in peak production in 2037, followed by a precipitous 6 to 8 percent initial decline. The more traditional exhaustion pattern used in this report applies a 2% per year decline, which results in an earlier production

* Estimated ultimate resources includes cumulative production, known reserves, projected reserve expansion, and undiscovered oil.

Figure 2: Illustrative World Conventional Oil Production Paths



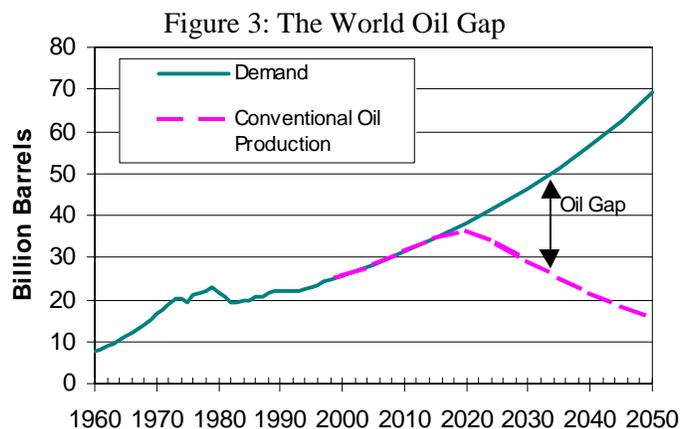
Note: Production paths ignore price feedbacks and are illustrative only.
 Source: EIA, Long Term World Oil Supply, July 28, 2000.

peak in 2016, but a more gradual decline. The two projections result in similar production in 2050.²

Because of the time required for investments in capital replacement, oil production is unlikely to decline sharply. Therefore, the analysis presented here further assumes that conventional oil production will level off slightly and peak around 2020, then begin a long-term decline. The dashed line in Figure 3 illustrates such a production path. Whether this particular projection is accepted or not, there is considerable consensus that world oil production will be

declining early in the 21st Century. Even the USGS’s most optimistic assessment of remaining conventional oil resources, matched with the EIA’s Low Economic Growth Case for world oil demand, implies that 50 percent of the world’s total endowment of oil will be used up before 2040. Pessimistic assumptions and high economic growth would put the 50 percent exhaustion point at 2010. The world’s economies cannot and will not blindly consume conventional oil to the very last drop and only then begin to look for substitutes -- that would be a recipe for economic disaster that market dynamics will preclude from happening. Long before 50 percent exhaustion is reached, a transition to alternative energy sources must begin.

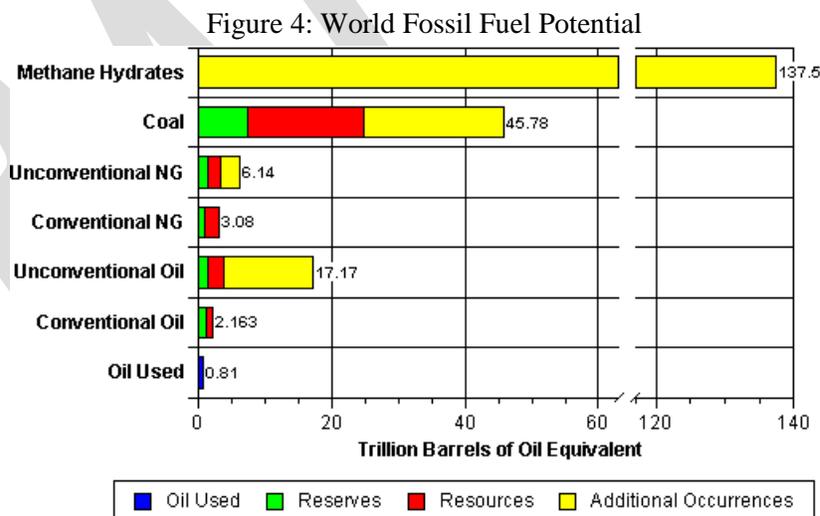
As shown in Figure 3, this analysis assumes that the demand for world oil products will continue to grow at 2% per year. After 2020, however, conventional oil production is assumed to peak once 50% of ultimate resources have been produced and begin a continual decline. As illustrated in Figure 3, *the gap between continuing demand growth and declining production could be around 50 billion barrels of oil equivalent (145 mbpd) by 2050, or almost twice current conventional oil production.* In the Baseline case, the gap is filled by conventional hydrocarbon fuels derived from unconventional fossil energy sources. If the price of the fuels from unconventional fossil resources is not markedly greater, the substitution may occur with little change in energy efficiencies or transportation demand. Otherwise, a tightening of conventional petroleum supply will raise fuel prices, which will stimulate some combination



of reduced (or slower growth in) travel demand, higher vehicle efficiencies, and substitute fuels. Can the discovery and development of new fields not adequately accounted for in current estimates change the prospects for a near-term peak in world oil production? The potential for developing large new fields can be important in the short run, but is unlikely to affect long term prospects for supply. For example, estimates of oil reserves in the Arctic National Wildlife Refuge range from 6 to 16 billion barrels of oil, while a recent Caspian Sea discovery claims 8 to 50 billion barrels of oil.^{3,4} Meanwhile, the USGS high value for undiscovered oil would account for discoveries of 1,200 billion barrels compared to a mean estimate of 700 billion barrels. With world demand growth of 2% per year, the additional 500 billion barrels – equivalent to 10 to 60 Caspian Sea discoveries – would delay the peak production by only 5 years, assuming a symmetric 2% decline. Domestically, the oil contained in a 6-16 billion barrel field of oil, which represents 0.3-0.8% of estimated remaining reserves worldwide, would fuel the U.S. light-duty vehicle fleet for only about three to eight years. *Put another way, over the life of the oil field, this supply would be equivalent to a light-duty vehicle fuel economy improvement of about 2.5 to 6.7 mpg -- except that the oil field will be exhausted after twenty years while the fuel economy improvement would continue to save oil.*

Non-petroleum Resources

While conventional oil resources are nearly half depleted, the total fossil resource base is vast. As shown in Figure 4, the total resource base conceivably could be 100 times larger than the base of conventional oil, though estimates vary widely. Also, resources[†] (occurrences that have not been accurately measured and may not be economically recoverable with today's level of technology and fuel prices) could be twice as large as reserves, which have been measured in known reservoirs and can be economically extracted. Additional occurrences with unknown degrees of assurance and unknown or speculative economic significance could be 10 times as large, though quantities are highly uncertain.⁵ Estimates of unconventional petroleum resources, in the form of heavy oil, tar sands and oil shale are many times larger than conventional oil resources.



Source: H. H. Rogner, "An Assessment of World Hydrocarbon Resources," Annual Review of Energy and Environment, 1997.

With unconventional fossil energy resources estimated at 10 to 100 times conventional oil resources, the world could conceivably continue to use liquid fossil fuels far into the future if it were willing to cope with increasing levels of environmental damage from greenhouse gas

[†] Rogner provides resource estimates for all fossil fuels in a common metric, namely barrels of oil equivalent. The definitions of reserves, resources, and additional occurrences are taken from Rogner and vary from those used by USGS for petroleum due to the inclusion of other fossil quantities.

emissions, air and water pollution, solid wastes, and oil spills. For example, producing crude oil from tar sands and oil shale requires large strip or open-pit surface or underground mines which disturb the natural environment. Processing and upgrading to crude oil produces solid and liquid tailings, toxic heavy metals, and gaseous wastes that require after-treatment and/or long term storage. These challenges add to the familiar environmental problems associated with oil use.

Converting conventional natural gas to liquid fuels could be a more desirable path, and could enable liquid fuel production to continue to increase for about another decade after conventional crude oil supplies begin to decline.⁶ However, because the known reserves of inexpensive natural gas (flared, stranded and remote) are outside the U.S., liquids made from natural gas would likely be imported. If methane hydrates could be successfully developed, liquid fuels from natural gas could support the world economy for a very long time. Although large-scale gas-to-liquids (GTL) production might help reduce local air pollution⁷, it would do nothing to reduce greenhouse gas emissions unless environmentally acceptable methods were developed to sequester the carbon produced in fuel conversion. Furthermore, the environmental impacts of methane hydrate extraction and processing are unknown. Alternately, developing and using competitive, yet dramatically more efficient vehicle technologies and cleaner, renewable fuels, could provide an option that reduces these environmental impacts by reducing demand for fossil fuels.

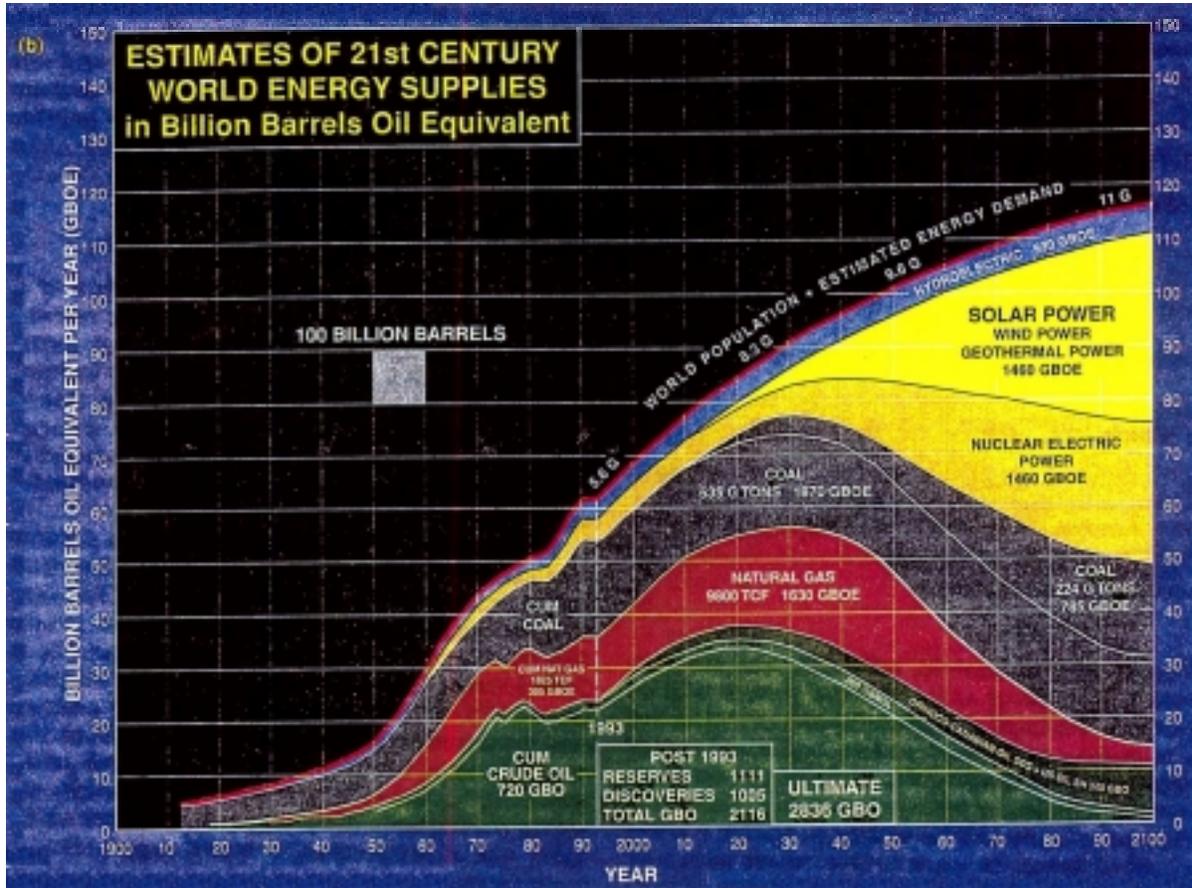
Filling the World Conventional Oil Gap

How can one interpret the post-2020 world oil situation indicated in Figure 3? One answer is provided by Figure 5, which shows a recent attempt by Edwards to describe a strategy of how world energy needs might be met in an era when traditional resources—most notably petroleum—are in decreasing supply while world energy demand continues to increase.⁸ Although Edwards' analysis is not necessarily consistent with the most recent resource estimates by USGS and others, Figure 5 does illustrate a transition away from conventional oil after 2020. A variety of resources are tapped to fill the widening gap between energy supply and demand. These resources span other traditional fossil energy forms, such as natural gas and coal, nuclear, and renewables such as solar and wind power. A number of analysts, such as IASA, Shell Oil, and BP Amoco, have developed other strategies of future world energy supplies. In the context of this paper—fuels for transportation—contributors to filling the gap can be expected to include natural gas in a broad variety of formulations, coal, oil shale, renewables for increased electricity to produce hydrogen and for direct use in transportation, and alcohols—also produced from renewable resources.

