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TOWARD ALTERNATIVE TRANSPORTATION FUELS AND INCENTIVE-BASED REGULATION OF VEHICLE FUELS AND EMISSIONS

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EXECUTIVE SUMMARY

Transportation energy issues are moving to the forefront of public consciousness in the United States and particularly in California, and gaining increasing attention from legislators and regulators. The three principal concerns motivating this interest in transportation energy are global warming, oil import dependency, and urban air pollution. Transportation fuels are a principal contributor to each of these. The transportation sector, mostly motor vehicles, contributes roughly half the urban air pollutants and one-third of carbon dioxide in California, and consumes almost three-fourths of all petroleum.

One promising strategy for resolving pollution and energy problems is the use of alternative fuels. Alternative fuels are an appealing technical solution. They require much less change in personal behavior than mass transit and ridesharing, and ease the pressure to coordinate and manage growth on a regional level. They are politically and institutionally easier to implement than strategies based on the reduced use of single-occupant autos and changes in land use. Indeed, because alternative-fuel vehicles could eventually prove to be environmentally benign, alternative fuels tantalize us with the prospect of never having to restrict motor vehicle use.

Moreover, using practically any set of conceivable assumptions, it can be argued that alternative fuels are inevitable. They are surely an important part of any long-term solution to energy security, global warming, and urban air pollution. But are alternative fuels also a short-term solution? Should government intervene now in support of alternative fuels? If so, on behalf of which fuels and when? And what form should this intervention take?

The authors conclude that definitive evidence cannot be marshaled to justify a massive near-term introduction of a particular alternative fuel or of alternative fuels in general. But neither can definitive evidence be marshaled to justify the contrary. Because the different fuels have very different and in some cases very large social benefits, the choice of fuels and the sense of urgency for introducing them depends on one's values, forecasts of future energy prices, predictions of future political events and technological advances, and increased knowledge about the greenhouse effect.

The decision to emphasize one social goal over another—for example, energy security over air quality and global warming—would dramatically alter the relative attractiveness of particular fuel options and the urgency for introducing them. Different views and expectations regarding energy prices, political and military conflicts, and technological improvements will similarly lead one to very different conclusions.

Nonetheless, decisions and choices must be made in the face of limited knowledge and foresight. Judgments based on certain values and visions of the future suggest the recommendations that follow.

FUEL CHOICES

Efforts to introduce methanol and compressed natural gas (CNG) fuel should continue. While they are not the ultimate solution, they may prove to be the preferred fuels during some part of the first half of the twenty-first century.

Methanol, when used in vehicles designed and optimized specifically for it, will provide modest ozone benefits in most California cities and small energy security benefits, but essentially no greenhouse benefits, and will probably cost a little more than conventional gasoline. The benefits of methanol are small, but so are the costs. A key advantage of methanol, largely explaining its popularity, is the technical and institutional ease with which it can be implemented. This relative ease of implementation is due principally to the fewer problems and less risk faced by automakers in designing and marketing a transitional multifuel methanol-gasoline vehicle—one that is optimized for neither gasoline nor methanol. A strategy based on the use of these multifuel methanol vehicles (commonly known as fuel-flexible vehicles) is questionable, however, since these vehicles provide essentially no environmental benefit (possibly even degrading air quality) and probably negative greenhouse impacts. Nor do fuel-flexible vehicles necessarily lead to the establishment of a fuel infrastructure since drivers prefer the cheapest fuel, which will be gasoline in the foreseeable future.

CNG provides slightly more ozone benefits, a 0 to 20 percent reduction in greenhouse gases, and major energy-security benefits, and will cost about the same or slightly less than methanol on a life-cycle cost basis. CNG, as well as electricity, has the political advantage of being supported by a major domestic industry, but it faces more difficult start-up barriers than methanol. The principal problem is that transitional multifuel CNG-gasoline vehicles are more expensive, less energy efficient, and more polluting than single-fuel CNG vehicles, and that single-fuel CNG vehicles would require considerable redesign to accommodate the larger fuel-tank volume. Automakers are therefore more reluctant to invest in CNG vehicles than methanol vehicles, even though from a social perspective CNG vehicles are more attractive.

Electric vehicles (EVs) would provide large ozone, global warming, and energy security benefits in California, and with continued improvements in vehicle and battery technology should have life-cycle costs similar to those of gasoline cars by the end of the century. Their major drawback is a short driving range between charges and a long recharging time. Consumer expectations and vehicle usage patterns will have to change if EVs are to be widely used. EVs provide the largest social benefits of all the near- and medium-term options, but they face the greatest marketing and consumer acceptance challenge.

Hydrogen is the most environmentally attractive option when made from water using solar electricity, but will cost much more than the other options into the foreseeable future. It will not be a viable option until at least 2010.

