Executive Summary

OVERVIEW

Recent interest in alternative fuels for light-duty highway vehicles (automobiles and light trucks) is based on their potential to address three important societal problems: unhealthy levels of ozone in major urban areas; growing U.S. dependence on imported petroleum; and rising emissions of carbon dioxide and other greenhouse gases. This assessment examines the following alternative fuels: methanol, ethanol, natural gas (in either compressed (CNG) or liquid (LNG) form), electricity (to drive electric vehicles (EVs)), hydrogen, and reformulated gasoline.

Substituting another fuel for gasoline affects the entire fuel cycle, with impacts not only on vehicular performance but on fuel handling and safety, materials requirements, feedstock requirements, and so forth. The variety of effects, coupled with the existence of the three separate "policy drivers" for introducing alternative fuels, create a complex set of trade-offs for policymakers to weigh. Further, there are *temporal* trade-offs: decisions made now about promoting short-term fuel options will affect the range of options open to future policymakers, e.g., by emplacing new infrastructure that is more or less adaptable to future fuel options, or by easing pressure on oil markets and reducing pressure for development of nonfossil alternative fuels. Table 1 presents some of the trade-offs among the alternative fuels relative to gasoline.

Much is known about these fuels from their use in commerce and some vehicular experience. Much remains to be learned, however, especially about

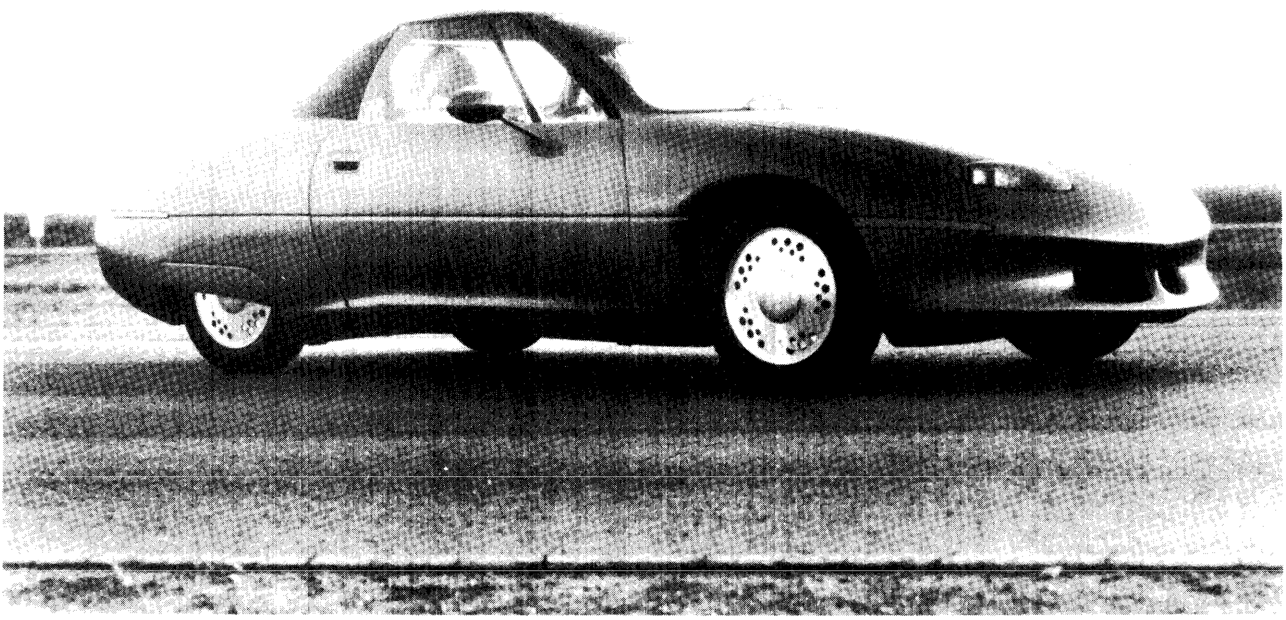

Photo credtt General Motors Corp.

GM's **Impact electric vehicle, though a prototype requiring much additional testing and development, represents a promising direction for alternative fuel vehicles: a "ground up," innovative design focused on the unique requirements of the fuel sources, in this case electricity.**

Table I—Pros and Cons of Alternative Fuels

	Advantages	Disadvantages
Methanol	Familiar liquid fuel Vehicle development relatively advanced Organic emissions (ozone precursors) will have lower reactivity than gasoline emissions Lower emissions of toxic pollutants, except formaldehyde Engine efficiency should be greater Abundant natural gas feedstock Less flammable than gasoline Can be made from coal or wood (as can gasoline), though at higher cost Flexfuel "transition" vehicle available	Range as much as 1/2 less, or larger fuel tanks Would likely be imported from overseas Formaldehyde emissions a potential problem, esp. at higher mileage, requires improved controls More toxic than gasoline M100 has non-visible flame, explosive in enclosed tanks Costs likely somewhat higher than gasoline, esp. during transition period Cold starts a problem for M100 Greenhouse problem if made from coal
Ethanol	Familiar liquid fuel Organic emissions will have lower reactivity than gasoline emissions (but higher than methanol) Lower emissions of toxic pollutants Engine efficiency should be greater Produced from domestic sources Flexfuel "transition" vehicle available Lower CO with gasohol (10 percent ethanol blend) Enzyme-based production from wood being developed	Much higher cost than gasoline Food/fuel competition at high production levels Supply is limited, esp. if made from corn Range as much as 1/3 less, or larger fuel tanks Cold starts a problem for E100
Natural Gas	Though imported, likely North American source for moderate supply (1 mmbd or more gasoline displaced) Excellent emission characteristics except for potential of somewhat higher NO_x emissions Gas is abundant worldwide Modest greenhouse advantage Can be made from coal	Dedicated vehicles have remaining development needs Retail fuel distribution system must be built Range quite limited, need large fuel tanks w/added costs, reduced space (LNG range not as limited, comparable to methanol) Dual fuel "transition" vehicle has moderate performance, space penalties Slower refueling Greenhouse problem if made from coal
Electric	Fuel is domestically produced and widely available Minimal vehicular emissions Fuel capacity available (for nighttime recharging) Big greenhouse advantage if powered by nuclear or solar Wide variety of feedstocks in regular commercial use	Range, power very limited Much battery development required Slow refueling Batteries are heavy, bulky, have high replacement costs Vehicle space conditioning difficult Potential battery disposal problem Emissions for power generation can be significant
Hydrogen	Excellent emission characteristics-minimal hydrocarbons Would be domestically produced Big greenhouse advantage if derived from photovoltaic energy Possible fuel cell use	Range very limited, need heavy, bulky fuel storage Vehicle and total costs high Extensive research and development effort required Needs new infrastructure
Reformulated Gasoline	No infrastructure change except refineries Probable small to moderate emission reduction Engine modifications not required May be available for use by entire fleet, not just new vehicles	Emission benefits remain highly uncertain Costs uncertain, but will be significant No energy security or greenhouse advantage

SOURCE: Office of Technology Assessment, 1990.

what a large-scale supply system would cost and how it would perform relative to the gasoline system. Key sources of uncertainty are:

- rapidly changing vehicle and fuel supply system technology;
- for most of the fuels, limited experience with transportation use, often confined to laboratory or prototype systems that don't reflect constraints imposed by mass production requirements or ''real world" maintenance problems;
- sensitivity of costs and performance to numerous (and difficult to predict) future decisions about regulating, manufacturing, financing, and marketing the fuel systems—for example, design decisions trading off vehicle performance and fuel efficiency; and
- continuing evolution of the competing gasoline-based system, for example, further improvements in catalytic controls.

In particular, most of the fuels have substantial potential for long-term technology advances that could drastically alter costs and impacts: advanced batteries for EVs, enzyme hydrolysis processes for producing ethanol from lignocellulose materials, and so forth.

Given these uncertainties and potentialities, projections of the costs and benefits of alternative fuels rely on a series of assumptions about technology successes, capital charges, feedstock costs, vehicle efficiencies, shipping methods, and so forth that are single points in a range of possible values. Changing these assumptions to other still-plausible values will change the cost and benefits results, sometimes drastically.

Meeting Society's Goals

Air Quality Effects

All of the fuels offer some potential to reduce urban ozone and toxic emissions. Hydrogen, electricity, and natural gas offer large and quite certain *per vehicle* reductions (though emissions from power generation must be considered in evaluating electricity's net impact on air quality). Methanol and ethanol (as M85 and E85, mixtures of the alcohols with 15 percent gasoline to improve cold starting), offer smaller and, at this time, less quantifiable but probably still significant reductions. For methanol, improved control of formaldehyde is critical to its emissions benefits. The potential for reformulated gasoline is speculative, because the makeup of this fuel is not yet known. *For most of the fuels, insuring that the potential benefits are actually obtained requires vehicle emission standards that properly account for the differences in chemical composition (and ozone-forming potential) between alternative fuel-related emissions and gasoline-related emissions.*

The areawide ozone-reduction benefits of all fuels are limited by projected reductions in the emissions "target' for the fuels-the share of urban ozone precursor emissions attributable to light duty vehicles. This share is expected to decrease from 45 to 50 percent during the mid to late 1980s to 25 to 30 percent by 2000.

Energy Security

The most likely near-term alternative fuels—reformulated gasoline, methanol, and CNG--do not offer the kinds of energy security advantages expected from options such as coal-derived liquid fuels, which rely on a domestic feedstock. Moderate quantities of CNG--enough to replace at least a few hundred thousand barrels per day of gasoline, perhaps somewhat more-could come from domestic and other North American sources; the rest would be imported by ship, as LNG, from distant sources. Most likely, virtually all methanol will be imported by ship. And reformulated gasoline, which merely reshapes gasoline rather than replacing it, should have little effect beyond that caused by the addition of oxygenates that may be made from natural gas or biomass. Nevertheless, use of methanol and CNG still can enhance energy security by reducing pressure on oil markets and diversifying to an energy feedstock (natural gas) whose resource base is less fully developed than oil's, and thus has a greater potential for new sources of supply—and a less easily manipulated market. The degree of additional security may be enhanced if the United States supports the development of secure methanol or LNG supply sources and if investors insist that supplier nations be large equity holders (and thus, risk-sharers) in the capital-intensive supply system.