Left to market forces, the conventional oil gap likely will be filled with the cheapest liquids from fossil fuels, referred to here as synthetic fuels, that are currently under development and which would be compatible with existing infrastructure. Unconventional petroleum and GTL would likely be the first of these to enter the market. For example, heavy crude oil requires enhanced oil recovery methods and currently accounts for 8% of world oil production. In Venezuela, the cost of producing a barrel of oil from heavy crude is around \$10.⁹ In Canada, ongoing research in producing crude oil from tar sands has decreased production costs from \$26 per barrel in 1976 to under \$10 in 1996.¹⁰ While oil prices fell to \$10 per barrel in late 1998, the marginal cost of production of a barrel of conventional oil is below \$10, with costs in the Middle East as low as \$2-\$3.¹¹ Countries in OPEC and the FSU control nearly 90% of world heavy crude resources,

with more than half in Venezuela. A significant fraction (35%) of estimated tar sands resources are located in North America.¹²

Figure 5: Future World Energy Supplies



Including capital investment, the production cost of GTL has been estimated at \$16 per barrel of crude oil equivalent for a natural gas feedstock price of \$0.50 per million BTU. Each additional \$0.50 per million BTU adds about \$5 per barrel.¹³ U.S. wellhead natural gas prices since 1996 have held around \$2.00 per million BTU.¹⁴ Between 60% and 75% of estimated conventional natural gas reserves are located in the Middle East, North Africa and Former Soviet Union.^{15,16,17} The U.S. holds substantial unconventional natural gas resources in the form of coalbed methane and vast amounts of methane hydrates.

The Base Case assumes that a mix of synthetic fuels from fossil sources will be brought into the market. The quantities produced, timing of development, and market prices will depend on production costs for both conventional and unconventional feedstocks. However, as shown in Figure 3, if economic growth and the associated growth in fuel demand is to be maintained, the required phase in for new fuels will be rapid. The actual transition would probably involve economic dislocations and price increases. Higher prices for the alternative liquids would reduce demand growth relative to the 2% growth shown in Figure 3.

Transportation

Currently, the U.S. transportation system generates more than 2.5 trillion vehicle miles of travel and 4 trillion ton-miles of freight movements annually. The transportation sector accounts for 11 percent of Gross Domestic Product (GDP), as measured by transportation-related final demand. Each year, consumers spend around \$600 billion on transportation -- \$120 billion on gasoline alone. One out of nine U.S. workers is employed in transportation and related industries. Yet even these statistics do not convey the critical importance of transportation to the U.S. economy and way of life. Ours is a mobile society, and transportation touches nearly every aspect of our daily lives.

Fuel Demand

Today, transport accounts for 40% of world oil consumption of nearly 75 million barrels of oil per day (mbpd). The U.S. and world transportation systems are almost entirely dependent on fuels derived from conventional petroleum. According to IEA statistics, fuels derived from oil supplied 96% of the energy to move people and goods worldwide.¹⁸ The 29.6 million barrels per day (mbpd) consumed in transportation in 1997 was 75% more than used in 1973, implying an average annual growth rate in oil use by transport of 2.4%. The 12.7 mbpd increase in transportation oil consumption accounts for 81% of the increase in world oil consumption from 1973 to 1997. The EIA projects that between 1997 and 2020, world demand for transportation oil will grow at twice the rate of that for non-transportation oil.

Table 1: U.S. and World Transportation Oil Demand

	Oil Demand (Million Barrels per Day)	
	2000	2050 Base Case
U.S.	19	44
Transportation	13	30
Light Vehicles	8	16
Heavy Vehicles	2	5
World	75	186
Transportation	30	170
Light Vehicles	16	77
Heavy Vehicles	8	50
Ratio (U.S./World)		
Light Vehicles	50%	21%
Light + Heavy	42%	17%

Subsequent to the oil crisis of the early 1970s, key sectors of the U.S. economy (utilities, residential and commercial) were able to make a wholesale or substantial switch to non-petroleum fuels. According to EIA, electric utilities reduced their petroleum use from 17% of electricity generated in 1973 to about 1.5% in the first four months of 2000, and the residential and commercial sector reduced its petroleum use from 18% to about 6% of energy consumption during the same period. Transportation, however, remained almost totally dependent on oil.

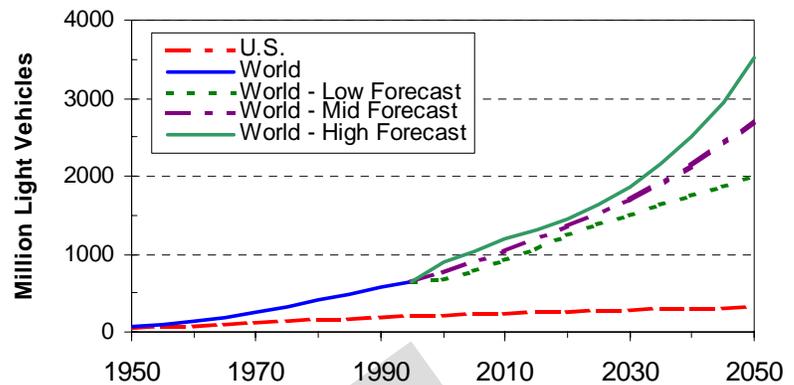
As shown in Table 1, the U.S. consumes 25% of world oil, with approximately 13 mbpd going toward transportation. Light vehicles (8 mbpd) are the largest portion at 60% of the transportation share. U.S.

light and heavy vehicles combined account for 47% of the oil consumed by vehicles of this type worldwide. Future demand for transportation fuel will depend on the size of the vehicle fleet, rates of travel, and vehicle efficiency, as discussed in detail below. If the fuel economy of light vehicles in this country remains at current levels, while vehicle miles of travel continue to grow,

this segment might require 16 mbpd by 2050. However, this increase would be dwarfed by the projected growth in demand for liquid fuels worldwide. Meeting this demand will present significant challenges in the next 50 years.

Vehicle Population: The motorization of the world has been a major development over the last fifty years. The U.S. accounted for an astonishing 70% of the world’s light vehicles in 1950, but only 30% by 1998 after the world’s total number of light vehicles increased ten-fold to 700 million. A simple model of world vehicle ownership as a function of income (GDP), combined with population projections from the World Bank, was employed to

Figure 6: World Light Vehicle Population



explore future world transportation energy demand. As shown in Figure 6, this analysis projects that the total number of light vehicles is likely to increase by a factor of 3 to 5 over the next fifty years, resulting in two to three and a half billion worldwide. Other analyses have yielded similar results, notably Gately (3.1 billion in 2050) and the World Business Council for Sustainable Development (1.25 billion in 2025).^{19,20} In addition to impacts on world energy use, this dramatic increase in vehicles would require phenomenal growth in manufacturing, which has significant implications for materials use and capital infrastructure, particularly after 2040.

Figure 7: World Vehicle Ownership Rates

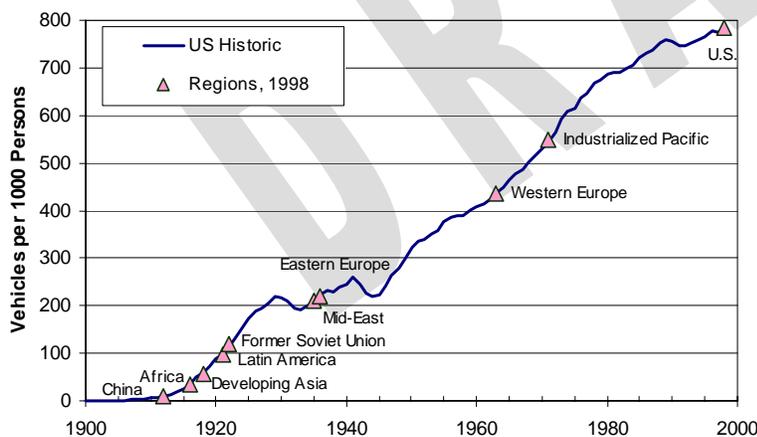


Figure 7 illustrates that most of this growth in world vehicle ownership will take place in emerging economies, where the current level of vehicle ownership is very low. *In China, for example, the ownership rate is about 8.5 vehicles per 1000 persons, which is less than the level reached by the United States in 1912.* Since the size of the future vehicle fleet is highly dependent on assumptions regarding population and income growth, a midrange forecast of 2.7

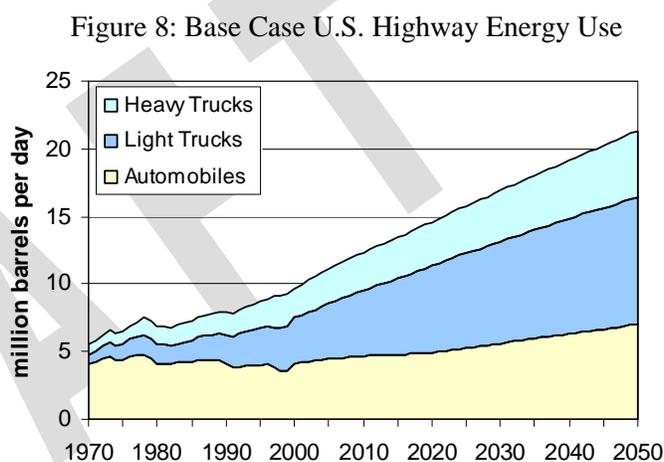
billion is used in this analysis. The ownership rate for the world as a whole grows from 100 per thousand to 300 per thousand in 2050, compared to an estimated 780 per thousand in the U.S. in 1998.

Vehicle Miles of Travel: Vehicle miles of travel (VMT) are a second determining factor in demand for transportation fuels. Growth in VMT in the U.S. has outpaced growth in the vehicle

population, rising at about 2.5% over the last decade. Consequently, VMT per vehicle has risen at a rate of 1% per year over the same period, reaching 11,800 miles per year in 1998.²¹ This analysis assumes that total U.S. VMT grows at the current rate of 2.5% in 2001, but that the rate declines linearly to 1% by 2050. VMT per vehicle for the world is much smaller than in the U.S., although there are no reliable statistics available. However, it is plausible to expect that travel, as a function of per capita income, will approach current U.S., European, or Japanese levels by 2050 in many world regions.

Vehicle Fuel Economy: Nearly all transportation modes, including air, rail, and highway, became much more energy efficient after the energy crises in the early 1970s. However, low fuel prices during the past 15 years have virtually eliminated demand for improved fuel efficiency. New car fuel economy has not improved for more than a decade. In addition, light trucks (pickups, vans, minivans, and sport utility vehicles) that are less efficient than cars are increasingly used in place of automobiles. The fuel economy of new light vehicles (cars and trucks combined) rose from about 14 mpg in 1973, peaked in 1987 at 26 mpg, and has since declined more than 2 mpg as the share of trucks has increased to 50% of light vehicle sales.

The Base Case assumes that light vehicle fuel economy does not improve over the next 50 years. This could happen even if fuel prices increase somewhat (as is assumed in the Base Case), because current fuel economy is higher than it would be if there were no CAFE standards.²² If these standards had not been in place, new vehicle fuel economy might have gone down even further in response to the decline in the cost to drive a mile in a new light vehicle (which dropped from \$0.105 in 1980 to \$0.045 in 1998 in 1998 dollars).[‡] As shown in Figure 8, total passenger vehicle energy use (auto and light trucks) is forecast to continue to increase (as VMT increases) even though petroleum use by automobiles has leveled off. Heavy truck energy use, which is a reflection of economic activity, is also projected to rise.