Reformulated gasoline was not treated in detail in the report because of limited experience and information, but more importantly because it will simply become the new base gasoline in California in the near future. Reformulated gasoline will cost up to 20 cents more than today's "conventional" gasoline per gallon and will provide somewhat reduced emissions.

In conclusion, CNG and methanol may be acceptable substitutes as gasoline use is gradually reduced, but the long-term and possibly permanent transportation fuels for California will probably be a mix of electricity and hydrogen. These fuels provide the potential for a qualitatively superior and sustainable future.

MOVING TOWARD INCENTIVE-BASED REGULATION

How should the findings be translated into government policy and action? If it was known which fuels would be introduced and when, then it would be a fairly straightforward task to create the appropriate rules, subsidies, and informational campaigns. But since the optimal choices cannot be entirely anticipated, the path of action should not be rigid and inflexible. A framework is needed to guide choices and decisions that are responsive to shifting priorities and continuing new information and that is able to handle a wide range of options.

The current governmental system for regulating fuels and vehicles does not provide this framework. It was designed with narrowly defined rules specific to gasoline (with rules later appended for diesel fuel). Indeed, as part of the emissions regulatory process, rules were established to discourage the use of fuels and fuel additives dissimilar to conventional gasoline. Nevertheless, the system has performed satisfactorily, since, from a transportation end-use perspective, the air pollution, energy security, and greenhouse gas attributes of gasoline are essentially identical for all gasoline mixtures. It no longer is acceptable to ignore these other attributes, however, now that alternative fuels (and reformulated gasoline) are serious options.

A new system is needed that is designed to handle the very different emission characteristics (and emission sources in the case of electric vehicles) of alternative fuels, and to take into account their varying greenhouse gas emission and energy security impacts. The current regulatory system is being rendered anachronistic by the emergence of alternative fuels as an important strategy for reducing urban air pollution.

What is needed, and what will best serve in the long run, is the establishment of an institutional framework that is flexible in responding to new information and shifting values and beliefs, that incorporates multiple social goals, and that is amenable to region-specific initiatives. These needs are served by incentive-based regulatory approaches. There are fundamentally two different incentive-based approaches: (1) creating artificial markets for fuel and vehicle attributes (e.g., emissions) using marketable credits and (2) altering price signals in existing markets using fees, credits, and taxes.

The primary plans to introduce alternative fuels on the national level and in other states have been based on a mix of rules, subsidies, and incentives: requiring certain vehicle fleets to use alternative fuels and gasoline marketers to blend a prescribed amount of "oxygenated" chemicals (i.e., alcohol or alcohol derivatives) into the gasoline, providing subsidies specifically targeted at farm-based ethanol, and easing CAFE (Corporate Average Fuel Economy) standards for automakers who sell alternative fuel vehicles. California regulators and legislators have been far more innovative and responsive to the opportunities presented by alternative fuels. One proposal passed by the legislature in 1990 but vetoed by the governor would have established a schedule of rebates to buyers of more fuel-efficient and low-emitting vehicles, along with fees for buyers of inefficient and more polluting vehicles. This rebate-fee structure would have altered price signals by providing an incentive to consumers to buy more energy-efficient and less polluting vehicles and to vehicle manufacturers to supply those vehicles.

Another attractive incentive-based proposal is the use of marketable credits. It has the potential of having greater impact than the rebate-fee proposal, and can be implemented either in conjunction with or independently of it. A limited form of marketable credits was adopted by the California Air Resources Board (CARB) on September 28, 1990 as a replacement for the current regulatory system of uniform emission standards. As adopted, manufacturers would be allowed to average emissions across their vehicle fleet to meet the average, bank their emission credits when they beat the standard, and sell (i.e., trade) those emission credits to other manufacturers who are not meeting the standards. Trading emission credits constitutes the creation of an artificial market for emissions and provides an incentive to vehicle manufacturers to build and sell ever more clean-burning vehicles.

An important advantage of marketable credits relative to price-altering incentives from a political perspective is that the system remains invisible to consumers (voters), imposing no taxes or fees of any type on them. Major changes in fuel attributes or emissions, of the magnitude sought by CARB and the South Coast Air Quality Management District (AQMD), would require huge fuel or vehicle taxes, well beyond what would probably be politically acceptable; the same changes could be accomplished by marketable credits with no taxes or fees. Another advantage of the marketable credits approach is that the debate is highly focused and directly addresses specific tradeoffs. Without this structure, and working only with the current system of uniform emissions standards coupled with a potpourri of policy instruments, the debate undoubtedly would continue to degenerate into a cacophony of self-serving interest-group arguments.

CARB's proposed marketable credits program, although revolutionary, falls short of what is needed. The major shortcomings are: First, marketable credits are created only for the traditional pollutants; greenhouse gases are ignored. Second, the important and closely linked goal of energy security is also ignored. Third, a companion marketable credits program for fuels was abandoned. CARB is reluctant to take on greenhouse gas reduction responsibilities and does not have the authority to deal with energy security issues. The same division of responsibilities exists on the national level. Political leadership and analytical creativity are needed to meld these other closely related social concerns together with air pollution regulatory responsibilities. This division of responsibilities can be crippling in developing a coherent and rational energy and environmental strategy.