The longer term options, e.g., hydrogen and electric vehicles, and ethanol or methanol from lignocellulosic materials, offer excellent energy security benefits if their costs are competitive with alternatives.

Global Warming

The potential of alternative fuels to affect greenhouse gas emissions is primarily a *long-term* potential. Those fuels and technological systems most likely to be used in the next few decades should *not* have a large impact, either positive or negative, on net emissions. For example, combustion of methanol or natural gas produces less CO_2 per unit of energy output than gasoline; however, producing and transporting these fuels will, in most cases, be more energy intensive than producing and transporting gasoline. Their net emissions of CO_2 and other gases, weighted by their relative warming impact and added over the entire fuel cycle, are likely to be only slightly smaller than the emissions generated by gasoline. Ethanol's net greenhouse emissions gain some benefit from the regrowth of the feedstock corn, but most or all of this benefit will be counteracted by other energy losses in the farming and fuel production system. Electricity for recharging EVs, if generated with today's power system, will rely heavily on coal-fired powerplants and cannot reduce greenhouse emissions significantly.

And reformulated gasoline is most likely to have slightly higher greenhouse emissions, assuming that refining energy will increase somewhat.

All of these fuels, and hydrogen as well, have the *long-term* potential to generate much lower levels of greenhouse gases if they turn to renewable, low-chemical-input biomass feedstocks or solar or nuclear-generated electricity. For example, both ethanol and methanol can be produced from wood and other lignocellulose material, methanol by gasification, ethanol by enzyme hydrolysis. Though neither process currently is economically competitive with standard alcohol production methods, further development of both processes should reduce costs. Electric and hydrogen-powered vehicles (the latter using hydrogen produced by electrolyzing water) can use electricity produced essentially without CO_2 emissions from nuclear or solar sources or biomass materials. Even gasoline can be produced by gasifying lignocellulose materials, with strong net greenhouse benefits. Also, for all the fuels, there are numerous shorter term efficiency improvements and process changes that can produce small reductions in net greenhouse emissions.

Other Key Issues

costs

Estimates of the likely cost of alternative fuels at the pump may plausibly vary over a wide range because of their dependence on assumptions about the relative success of solutions to existing technical problems, feedstock sources and prices, manufacturer design decisions, and other uncertain factors. OTA's examination of the potential costs of methanol, for example, reveals a range from below gasoline costs to 50 percent above gasoline costs. In a transition period when it is being introduced, however, methanol should be significantly more expensive than gasoline unless oil prices escalate during this period. Over time, costs could come down because of economies of scale realized as the system gets larger, better technology, and lower demanded returns as the supply system is stabilized and risk is reduced; on the other hand, at some point the natural gas feedstock costs will rise with increasing demand. The midpoint of the long-term cost range is somewhat higher than gasoline cost.

Similar wide ranges of potential costs apply to all of the fuels (except reformulated gasoline, which is expected to be perhaps $0.10 to $0.30/gallon more expensive than gasoline), though the ranges may be shifted upwards or downwards from methanol's range. Ironically, the cost to society of introducing alternative fuels will rise if gasoline conservation programs succeed in stopping the growth of gasoline demand, because the cost of new infrastructure for the fuels would not then be offset by a reduced need for new gasoline infrastructure.

Commercialization Hurdles

Commercialization of alternative fuels is made difficult by gasoline's entrenchment in the light-duty fuels market. Gasoline has the advantages of very large investments in existing supply infrastructure; long years of consumer acceptance and familiarity; and a regulatory structure for fuels handling and use designed specifically for that particular fuel. For example: with the exception of reformulated gasoline, which can be considered simply an additional, more expensive grade of gasoline rather than a true alternative, none of the alternative fuels will permit a vehicle to travel as far as would an equal volume of gasoline. For hydrogen, electricity, and CNG, the decrease in range is at least fourfold; for methanol, ethanol, and LNG, the difference is two to one or less. Other differences that can affect consumer acceptance include, for some but not all fuels, slower refueling, different handling requirements, and lower availability for several years after introduction. Consumer response to any of these differences, or to the design changes necessary to overcome them (for example, larger fuel tanks to overcome reduced range), is uncertain.

SUMMARY AND CONCLUSIONS

During the oil crises of the 1970s, Federal policymakers initiated a variety of programs designed to enhance U.S. energy security, mainly by supplementing or replacing gasoline with alternative fuels produced from domestic coal and oil shale. These programs generally were not viewed as successful, and they were largely abandoned with the perceived end of the oil crisis in the early 1980s.

During the past year, the debate on reauthorizing the Clean Air Act caused a resurgence of interest in alternative transportation fuels as an option for reducing ozone levels in urban areas that cannot otherwise meet air quality standards. In addition, the original concerns about energy security and the mounting trade deficit have reemerged as oil imports have grown rapidly over the past few years and as petroleum-driven conflict louves in the Middle East. A third concern—the possibility of greenhouse climate change—has increased interest in those alternative fuels that do not rely on fossil fuel feedstocks or that can otherwise offer a net reduction in greenhouse emissions.

The alternative fuels of primary interest for the U.S. fleet of automobiles and light trucks are:

- the alcohols methanol and ethanol, either alone or blended with gasoline;
- compressed or liquefied natural gas (CNG or LNG);
- liquefied petroleum gas (LPG) and propane;
- hydrogen; and
- electricity.

In addition, gasoline that has been reblended to reduce emissions, so-called ‘‘reformulated gasoline,’ is a recent addition to the list of new fuels. The fuels and their basic characteristics are described in box A.

This report provides abroad overview of the costs and benefits of introducing methanol, ethanol, natural gas, electricity, hydrogen, and reformulated

Box A—Alternative Transportation Fuels

gasoline-a motor vehicle fuel that is a complex blend of hydrocarbons and additives, produced primarily from the products of petroleum and natural gas. Typical octane (R+M/2[1]) level is 89.

methanol--commonly known as wood alcohol (CH_3OH), a light, volatile, flammable alcohol commonly made from natural gas. Volumetric energy content is about half that of gasoline (implies range for the same fuel volume is about half that for gasoline, unless higher efficiency is obtained), Octane level of 101.5, which allows use in a high compression engine. Much lower vapor pressure than gasoline (low evaporative emissions, but poor starting at low temperatures).

natural gas-a gas formed naturally from buried organic material, composed of a mixture of hydrocarbons, with methane (CH_d) being the dominant component. Octane level of 120 to 130. Volumetric energy content at 3,000 psi is about one-quarter that of gasoline.

liquid petroleum gas, LPG--a fuel consisting mostly of propane, derived from the liquid components of natural gas stripped out before the gas enters the pipeline, and the lightest hydrocarbons produced during petroleum refining.

ethanol—grain alcohol ($C_{25}OH$), generally produced by fermenting starch or sugar crops. Volumetric energy content is about two-thirds of gasoline. Octane level is 101.5. Much lower vapor pressure than gasoline.

hydrogen—H_2, the lightest gas. Very low energy density even as a cryogenic liquid, less than that of compressed natural gas. Combustion will produce no pollution except NO_x. Can be used in a fuel cell, as well as in an internal combustion engine.

electricity-would be used to run electric motors, with batteries as a storage medium. Currently available batteries do not attain a high energy density, creating range problems.

reformulated gasoline-gasoline that has been reblended specifically to reduce exhaust and evaporative emissions and/m to reduce the photochemical reactivity of these emissions (to avoid smog formation). Lower vapor pressure than standard gasoline (which reduces evaporative emissions), obtained by reducing quantities of the more volatile hydrocarbon components of gasoline. Addition of oxygenates to reduce carbon monoxide levels.

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[1] The average of research octane (R) and motor octane (M), which is the value found on the retail pump.

gasoline[1] into the U.S. light-duty fleet, and additionally provides more detailed analysis of a few particularly contentious issues such as the air quality impacts and costs of methanol use. This report is an interim product of an ongoing OTA assessment of *Technological Risks and Opportunities for Future U.S. Energy Supply and Demand. The* focus of the assessment and this report is the next 25 years in the U.S. energy system. While 25 years seems a long time period for projection purposes, it is short in terms of major transitions in energy sources, greenhouse warming strategies, and other similar concerns. Consequently, some of the longer term greenhouse options, such as using wood and other lignocellulose materials to produce methanol or ethanol, and the longer term greenhouse concerns such as the potential for an eventual turn to coal as a liquid fuel feedstock, are not addressed in detail in the report. However, policymakers addressing decisions for the short-term should recognize that decisions ranging from establishing research priorities to constructing new fuel infrastructures affect prospects for the longer term options.

A recent report from the National Research Council, *Fuels to Drive Our Future,*[2] discusses in detail the potential for producing motor fuels from domestic sources such as coal, oil shale, and biomass. Similarly, hydrogen as a potential motor fuel is addressed in a recent World Resources Institute report entitled *Solar Hydrogen: Moving Beyond Fossil Fuels.*[3]

The Perceived Benefits of Alternative Fuels

Ozone Control

Ozone control has become a primary driving force behind the push to alternative fuels because, 15 years after the passage of the original Clean Air Act, ozone pollution remains a serious national concern. About 100 cities, housing about half of the American population, do not meet the standard for ozone, the principal component of urban smog. At concentrations above the standard, ozone can cause coughing, painful breathing, and temporary loss of some lung function in healthy children and adults after exercising for about an hour or two. Medical concern centers as much-or even more-on possible chronic damage from long-term exposure as on short-term effects, although research on chronic risks is limited and inconclusive.