Advanced vehicle technologies provide opportunities to follow alternative paths instead of this Base Case. However, due to replacement rates, the inertia in the current stock of vehicles results in a substantial delay between initial deployment and realization of energy saving benefits.²³ Figure 9 illustrates two deployment schemes for new vehicles with twice the fuel economy of current new vehicles. If the advanced vehicles follow a 10 year market penetration curve, starting at 10% of the market in 2001 and reaching 100% by 2010, the on-road fuel economy of the stock would not double until about 2030. This aggressive deployment is somewhat more ambitious than recent history. Over a thirteen-year period between 1975 and 1988, the fuel

[‡] Policy Dialogue Advisory Committee to Develop Options for Reducing Greenhouse Gas Emissions from Personal Motor Vehicles (Cartalk) negotiators agreed that the price of gasoline in 1995 would have to go up by \$0.25 per gallon before the full impact of the elasticity of fuel economy with respect to fuel price would take effect.

economy of new cars sold in the U.S. increased by a factor of 1.8, and has held steady since. In the 25-year period since 1975, the on-road fuel economy of the automobile stock has increased by a factor of 1.5 and is rising slowly. In the second deployment situation illustrated in Figure 9, the advanced vehicles take 20 years to penetrate 100% of the market, and the stock fuel economy takes 38 years to double.

Non-Petroleum Fuels

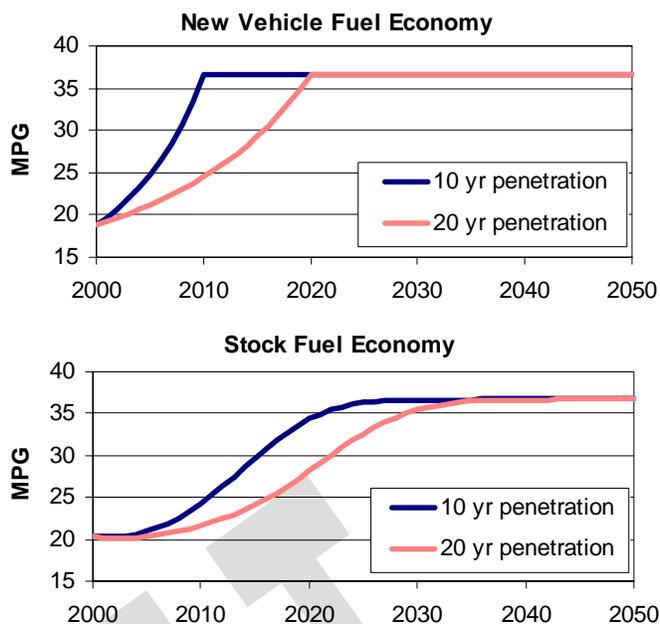
In the United States, transportation consumed 13 mbpd of energy in 1998 of which almost 97% was petroleum, according to EIA statistics.²⁴ However, the EIA data include ethanol and MTBE blended with gasoline in the petroleum total, so that a more accurate estimate of the petroleum share would be closer to 95%.²⁵ This level of petroleum dependence has remained essentially constant since 1973. The EIA reports that of the 10.38 mbpd of motor fuel consumed by motor vehicles in the U.S. in 1999, 0.28 mbpd (2.7%) is comprised of alternative or replacement fuels.²⁶ However, more than 90% of this consists of MTBE (0.2mbpd) and ethanol (0.06 mbpd) blended with gasoline. Alternative fuels, such as compressed natural gas, methanol, and LPG comprise only 0.02 mbpd.

Emissions

Criteria Pollutants: Over the past four decades, the combination of steadily more demanding emissions regulations, improved fuels, and continued advances in pollution control technology have enabled significant strides in reducing total air emissions and improving air quality. However, at the end of 1999, over 100 million people in the U.S. -- nearly 40% of the country's population -- still lived in non-attainment areas. Most of these people live in 32 areas that do not meet the Environmental Protection Agency's National Ambient Air Quality Standards for ozone, a prime ingredient of smog and a major urban area problem in the summer. Ozone is formed by a photochemical reaction of nitrogen oxides and reactive hydrocarbons (organic) vapors in the presence of sunlight. Transportation accounts for 50% of nitrogen oxides and 40% of volatile organics. Transportation is also responsible for nearly 80% of the nation's carbon monoxide emissions.

In California air basins, the 'worst case' is the South Coast Air Quality Management District. It is projected that this district will meet the Federal Ambient Air Quality Standards by the year 2010 and will be maintained through the year 2020. Continued growth in population and transportation could require new limitations on automotive emissions in order to remain in compliance through 2050. The California Air Resources Board has encouraged the development of zero emission vehicles as a means of combating the region's chronic air pollution problem. In

Figure 9: Time Lag Between Deployment and Stock Turnover



other areas of the United States, including the Northeast States and Texas, ozone and other air quality problems are more complex. Current understanding of these problems is incomplete, and what emissions control measures are needed for long-term attainment and maintenance of the Federal Ambient Air Quality Standards are uncertain.

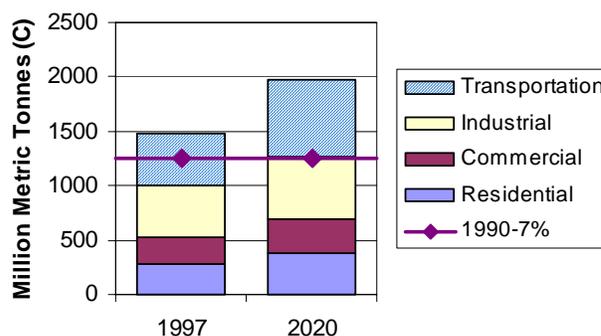
Concern over air toxics from mobile sources, including benzene, formaldehyde, and 1-3 butadiene, also will affect choice of technologies for future vehicles. Better understanding of the health effects of nanometer-sized particles produced by internal-combustion engines may well lead to continued tightening of emission controls, further increasing the cost of vehicles and conventional fuels to meet stricter standards. Since some of the vehicle and fuel technologies that could reduce oil dependence could either improve or exacerbate air quality problems, emissions should be a major consideration in planning for the future.

Greenhouse Gas Emissions: Greenhouse gases, such as carbon dioxide, trap solar heat in the atmosphere, raising its temperature. Since the beginning of the industrial age (around 1750), human activities, mostly the burning of fossil fuels, land use changes and agriculture have been the principal sources for observed increases in the atmosphere of carbon dioxide (up 30%), methane (up 145%), and nitrous oxide (up 15%). The Intergovernmental Panel on Climate Change (IPCC) has concluded that these increases have had a discernable impact on the earth's climate and are believed to be responsible for a significant (1° to 2°F) increase in the average global temperature since pre-industrial times.²⁷ Even if carbon dioxide emissions could be returned to 1994 levels, scientists have estimated that the atmospheric concentration of the gas would double by the end of the century. In fact, carbon emissions are growing worldwide, and will continue to do so as long as the combustion of carbon fuels and resulting emissions continue to increase. The precise consequences of continued GHG emissions are not well understood, but potential adverse consequences include major changes in precipitation and temperature patterns, increased catastrophic storm activity, and higher sea level.

On a greenhouse warming potential basis, U.S. emissions of CO₂ constitute more than 80% of the nation's total greenhouse gas emissions. While comprising only about 5% of global population, the US is responsible for nearly one fourth of global annual CO₂ emissions. Transportation accounts for a third of all carbon dioxide emissions in the country, and about one fourth worldwide. U.S. passenger cars and light trucks account for nearly two thirds of the net carbon equivalent emissions from transportation, or 16% of total U.S. greenhouse gas emissions.²⁸ As shown in Figure 10, the EIA projects that, between 1997 and 2020, CO₂ emissions from transportation fuel use will grow faster than any other sector at 1.7% annually, increasing by 50% over the period.

The Framework Convention on Climate Change (FCCC), negotiated at the Earth Summit in Rio in May 1992, states as its

Figure 10: Projected U.S. Carbon Emissions from Combustion of Fossil Fuels



Source: EIA, *Annual Energy Outlook 2000*

ultimate objective the "...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." The Parties to the FCCC drafted the Kyoto Protocol in 1998 as an initial step toward this goal. The Protocol calls for the U.S. to reduce greenhouse gas emissions by 2010 to 7% below 1990 levels. As illustrated by Figure 10, significant action would be required to achieve this goal.

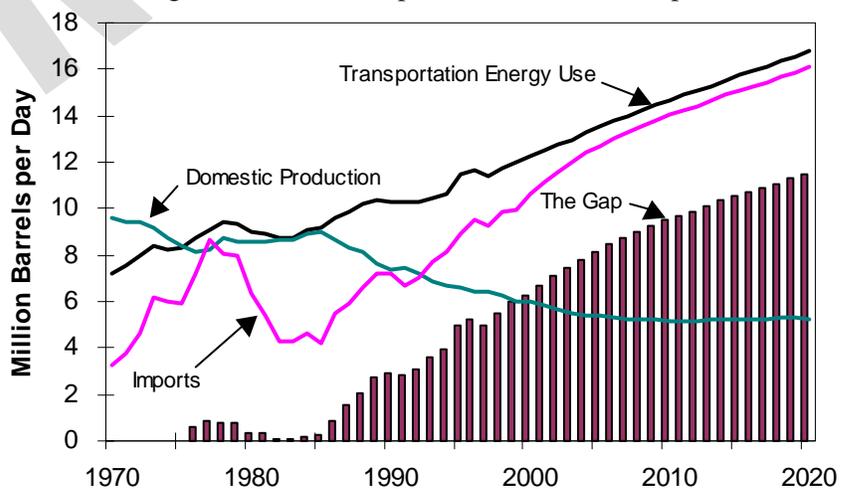
Economics of Oil

Much of the proved and ultimate future oil resources are in nations that are members of the Organization of Petroleum Exporting Countries (OPEC). As illustrated in Figure 1, OPEC nations control 57% of proven oil reserves and 51% of the world's remaining ultimate resources of conventional oil.²⁹ OPEC has demonstrated time and again that when its market share approaches 50% and world oil demand is growing, it can and will use its monopoly power to raise prices, which is likely to result in economic disruption. In 1999, OPEC proved that it can and will increase its effective market share by forging alliances with other major oil producing states (e.g., Mexico, Norway, Oman, and Russia) with effective results: oil prices tripled between January 1999 and mid-2000. ***This OPEC+4 cartel holds 68% of the world's remaining conventional oil.*** Given growing U.S. and global demand for petroleum, coupled with limited and concentrated oil resources, it is important to consider whether the U.S. is on a path that places the country in an increasingly vulnerable position for generations to come.

Manipulation of oil prices by OPEC does significant harm to the U.S. economy. Every major oil price shock of the last 30 years was followed by a recession and every major recession was preceded by an oil price shock. The most recent price shock in 1999 may not lead to a recession because of the robustness of recent economic growth and because the price increase immediately followed a price decline from \$20 to \$10/bbl. However, economic growth slowed by (X) percentage points in 2000 (*advance estimates of GDP growth for fourth quarter of 2000 due from BEA on January 31*). ***Total oil dependence costs since 1970 have been estimated at \$7 trillion (present value, 1998 dollars), which is equivalent to 70% of current GDP.***³⁰

Since 1998, more than half of the petroleum the U.S. economy requires has been supplied by imports. The almost inexorably increasing share of imports is due partly to the steady growth in transportation fuel demand, but a crucial cause is the depletion of domestic oil reserves. Whereas world oil production has yet to peak, domestic production has been in decline almost continuously since 1970. Domestic oil production now stands at 5.9 mbpd, well below the peak of 9.6 mbpd in

Figure 11: U.S. Transportation Petroleum Gap



Source data: Energy Information Administration

1970. As illustrated in Figure 11, declining domestic production has created a gap between the oil demands of transportation and domestic supply. This gap is projected to roughly double by 2020 as domestic resources continue to decline and demand continues to grow. Oil imports amounted to \$60 billion in 1999, equal to 18% of the U.S. trade deficit. In 2000, oil imports were 25% of the trade deficit.