CONCLUSIONS AND RECOMMENDATIONS

1. The automotive industry should be directing much more basic R&D toward the design of engines and fuel storage systems optimized for methanol and natural gas. No vehicular engine that is optimized in all respects for these fuels is now known to exist. It appears that most automotive industry research on alternative fuels is now devoted principally to multifuel (fuel-flexible) alcohol-gasoline engines, not optimized methanol

and natural gas vehicles or other environmentally superior options such as electric and hydrogen vehicles. Engines optimized with respect to performance and emission parameters should be built and evaluated for each fuel type. The state of California should investigate options to accelerate these activities.

2. California should encourage auto manufacturers to increase the R&D of electric and hydrogen vehicles and fuel cells and batteries, and increase government participation in these activities. The first major use of electric and hydrogen vehicles will undoubtedly be in the Los Angeles area. Yet R&D on electric and hydrogen vehicles at the major automakers has languished. The California Energy Commission (CEC), South Coast AQMD, and CARB have directed minimal resources to these technologies and should dramatically increase their R&D support for these promising options. The proposal by Los Angeles to purchase 10,000 electric vehicles and the adopted rule by CARB that 10 percent of vehicles in the year 2003 be zero emitting send the correct signal. Expanded initiatives would be desirable.

3. Given that future fuels and vehicles will have varying attributes and be used differently than today's gasoline-powered vehicles, consumer reaction to large batteries and fuel storage tanks, longer refueling times, and reduced vehicle range should be studied carefully. These are important aspects of the attractiveness of hydrogen and electric vehicles and, to a lesser extent, natural gas and methanol vehicles. California agencies have invested practically no effort in understanding consumer preferences and purchasing behavior. New and more creative survey research is needed that acknowledges the changeability of consumer behavior and attitudes and the reality that current behavior and attitudes simply reflect today's choices and experiences and are not necessarily good predictors of future fuel and vehicle purchasing behavior. A new approach to consumer behavior research is critical to developing R&D priorities and designing effective and efficient incentives.

4. Investigations of alternative designs of incentive-based regulation of fuels and vehicles need to be greatly expanded. Scarcely any effort has been made to answer questions regarding the use of incentive-based regulatory programs in the transportation sector. Much more progress has been made in understanding and implementing incentive-based programs in other energy-consuming sectors of the economy. In this report, insights and knowledge about transportation and energy sectors have been applied in recommending a shift toward incentive-based regulation—using marketable credits for both fuel and vehicle regulation and adjusting price signals to incorporate air pollution, global warming and energy security externalities. For both economic and environmental reasons, immediate efforts should be made to incorporate these general principles and strategies.

INTRODUCTION

Transportation energy issues are moving to the forefront of public consciousness in the United States and particularly in California, and gaining increasing attention from legislators and regulators. The three principal concerns motivating this interest in transportation energy are national energy security, global warming, and urban air quality. Transportation fuels are a principal factor for each of these. The transportation sector, mostly motor vehicles, contributes roughly half the urban air pollutants, creates one-third of the carbon dioxide in California, and consumes almost three-quarters of all petroleum used.

A TECHNICAL SOLUTION

One promising strategy for resolving pollution and energy problems is the use of clean-burning alternative fuels. Alternative fuels are an appealing technical solution, requiring much less change in personal behavior than mass transit and ridesharing, and minimal changes in the behavior and organization of local governments. They relieve the pressure to coordinate and manage growth on a regional level. Alternative fuels are attractive because they are less disruptive politically and are institutionally easier to implement than strategies based on reduced use of single-occupant autos and changes in land use. Indeed, they tantalize us with the prospect of never having to restrict motor-vehicle use, because the vehicles could prove to be environmentally benign. It can be argued, using practically any set of conceivable assumptions, that alternative fuels are inevitable. They are clearly an important part of any long-term solution to diminishing energy security, global warming, and urban air pollution.

STUDY OBJECTIVES

But are alternative fuels also a short-term solution? How urgent and how critical are these problems and how appropriate are alternative fuels as a near-term response? Should government intervene now in support of alternative fuels? If so, which fuels and when? And what form should this intervention take?

The authors conclude that definitive evidence cannot be marshaled to justify a massive near-term introduction of alternative fuels. But neither can definitive evidence be marshaled to justify the contrary. Because different fuels have very different and in some cases very large social benefits, the choice of fuels and the sense of urgency for introducing them depends on one's values, forecasts of future energy prices, predictions of future political events and technological advances, and increased knowledge about the greenhouse effect. For instance, which goal will dominate in ten years: Will it be air quality, energy security, or slowing climate change? The decision to emphasize one social goal over another dramatically alters the relative attractiveness of particular fuel options.