Ozone is produced when volatile organic compounds (VOCs) and nitrogen oxides (NO,) combine in sunlight. VOCs, a broad class of air pollutants that includes hundreds of specific compounds, come primarily from such manmade sources as automobile and truck exhaust, evaporation of solvents and gasoline, chemical manufacturing and petroleum refining (in some rural areas, however, natural emissions sources can dominate). NO_x arises from fossil fuel combustion. Major sources of NO_x include highway vehicles and utility and industrial boilers.

In a recent OTA study, *Catching Our Breath,*[4] *we* concluded that much of the Nation will still not be able to meet the goals of the Clean Air Act even by 2000. Over the next 5 to 7 years, available technology can lower summertime manmade VOC emissions by 35 percent (3.8 million tons/yr) compared to 1985 levels, bringing into compliance about half of all areas that now fail to attain the standard for ozone. Existing control methods can substantially improve the air quality of the other half of the areas, but meeting the ozone standard in these areas will require new, innovative, and nontraditional control methods.

The Nation has already failed several times to meet the deadlines set by Congress--first in 1975 and again in 1982 and 1987. In *Catching* ***Our*** *Breath, we* stated that when amending the Act, Congress must include *both* measures to achieve near-term emissions reductions using today's control methods and measures to insure that the Nation can continue to make progress after 2000. We view alternative fuels as one of several promising longer term measures.

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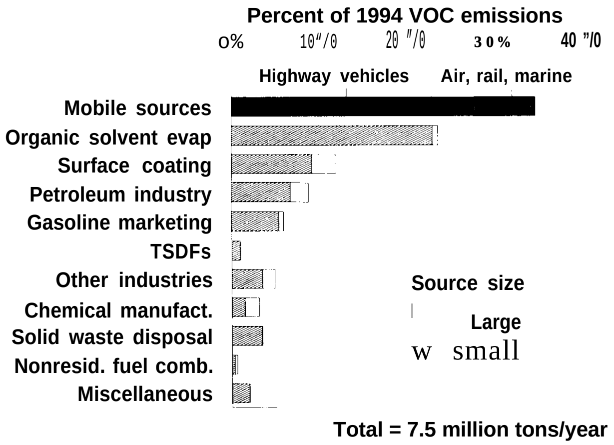
[1] LPG is not addressed because its supply limitations prevent it from playing a major long-term energy security role. Were alternative fuels use be confined to the primary ozone nonattainment cities, LPG would be a viable option.

[2] Committee on Production Technologies for Liquid Transportation Fuels, National Research Council, *Fuels to Dive Our Future* (Washington, DC: National Academy Press, 1990).

[3] J.M. Ogden and R.H. Williams, *Solar Hydrogen: Moving Beyond Fossil Fuels* (Washington, DC: World Resources Institute, October 1989).

[4] U.S. Congress, Office of Technology Assessment, *Catching Our Breath: Next Steps in Reducing Urban Ozone*, OTA-O-412 (Washington, DC: U.S. Government Printing Office, July 1989).

Figure I—Volatile Organic Compound (VOC) Emissions in Nonattainment Cities in 1994, by Source Category, After All Additional Control Methods Are Applied



Stationary sources that emit more than 50 tons per year of VOC are included in the "Large" categories. (See figure 2-3 for 1985 emissions in nonattainment cities before additional controls applied.)

SOURCE: Office of Technology Assessment, 1989.

Ozone control efforts have traditionally focused on reducing VOC emissions. As shown in figure 1, about 25 to 30 percent of VOC emissions remaining after today's controls are applied will come from cars and trucks. Programs to introduce cleaner, alternatively fueled vehicles by using, for example, methanol or compressed natural gas (CNG) instead of gasoline, should lower emissions further, as would measures to reduce the Nation's use of cars.

Another quarter of the remaining VOC emissions will come from solvents used in a wide variety of industrial, commercial, and home uses, from painting and cleaning heavy equipment to washing paintbrushes. Further control of these sources is possible. And for some areas, controlling NO, emissions in addition to VOCs maybe an important ozone control measure, both locally and in areas upwind of certain nonattainment cities.

How do alternative fuels fit into the Nation's ozone control requirements? All of the fuels discussed here have the *potential* to reduce either (or both) the mass emissions of VOCs from highway vehicles or the reactivity of the VOCs, that is, their likely contribution to ozone formation per gram of gas emitted. The attractiveness of using alternative fuels as an ozone control measure clearly depends on the costs and effectiveness of such use relative to the costs and effectiveness of competing measures. As discussed below, the costs of alternative fuel use are as yet quite uncertain, while the effectiveness is reasonably well known only for some of the fuels.

An additional uncertainty is the extent to which further improvements maybe achieved in emission controls for gasoline-fueled vehicles. If highway vehicles' share of urban VOC emissions is reduced even below the projected 25 to 30 percent level representing the frost round of emission requirements expected from the new Clean Air Act, the emissions reduction benefits of moving to the alternative fuels will be reduced.

Aside from controlling ozone, alternative fuels should help to reduce the emissions of toxic pollutants associated with gasoline use. These include benzene, gasoline vapors, 1,3-butadiene, and polycyclic organic matter. With the exception of methanol vehicles' increased emissions of formaldehyde, use of the alternative fuels is not likely to produce any counterbalancing emissions of similar toxicity. And with methanol vehicles, their higher direct emissions of formaldehyde are partly offset in the ambient air by the shift in VOC emissions associated with methanol use. Some of the VOCs are chemically transformed in the atmosphere into formaldehyde, and a methanol vehicle is a smaller "indirect" source of formaldehyde than a comparable gasoline vehicle.

Energy Security

After a few years of quiescence, energy security has again become a major U.S. concern. The key statistic driving that concern is the annual level of net U.S. oil imports, which had dropped to 27 percent of requirements by 1985 but rose to 46 percent in 1989, and continues to rise steadily as U.S. oil production drops. As illustrated by figure 2, which displays the Energy Information Administration's latest forecast, U.S. oil imports are expected to grow rapidly over the next few decades, to nearly 61 percent of demand by 2010 in the base cases The United States paid $44.7 billion for its 1989 oil imports, representing nearly half of its merchandise trade deficit of$111 billion, and expenditures would

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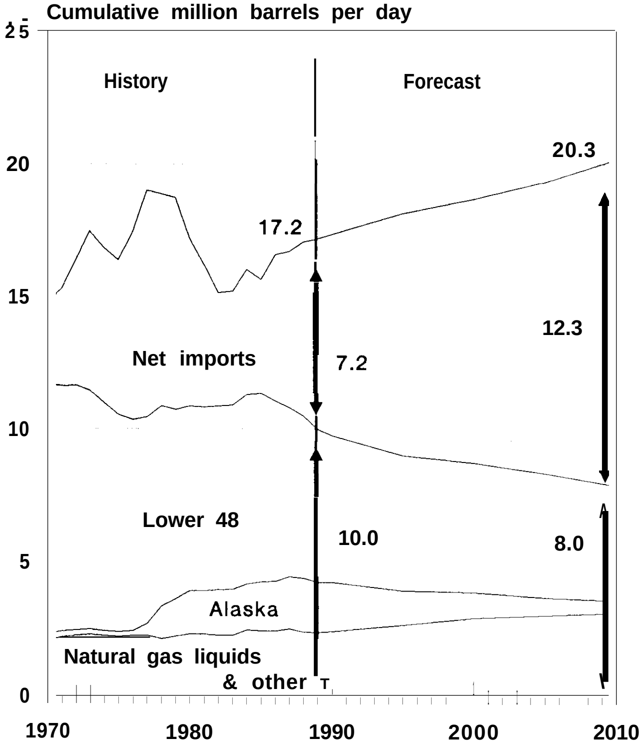
[5] Energy Information Administration, *Annual Energy Outlook 1990,* DOE/EIA-0383(90), January 1990.

Figure 2—EIA Projections of Petroleum Supply, Consumption, and Import Requirements to 2010, Base Case



SOURCE: Energy Information Administration, *Annual Energy Outlook, 1990.*

rise with expected increases in import volumes and oil price. As in the 1970s, four basic elements underlie the concern: the near-total dependence of the U.S. transportation sector on petroleum; the United States' limited potential to increase oil production; the preponderance of oil reserves in the Middle East/Persian Gulf area; and the political instability and hostility to the United States existing in parts of that area.

In some ways, the first two of these elements have grown more severe since the energy crises of the 1970s. During the past 10 years, the share of total U.S. petroleum use by the transportation sector—whose prospects for fuel switching in an emergency are virtually zero-has grown from 54 to 64 percent. In addition, the prospects for a rapid rebound of U.S. petroleum production in the event of a price rise seem weaker than in the 1970s. The boom and bust oil price cycle of the post-boycott period, and especially the price drop of 1985-86, has created a wariness in the oil industry that would substantially delay any major boost in drilling activity in response to another price surge. And, with the passage of time, the industry's infrastructure, including skilled labor, that would be needed for a drilling rebound is eroding.

Despite these problems, OTA concludes that, on balance, the United States' energy supply is somewhat more secure today than in the 1970s. Shifts in the oil market that we consider to be supportive of increased short- to medium-term energy security include:

- the existence of the Strategic Petroleum Reserve and increased levels of strategic storage in Europe and Japan;
- increased diversification of world oil production since the 1970s, with OPEC losing 17 percentage points of world market share from 1979-89;
- the end of U.S. price controls on oil and most natural gas, allowing quicker market adjustment to price and supply swings;
- the increasing role of the spot market, adding flexibility to oil trade;
- the major investments of OPEC producers in the economies of the Western oil-importing nations, especially in their oil-refining and marketing sectors;
- the lessening importance of the Strait of Hormuz as a potential bottleneck due to the construction of new pipelines out of the Persian Gulf; and
- the recent political changes in the Eastern Bloc nations and lowering of East-West tensions.