In addition to the economic costs cited above, oil dependence imposes military (e.g., the Persian Gulf War) and political costs since the need for access to oil may conflict with other national objectives. Estimates of the military costs of defending Mid-East oil supplies vary widely depending on the assumptions made. The General Accounting Office, with a mid-range estimate, calculated the costs at \$33 billion per year for the period 1980 to 1990.³¹ The annual subsidy for the Strategic Petroleum Reserve has been estimated to range from \$1.5 to \$5.4 billion.³²

U.S. Highway Transportation Future

The strategies analyzed in this paper include a range of vehicle technologies and alternative fuels. This section introduces the technologies and fuels that were examined. Because none of these technology and fuels "pathways" is in widespread use, it can be anticipated that there are both advantages and disadvantages to their adoption. Critical deployment issues are summarized in Tables 2 and 3. Five vehicle system pathways and seven fuel / energy resource pathways have been identified to illustrate the range of options available.

Table 2: Vehicle Systems Comparison

	Vehicle System Pathway	Fuel Economy Improvement Potential	Criteria Emissions	Years to Mass Market Introduction*	Current Incremental Cost	Other Issues
1	Enhanced Conventional	Moderate (50%)	Continued though reduced	Very near term (0-5 years)	Minimal (5%)	High consumer acceptance; continued petrol. Dependence
2	Hybrid	Substantial** (100-200%)	Some zero emission range possible	Near term (2-7 years)	Substantial (10-20%)	Grade climbing ability or towing capacity may be reduced
3	Fuel Cell	Very High** (150-300%)	Low to zero tailpipe and total	Mid term (7-12 years)	Very high (>20%)	Potential petroleum independence
4	Battery-Electric	Very High** (300%)	Zero tailpipe	Near term (2-7 years)	Very high (>20%)	Energy storage, range concerns; Low petrol. use
5	Advanced	Very High (400%)	Unknown	Long term (15-20 years)	Unknown	No way to characterize

* This time frame does not necessarily indicate when the technology would be economically viable, but rather when it could be developed enough to be promoted with public policy.

** In combination with elements of "Enhanced Conventional" pathway.

Table 3: Alternative Fuels Comparison

	Fuel	Ultimate Availability	Source	State of Technology	Infrastructure Needs/Cost	Other Barriers
1	Conventional liquid fuels from:					Continued high carbon emissions
	Petroleum	Finite	Largely foreign	Mature	None	
	Natural gas	Finite	Largely foreign	Near term (2-7 years)	Moderate	Rising U.S. NG cost
	Unconventional oil	Finite but large	Foreign and domestic	Near to medium term (5-10 years)	Minimal	High extraction cost
	Methane hydrates	Finite but vast	Foreign and domestic	Far term (7-12 years)	Moderate	Unknown technology
2	Bio-Ethanol	Renewable, Land limited	Domestic	Near term (2-7 years)	Minimal	High cost
3	Bio-Diesel	Renewable, Land limited	Domestic	Near term (2-7 years)	Minimal	High cost
4	Methanol	Finite but large	Foreign and Domestic	Mature	Moderate	Toxicity
5	Natural gas	Finite	Largely foreign	Mature	Substantial	Storage, range, rising U.S. price
6	Grid Electricity	Depends on primary fuel	Diversified	Mature	Substantial	Storage, range
7	Hydrogen	Potentially vast, depending on source	Depends on feedstock and production process	Near to long term (5-12 years)	Very high	Storage, range, safety

Future Vehicles

The vehicles that will be in use in 2050 are likely to be quite different technologically from the current fleet in many unknown ways. However, a number of basic assumptions about this fleet may be drawn from recent experience. It is assumed for the timeframe of this analysis that half of new vehicle sales in the U.S. are light trucks, i.e. no further switching to light trucks from automobiles over today's purchase patterns. While innovations have altered the vehicles' features and performance, they may not necessarily achieve higher fuel economy. Total sales of vehicles and the resulting fleet size depend on income. This analysis applies GDP growth rates from EIA, extrapolated from 2020 through 2050, in a U.S. stock model calibrated to historic sales, scrappage, and stock numbers. The passenger vehicle fleet grows from 212 million in 2000 to 317 million by 2050.

Vehicle System Pathways

Enhanced Conventional Vehicles: Conventional vehicle technology is enhanced by multiple incremental improvements in all vehicle systems while retaining current engine/transmission drivetrain configurations. Improvements include aerodynamic and tire enhancements; engine efficiency improvements including direct injection and variable valve control; transmission improvements (more speeds, continuously variable transmission); more efficient accessories; and vehicle weight reduction.

Hybrid Electric Vehicles (HEV): Conventional drivetrains are replaced with a hybrid-electric system consisting of a downsized engine, operating on gasoline, diesel, methanol, and/or ethanol blends, coupled to an electric drive – electric motor, controller, and battery (or other nonfuel storage device, e.g. ultracapacitor). Presumably, hybrids and other advanced vehicles with unconventional drivetrains would incorporate the non-drivetrain improvements embodied in the Enhanced Conventional vehicle systems. Hybrids may be independent of the grid, recharging their batteries solely from regenerative braking and from using the engine to generate electricity, or they may obtain some of their energy from the grid. Such grid-connected HEVs will have larger batteries and, in some configurations, larger motors than grid-independent designs. Given limitations on their likely battery capacity because of high costs, electricity from the grid will likely supply about 50% of their needs.

Fuel Cell Vehicles (FCV): Fuel cells are electrochemical engines in which the onboard fuel source is either hydrogen to be fed directly into the fuel cell, or a hydrocarbon fuel acting as a hydrogen carrier. For the latter, an onboard fuel processor generally would reform the fuel to create a hydrogen-rich gas stream to be fed into the fuel cell. The fuel cell vehicle has an electric drivetrain system.

Battery-Electric Vehicles (EV): These vehicles use batteries for energy storage (and must be recharged from the electric utility grid) and have electric drivetrains, including electric motor/controller and battery.

Advanced Vehicles: While technical assessments and projections out to 2050 require that we rely on the technologies we know, ongoing research in high energy physics and quantum mechanics may enable radically new propulsion systems, leading to new energy strategies. Therefore, the next fifty years may see innovations far beyond what we can currently imagine. The Advanced Vehicle Pathway represents undefined departures from conventional vehicle systems that may be reflected in strategies with efficiency improvements that exceed the limits of current experimental technology.

Fuel Pathways

Synthetic Fuels from Fossil Sources: Though somewhat costly, the technology exists to manufacture gasoline and diesel fuels, such as Fischer-Tropsch diesel from oil shale, tar sands, coal, and conventional natural gas. In the future, fuels may also be made from methane hydrates. As shown in Figure 2, these hydrocarbon resources are vast.

Biomass Ethanol: Ethanol can be produced from cellulosic sources, including energy crops and agricultural, forestry, and municipal wastes. Feedstocks include rice hulls, bagasse, corn stover, switchgrass, hybrid poplar trees, and willow trees. Though a renewable resource, ethanol is limited by available land.

Bio-diesel: Bio-diesel fuel is manufactured from agricultural sources, such as rapeseed and soybeans, as well as from tallow, used fry oil, and bio-wastes. Though a renewable resource, bio-diesel is limited by available land.

Methanol: Methanol may be produced from natural gas, coal or biomass.

Natural gas: Natural gas may be used directly to fuel vehicles as either a compressed gas or in (cryogenic) liquid form, with propane fuel available as a by-product of natural gas production.

Electricity from the Grid: Electricity can be obtained via the power infrastructure and stored on-board the vehicle in either exclusively electric vehicles or grid connected hybrids.

Hydrogen: Hydrogen, stored on-board as a gas, liquid, or potentially in hydrates or other advanced storage systems, such as nano-tubes, may be used to fuel vehicles powered by fuel cells. Hydrogen can be produced from any hydrocarbon fuel (today hydrogen is primarily made from natural gas), or via electrolysis from water. The electricity for electrolysis could potentially be renewable (wind, solar, hydroelectric, biomass). In the future, hydrogen may be produced from methane obtained from methane hydrates if they become a viable resource.

Oil Supply and Gasoline Prices

As previously discussed, this analysis assumes that, for a Base Case with no new energy policy initiatives, conventional oil production peaks around 2020 and then begins a long-term decline. The tightening supply of conventional oil is assumed to stimulate the entry into fuels markets of conventional transportation fuels derived from unconventional fossil sources. Depending on the status of technology for converting unconventional fossil fuels into conventional transportation fuels, the abundance of unconventional fossil energy supplies, and the costs of mitigating environmental damages, the costs of such fuels may or may not be significantly greater than today's petroleum prices.

We have not attempted to predict the price trajectory of gasoline and other transportation fuels during this period, although price volatility is expected to become an increasing concern as conventional resources are depleted. But we note that a large part of the price of gasoline is composed of taxes, distribution and retailing costs, and refining. Given historical levels of gasoline taxes, refinery costs, retailing costs, and profits, a world oil price of about \$70 per barrel would be needed to sustain a \$2.50 per gallon gasoline price. It seems clear that acceptable transportation fuels can be made from unconventional resources at far lower prices. The implication here is that relatively large increases in world oil prices and high production costs for substitute liquid fuels may yield long term gasoline prices well below prices currently paid throughout Europe (though there could be short-term price spikes if supplies are not stable).

While it is impossible to predict the timing or magnitude of future oil price shocks, it is worthwhile to estimate their potential economic impact. A 1995 study by Oak Ridge National Laboratory estimated the potential effect of a 5.5 mbpd cut (13% of world output) in OPEC oil production in 2005, which is similar to the magnitude of past oil shocks.³³ Additional reductions in 2006 keep oil prices elevated. After 2006, OPEC is assumed to increase oil production to bring prices down to the \$28-\$30 per barrel range. The impact of this shock is quite dramatic, whether the Strategic Petroleum Reserve is used to offset OPEC's actions or not. Total losses to the U.S. economy were estimated to be about \$500 billion, or more than 5% of current GDP. Vulnerability to impacts of this magnitude is of critical importance to the country.

Light Vehicle Strategies and Results

This study combines the previously described projections of rising world oil prices, the number and type of vehicles, and the vehicle miles of travel to construct a baseline projection, called the Base Case. Total energy use, oil use, and carbon emissions are calculated for the projected travel. Six alternative strategies are then developed by postulating various levels of new light vehicle fuel economy improvements and alternative fuels use, using the technology and fuel pathways identified earlier. Half of conventional oil is produced domestically in 2000, but oil is assumed to be virtually 100% imported by 2050. Methanol is 75% imported in 2000, transitioning to 100% imported by 2050. CNG is assumed to be mostly domestic, with only 20% imported in 2050. Electricity, hydrogen, and ethanol are assumed to be domestically produced, while fossil liquids are assumed to be entirely imported. We do not, however, attempt to define a “best” strategy because each produces a mixture of impacts on oil use, greenhouse emissions, and other impacts, and because we have not evaluated their costs. Our intent in analyzing the several strategies is to provide a perspective about the range of potential outcomes from pursuing different technology (vehicles/fuels) alternatives.

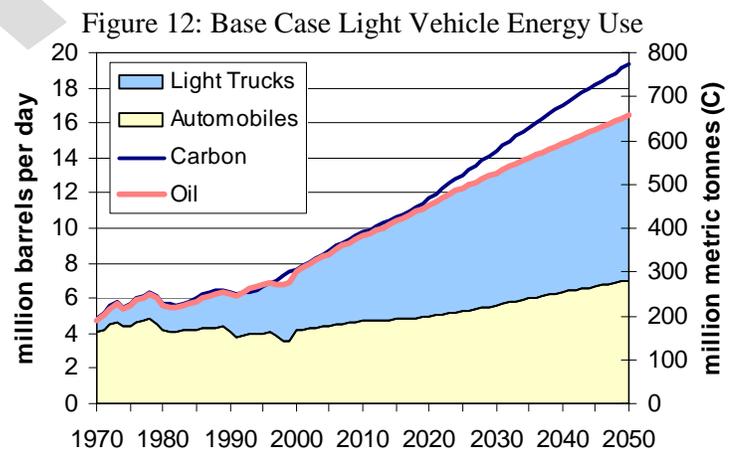
The vehicle population, VMT, and energy use are calculated using the Petroleum Oriented Worksheet (POW). This model includes a 20-year light vehicle stock model with age specific use and scrappage rates, and is calibrated to actual vehicle data from the Federal Highway Administration. For the sake of brevity, not all pathway combinations were used in the strategies described here.