Nonetheless, robust qualitative judgments can be made about the relative merits and drawbacks of each option, and those judgments are made in this report. Because of shifting values and goals and an uncertain future, large regional differences in the nature of the air pollution problem, and the existence of multiple social goals no one fuel option has emerged superior. Instead, the authors argue that a flexible fuel-neutral policy framework that relies on incentives rather than specific rules is an appropriate and desirable guide to future energy choices.

The objective of this study was not to specify the details of an incentive-based regulatory system for motor vehicles and fuels, but rather to provide the motivation for this revolutionary change and to provide the general outline for such a system.

The report is organized as follows. First, the costs and impacts associated with continued reliance on petroleum transportation fuels are analyzed. Then prospective fuel alternatives are evaluated and compared to other petroleum-based strategies. Lastly, current and proposed regulatory procedures for controlling emissions and introducing new transportation fuels are reviewed and general guidelines for creating an incentive-based regulatory system are proposed.

ENERGY RESOURCES

The energy problem is not that petroleum supplies will soon be used up. Proven reserves of world oil have been increasing steadily, with new discoveries keeping pace with increasing consumption.[1] If there was a willingness to rely on Persian Gulf countries for their oil supply, and if the Persian Gulf countries could be relied on to supply oil at their cost of production, there would be no need to worry about oil for many decades. Even if future oil discoveries began to lag significantly behind consumption, many other energy resources could be used to manufacture transportation fuels.

Indeed, because of the availability of these other resources, it will be a very long time before future prices of transportation energy exceed 1981 oil prices on a sustained basis. Natural gas can be economically used as compressed or liquefied gas or converted into methanol when oil prices are considerably less than $43 (1988 $), the prevailing price in 1981. At about that 1981 price, coal and biomass could be economically converted into methanol, natural gas, and possibly petroleumlike liquids, and oil shale could be processed into gasoline and diesel fuel.[2] Since natural gas, coal, and oil shale are all available in larger quantities than petroleum, worldwide as well as in the United States, that means sufficient energy resources are available at or near 1981 prices for at least another century.

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[1]T. Burns, "The Future of Oil: A Chevron View," in *Alternative Transportation Fuels: An Environmental and Energy Solution*, edited by D. Sperling (Westport, Conn.: Quorum Books/Greenwood Press, 1989), 11–20; U.S. Energy Information Administration, *Annual Energy Outlook 1989* (Washington, D.C.: DOE/EIA-0383(89), January 1989).

[2]D. Sperling, *New Transportation Fuels: A Strategic Approach to Technological Change* (Berkeley/London: University of California Press); National Research Council, *Fuels to Drive Our Future* (Washington, D.C.: National Academy Press, 1990).

After that time, if necessary and if desired, a permanent transition could be made to renewable resources: hydrogen made from water using photovoltaic solar energy, electricity made from solar and other renewable sources, and, to a limited extent, liquid and gaseous fuels made from biomass. Biomass fuels would cost about the same as coal-based fuels and be environmentally superior, although their production, especially in California, should probably be limited so as not to exacerbate soil erosion. The private production cost of hydrogen is currently much higher than that of other fuel options, but hydrogen does provide the nonmarket benefit of creating much less pollution.

The point is that the world is not in imminent danger of running out of energy, and with a well-functioning market system, energy prices will not increase dramatically in the foreseeable future. But the international petroleum market is not a well-functioning market; it is erratic and politicized, distorting energy decisions through inappropriate price signals and uncertainty, and it does not account for large environmental impacts.

SOCIAL AND NONMARKET COSTS

The design of a transportation fuel strategy should be predicated on an understanding of the full range of private market costs as well as nonmarket social costs: private market costs because they are the criteria that industry and individuals use in deciding whether to invest in and purchase alternative fuels, social costs because they are the justification for government intervention.

ENERGY SECURITY AND PETROLEUM DEPENDENCY

The concept of energy security is an autarchic notion that a country should not become excessively dependent on foreign suppliers. Dependency occurs when a particular good or resource can be acquired more cheaply outside the home country (and government actions do not restrict foreign purchases), is important to the economy, and cannot be replaced quickly in the event of a shortfall. The benefits of buying less expensive goods elsewhere are increased economic efficiency. The costs are those of being unable to respond quickly if foreign supplies are abruptly curtailed or if prices are abruptly increased.

The United States is becoming increasingly dependent on oil imports. The trend is unmistakable: domestic oil production is on a downward trajectory and domestic oil consumption is increasing. In 1989, United States crude oil production averaged 7.6 million barrels per day, the lowest in 26 years, a drop of 553,000 barrels per day from 1988. All projections indicate that domestic production will continue to drop; in 1989, the U.S. Department of Energy (DOE) projected average annual declines of 350,000 barrels per day.