Nevertheless, energy security concerns remain an important policy driver, and their importance could grow over time if current trends in U.S. oil supply and production continue and, as expected by many analysts, OPEC market power continues to grow. Futher, important and unsettling shifts in military power balances in the Middle East, in particular the greatly increased military capability of Iraq, introduce an important uncertainty into energy security assessments.

The development of alternative transportation fuels can have a positive effect on energy security, by:

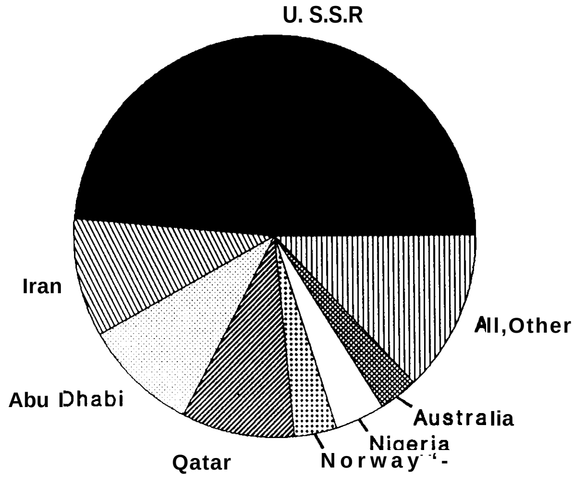
- diversifying fuel supply sources and/or getting supplies from domestic or more secure foreign sources,
- easing pressure on oil supplies through reduced demand for gasoline, and

- reducing the impact of an oil price shock.

The magnitude of the effect will depend on such factors as the feedstock used for the fuel and strategic arrangements for obtaining the feedstock or fuel, the volume of alternative fuel use, and the selection of dedicated vehicles or flexible fuel vehicles. The effect on energy security could be negative, however, if any Federal subsidies of the price of "secure" energy sources are too high, or regulatory requirements for their use too costly. The availability of ample foreign exchange is a powerful weapon in an energy emergency, so that the financial impact of an alternative fuels program that had a large negative net impact on the overall U.S. trade balance and/or on the Federal deficit conceivably could outweigh the positive value of reduced oil imports.

Although the security benefits of some fuels are indisputable, analysts disagree about others. Fuels such as electricity, hydrogen, and ethanol are likely to be domestically produced and thus unambiguously advantageous to energy security (if they can be produced cheaply enough). Corn-based ethanol's dependence on intensive agriculture, which may suffer on occasion from drought, may make it less secure than the others, however. Methanol or natural gas, on the other hand, will be imported from countries with large gas reserves (though a moderate level of natural gas vehicle use, perhaps up to several hundred thousand barrels per day of oil substitution, could be supported using North American gas sources), and their effect on energy security will depend on which countries enter the market, the type of financial arrangements made between producers and suppliers (the large capital requirements of a methanol or LNG supply system could enhance the stability of supply, but only if the producer nations are large equity holders), the worldwide price relationship between natural gas and oil (that is, will a large oil price rise automatically raise gas—and methanol-prices?), and other factors. Because two-thirds of the world's gas reserves, and a higher estimated share of the world's exportable gas surpluses (figure 3), reside in the Middle East and Eastern Bloc, some analysts deny that the United States would receive any security benefit from turning to natural gas-based methanol. OTA concludes that the Nation *can* derive a security benefit because large-scale methanol use will reduce pressures on world oil supplies; also, strategies such as establishing long-term trade pacts with secure methanol sources could enhance the potential benefits.

Figure 3--World Exportable Gas Surplus as of Dec. 31,1987



SOURCE: Jensen Associates, Inc., ***Natural Gas Supply, Demand, and Price,*** **February 1989.**

Another way to enhance energy security maybe to produce alternative fuels from domestic coal-an option not explored in this report. Problems with the use of coal include its adverse impact on greenhouse warming (unless the CO_2 produced can be captured and stored, which seems unlikely) and its high costs, though these may be lowered over time. Similarly, alternative fuels can be made from wood and other lignocellulosic materials, with substantial greenhouse benefits if the use of agricultural chemicals is minimized and the feedstock is managed in a truly renewable fashion.

The availability of a domestic feedstock is not confined to the alternative fuels; *gasoline* can be made from coal and wood. In fact, gasoline can be made from natural gas as well. Clearly, the energy security benefits associated with a particular fuel have little to do with that fuel's chemical makeup, and much to do with its feedstock materials.

Global Warming

The potential need to slow and reverse the growth of worldwide emissions of carbon dioxide ($C0_2$) and other greenhouse gases has altered thinking about energy supply sources, enhancing the perceived value of sources that do not use fossil fuels or that use fuels low in carbon.

The greenhouse effect is a warming of the Earth and atmosphere as the result of the thermal trapping of incoming solar radiating by CO_2, water vapor, methane, nitrous oxide, chlorofluorocarbons, and other gases, both natural and manmade. Past and ongoing increases in energy use and other anthropogenic (man-caused) emissions sources are pushing up atmospheric concentrations of these gases; CO_2 concentrations, for example, have increased by about 25 percent since the mid- 1800s. Scientists believe that these growing concentrations will lead to significant global temperature increases: a global average of 3 to 8 'F (1.5 to 4.5 'C) from a doubling of CO_2 concentrations or the equivalent.[7] Other effects of the warming include an expected rise in sea level, drastic changes in rainfall patterns, and increased incidence and severity of major storms.

Despite a substantial scientific consensus about the likely long-term change in average global temperatures, there is much disagreement and uncertainty associated with the rapidity of the changes, the effects of various temperature feedback mechanisms such as clouds, the role of the ocean, the relative greenhouse effect of the various gases, regional impacts, and other factors. These uncertainties affect arguments about the value of alternative fuels; for example, uncertainties about the differential role of the various greenhouse gases complicate analyses of the relative impact on warming of the various fuels, because each fuel emits, over its fuel cycle, a different mix of gases.

To what extent are the potential users of alternative fuels-in this case, light-duty vehicles-a major source of greenhouse gases, and thus a good target for action to reduce emissions? The U.S. light-duty fleet accounts for about 63 percent of U.S. transport emissions of CO_2, 3 percent of world CO_2 emissions, and about 1.5 percent of the total greenhouse problem. This latter value has been variously interpreted as being a significant percentage of the greenhouse problem, or as proving that focusing on the U.S. fleet to gain significant greenhouse benefits is a mistake. In OTA's view, few if any sectors of the U.S. economy are large enough, *by themselves*, to significantly alter the course of greenhouse warming; ignoring all emissions sources as small as the light-duty fleet would eliminate most options to curb the greenhouse effect. Further, U.S. adoption of alternative fuels will increase the likelihood that other nations will do the same. The U.S. fleet's emissions thus understate the potential benefit of U.S. action.[8] To successfully combat global warming, nations must be prepared to take actions that will have an important effect only over the course of decades and in concert with similar actions taken on a global scale.

Alternative fuels for light-duty vehicles are of concern for global warming for the following reasons:

1. *The fuels generate, over their fuel cycle, different amounts and mixes of greenhouse gases than does gasoline. In* general, however, the fuels and feedstock choices most likely for the near term-in particular, methanol from natural gas and natural gas itself-have the potential for only modest benefits over gasoline in their overall greenhouse effect; and reformulated gasoline would offer no benefits. Methanol and ethanol made from wood, which might become practical with further development of gasifiers (methanol) and enzyme-based conversion processes (ethanol), would yield significant greenhouse benefits. The longer term choices, e.g., hydrogen and electricity based on nonfossil sources, can yield very significant benefits. In contrast, fuels derived from coal-including gasoline-from-coal-would yield substantial increases in greenhouse gases over ordinary gasoline.
2. *Current choices about alternative fuels may influence future fuel choices with significant greenhouse effects.* For example, turning to natural gas as a feedstock for transportation fuels might conceivably have the effect of delaying a transition to nonfossil fuels, by holding down oil prices, providing additional fossil supplies, and, perhaps, by being more attractive than gasoline in some regards. As

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[6] That is, the incoming solar energy is reradiated by the Earth as heat (thermal energy) and then absorbed or 'trapped" in the atmosphere rather than radiating out to space.

[7] That is, other gases have a warming effect that is some multiple of CO_2's effect, so a combination of increases of various gases can be translated into an effective CO_2 increase by appropriately weighting the increased concentration of each gas.

[8] OTA's Oceans and Environment Program currently is conducting a study on policy options to curb U.S. greenhouse emissions, ***Climate Change: Ozone Depletion and the Greenhouse Effect.***

another example, building an EV system will generate electricity load growth that, by flattening the daily demand curve, could encourage utilities to consider nuclear plants (with zero CO_2 emissions) for their new generation capacity, since nuclear is most economical serving this type of demand pattern. Further, building of new infrastructures for near-term alternative fuels may affect our ability to move to longer term fuels, e.g., a natural gas system might possibly ease the way for hydrogen, another gaseous fuel, whereas the construction of a new infrastructure for methanol may hinder the later adoption of a system using gaseous fuels. And finally, premature introduction of any technology can have sharply negative effects on future consumer acceptance of that technology. The importance of these effects is extremely sensitive to the timing of technology development and other uncertain factors and, as shown by the example of natural gas, there may be plausible greenhouse arguments both for promoting the commercialization of a particular fuel, and for opposing such commercialization.