Base Case

The Base Case assumes that the oil gap discussed earlier will be filled with synthetic fuels from fossil sources, such as liquids from natural gas. This analysis assumes that carbon emissions per barrel of alternative liquids would be 20% higher than for conventional oil, due to conversion losses. It is also assumed that all such fuels used to replace conventional oil are imported. Domestic liquids from fossil fuels are used in some of the alternative strategies.

The Base Case is a 50-year projection in which the growth in transportation (and the fuels needed for it) reflect: 1) continued population and economic growth, 2) modest, but steady, increases in fuel prices, and 3) a declining rate of growth in vehicle miles of travel (VMT). VMT is projected to continue the current trend toward slower growth, decreasing from the current 2.5% annual rate to 1.0% growth by 2050. Modest fuel price increases over the forecast period

are presumed to provide little incentive for increasing the vehicle fuel economy beyond the current 28 mpg for new cars and 19 mpg for light trucks. Consequently, the Base Case is one in which vehicle fuel economy remains stagnant; new technology provides performance, not



efficiency, improvements. The resulting light-duty vehicle fuel use projections are illustrated in Figure 12. In the Base Case and all subsequent strategies, new light truck sales remain at the 1999 market penetration of 50%. Therefore, the stock of light trucks grows after 2000. As a result, although passenger car energy use in the year 2000 is greater than light trucks, the situation is reversed in 2050, with light trucks consuming one third more energy than cars. This Base Case generates a reference forecast against which various strategies can be compared.

The Base Case assumption of no improvement in vehicle fuel economy may appear pessimistic to some given the recent introduction of hybrid electric vehicles (Toyota Prius, Honda Insight), the ambitious goals of the Partnership for a New Generation of Vehicles, and recent announcements of light truck fuel economy improvement targets by Ford and General Motors. However, over the past 15 years, stagnant fuel economy levels have coexisted with significant technological improvements, and there appears to be no market reason why this situation could not continue for the foreseeable future. Technologies may instead enable manufacturers to meet current CAFE standards despite the continuing shift to larger vehicles with better performance. Although a slightly more optimistic case might be chosen by some analysts, the claim here is only that the Base Case represents a plausible baseline with which to compare alternative strategies.

The levels of oil use and carbon emissions shown in Table 4 for the year 2050 reflect the environmental effects of remaining dependent on petroleum to this extent. Carbon emissions track oil consumption to 2020, and then rise more rapidly as synthetic fuels are substituted for conventional oil. Total emissions more than double from 2000 to 2050, leading in the opposite direction from reducing greenhouse gas emissions.

Table 4: Base Case Projected U.S. Light Vehicle Situation in 2050

		Base Case			
		Year 1990	Year 2000	Year 2050	Year 2050 Ratio to 2000
Oil Use	(million barrels per day)	6.2	7.5	16.4	2.19
Carbon Emissions	(million metric tons)	255	306	773	2.53

The Base Case also assumes that no alternative fuels (other than synthetic fuels) are used, apart from the small amounts being used today. Strategies are used to project the impacts of significant increases in the use of natural gas, biofuels, hydrogen or electricity.

Strategies

The following strategies are defined in terms of vehicle efficiency improvements and/or alternative fuel substitutions for oil and presumed market penetrations. One strategy includes vehicle travel reductions that may be due to telecommunications, land use change, or mode shifts. Historically, efforts to reduce the use of personal vehicles have met little success, since significant travel reductions entail large-scale lifestyle modifications. However, advances in electronics and telecommunications and/or shifting environmental and social priorities could enable substantial reductions over a 50 year period.

In the strategy definitions and descriptions, the amount of the increase in light vehicle fuel economy is represented by the “times” symbol – X. For example, 2X means that the fuel economy has been doubled (or increased by 100%). The notation of 1.5X means that fuel economy has been increased by 50%. Each of the strategy titles includes the increase in fuel economy for the total stock of light vehicles in 2050, e.g. the (1.4X) in the Strategy 1 title.

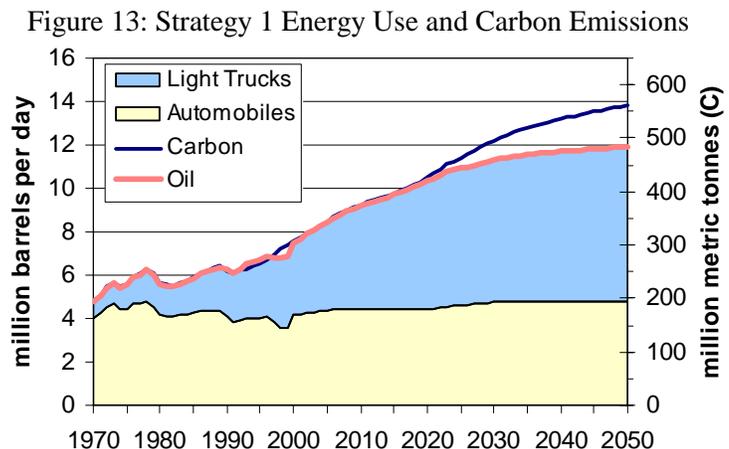
Unless otherwise stated, in each strategy, light trucks gain 75% of the stated fuel economy improvement given for cars. This assumption reflects that fuel efficient technologies like weight reduction, aerodynamic improvements, tire improvements, and hybridization have less effect on or are less applicable to light trucks because of truck performance requirements.

All stated fuel economies are unadjusted EPA test values, not on-road values. The model employed calculates fuel use by applying on-road mpg values for conventional vehicles that are 20% lower than the tested values, consistent with actual data. Currently, the model applies the same factor to HEVs, because there is insufficient data to determine whether or how much on-road fuel economy of HEVs will differ from tested values. EVs are currently assumed to have no mpg degradation at all.

Strategy 1: Enhanced Conventional Vehicles (1.4X)

In this strategy, new light vehicle fuel economy increases by 50% over the forecast period, resulting by 2050 in new cars averaging 42 mpg and new light-trucks averaging 29 mpg. These increases might be consistent with a fairly high cost of synthetic fuels from fossil sources. Fuel economy increases occur through incremental improvements (e.g., weight reduction, engine/transmission enhancements, aerodynamics, etc.) consistent with the “enhanced conventional vehicle technology” pathway. The introduction of some of these efficiency improvements begins immediately and continues steadily throughout the forecast period. Petroleum and synthetic fuels, from conventional or unconventional sources, continue to be used; no alternative fuels are included in this strategy.

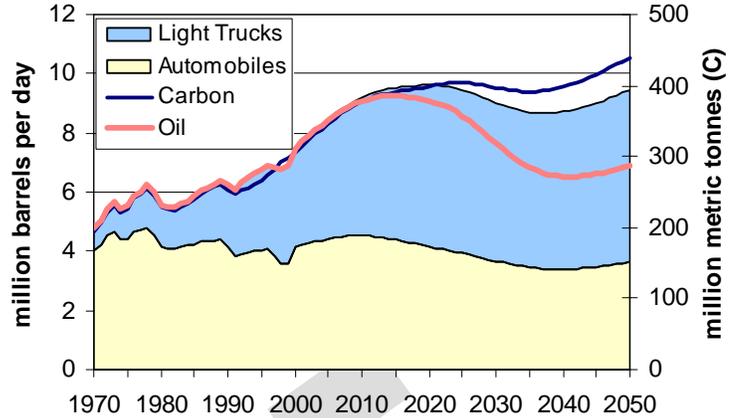
Annual energy savings grow as a result of new vehicles becoming more efficient each year and the cumulative effect of more efficient cars and light trucks in the total stock of vehicles as time passes. Figure 13 shows the energy and carbon emissions of this strategy. By 2050, energy (as well as oil consumption) and carbon emissions are almost 30% lower than the Base Case. This level of energy use and carbon emissions, however, is still an 80% increase over the level in the year 2000. The fuel economy improvement is more than offset by the growth in VMT, despite the expected slowdown in its rate of growth. As a result of VMT growth and the continuing shift of the stock from cars to trucks, automobile fuel use remains flat after 2030, while light truck energy use continues to grow through 2050.



Strategy 2: Hybrid Electric Vehicles and Electricity (1.7X)

In this strategy, the fleet is transformed by large numbers of efficient hybrid vehicles, half of which are grid-HEVs that, on average, obtain 50% of the energy they use from electricity from the grid. Vehicles with a 100% improvement in efficiency over current vehicles (2.0X), resulting from the use of hybrid drivetrains and incremental improvements in materials and structural design, tires, and aerodynamics, are introduced in 2005, gradually increasing to 100% market penetration in year 2030. Trucks achieve 75% of the fuel economy increase for cars. By 2050, hybrids make up essentially 100% of the light vehicle fleet, and half of these are grid-connected, allowing electricity to fuel 25% of the miles driven.

Figure 14: Strategy 2 Energy Use and Carbon Emissions

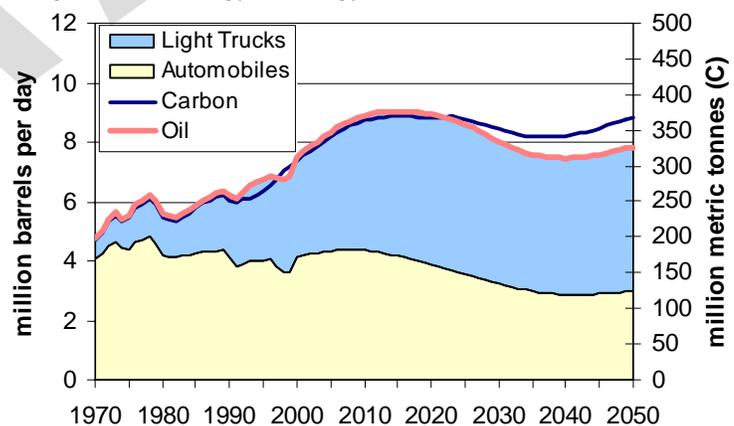


This strategy yields substantial reductions in energy use and greenhouse emissions. By 2050, energy use is 42% lower than the Base Case, with oil use still lower (58%) because of the significant electricity use. As shown in Figure 14, energy use levels off and falls after 2010. However, continued growth in vehicle stock and VMT beyond the period of this analysis would eventually drive energy consumption up, unless further efficiency improvements are realized. Carbon emissions are 43% lower than the Base Case, though they are still 44% higher than emissions in the year 2000.

Strategy 3: Travel Reductions Plus Efficiency (1.8X)

In Strategy 3, 2.0X HEVs are introduced as in Strategy 2 and obtain the same market penetrations, but none are grid connected. In addition to the efficiency improvements, vehicle travel grows more slowly than in the Base Case, resulting in a 15% reduction in total VMT by 2050. These reductions might be realized through a combination of modal shifts, changes in land use patterns, telecommuting, e-commerce, and other uses of telecommunication.

Figure 15: Strategy 3 Energy Use and Carbon Emissions



In 2050, the fleet is composed almost entirely of 2X vehicles, and the average per vehicle VMT is reduced from 16,622 to 14,138 miles, yielding a 52% reduction in energy use, oil use, and carbon emissions relative to the Base Case. Year 2050 carbon emissions are 20% greater than in 2000.