At the same time, domestic oil consumption continues to increase slowly, mostly due to increased diesel fuel and jet fuel use. The result is expanding imports. In 1988, oil imports rose to 7.9 million barrels per day, an increase of 8.2 percent over the previous year and an increase of nearly 60 percent since 1985. Imports accounted for 46 percent of consumption in 1988, the second highest on record, exceeded only in 1977. Barring dramatic and unforeseen events, oil imports will continue to increase.

The transportation sector, unlike other energy-consuming sectors, has remained almost completely dependent on petroleum fuels. As a result, transportation has gradually increased its share of the petroleum market. In the United States, transportation increased its share from 53 percent of petroleum consumption in 1977 to 63 percent in 1987.[3] In California, transportation accounts for about three-quarters of oil

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[3]U.S. Energy Information Administration, *Annual Energy Outlook 1987* (Washington, D.C.: DOE/EIA-0383(87), 1988).

consumption.[4] Already, the United States transportation sector by itself consumes more petroleum than is produced in the entire country. This level of dependency cannot continue indefinitely; eventually the transportation sector will have to shift to other energy sources.

The importance of this import dependency problem is unclear. The severity of the problem depends on one's view of the future: Will OPEC be able to regain market control and escalate oil prices? Will Saudi Arabia succumb to revolution? Will radicalized oil producers decide to use oil as a political weapon? Will Iraqi and Kuwaiti oil production be resumed at pre-1990 levels? The cost of oil dependency is difficult to measure; it depends not only on determinations of the probability of the foregoing types of events occurring, but also on how the cost of military expenditures in the Middle East and other important supply regions are allocated, the cost of maintaining the Strategic Petroleum Reserve (now containing over 500 million barrels), the risk of supply disruptions, and losses in national income from contraction of demand for United States goods and services. The sum of these costs have been estimated at $21 to $125 billion per year.[5]

Import dependency will probably not be a principal motivation for initiating a transition to alternative fuels in the near future, even with disruptions such as the Persian Gulf war. Nevertheless, oil-import dependency will continue to increase and therefore gain increasing political attention, resulting in the dependency issue becoming an increasingly important force in motivating an energy transition.

Dependency on oil imports is not just a problem of security, however. It is also a problem of large indirect economic costs caused by price volatility and increasing world oil prices, resulting in increased revenues for exporters and increased costs to importers. The availability of a credible alternative (and/or reduced petroleum consumption) would dampen oil price volatility and restrain oil price increases. Price volatility is due in part to the uncertain cost and availability of still undiscovered oil, but more so to the concentration of easily accessible (and therefore low-cost) oil in a few lightly populated countries. The finite nature of the resource and, for a few fortunate countries in the Middle East, huge supplies of cheap oil, tempts those countries to manipulate oil prices and supplies.

Price volatility creates uncertainty and distorts investment decisions, resulting in a preference for short-term investments. Erratic and uncertain petroleum prices result in wasted investments, such as delays in introducing energy-efficient equipment in the 1960s and early 1970s, billions of dollars of losses on over-enthusiastic investments in synthetic fuel plants in the late 1970s and early 1980s, the apparently premature filling in of oil wells with high production costs in the late 1980s, and missed opportunities to use enhanced recovery techniques to extract oil from existing oil fields.

The absence of a credible alternative to petroleum transportation fuels also results in oil prices being higher than they would otherwise be. This effect holds for the long

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[4] California Energy Commission, *Fuels Report* (Sacramento, Calif.: P300-89-018, 1989).

[5] M. A. DeLuchi, D. Sperling, and R. A. Johnston, *A Comparative Analysis of Future Transportation Fuels* (Berkeley, Calif.: Institute of Transportation Studies, UCB-ITS-RR-87-13, 1987), 364.

term as well as in response to rapid price escalations. Initial efforts at modeling the effect of alternative fuels on world petroleum prices indicate that substituting an alternative fuel for 2 million barrels per day of gasoline fuel would lower the world oil price by about $1 per barrel.[6] Thus the price suppression benefit to the United States in 1995 of those 2 million gasoline-equivalent barrels would be about $9 million per day or $3.3 billion per year.

The effect is even more dramatic for short-term price "spikes." If, for instance, petroleum prices were to increase quickly to 1981 levels, which is plausible once excess world capacity is used up in the 1990s or later, then oil importers would be faced with steeper spikes that dropped off slower than otherwise. If oil importers wait for the higher prices, they will not be able to react with substituted fuels for many years. High prices could be maintained for 20 years or more as the United States and other oil importers struggle to expedite the transition to nonpetroleum fuels and to replace vehicles that consume only gasoline and diesel fuel.

Indirect economic costs are a powerful motivation for introducing alternative fuels, but because the costs cannot be accurately quantified and because they are so diffuse, they probably will not play a principal role in motivating the introduction of new fuels.