Introducing Alternative Fuels Into the Light-Duty Fleet

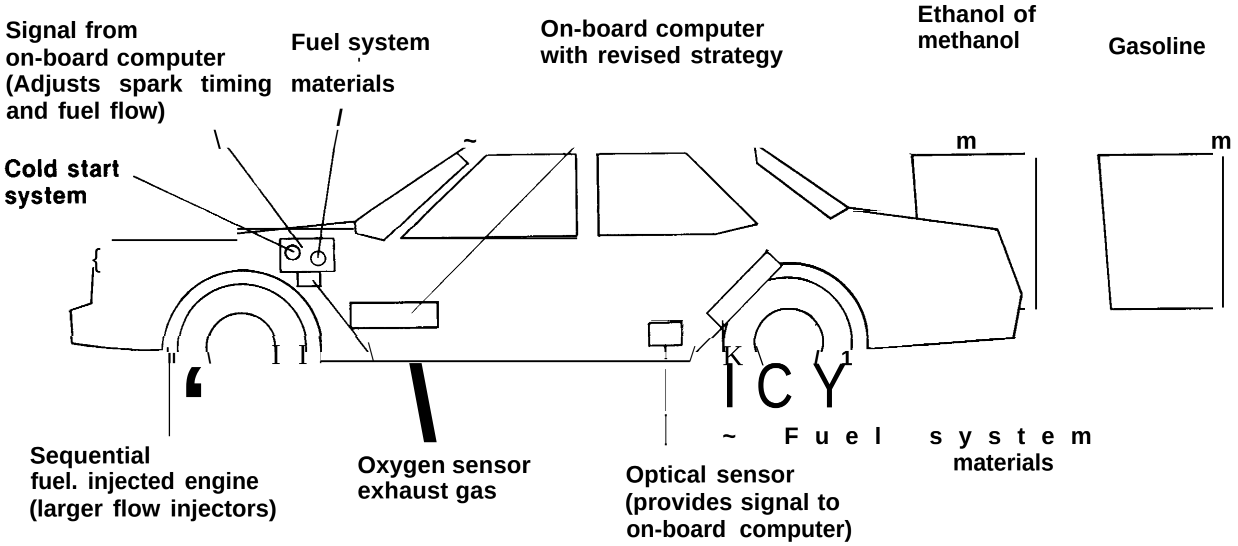
Although the physical characteristics of the alternative fuels are in some ways superior to that of gasoline, there are substantial barriers to introducing such fuels into transportation markets. Aside from the potential that the alternative fuels will cost more to produce than gasoline, these fuels have limited or no established transportation markets or infrastructure, whereas gasoline has both. The physical system for producing, storing, and distributing gasoline is in place and operating smoothly; massive amounts of capital and engineering time have been invested in engine modifications to optimize performance for gasoline; the regulatory system for controlling the safety and environmental impacts of light-duty vehicles is designed specifically for gasoline; and most consumers have a close familiarity with and acceptance of gasoline and its capabilities and dangers. In contrast, important facets of the infrastructure for the alternative fuels will have to be built virtually from scratch, the fuels will alter vehicle performance, in some ways for the worse (particularly with regard to range), and they will introduce new dangers, though possibly easing old ones associated with gasoline. It is difficult to predict how consumers will react to these differences in fuel characteristics.

With a few exceptions (electric and CNG vehicles designed to be recharged at home), the fuel distribution network will be severely limited geographically in the early years of an alternative fuels program. Consequently, early vehicles will either be limited in operation to those areas with available fuel supplies or, more likely, will be designed to operate as multifuel vehicles. For example, prototype flexible fuel vehicles (FFVs) can operate on any blend of gasoline and either methanol or ethanol up to about 85 percent alcohol (at higher concentrations, cold starting is a problem). As shown in figure 4, several vehicle systems must be modified to allow the vehicle to operate in this mode. Commercially available dual-fuel vehicles can operate on either gasoline or natural gas by the flip of a switch. And hybrid electric vehicles (EVs) would combine a battery/electric motor combination with a fuel tank and either a small internal combustion engine or a fuel cell.

To gain increased travel flexibility over single-fuel vehicles, multifuel vehicles must sacrifice some potential advantages afforded by the alternative fuels' special characteristics. For example, methanol, ethanol, and natural gas are high octane fuels; a vehicle dedicated to their use, which did not have to operate well on gasoline, could use a high compression engine with improved efficiency and power. To retain operability with gasoline, engines in multifuel vehicles must stay at lower compression levels. Consequently, as fuel availability for the alternative fuels improves over time, manufacturers are likely to shift their production lines towards vehicles dedicated to these fuels, with significantly improved performance and efficiency.

The large barrier to commercialization of alternative fuels caused by gasoline's entrenchment in the market, coupled with the likelihood that, *at least in the beginning,* alternative fuels will be more costly than gasoline, implies that alternative fuels may get a decent chance for market share only if government gives them a strong push. The primary dilemma for government policymakers is, then, is it worthwhile to do so? The alternative fuels certainly do have some intriguing potential, as discussed below, but they also have disadvantages and risks. A reasoned decision concerning government incentives for these

Figure 4—Technical Difference Between Flexible-Fuel and Conventional Automobiles



SOURCE: Ford Motor Co.

fuels requires a dispassionate analysis of these fuels' pros and cons relative to gasoline.

Conclusions about the costs, problems, and likely performance of the alternative fuels are based on a variety of evidence. First, their long use in nonvehicular applications has yielded considerable experience with distributing and handling the fuels. Second, many of the fuels have been used in vehicles for years, and although these vehicles perform less well than advanced vehicles are expected to, much of this experience still is relevant to projections of future, wider use. Third, limited testing of advanced vehicle prototypes has begun to clarify the potential of the fuels, as well as their problems. And fourth, unlike gasoline, which is a complex and nonuniform blend of hydrocarbons, most of the suggested alternative fuels have simple chemical structures and are relatively uniform in quality, which should help improve the accuracy of performance projections.

Despite this evidence, participants in the alternative fuels debate disagree sharply about virtually all aspects of fuel performance and cost. Part of these disagreements undoubtedly are due to the usual hyperbole associated with strong and opposing commercial interests and environmental values. There also are strong *technical* reasons, however, why the disagreements exist. In particular:

1. Changing technology. The technology for producing alternative fuels is still developing and changing, with the outcome of development and problem-solving programs highly uncertain. For example, full success of ongoing research on low-cost manufacture of ethanol from lignocellulose materials (e.g., wood waste) would radically improve ethanol's environmental and economic attractiveness. Similarly, successful development of catalysts that can reliably control exhaust formaldehyde levels over a vehicle lifetime would enhance significantly the standing of methanol as an option for ozone control.
2. Moving from lab to marketplace. The transition from successful research project to commercial, mass-produced product is a complex process involving massive scaleups and design and performance trade-offs. The unpredictability of this process limits the reliability of projections based only on laboratory or vehicle prototype testing. In particular, consumer reactions to differences in vehicle and fuel distribution characteristics (shorter range or less luggage space, slow refueling, less or more power, etc.) will profoundly influence system design, yet these reactions will become clear only as the fuels are introduced, and they might still change over time.
3. Effects of program size. The scale of alternative fuels development is a key determinant of the costs and characteristics of fuel supply systems and vehicles, yet there is little possi-

bility of predicting how large a program would be, or if it were likely to spread worldwide. For example, domestic gas sources or pipeline imports from Canada or Mexico could supply a moderate-sized program of natural gas vehicles, but larger scale development would require LNG imports from abroad—with different costs and energy security implications.

4. Continued evolution of the gasoline system. The relative benefits of any new alternative fuel depend on its comparison with the gasoline system, and this system may change markedly within the next decade. For example, there is some evidence that improved catalytic converters will reduce the photochemical reactivity of exhaust emissions from gasoline-fueled vehicles and thus reduce ozone formation from these vehicles. If confirmed, this would reduce the *relative* benefits of alternative fuels.

Although it may be impossible to rank the alternative fuels in a reamer that is relatively impervious to shifting assumptions and conditions, it *is* possible to describe the major advantages and disadvantages of the alternatives and to show the kinds of conditions that would tend to favor or discourage them.

Methanol's major advantages in vehicular use are that it is a convenient, familiar liquid fuel that can readily be produced from natural gas using well-proven technology; and as a blend of 85 percent methanol/15 percent gasoline (M85), it is a fuel for which vehicle manufacturers can, with relative ease, design either a dedicated or flexible fuel vehicle (FFV) that will outperform an equivalent gasoline vehicle and obtain an advantage in some combination of emissions reduction and efficiency improvement. The availability of a ''transition vehicle"--the M85 FFV--with few drawbacks from, and some advantages over, a gasoline-fueled vehicle is particularly important because it greatly eases the difficulties of introducing methanol into the fleet. Another important advantage of methanol is that world resources of natural gas, its primary feedstock, are plentiful.

Methanol can also be made from coal, though at higher costs and environmental impacts than from natural gas. As noted earlier, this does not represent an advantage over gasoline because gasoline too can be made from coal. Methanol also can be made from wood and other lignocellulose materials, though at still higher costs with current technology. Substantial improvements in wood gasifiers appear likely with further research.

Major disadvantages of methanol are the likelihood that it will cost more than gasoline, especially during the early years of a methanol fuels program; loss of as much as half of the driving range without a larger fuel tank; the loss of some of the air pollution benefits if FFV users frequently select gasoline instead of M85; and the need for a separate fuel delivery infrastructure. Methanol is more toxic than gasoline, and there is concern that accidental poisonings could increase with development of methanol fuels programs. However, methanol's lower flammability would likely lead to substantial reductions in injuries and fatalities from vehicle frees, probably more than offsetting any rise in poisonings.