Strategy 4: HEVs with Accelerated Biomass (1.8X)

Strategy 4 combines HEVs with the same efficiency as those in Strategy 2 and an emphasis on renewable fuels. This approach might be especially desirable if the need to combat global warming becomes more urgent. As in Strategy 2, 2.0X hybrids are introduced into the light vehicle market in year 2005. By 2030, 2.0X gasoline hybrids obtain 100% penetration of new vehicle sales. As shown in Table 5, biomass ethanol blends are introduced in 2005. By 2050, ethanol provides 45% of fuels used in gasoline vehicles, in blends up to E-85.

Table 5: Strategy 4 Ethanol Production and Blends

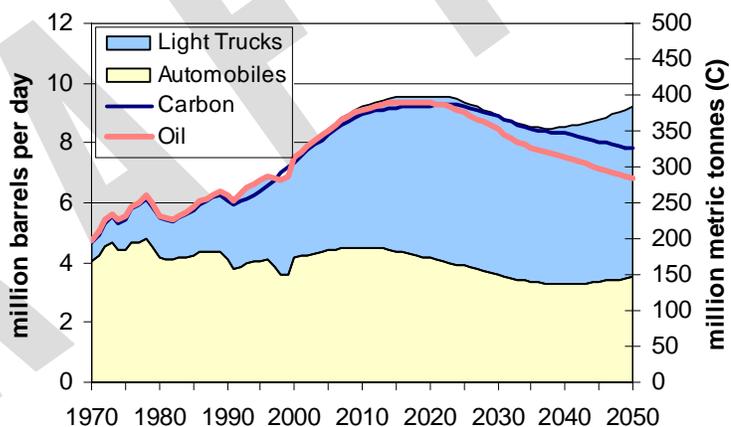
	2010	2020	2030	2040	2050
Ethanol (quads)	0.283	0.846	1.69	3.00	5.00
Percent Blends	1.5%	4.8%	12.5%	28.2%	45.0%

The 5 quads of ethanol in 2050 are produced from four sources:

- Cropland: 44% of the ethanol, using 10% of current total U.S. cropland, including Conservation Reserve Program acreage
- Grassland: 19% of the ethanol, using 10% of current grassland
- Agricultural waste: 25%
- Waste wood: 12%

As shown in Figure 16, this strategy yields reductions in energy and oil use similar to Strategy 2, but larger carbon reductions. By 2050, energy use is 44% below the base case, and both oil use and carbon emissions are 58% below the Base Case because of the substantial shift to a non-petroleum, renewable fuel. Carbon emissions in 2050 are 6% above today's levels.

Figure 16: Strategy 4 Energy Use and Carbon Emissions



Strategy 5: HEVs/FCVs with Hydrogen and Fischer-Tropsch Diesel (2.2X)

This strategy reflects a more radical shift to new fuels and technologies in response to perceptions of a strong need to move away from oil use. The strategy assumes that usable resources of domestic natural gas will be greatly expanded by the development of technologies enabling the eventual use of methane hydrates. By converting natural gas to Fischer-Tropsch (FT) diesel, the world might then have a supply of clean hydrocarbon fuels, possibly for centuries to come. However, no carbon sequestration was assumed. Because of the cost of these fuels, and because they will still produce both conventional pollutants and greenhouse gases, there remain important issues of energy efficiency, pollution minimization, and carbon emissions management.

This strategy applies a progression of vehicle introductions from 2.0X in year 2005 to 3.5X by 2040, and uses cleaner distillate fuel (Fischer-Tropsch diesel) and hydrogen from domestic natural gas for fuel cells. Some car and light truck hybrids use diesel, allowing for higher fuel economy. Methane hydrates emerge as a new energy source after 2020. This leads to extensive use of domestic FT diesel fuels for distillate, comprising up to 50% of the diesel fuel supply by 2050. Tables 6 and 7 summarize the fuel efficiency and market penetration of these vehicles.

Table 6: Strategy 5 Vehicle Efficiency

	2010	2020	2030	2040	2050
HEV Gasoline	2.0	2.0	2.0	2.0	2.0
HEV Diesel	2.5	2.5	2.5	2.5	2.5
FCV Hydrogen		3.0	3.0	3.5	3.5

Note: Light trucks get 75% of the stated improvement.

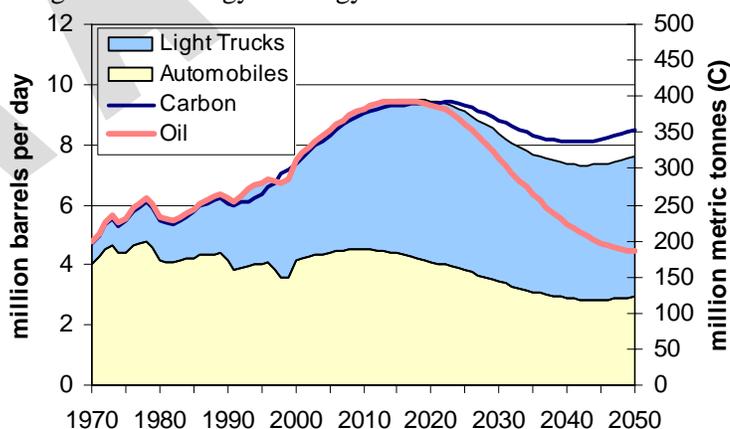
Table 7: Strategy 5 New Sales Market Penetration by High Efficiency Light Vehicles

	2010	2020	2030	2040	2050
HEV Gasoline (cars)	20.0%	45.0%	50.0%	30.0%	30.0%
HEV Diesel (cars)	0.0%	7.5%	30.0%	40.0%	40.0%
FCV Hydrogen (cars)	0.0%	7.5%	20.0%	30.0%	30.0%
HEV Gasoline (lt trucks)	20.0%	40.0%	50.0%	30.0%	30.0%
HEV Diesel (light trucks)	0.0%	12.5%	30.0%	40.0%	40.0%
FCV Hydrogen (lt trucks)	0.0%	7.5%	20.0%	30.0%	30.0%

Conversion of methane to hydrogen for fuel cell vehicles begins around 2015 and expands about as fast as the fleet of hydrogen fuel cell vehicles can expand. Initially, this is based on reformation of methane to hydrogen at the refueling station. After 2015, with this level of demand, a commitment is made to hydrogen infrastructure with centralized reforming and distribution.

This strategy yields a 54% reduction in energy use from the Base Case similar to Strategy 3. However, this strategy substitutes hydrogen from fossil sources, and yields larger oil use reductions at 73% over the Base Case. Strategy 5 reduces year 2050 carbon emissions by only 54% from the Base Case, so that emissions remain 15% above year 2000 emissions. The drop in carbon emissions is equal to the energy reduction because domestic natural gas is the source for the alternative fuels used, and no carbon sequestration is included.

Figure 17: Strategy 5 Energy Use and Carbon Emissions



Strategy 6: Three Fuel Future (2.8X)

Strategy 6 illustrates one possible path toward the elimination of fossil liquid fuels in light vehicles after 2050. By switching to three domestic fuels (biomass ethanol, electricity, and hydrogen), this strategy also significantly reduces reliance on imported fuels. A future with light vehicles using three very different fuels (a liquid, a gas, and electricity) would require a dramatic shift from what exists today. Given the higher fuel and infrastructure costs, resource limitations, and storage considerations of two of the three alternatives, fuel switching must be combined with very aggressive fuel economy improvements. In this strategy, the stock of light vehicles in 2050 is comprised of fuel cell vehicles operating on hydrogen, very efficient HEVs operating on ethanol, EVs operating on electricity, and enhanced conventional vehicles. The combination of low carbon fuels and high fuel economy also minimizes carbon emissions.

As shown in Table 8, HEVs operating on ethanol, FCs running on compressed hydrogen, and EVs that plug into the grid each achieve a small share of the new vehicle market by 2020 and grow to 100% of new vehicle sales by year 2050 (the 2020 penetration would be a remarkable achievement and clearly could occur only with an aggressive policy environment or the willingness of vehicle manufacturers to assume strong market risks). Each vehicle system achieves at least 3X on a total fuel cycle basis by 2050. Conventional vehicles are eliminated from the market as early as 2030. Light trucks achieve 75% of the stated fuel economy improvement.

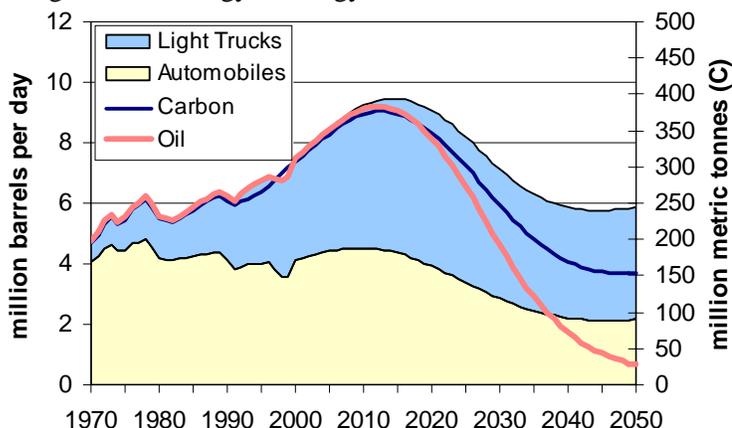
Table 8: Strategy 6 Vehicle Market Penetration

	Fuel Economy	2010	2020	2030	2040	2050
Enhanced Conventional	1.5X	8.0%	10.0%	0.0%	0.0%	0.0%
	2.0X	0.0%	10.0%	0.0%	0.0%	0.0%
HEV Gasoline	2.0X	5.0%	15.0%	10.0%	0.0%	0.0%
	3.0X	0.0%	7.5%	15.0%	10.0%	0.0%
HEV ETOH	2.0X	5.0%	15.0%	10.0%	0.0%	0.0%
	3.0X	0.0%	7.5%	20.0%	35.0%	35.0%
EV	3.15X	2.0%	5.0%	10.0%	10.0%	10.0%
FCV Hydrogen	3.0X	0.0%	10.0%	15.0%	10.0%	0.0%
	3.5X	0.0%	0.0%	20.0%	35.0%	55.0%

The hydrogen in 2050 could come from reforming domestic natural gas, the electrolysis of water with electricity (renewable or nonrenewable), or from biomass or coal. This strategy assumes the reforming of natural gas. The electric utility mix of fuels follows the projections in the AEO'00 reference case out to 2020. After that, a greater fraction of electricity is assumed to be generated from renewable resources; we note, however, that the policy environment that would allow this strategy should also be expected to move the electric utility sector strongly in the direction of more efficiency and renewable resources well in advance of 2020.

This strategy yields the strongest energy, oil, and carbon reductions. High vehicle stock fuel economy results in a 64% reduction in energy use over the Base Case. Oil use is nearly eliminated through substitution of alternative fuels, with only small amounts of gasoline still used in ethanol blends (15% gasoline by volume). Carbon emissions are reduced by 80% over the Base Case, are 49% *below* current emission levels, and are 35% *below* 1990 light vehicle emission levels minus 7%. Since the market penetration of 3.5X FCVs is still increasing in 2040 and 2050, stock fuel economy would continue to rise after 2050, resulting in continued reductions beyond the period of analysis.

Figure 18: Strategy 6 Energy Use and Carbon Emissions



Summary Results

As shown in Table 9, all but the first strategy reduce oil use by more than 50% compared with the Base Case. All but Strategy 1 reduce carbon by 40% or more relative to the Base Case. However, as shown in Table 10, Base Case carbon emissions are 2.5 times the current level, and three times 1990 levels minus 7%. Only Strategy 6 reaches 7% below 1990 light vehicle emissions by 2050.

The levels of fuel economy achieved by all vehicles on the road are shown in Table 11. These values take into account the difference between tested and on-road mpg (i.e., the degradation factor mentioned in the note at the bottom of the table). Table 12 shows the overall oil reduction percent and how it is split between efficiency improvements and the substitution of alternative fuels. Strategy 6 has the largest oil reduction from both efficiency and alternative fuel. The percent of the fuel that is imported is also shown in Table 12. Note that Strategy 6 has nearly eliminated dependence on imported fuel.