GREENHOUSE EFFECT

Another problem, global warming, is caused by emissions of carbon dioxide and other trace gases that create a greenhouse effect. It attracts much more attention than energy security or indirect economic impacts, in part because the potential costs are much greater, though more speculative. At this time a strong commitment does not exist to mitigate the greenhouse effect, neither in the United States nor elsewhere, in large part because of uncertainty over the severity, location, and timing of the impacts.

The scientific community is in agreement that the earth's temperature will increase and climate patterns will change if emissions of carbon dioxide and other greenhouse gases in the atmosphere continue to increase.[7] Still uncertain is how fast this effect will occur and how climatic patterns will change. It is expected that the warming will be disproportionately near the poles, causing melting of ice masses and increases in ocean levels. Gradual but ultimately dramatic changes could occur in local and regional climates. Rainfall might increase in some areas and decrease in others, and atmospheric temperatures might increase in most but not all locations. Unfortunately, these climatic changes cannot be predicted accurately with existing meteorological models. In any case, the potential is there for major environmental and economic damage.

The principal source of carbon dioxide and other greenhouse gas emissions are carbon-bearing fossil fuels: oil, coal, natural gas, and oil shale. Transportation accounts for 34 percent of the carbon-dioxide gases emitted in California. As scientific evidence becomes more certain, the possibility exists that a strong commitment will be made to reduce the use of carbon fuels. It is unlikely that carbon-dioxide emissions could be

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[6] Carmen Difiglio, 1989. Results from U.S. Department of Energy Alternative Fuels Trade Model, personal communication.

[7] "New Greenhouse Report Puts Down Dissenters," *Science* 249, August 3, 1990: 481.

reduced economically using control technologies on vehicles or refineries. The most effective strategies for reducing greenhouse gas emissions from transportation is the reduced use of chlorofluorocarbons (CFCs) in air conditioners and less consumption of petroleum, either through fuel efficiency or the use of nonfossil fuels, including biomass, hydrogen made from water with nonfossil electricity, and electricity made from nonfossil fuels.

AIR POLLUTION

The third imperative for introducing alternative transportation fuels is, in California, politically the most potent: air pollution improvement. The use of petroleum for transportation results in large quantities of pollutant emissions from vehicles, refineries, and fuel stations. What makes the air pollution imperative most salient in the public policy arena is the existence of a set of institutions and rules for improving air quality.

Virtually all metropolitan areas of the country experience high levels of air pollution. Roughly 60 to 100 metropolitan areas (representing 80 to 130 million people) do not meet the statutory ambient air quality standards of the United States Clean Air Act for ozone, including all the metropolitan regions in California. In 1988, the state of California, responding to evidence that the health effects of ozone may be even more severe than had previously been thought, established more stringent ambient ozone standards than the federal government (0.09 versus 0.12 ppm over a 1-hour period, with no excedances allowed versus 3 excedances per 3 years allowed in the federal rules).

As shown in Table 1, most of the metropolitan areas in California are so far above the ozone standard and are growing so fast that they have little hope of attaining the standards in the foreseeable future. These same areas are also in severe violation of the particulate standard and most of them also violate the carbon monoxide standard. These high pollution levels threaten human health and create the risk of federal and state sanctions.

The external (nonmarket) costs of this air pollution are huge. Estimates for the United States range from $11 to $187 billion per year, the large range depending mostly on uncertainty of the number of deaths and illnesses due to pollution and the monetary value assigned to deaths and illnesses.[8] As an indication of how large the costs and benefits are, it is estimated that implementation of the Los Angeles area (South Coast) air quality plan will generate benefits of $1.5 to $7.4 billion per year in that region.[9]

Motor vehicles are a principal cause of urban air pollution. The California Air Resources Board (ARB) estimates that cars and trucks contributed 43 percent of the hydrocarbons (also categorized as reactive organic gases), 57 percent of the nitrogen oxides, and 82 percent of the carbon monoxide emitted in the major urban areas of California in 1987. (Motor vehicles emit relatively few particulates from their exhaust, but airborne particulates (PM10) are composed of up to 35 percent aerosols that are largely the result of atmospheric chemical reactions of the NO_x and hydrocarbons largely

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[8]DeLuchi et al., *A Comparative Analysis of Future Transportation Fuels.*

[9]Paul R. Portney et al., "To Live and Breathe in L.A.," *Issues in Science and Technology* 5 (1989): 68–73.