The use of methanol made from natural gas is unlikely to provide a large greenhouse benefit, no more than a 10 percent reduction in net emissions with quite optimistic assumptions. Methanol from coal would be a large net greenhouse loser without some way of disposing of the CO_2; methanol produced from woody biomass could be a strong greenhouse net winner, though it would introduce other environmental concerns.[9]

Although methanol would likely be imported,[10] it could play a positive security role because of the nature of the suppliers or differences between the oil and methanol markets. There are enough potential suppliers of methanol in relatively secure areas that a concerted effort at promoting specific preferred supply sources-through trade agreements or other means[11]--could bring the United States significant benefits over dependence on Middle Eastern oil. Several South American nations as well as Trinidad and Australia have sufficient reserves and locational advantages to be viable methanol suppliers (figure 5 shows the locations of gas-rich areas that could

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[9] Especially about the *long-term* renewability of the wood feedstock.

[10] The North Slope of Alaska does contain enough reserves of natural gas to be a technically viable methanol supplier to the lower 48 States, but North Slope methanol would not be competitive economically with methanol from other sources. However, the United States does, of course, retain the option of subsidizing North Slope methanol production (or forcing industry to subsidize it via legislative mandate) for energy security purposes.

[11] There may, however, be difficulties with fair trade agreements were the United States to attempt to establish such a closed fuel market relationship.

Figure 5—Potential Low-Cost Suppliers of Methanol

SOURCE: Energy and Environmental Analysis, Inc., 1988.

become low-cost suppliers of methanol[12]). And because natural gas development is decades behind oil development, with a much greater proportion of gas reserves still undeveloped, entry into the market of new suppliers is much easier for methanol than it is for oil-adding to market stability. And finally, the high capital investments necessary to develop methanol supplies bring further stability to markets, by increasing the financial costs to the supplier of a trade cutoff.

Under certain circumstances, the energy security of developing methanol as a transportation fuel might last only for a few decades. After a period of rapid resource development, if large new reserves of natural gas are not found, market power could evolve towards the holders of the largest blocks of resources-the Middle Eastern OPEC countries and the Eastern Bloc. At this time, security advantages of these alternative fuels could fade. Of course, if the current positive shift in the strategic relationship between the West and the Eastern Bloc continues, reliance on these nations might seem quite acceptable from a security standpoint.

Proposals for introducing methanol into ozone nonattainment areas have been extremely controversial, because competing claims about its expected costs and air quality benefits have varied over an unusually wide range.

Claims for the "per vehicle" reduction in ozone forming potential available by substituting M85 for gasoline range from 30 percent or higher (Environmental Protection Agency, California Air Resources Board) to little or none (some industry and consultant studies). Although considerable effort has been expended to estimate the ozone impacts of introducing M85 vehicles, especially for the Los Angeles Basin, a number of factors confound the estimates and lead OTA to conclude that M85 has significant *but poorly quantified and highly variable* potential to reduce urban ozone. In particular, there have been few tests of M85 vehicles that have measured the individual compounds in their emissions, even though such ''speciation' of emissions is important in accurately determining their photochemical reactivity. Other confounding factors include the essentially prototype nature of available methanol vehicles, potential future changes in the reactivity of *gasoline* exhausts (altering the trade-off between methanol and gasoline), and uncertainty about future progress in controlling formaldehyde emissions. And whatever net emissions changes are caused by using methanol vehicles, the effect of these changes on levels of urban ozone will vary with location and meteorological conditions. Ozone benefits from reduced organic emissions will occur only in urban areas where ambient concentrations of volatile organic compounds are low enough, relative to NO_x concentrations, that reducing organic emissions is an effective ozone strategy. In a few urban areas—Atlanta, for example-and in many rural areas, controlling NO_x, is a more promising ozone control strategy, and methanol use would provide little or no ozone benefits. To conclude, we do not reject the 30 percent reduction as a possible *average* effect, but some of the available data suggest smaller benefits, and whatever the average effect, the actual outcome would vary widely around that average.

Claims about the expected costs of methanol similarly have ranged from "competitive with and possibly below gasoline costs" to "much higher than gasoline. " Much of the range can be accounted for by legitimate differences in assumptions about the scale of a methanol program, likely gas feedstock sources, capital risk factors, and so forth. The extremes of the range, however, tend to assemble several low probability assumptions (either all optimistic or all pessimistic) together at once, and in a few instances choose values for key parameters that seem unlikely. OTA concludes that methanol will most likely be more expensive than gasoline (at current prices) in the early stages of an alternative fuels program. There may, however, be a few countries willing to subsidize some methanol production to obtain hard currency or for other reasons, making available a modest supply at low cost. Without government guarantees, the methanol's gasoline-equivalent price is likely to be at least $1.50/gallon during this period; government guarantees could bring it down as low as $1.20 if natural gas feedstock costs were very low. If the program were to grow quite large over time and were perceived to be stable, scale economies and lower costs of capital would significantly lower methanol costs relative to gasoline, with the lower end of the range dipping below $1.00/equivalent gallon. However, the uncertainty of the costs, and their sensitivity to various government decisions and other factors, remains

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[12] Some areas, especially the Alaskan North Slope and Canadian frontier, would require technological advances to become low-cost suppliers.

Table 2—Two Scenarios of Methanol Costs, $/Gallon (Base Cases: $l.OO/mmBtu[a] natural gas cost)

	Scenario	
Part of fuel cycle	Transition period, free market scenario few guarantees, flex fuel vehicles (cost, $/gallon)	Established market, some government guarantees, dedicated vehicles (cost,$/gallon)
Production	0.55-0.65	0.28-0.30
Shipping	0.03-0.08	0.02-0.03
Distribution	0.03	0.05-0.06
Markup	0.09-0.12	0.06-0.09
Taxes	0.12-0.13	0.12
Retail price	0.82-1.01	0.53-0.60
Midrange price	0.85-0.95	0.53-0.60
Efficiency factor	1.9	1.67-1.82
Gasoline equivalent price	1.61-1.81	0.89-1.09
Gasoline equivalent prices if natural gas costs change		
$0.50/mmBtu gas	1.51-1.71	0.81-1.06
$1.50/mmBtu gas	1.71-1.81	0.96-1.15

[a] mmBtu = millions of British thermal units

SOURCE: Office of Technology Assessment.

very high. Table 2 illustrates the components to two cost ‘‘scenarios” that represent relative extremes in methanol/gasoline competitiveness.

Methanol prospects for market success would benefit from the following:

- commercialization of direct oxidation methods of methanol production from natural gas (see figure 6),
- development of a world trade in methanol produced from remote sources of natural gas,
- freer evidence of major air quality benefits, particularly in cities other than Los Angeles,
- development of practical cold-starting methods for M1OO, and
- development of improved controls for formaldehyde emissions.

Ethanol is, like methanol, a familiar liquid fuel that can be quite readily used, with few problems, in vehicles competitive in performance with gasoline-fueled vehicles. Important advantages are its ease of use as a fuel component of gasoline suitable for existing vehicles and its attractiveness as a stimulus to the farm economy, since its primary feedstock is corn.

Ethanol made from food crops appears to be the most expensive of the major alternative fuels. Current ethanol production is profitable only because of a $0.60/gallon subsidy provided by the Federal Government through exemption of “gasohol,” a 10 percent blend of ethanol with gasoline, from $0.06/gallon of Federal gasoline taxes. Some farm States allow gasohol a further exemption from State taxes.

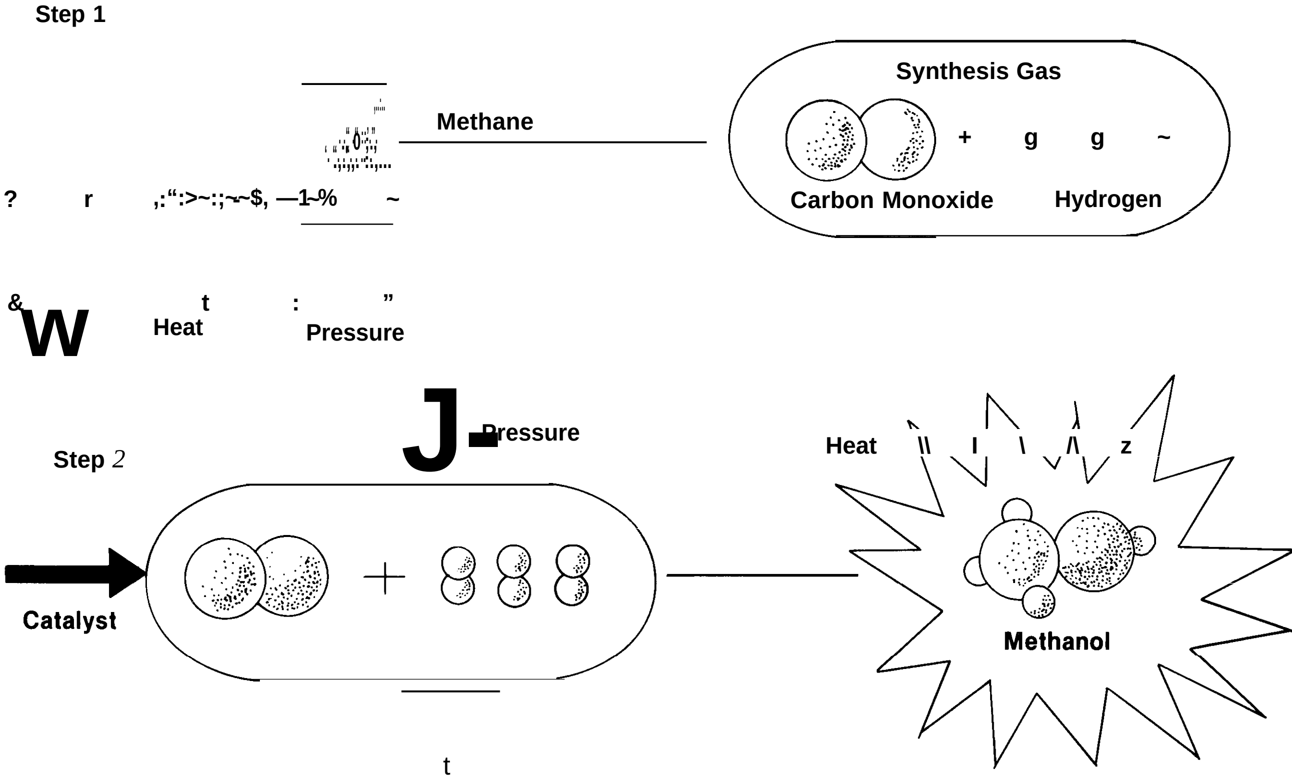
Under certain grain market conditions, ethanol production may generate reductions in required Federal crop subsidies and other significant secondary economic benefits to the Nation (aside from the benefits generated by *any* reduction in oil use). Under other conditions, however, it may generate large secondary costs. In particular, a major expansion of ethanol use might raise the Nation’s food bill by billions of dollars.