Table 9: Light Vehicle Strategy Results: Percent Reductions Relative to Base Case

Strategy	Description	Year 2050 Results		
		Energy mbpd	Oil* mbpd	Carbon Million Metric Tons
Base Case	Stagnant fuel economy	16.4	16.4	773.0
		Percent Reductions Relative to Base Case		
1	Enhanced Conventional Vehicles (1.4X)	27%	27%	27%
2	HEV and Electricity (2.3X)	42%	58%	43%
3	Travel Reduction and Efficiency (1.8X)	52%	52%	52%
4	HEVs with Accelerated Biomass (2.3X)	44%	58%	58%
5	HEVs/FCVs with H ₂ and FT Diesel (2.5X)	54%	73%	54%
6	Three Fuel Future (1.8X)	64%	96%	80%

* Includes synthetic fuels from non-domestic fossil sources

Table 10: Light Vehicle Strategy Results: Carbon Emissions

		Carbon Emissions in 2050 Ratio To		
		MMTC	1990 -7%	2000
Base Values, U.S. Light Vehicles				
	1990 Minus 7%	237	-	-
	2000 Estimate	306	-	-
Strategy Values, 2050				
Base Case	Stagnant Fuel Economy (1.0X)	773	3.27	2.52
1	Enhanced Conventional Vehicles (1.4X)	561	2.37	1.83
2	HEV and Electricity (1.7X)	439	1.86	1.44
3	Travel Reduction and Efficiency (1.8X)	369	1.56	1.20
4	HEVs with Accelerated Biomass (1.8X)	325	1.37	1.06
5	HEVs/FCVs with H ₂ and FT Diesel (2.2X)	353	1.49	1.15
6	Three Fuel Future (2.8X)	155	0.65	0.51

Table 11: 2050 Light Vehicle Fuel Economy

Strategy	Total Stock Fuel Economy (mpg)*			
	Cars	Light Trucks	Light Vehicles	
Base Stagnant Fuel Economy (1.0X)	22.5	16.4	19.0	1.0X
1 Enhanced Conventional Vehicles (1.4X)	33.3	21.4	26.2	1.4X
2 HEV and Electricity (1.7X)	43.4	26.5	33.0	1.7X
3 Travel Reduction and Efficiency (1.8X)	45.0	27.0	33.8	1.8X
4 HEVs with Accelerated Biomass (1.8X)	45.0	27.0	33.8	1.8X
5 HEVs/FCVs with H ₂ and FT Diesel (2.2X)	54.0	33.1	41.1	2.2X
6 Three Fuel Future (2.8X)	73.0	41.6	53.2	2.8X

*Includes on-road degradation factor of 20% for all vehicles, excluding electric.

Table 12: Light Vehicle Oil Reductions from Efficiency and Substitution

Strategy	Oil Reduction Relative to Base			Percent Fuel Imported
	Efficiency	Alternative Fuel*	Total	
1 Enhanced Conventional Vehicles (1.4X)	27%	0%	27%	100%
2 HEV and Electricity (1.7X)	42%	15%	58%	73%
3 Travel Reduction and Efficiency (1.8X)	52%	0%	52%	100%
4 HEVs with Accelerated Biomass (1.8X)	44%	14%	58%	74%
5 HEVs/FCVs with H ₂ and FT Diesel (2.2X)	54%	10%	64%	79%
6 Three Fuel Future (2.8X)	64%	32%	96%	11%

* FT diesel and other synthetic fuels are not included in alternative fuel.

Cost Considerations

While purchase and operating costs are very important determinants of commercial viability, cost projections for any developmental technologies are problematic at best. The results of a cost analysis are heavily dependent on projections of vehicle incremental costs and fuel prices. While research goals can be used as a starting point for *cost* projections, market forces will largely determine consumer *prices*. The varying demand for conventional and alternative fuels under the strategies examined here would result in different prices, which would in turn affect demand. Due to these complicated feedbacks, this analysis has not considered the costs or monetary benefits of the strategies explored, nor made any attempt to pick winners. The methodology instead relies on assumptions concerning technological advances and their market success, and demonstrates that plausible alternatives exist. However, achieving them will require continued advances in the technologies of vehicles and fuels, as well as effective public policies. Insights into which paths may be most desirable can be gained through further analysis.

Heavy Vehicle Strategies

For the purposes of this paper, heavy trucks include all highway vehicles above 8,500 pound gross vehicle weight. Therefore, medium size urban delivery vehicles, buses of all types, and

over-the-road 18-wheelers are part of this category. Rail is included, but only to track changes in mode of freight shipment.

In 2000, heavy trucks used 30% as much fuel as light vehicles. This percentage is the same in 2050, as the rate of declining growth in light vehicle travel is matched by the declining need for freight travel per dollar of GDP.

To obtain market penetration estimates and energy impacts, information from a previous, unpublished study on technology was updated to 2050, and fuel-cell technology was added. In the previous unpublished study, Argonne National Laboratory (ANL) gathered information and estimated technical and cost characteristics of various advanced medium- and heavy-duty truck technologies.³⁴ A market penetration model was developed and integrated with a simple payback model (developed from an American Trucking Association [ATA] survey). A demand curve was plotted projecting sales of the new technology over time using an expected market introduction date, maximum market penetration, and fuel price (a fuel price of \$2.50/gallon was used for this analysis). The market penetration results were applied to vehicle population, VMT, and energy use based on the Truck Inventory and Use Survey (TIUS) and Argonne National Laboratory fleet projections^{35,36} to obtain energy and GHG projections. Information on the potential for fuel-cell trucks was obtained from a recent draft report for Argonne National Laboratory.³⁷ Heavy hybrid assumptions were based on a study by An et al.³⁸

Using this analytical approach, six strategies of heavy truck efficiency improvement and rail efficiency improvement and/or fuel substitution were developed and are described below. These strategies mirror somewhat the six light vehicle strategies. They are suffixed with the letter “T” to denote “truck.” Table 13 shows fuel economy for the six strategies. Table 14 shows the percent reductions in energy use, oil use, and carbon emissions relative to the Base Case for the six strategies. As was the case for the light vehicle strategies, the largest reductions are for the last strategy. One strategy includes modal shift from truck to rail.

Strategy 1T: Enhanced Conventional Diesel Trucks

In this strategy, advanced diesel engines, drivetrains, and tires penetrate the market for conventional Class 7-8 trucks. In 2050, we assume the Class 7-8 truck fleet fuel economy is 7.3 mpg, or 1.2X the fuel economy of the fleet in 2000. Class 3-6 trucks share most of the Class 7-8 technologies, with the added benefit of improved performance in city driving, and a shift from gasoline engines to more efficient diesel engines. The Class 3-6 fleet is assumed to achieve a fuel economy of 1.6X the fuel economy of the fleet in 2000, or 15 mpg, and rail efficiency remains the same at 478 T-mi/gal.³⁹ As summarized in Table 14, energy, oil, and carbon are reduced by 20% in 2050.

Strategy 2T: Advanced Technology Diesel and HEV Medium Trucks

In this strategy, additional advances in diesel engines for Class 7-8 trucks (e.g., higher pressure fuel injection) are assumed along with increased use of lightweight materials. In 2050, the Class 7-8 truck fleet fuel economy is 8.6 mpg, or 1.4X the fuel economy of the fleet in 2000. Class 3-6 trucks improve from the additional benefit of hybridization, which increases fuel economy to 20.8 mpg, or 2.3X. In this strategy, energy, oil, and carbon are reduced by about 33% in 2050.

Strategy 3T: Freight Modal Shift and Efficiency

In this strategy, in addition to enhanced conventional diesel trucks (Strategy 1T), advanced locomotive technologies improve rail fuel efficiency by 18% over the next 30 years, and freight is increasingly shifted from truck to rail starting in 2001 and reaching 10% (by weight) in 2050. Freight hauled by train is three-times more energy efficient (on a revenue ton-mile basis) than if hauled by truck.⁴⁰ In this strategy, energy, oil, and carbon are reduced by 26% in 2050 as compared to Strategy 2T, where a maximum-technology case for diesel trucks achieves an oil reduction of 33% relative to the base case. A shift of 10% of the freight ton miles from trucks to the more efficient rail mode has the equivalent energy savings of increasing heavy truck fuel economy from 7.3 mpg (Strategy 1T) to 8.6 mpg (Strategy 2T).

Strategy 4T: Advanced Technology Diesel and HEV Medium Trucks and Accelerated Biomass

This strategy assumes 1/3 of the diesel fuel market is biodiesel, and the advanced trucks are the same as those described in Strategy 2T. Rail also uses biodiesel. The energy reduction is the same as Strategy 2T; carbon is reduced by 42% with 67% of the fuel imported.

Strategy 5T: Advanced Technology Diesel, Solid-Oxide Fuel-Cell, and HEV Medium Trucks and FT Diesel

In this strategy, consistent with light vehicle Strategy 5, Fischer-Tropsch (FT) diesel from domestic natural gas, introduced in 2020, replaces 50% of the diesel fuel by 2050. The energy conversion efficiency of FT diesel production from natural gas to liquids production increases over time, from 52% (2000) to 72% (2050) as a result of technological advances. Diesel production efficiency is assumed to remain at 84%. The advanced diesel engine technologies are in-place (Strategy 2T) and are joined by diesel-fueled solid oxide fuel-cell (SOFC) trucks, which become commercial in 2020 and penetrate 20% of the market in 2050. Market penetration assumptions are consistent with those for light-duty fuel-cell vehicles. Based on preliminary analyses of SOFC technology, fuel economy of a fuel-cell truck is estimated to be 35% greater than a diesel-engine truck. This percentage improvement over diesel engines is maintained, as a result of future advances in fuel-cell technology over time. Rail efficiency does not change from the base case. The percent of fuel imported is 50%, (if domestic natural gas can be used to produce the FT diesel fuel); energy and carbon are reduced by 40% in this strategy.

Strategy 6T: Three Fuel Future: Hydrogen, Biodiesel, Petroleum Diesel

This strategy is consistent with Strategy 6 for light vehicles, but is modified to reflect the different requirements for freight transport. The aggressive fuel economy improvements in Strategy 5T are combined with hydrogen (from natural gas) fuel-cells, and diesel engines running on biodiesel and petroleum diesel. Hydrogen fuel-cell and SOFC systems have the same efficiency. The fuel and vehicle strategies are combinations of the above strategies, but with the addition of hydrogen fuel cells for some trucks. For fuels, we assume 5% hydrogen, 33% biodiesel, 50% FT diesel, and 12% petroleum diesel. For trucks, we assume 5% hydrogen fuel-cell, 20% SOFC, 75% advanced technology diesel and HEV medium trucks. In this strategy, energy is reduced 43%; oil is reduced 96% through the use of FT diesel and hydrogen, both produced from domestic natural gas, and biodiesel; carbon emissions are reduced 59% through higher vehicle efficiency and the extensive use of biodiesel.

Figure 19: Strategy 6 and 6T Compared to Base Case

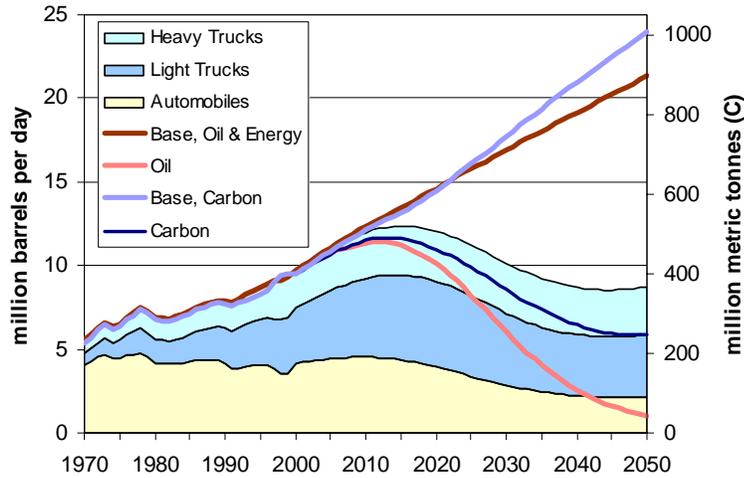


Figure 19 illustrates the combined impact of light vehicle Strategy 6 and heavy vehicle Strategy 6T on highway energy use and carbon emissions. Energy use is reduced 59% from 21 to 9 mbpd; oil is dramatically reduced 96% to less than 1 mbpd; and carbon emissions are reduced 75% from 1,005 to 250 million metric tonnes of carbon. Note, however, that energy and oil use have leveled out by 2050, and would begin to rise thereafter if the vehicle stock, VMT, and freight ton-miles continued to grow.