TABLE 1
PERCENT OF DAYS OVER STATE STANDARD
(1987 Summer and Winter Seasons)

	O_3 *1-hr, summer*	*CO* *8-hr, winter*	*PM10*[*] *24-hr*
South Coast	90%	42%	78%
SF Bay Area	22%	1%	37%
Sacramento	35%	4%	23%
San Diego	56%	1%	19%
Fresno	59%	3%	59%
Ventura	54%	0%	25%
Kern	61%	0%	66%

[*]Particulate matter less than 10 microns in diameter.
Source: California Air Resources Board, *California Air Quality Data: Summary of 1987 Air Quality Data*, Vol. 19 (Sacramento, Calif., 1988).

emitted by motor vehicles. The ARB estimates that over half the PM10 that is directly emitted from anthropogenic sources is dust kicked up by motor-vehicle activity on roadways.)

One of the problems to keep in mind in the later evaluation of fuel alternatives is the uncertain nature of estimated air quality impacts. While it is certain that air quality benefits would occur with the use of natural gas, electricity, and methanol, data and modeling results are not in agreement on how large those benefits would be, especially for ozone.[10] It is difficult and misleading to specify precisely the differences in emissions and air quality impacts between different fuels, especially for ozone.

First, emission rates are determined by tradeoffs between emissions, costs, performance, and driveability. If a particular fuel is less polluting, then engines will be

[10]J. D. Murrell and G. K. Piotrowski, *Fuel Economy and Emissions of a Toyota T-LCS-M Methanol Prototype Vehicle* (Society of Automotive Engineers, Warrendale, Penn., SAE 871090, 1987); W. P. L. Carter et al., *Effects of Methanol Fuel Substitution on Multi-Day Air Pollution Episodes* (Riverside, Calif.: Statewide Air Pollution Research Center, UC, ARB-86, 1986); J. N. Harris et al., *Air Quality Implications of Methanol Fuel Utilization* (Society of Automotive Engineers, Warrendale, Penn.: SAE 881198, 1988); M. A. DeLuchi, R. A. Johnston, and D. Sperling, *Methanol Versus Natural Gas Vehicles: A Comparison of Resource Supply, Performance, Emissions, Fuel Storage, Safety, Costs, and Transitions* (Society of Automotive Engineers, Warrendale, Penn.: SAE 881656, 1988); U.S. Office of Technology Assessment, *Replacing Gasoline: Alternative Fuels for Light-duty Vehicles* (Washington, D.C.: Government Printing Office, 1990).

designed to emit the maximum allowed and will gain the benefit by other means: reducing the cost of pollution control equipment, increasing engine power, etc. Actual emissions will be likely to vary considerably across vehicle make and model.

Second, pollutant production is sensitive to the air/fuel ratio of engines. If future engines are designed to run "lean" (high air/fuel ratio) to gain higher fuel efficiency, then NO_x levels would be relatively higher and CO and HC emissions and engine power would be lower than engines operating at stoichiometric ratios, as are most of today's gasoline engines.

Third, a distinction must be made between single-fuel optimized engines and retrofitted or bifuel engines.

Fourth, the fuel must be specified, since, for instance, some methanol emission data are based on a fuel consisting of 100 percent methanol, while others assume 10 percent or 15 percent gasoline mixed into the methanol. It becomes even more complicated for multifuel methanol/gasoline engines, since they operate on varying blends of methanol and gasoline.

Fifth, the ozone formation process is highly complex and even the most sophisticated photochemical air quality models have large error margins of 30 percent or more.[11]

Sixth, only in the Los Angeles area have sufficient meteorological and spatial pollutant concentration data been collected to operate multiday photochemical airshed models; these results cannot be generalized to other regions.

Seventh, emission data for dedicated single-fuel compressed natural gas (CNG) engines are much sparser and less accurate than for methanol engines. The point is that emission and air quality data for alternative fuels are uncertain and should be viewed with a certain amount of skepticism. Still, crude relationships can be drawn with some reliability, as they are later in the report.

The meager impacts projected for other urban air pollution control strategies illustrate the notion that it is easier and more effective to introduce the technical solution of alternative fuels. For instance, a current analysis of the emission impacts of various control strategies in the San Francisco Bay Area produced the following results: Providing free mass transit to riders with incomes of less than $25,000; doubling transit service outside the center of cities; managing freeway traffic more intensely through the use of metering lights, warning signs, and lane direction changes; imposing $1 daily parking surcharges in cities; increasing bridge tolls by $2; and imposing a surcharge of 2 cents per mile on vehicles would each reduce hydrocarbon emissions by only 1 to 2.5 percent. Each of these strategies would require huge subsidies or face major opposition, and yet would provide minimal benefits.[12] It should noted that the emission and vehicle usage impacts of these transportation control strategies are small because of current dispersed land use patterns. If land use patterns were reorganized on a regional level to assure coordination in a transportation sense between housing, work, and services, then

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[11]T. W. Tesche, "Photochemical Dispersion Modeling: Review of Model Concepts and Applications Studies," *Environment International* 9 (1984): 465-89.

[12]G. Harvey, Analysis for Metropolitan Transportation Commission, Oakland, Calif., March 1990, unpublished.

vehicle drivers would be much more responsive to incentives to share rides and shift to transit.