The environmental effects of increasing corn production for ethanol manufacture are a matter of concern, because corn is an energy-intensive, agricultural-chemical-intensive, and erosive crop (see table 3). The net environmental impacts of ethanol use will be highly dependent on the overall adjustment of the agricultural system to large-scale ethanol production. The stillage byproduct of ethanol production is a high protein cattle feed that can displace soybean production. As long as this displacement occurs, the net agricultural impacts such as soil erosion and pesticide use are reduced; if byproduct markets become saturated, net environmental impacts may increase sharply. The level of ethanol production that would saturate the byproduct market is uncertain.

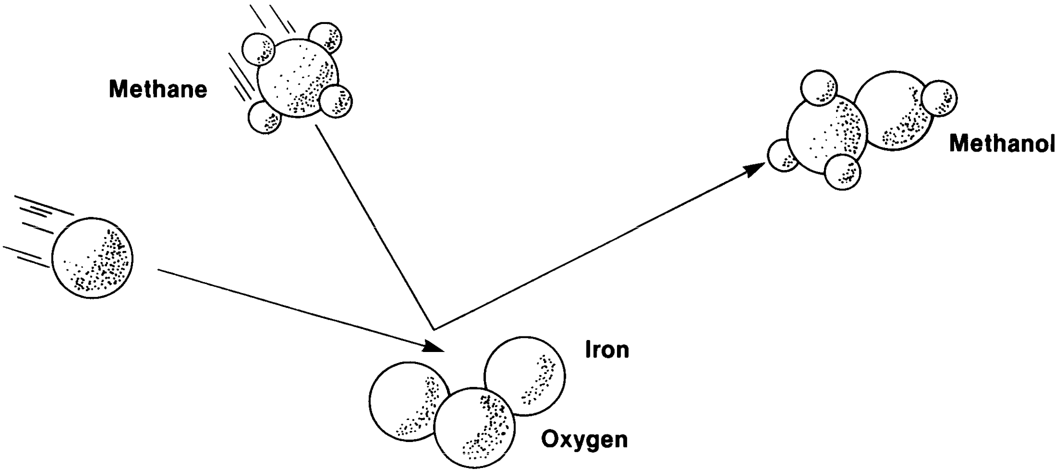
An important claim made for crop-based ethanol is that it will generate significant greenhouse bene-

Figure 6-Converting Methane to Methanol

Making methanol from methane with today’s technology generally involves a two-step process. The methane is first reacted with water and heat to form carbon monoxide and hydrogen—together called synthesis gas. The synthesis gas is then catalytically converted to methanol. The second reaction unleashes a lot of heat, which must be removed from the reactor to preserve the activity of the temperature-sensitive catalyst. Efforts to improve methanol synthesis technology focus on sustaining catalyst life and increasing reactor productivity.



In a novel alternative to the two-step method, chemical catalysts are being developed that mimic the biological conversion of methane by enzymes. The iron-based catalyst captures a methane molecule, adds oxygen to it, and ejects it as a molecule of methanol. If this type of conversion could be performed on a commercial scale, it would eliminate the need to first reform methane into synthesis gas, a costly, energy-intensive step.



SOURCE: *EPRI Journal,* “Methanol: A Fuel for the Future?” October/November 1989.

Table 3-Environmental Impacts of Agriculture

Water
- Water use (irrigated only) that can conflict with other uses or cause ground water mining.
- Leaching of salts and nutrients into surface and ground waters, (and runoff into surface waters) which can cause pollution of drinking water supplies for animals and humans, excessive algae growth in streams and ponds, damage to aquatic habitats, and odors.
- Flow of sediments into surface waters, causing increased turbidity, obstruction of streams, filling of reservoirs, destruction of aquatic habitat, increase of flood potential.
- Flow of pesticides into surface and ground waters, potential buildup in food chain causing both aquatic and terrestrial effects such as thinning of egg shells of birds.
- Thermal pollution of streams caused by land clearing on stream banks, loss of shade, and thus greater solar heating.

Air
- Dust from decreased cover on land, operation of heavy farm machinery.
- Pesticides from aerial spraying or as a component of dust.
- Changed pollen count, human health effects.
- Exhaust emissions from farm machinery.

Land
- Erosion and loss of topsoil decreased cover, plowing, increased water flow because of lower retention; degrading of productivity.
- Displacement of alternative land uses-wilderness, wildlife, esthetics, etc.
- Change in water retention capabilities of land, increased flooding potential.
- Buildup of pesticide residues in soil, potential damage to soil microbial populations.
- Increase in soil salinity (especially from irrigated agriculture), degrading of soil productivity.
- Depletion of nutrients and organic matter from soil.

Other
- Promotion of plant diseases by monoculture cropping practices.
- Occupational health and safety problems associated with operation of heavy machinery, close contact with pesticide residues and involvement in spraying operations.

SOURCE: Office of Technology Assessment, 1990.

fits, with the regrowth of its feedstock corn crop compensating for much of the CO_2 produced by its combustion in vehicles. As with its other environmental impacts, the greenhouse impact also depends on factors such as avoidance of byproduct market saturation. Even under the best circumstances, however, substantial amounts of CO_2 will be produced by corn growing and harvesting, ethanol distillation, and other parts of the ethanol fuel cycle. OTA concludes that it is unlikely that ethanol production and use *with current technology and fuel use patterns will* create any significant greenhouse benefits.

Both ethanol costs and environmental consequences would improve significantly if technologies for ethanol production from wood and lignocellulosic materials materials are substantially reduced in cost—a goal of current research programs at the Solar Energy Research Institute and elsewhere. In particular, ethanol from these sources should provide a significant greenhouse benefit in addition to the elimination of the food/fuel competition problem inherent in a corn-to-ethanol production system.

Ethanol's likely contribution to improved air quality has been another area of some contention. Recent testing and air quality modeling indicate that use of gasohol, a 10 percent ethanol blend in gasoline, reduces carbon monoxide emissions even in newer vehicles (previously it was thought that newer vehicles would not benefit). Also, although addition of ethanol to gasoline increases its vapor pressure and thus its evaporative emissions, this negative effect is compensated for by the emissions' lower photochemical reactivity and a reduction in ozone formation caused by the lower CO emissions. Thus, the use of blends is unlikely to increase ozone concentrations even if fuel vapor pressure is not adjusted back to the original level.

The ability of high concentration ethanol fuels to reduce ozone levels is essentially untested with modern U.S. vehicles, and this potential remains a source of contention. Assumming that emissions of acetaldehydes (which are high for ethanol fuels, low for gasoline) can be satisfactorily controlled, it seems likely that ethanol use *will* offer an ozone reduction benefit, given ethanol's physical characteristics—but this remains untested. Recent testing should offer needed evidence on this potential.

Introduction of ethanol as a transportation fuel would benefit from:

- testing of its emissions performance as a neat fuel in catalyst-equipped vehicles;
- development of low-cost production systems using woody biomass as a feedstock;
- indications that other markets for American corn will remain depressed for the long term;
- improvements in distillation technology, or commercialization of membrane or other advanced separation technologies; and
- development of an international market in the fermentation byproducts from ethanol production.

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[13] The total consumer cost may be higher once vehicle costs are factored in.

Natural gas may be cheaper *as a fuel* than gasoline[13]; the net cost to the consumer depends on the precise parameters of the distribution system. It can fuel a dedicated vehicle of equal performance to gasoline-powered vehicles, with generally lower emissions (except for potentially higher NO_x emissions) and equal or higher efficiency. In particular, natural gas' ability to yield large ozone benefits is much clearer than is the case with M85. Other important advantages include the availability of the United States' extensive pipeline network and extensive U.S. experience in gas handling. The use of natural gas may also confer some moderate greenhouse benefits, because of natural gas' low carbon/hydrogen ratio (yielding low CO_2 emissions per unit of energy), but the effect is highly sensitive to several system variables that can vary over a wide range. Because methane, the principal constituent of natural gas, is itself a powerful greenhouse gas, high tailpipe methane emissions coupled with distribution system leakage conceivably could cause a net greenhouse loss.

The use of natural gas could confer energy security benefits, though these will depend on the nature of the market structure. Suppliers of natural gas will not necessarily be the same as supplers of methanol; methanol's natural gas feedstock *must* be very low in cost to be competitive, whereas natural gas suppliers can use a higher priced feedstock so long as transportation costs to market are not too high. If a natural gas program were to grow very large, however, eventually the marginal suppliers would be the same countries that could serve as methanol suppliers.

Potential natural gas suppliers for a U.S. transportation market are, in order of probability, Canada, Mexico, and then a variety of nations shipping gas in the form of LNG. According to the Department of Energy, likely LNG suppliers for the United States are Algeria, Norway, Nigeria, and Indonesia, which may be viewed as a group as reliable suppliers. And, as with methanol, factors such as high capital costs of the supply system, the early stage of development of world gas resources, and ongoing changes in U.S./Eastern Bloc relationships are all positive factors for improved energy security.