Table 13: Heavy Truck Strategy Results: Percent Reductions Relative to Base Case

Strategy	Description	Year 2050 Results		
		Energy mbpd	Oil mbpd	Carbon Million Metric Tons
Base Case		5.0	5.0	232
Percent Reductions Relative to Base Case				
1T	1.25X	20	20	20
2T	1.5X	33	33	33
3T	1.25X & Modal Shift	26	26	26
4T	1.5X & Biodiesel	33	55	42
5T	1.7X & FT Diesel	40	70	40
6T	1.7X & Biodiesel, FT Diesel, H ₂	43	96	59

Table 14: 2050 Results: Heavy Vehicle Fuel Economy

Strategy	Fleet Fuel Economy				Percent Fuel Imported
	Class 3-6	Class 7&8	Class 3-8 Fleet		
Base	9.2	6.0	6.4	1X	100
1T	15.0	7.3	8.1	1.25X	100
2T	20.8	8.6	9.9	1.5X	100
3T	15.0	7.3	8.1	1.25X	100
4T	20.8	8.6	9.9	1.5X	67
5T	22.3	10.0	11.1	1.7X	50
6T	22.6	10.1	11.4	1.7X	12

Policy Considerations

Absent sharp changes from current trends, the combination of physical limits to conventional oil supply, continued worldwide growth in demand, and little vehicle efficiency improvement will create the need for a substantial shift to new sources of transportation fuels sometime within the next few decades. The most likely source of these fuels will be unconventional petroleum and liquids from natural gas. Initially, the increased cost of fuel production and relative scarcity during phase-in will put upward pressure on fuel prices. More importantly, the fuels transition likely would be accompanied by price instability and resulting damage to the U.S. economy. Coupled with continued reliance on imported fuel, large increases in greenhouse gas emissions and the potential for other serious environmental consequences, such a transition may not be viewed by key policymakers as the most desirable future for the nation.

Future transportation fuel supply is a global issue, and the U.S. cannot dictate efficiency trends and fuel choices to the rest of the world. However, the nation has a number of policy options that could reduce its own vulnerability to economic and environmental damage associated with the imminent transition to new fuels, and *indirectly* influence worldwide trends and choices in fuels and efficiency. The range of available policies include those that directly address fuel supply by stimulating an earlier, smoother transition to more desirable fuels, and those that focus on reducing fuel demand by stimulating increased efficiency in the U.S. vehicle fleet.

Policy options fall into the following classes: 1) Research, Development and Demonstration, 2) Information and Education, 3) Regulatory and, 4) Fiscal. Available policies can directly affect the supply of new fuels and efficiency technologies with measures aimed directly at researchers and manufacturers – including tax credits for RD&D, government/industry partnerships, regulatory targets, fuel subsidies, and so forth. Complementary measures that increase the demand for new technologies and fuels – including information programs, rebates or tax credits to vehicle purchasers, government fleet vehicle and fuel purchases, and taxes on conventional fuels (or tax breaks on new fuels) – will also stimulate supply as automakers and fuel suppliers respond to market demands.

Recent U.S. federal government policy has focused primarily on research, development (e.g., PNGV), and demonstration and has made important progress. Policies that more directly affect

the marketplace, e.g. CAFE standards and fleet alternative fuels requirements, have been allowed to languish or have been actively blocked from being updated. While RD&D programs are essential to achieving dramatic changes in transportation energy consumption patterns, many analysts believe that successful RD&D results *by themselves* will not assure the commercial adoption of advanced transportation technologies and alternative fuels. Further action may be required to correct for a market characterized by imperfect information, inadequate price signals (e.g. the existence of external costs not included in market prices), significant barriers to entry, and the inability of automakers and equipment suppliers to capture many of the benefits of their R&D investments. This situation suggests that a strong need exists for new policies -- at least some of which are likely to meet resistance from the general public and/or the auto industry -- to assure an orderly transition from conventional fuels and stagnant fuel economy to new fuels and a more efficient fleet.

Conclusions

The availability of energy resources to fuel the world's transportation systems will depend on both the supply of fuels and the demand for them. U.S. energy needs will necessarily have to be met within a global context: energy supplies around the globe and energy demand throughout the world. The review of world energy supplies and analysis of U.S. transportation energy demand summarized in this paper leads to the following observations.

Transportation Energy Supplies

- U.S. oil production has been steadily declining since 1970 when approximately half of all our petroleum resources had been extracted.
 - Even the addition of the Alaskan North Shore fields has not halted the declining production.
 - With more than half of our oil resources already consumed, reliance on domestic oil resources to meet just our transportation energy needs (two-thirds of our oil consumption is for transportation) is no longer a feasible option.
- The best estimates of world oil resources (coupled with projected oil demand) indicate that half of the world's crude oil will be consumed by 2010 at the earliest or 2040 at the latest.
 - With OPEC controlling over half of the world's oil resources, continued reliance on conventional petroleum will increase the probability of future oil price shocks, which, when combined with losses due to monopolistic pricing, has already cost the U.S. an estimated \$7 trillion.
- The earth contains vast amounts of unconventional petroleum resources (heavy oil, tar sands, and oil shale) as well as natural gas, coal, and methane hydrates that could be used to produce transportation fuels. Development of new sources of energy will undoubtedly be an integral part of the nation's energy future, although some issues that will still need to be addressed will include:
 - reducing costs, as these fossil fuels will be more expensive than conventional petroleum,
 - recovering energy resources in an environmentally sound manner, and

- reducing the greenhouse gas emissions that come from the continued use of fossil fuels

Transportation Energy Demand

- The world's transportation systems are 96% dependent on petroleum products.
- World demand for conventional oil is outpacing our ability to find and produce this finite resource.
 - Economic growth and increases in population drive the continually increasing demand for transportation energy.
 - U.S transportation energy demand is expected to more than double by 2050.
 - Highway vehicles account for three-fourths of transportation energy use.
 - Light vehicles (cars and light trucks) use 60% of transportation energy.
 - Highway energy use is expected to grow two and a half times by 2050.
 - World transportation energy demand is forecast to grow by a factor of five by 2050.
 - China, India, South Korea, and Brazil are among the countries that will double their oil consumption in the next twenty years.
 - The number of motor vehicles in developing countries is expected to grow rapidly; vehicle ownership in China today is at the level the U.S was at in 1912.
- Reducing petroleum demand can be viewed as the same as finding and producing new oil supplies.
 - A 2 ½ mpg fuel economy improvement in light-duty vehicles is the equivalent to finding a major new oil field containing 6 billion barrels of oil
 - High-efficiency light vehicles (2½ to 3 times more efficient than today's cars and light trucks), coupled with the use of alternative fuels (biomass ethanol, Fisher-Tropsch diesel fuel, and/or electricity) could reduce U.S. transportation oil use to levels below current consumption. Findings from this study's analysis include:
 - As shown in Strategies 4 and 6, biomass ethanol, from a combination of sources that would mean no more than 15% of current cropland would be used, could provide significant oil substitution and substantial carbon emissions reduction
 - Fisher-Tropsch diesel fuel has oil substitution potential, but little carbon reduction benefit because it is made from natural gas. However, some carbon emission reductions might be realized from advanced, high efficiency diesel engines, as shown in Strategy 5.
 - Greater market potential exists for the use of electricity with grid-connected hybrid vehicles than with battery electric vehicles. Both could provide local air quality benefits while reducing energy use, oil use, and carbon emissions (depending on the utility feedstock mix). Strategies 2 and 6 illustrate application of these vehicles.

- As shown in Strategies 2, 4, 5 and 6, very dramatic reductions in oil use and carbon emissions are possible with an aggressive commitment to the commercialization of high fuel economy vehicles (hybrids and fuel cells) that utilize low carbon fuels (biomass ethanol, electricity, and hydrogen).
- Likewise significant efficiency improvements and the use of alternative fuel for heavy trucks can have dramatic effects on oil consumption, total energy use, and carbon emissions.
 - Simply enhancing conventional heavy trucks with improved technology (advanced diesel engines, drivetrains, and lower rolling resistance tires) could reduce energy and oil use (and carbon emissions) by a fifth, as illustrated in Strategy 1T.
 - Adoption of more advanced technology ((lightweight materials, hybridization of medium-duty trucks, etc.), as shown in Strategy 2T, could provide a one-third reduction in the energy, oil, and carbon categories.
 - A 10% mode shifts from trucks to the more energy-efficient (on a ton-mile basis) rail system can have equivalent energy and emissions impacts to a 20% improvement in heavy truck fuel economy (Strategy 3T).
 - Substitution of renewable fuels (biodiesel) for conventional fuels, when accompanied by the advanced vehicle technologies used in the earlier strategies, can a major effect on both oil use as well as the amount of imported fuel, as seen in Strategy 4T.
 - Very dramatic changes in oil consumption and carbon emissions are possible if aggressive improvements in fuel economy are achieved with fuel cells using hydrogen derived from natural gas and high-efficiency diesels using biodiesel fuel (Strategies 5 and 6).
- But, any major vehicle technology, including fuel economy improvements, takes about 20 to 30 years to penetrate the entire light vehicle stock.
 - If significant improvements in light-duty fuel economy (50%) take a long time (50 years), such as in Strategy 1, then the effect on energy demand is modest
 - Vehicle fuel economy improvements need to begin soon in order to be most effective in helping the transition beyond petroleum fuels.
- Travel reductions, illustrated in Strategy 3, could contribute significantly to demand management since advances in electronics and telecommunications and/or shifting environmental and social priorities could enable substantial reductions over a 50-year period. These reductions could be realized through a combination of modal shifts, changes in land use patterns, telecommuting, e-commerce, and other uses of telecommunication technologies.
- Vehicle fuel economy improvements and alternative fuels can play an important role in the nation's energy future, but several important issues need to be addressed.
 - Further research will be needed to reduce the costs of:
 - advanced vehicle technologies,

- alternative fuels, and
 - the required infrastructure for new fuels.
- If high economic costs during a transition to synthetic fuels are to be avoided, some new federal policies (incentives, regulations, mandates) would be needed to stimulate the introduction of vehicles with significantly greater fuel economy or the widespread availability of alternative fuels

Next Steps

This paper completes the first phase of a multi-phase analysis effort. The purpose in this phase was twofold:

- 1) to present evidence that a transition away from conventional oil will be necessary when world oil production peaks in the next several decades, and that, because of long lead times, the start of the transition needs to begin now, and
- 2) to illustrate a number of plausible alternative technology introduction strategies in the U.S. highway sector that yield more attractive results than the base case strategy with respect to energy use, oil use, and carbon emissions.

Market solutions to future transportation energy demand will not necessarily result in the most desirable future for society. However, choosing the future path and selecting effective policies requires more information than has been presented here. Therefore, the next phase of the analysis will address issues critical to making such decisions. The purpose of this future work is to provide estimates of the costs and investments associated with the U.S. strategies over the next 50 years. Since the U.S. fuel market and automotive industries are increasingly coupled with global markets, this analysis will also estimate how these strategies affect world energy markets and are affected by the actions of other nations.

To achieve these goals, the next phase will take world and U.S. fuel availability into account, model the feedbacks among fuel prices and travel, and explicitly account for how other nations introduce technologies (faster than, slower than, or the same as the U.S.). It will also take the costs of vehicle technologies, alternative fuels, and the fueling infrastructure into account. A regional element will be added to the analysis by use of at least three geographic regions (East, Central, and West). Since it is the fastest growing transportation sector, air travel will also be added to the analysis.

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