Natural gas in the form currently used in vehicles—as compressed natural gas, CNG—has some important drawbacks as a transportation fuel, primarily limited range (CNG at 3,000 psi has one-fourth the volumetric energy density of gasoline), higher vehicle cost, slow refueling, and a limited base of technology development for gas-powered vehicles. Also, the transition vehicles that must establish the market would likely be dual-fueled vehicles, which have high first costs and some performance penalties when using gas.[14] Some of these disadvantages, particularly the range limitations, may be ameliorated by using gas in its denser liquefied form, LNG. New storage technology for LNG, which must be kept at –258 'F, appears to offer the potential for practical vehicular use.

Electricity as a vehicular "fuel" has the important advantages of having an available supply infrastructure (except for home charging stations[15] or an alternative recharging mechanism) that is adequate now—if refueling takes place at night—to fuel several tens of million vehicles, and of generating no vehicular air emissions. The latter attribute is particularly attractive to cities with severe ozone problems. Also, with the exception of some imports from Canada, the electricity needed to run a fleet of electric vehicles would be domestically produced. Recent improvements in ac converters have improved the prospects for successful electric vehicles. Because current commercial batteries simply cannot compete in range and performance with gasoline-powered vehicles, however, the primary determinant of the future of EV's is the success of ongoing battery research and engineering development, and/or the willingness of the driving public to accept substantial changes in vehicle performance and refueling characteristics. The outlook for significant improvement in commercial battery technology—especially regarding energy density and power—now appears promising, but there remain substantial uncertainties about the costs and, in most cases, the durability of advanced batteries, and previous confident predictions about imminent breakthroughs in battery technology have repeatedly proved incorrect. The market prospects are further limited by the cost and difficulty of rapid recharge.

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[14] However, these penalties need not be as substantial as might appear from the performance of most current dual-fueled vehicles, which do not incorporate timing and other adjustments that will improve performance with gas.

[15] If the vehicle has an onboard charger, the recharging station will be simply an electric socket (probably with 220-volt capacity) with ground-fault protection. Adding this type of socket to an existing house can cost several hundred dollars, however.

Despite virtually zero vehicular emissions, EVs will have air emissions impacts because of the emissions from the electricity production needed for their recharging. Although EV fleets in different parts of the country would be recharged from quite different mixes of powerplants, in general, for at least the next decade or two, much of the power would likely come from coal-fired baseload steam-electric plants. Although nuclear and hydroelectric sources would be more desirable as recharging sources from the perspective of air emissions (including greenhouse emissions), they are less likely than coal-fired plants to be cycled down at night and to have excess capacity to contribute. Consequently, the use of EVs to replace gasoline vehicles trades off a reduction in urban hydrocarbon, carbon monoxide, and NO_x emissions (from the removal of the gasoline vehicles) against an increase in regional emissions and long range transport of NO_x and $S0_x$, (from the increase in power generation). The quantitative trade-off depends on the fuel burned and controls used; uncontrolled coal-fried powerplants burning high sulfur coal (typical of plants in the Ohio River Basin) can easily produce 10 or 20 times more SO_x than a modern plant with scrubbers burning low or medium sulfur coal. New Clean Air Act regulations governing acid rain emissions will likely narrow the environmental trade-offs among powerplants by imposing new emission controls on the worst polluters.

Some recent EV designs, in particular the General Motors Impact, may overcome some of the shortcomings generally associated with electric vehicles. The Impact achieves a substantial boost in range by attaining extremely high levels of vehicle efficiency, incorporating an extraordinarily effective aerodynamic design (drag coefficient of 0.19 v. 0.29 for the most efficient commercial gasoline vehicle) and ultra-low-friction tires among other measures. (Achieving high vehicle efficiencies is an important strategy for all alternative fuels because of their low energy content per unit volume. It is particularly critical for EVs and hydrogen powered vehicles, with the lowest densities of all the fuels.) However, the Impact and other vehicles remain much more expensive to operate than gasoline-powered vehicles, primarily because of the need for frequent battery replacement, and they have critical development needs that must be met before they can be successfully commercialized.

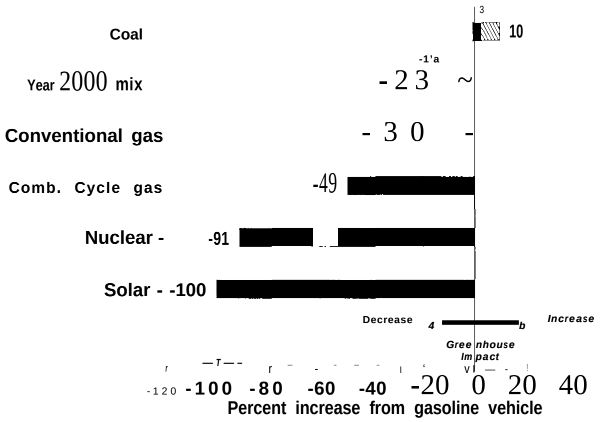
EVs, along with hydrogen vehicles, are often characterized as a primary means of reducing greenhouse emissions because nonfossil means of generating large quantities of electricity (e.g., nuclear, hydro) are in common use, while nonfossil means of creating large quantities of liquid and gaseous fuels are not. The greenhouse potential of EVs is obviously quite real, and could be realized with a resurgence in nuclear power and/or the large-scale commercialization of other nonfossil technologies. For generating plants based on renewable energy, plants using biomass are more likely to be used for recharging EVs than those using direct solar energy, because the latter are more suitable for providing daytime peak power. Development of new electricity storage systems would, of course, broaden the potential uses of solar electric powerplants.

In the near future, the greenhouse impact of an EV system is most likely to be small. The impact will depend on the mix of power generation facilities available to recharge the vehicles and the efficiency of both the EVs and the vehicles they replace. As noted above, except in the few areas where excess nuclear or hydro capacity is available, EV recharging will come from fossil-fueled plants, primarily coal-powered, with negative greenhouse implications. Also, the net impact depends on the vehicles actually replaced, not on some ‘‘average’ vehicle. The modest performance of likely EVs most resembles that characteristic of highly fuel-efficient vehicles; if the most efficient vehicles in the gasoline fleet are those being replaced, the net greenhouse advantage will be smaller than generally estimated. One analysis by researchers at the University of California at Davis of the net effect of using coal-fired power to charge EVs calculates that greenhouse emissions would increase 3 to 10 percent over gasoline vehicles. If new, efficient gas-fueled combined cycle powerplants can be used to recharge EVs over the next few decades, however, such a system would gain significant greenhouse benefits, up to 50 percent where such powerplants were the sole electricity source. Figure 7 illustrates the effect on net greenhouse emissions of changing the electricity recharging source.

Hydrogen’s primary appeal is its cleanliness-its use in vehicles will generate very low emissions of hydrocarbons and particulate (from lubricating oil consumption), virtually no emissions of sulfur oxides, carbon dioxide, or carbon monoxide, and only moderate emissions of NOx. Primary draw-

Figure 7—Effect of Electricity Source on Greenhouse Impact of Electric Vehicles

(Total fuel cycle considered except construction materials manufacture)



Vehicle: EV powered by sodium sulfur batteries, ac powertrain, 150-mile range, 650-pound weight penalty v. competing gasoline car.

SOURCE: D. Sperling and M.A. DeLuchi, *Transportation Fuels and Air Pollution*, prepared for Environment Directorate, OECD, March 1990, draft.

backs are high cost fuel, limited range (liquid hydrogen has one-sixth the energy density of gasoline), and difficult and expensive onboard storage--either in heavy and bulky hydride systems that will adversely affect range and performance, or in bulky cryogenic systems that will reduce available space onboard the vehicle. In several ways, hydrogen vehicles share many pollution and performance characteristics with EVs, but with the potential for rapid refueling, countered by more difficult fuel handling. As noted above, the development of vehicle efficiency technology is critically important for successful introduction of hydrogen vehicles (as it is for EVs) because of hydrogen's extremely low energy density.

At the moment, the least expensive source of large quantities of hydrogen (but still at substantially higher system costs than gasoline) is from fossil fuels, either from natural gas reforming or coal gasification, the latter of which would exacerbate problems with greenhouse gas emissions. Production of hydrogen from photovoltaic (PV) systems (using the electricity to electrolyte water) would yield an overall fuel supply system that generated virtually no greenhouse gases, but costs will be prohibitively high without major success in cost reductions such as those associated with improvements in PV module efficiency and longevity. Even the most optimistic projections about cost reductions have photovoltaic hydrogen systems competing with gasoline only when gasoline prices rise by about 50 percent. Many might consider this added cost to be quite acceptable, however, given hydrogen's potential value to reducing urban ozone and greenhouse emissions.

Reformulated gasoline is especially appealing as a potential fuel because it requires no vehicle adjustments (though these might be desirable under some circumstances to maximize performance) or new infrastructure, aside from modifications to existing refineries. Of particular value is the potential to use reformulated gasoline to reduce emissions from *existing* vehicles; market penetration-and the air quality benefits associated with such penetration—require only providing adequate fuel supplies, unlike the other fuels that must wait for fleet turnover. However, with the exception of a small quantity of supply available in southern California and a few other cities, reformulated gasoline is primarily a concept; formulas for fuel constitution, and likely costs, await the results of a just-started testing program being sponsored by the oil and automobile industries, and the ultimate ability of reformulated gasoline to lower emissions is unclear at this time. Further, it is impossible at this time to predict how much reformulated gasoline the petroleum industry will be capable of producing. And reformulated gasoline offers lesser benefits in energy security (except, possibly, to the extent that its use prevents refinery closures from competition with alternative, imported fuels) or greenhouse emissions. than other fuels, because it is primarily oil-based and may increase refinery energy use somewhat. The oxygenate component of reformulated gasoline may offer some energy security benefits since it will likely be produced from natural gas-based methanol or domestically produced ethanol.