The use of alternative fuels provides the promise of much larger emission reductions. For instance, if all light-duty vehicles were switched from gasoline to electricity, hydrocarbon emissions would be reduced by about one-third—electric vehicle use results in about 98 percent less hydrocarbon emissions, and gasoline-powered autos and light trucks emit about a third of total hydrocarbons. The use of methanol and compressed natural gas would provide substantially less hydrocarbon emission reduction, but the point is that alternative fuel use allows for large emission reductions with relatively little change in user behavior.

The problem associated with continued reliance on petroleum fuels, therefore, is not necessarily long-run supply, but rather ignored social costs (especially air pollution and global warming) and economic losses resulting from unpredictable oil prices, inflexible responses to oil price changes, and the absence of substitute fuels. Because the price of petroleum does not take into account these social costs and economic losses, and because of the disjoint and conservative nature of transportation energy systems, alternative fuels and increased vehicular efficiency are uneconomically delayed.

In summary, if market mechanisms were operating efficiently, then optimal consumption and production of oil would follow. But that is not the case. Efficiency improvements and alternative fuels are delayed beyond the time when they would otherwise be economically attractive by uncertain and low gasoline and diesel fuel prices that do not reflect their true cost to society.

Moreover, there are also large start-up barriers to alternative fuels. Because of the start-up barriers and a flawed market, new fuels will only be introduced if they receive strong support from government. Significant government intervention could be based on any of the public-good concerns discussed so far: the greenhouse effect, dependency on foreign oil supplies, the economic benefits of lower energy prices, and urban air pollution.

RECENT HISTORY OF ALTERNATIVE TRANSPORTATION FUELS

Methanol has received more attention than other alternative fuels since the mid-1980s. The explanation for this attention is that methanol can be made from a large number of materials, many of them available in abundance in the United States; it can be made less expensively than most other options; it emits less reactive air pollutants than petroleum fuels; and it is a liquid and therefore more similar to gasoline and diesel fuel than other leading candidates, thus requiring less costly changes in motor vehicles and the fuel distribution system.

The interest in methanol is partly explained by historical circumstance. In the mid-1970s, just after the 1973 Arab oil embargo, nations began searching for ways to attain energy independence. The major nonpetroleum domestic energy resources in the United States were coal, oil shale, and biomass. Natural gas was virtually ignored since it was considered even more scarce than petroleum. Curtailments of natural-gas deliveries to customers in accordance with the United States government's allocation scheme during the winter of 1976–77 served to reinforce the notion that natural gas was a scarce resource that should be reserved for winter heating needs.[13]

For the transportation sector, the most attractive options seemed to be petroleumlike fuels produced from coal and oil shale, methanol produced from coal, and ethanol made from corn and other biomass. Ethanol was quickly discarded as a major option by most energy analysts for being far too expensive (although not by the agricultural community, who saw ethanol as an answer to excess production and low prices of farm goods).

Methanol was rated below oil shale and other coal-liquids options because it would require major changes in motor vehicles and pipeline and fuel distribution systems and would not support existing investments in oil refineries.[14] At a fall 1973 conference on Project Independence sponsored by the U.S. Department of the Interior, "oil and automotive industry representatives voiced sharp opposition to a national energy program emphasizing methanol rather than synthetic gasoline fuels."[15] A 1976 report by Stanford Research Institute, International rated synthetic gasoline a far more promising alternative than methanol, arguing that oil companies would be extremely unlikely to adopt methanol because "production of synthetic crude allows it simply to be added to the natural crudes still available to refineries, . . . serving both the needs of oil companies wishing to maintain the usefulness of present investments and insulating the consumer from change."[16]

Virtually all the major energy studies in the 1970s and early 1980s, as well as government energy policy, favored petroleumlike fuels from coal and oil shale.[17] Public and private R&D was heavily weighted toward direct liquefaction of coal.[18] Indeed, as late as 1981, only 5 of the 31 most advanced synthetic fuel projects in the United States intended to produce methanol as a primary product and, of those, several intended to coproduce high Btu pipeline-quality substitute natural gas.[19] Two additional projects intended to manufacture methanol but planned to convert the methanol into synthetic gasoline in order to make the fuel compatible with the existing motor vehicle and fuel distribution systems, essentially downgrading the methanol into a lower-octane,

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[13]U.S. Department of Energy, *Energy Security* (Washington, D.C.: DOE, DOE/S-0057, 1987), 123.

[14]F. A. Kant et al., *Feasibility Study of Alternative Fuels for Automotive Transport*, 3 vols. (Springfield, Va.: National Technical Information Service, prepared by Exxon Research and Engineering Co. for US EPA, PB-23 5580, 1974).

[15]R. L. Bechtold, *Compendium of Significant Events in the Recent Development of Alcohol Fuels in the United States* (Springfield, Va.: National Technical Information Service, ORNL/Sub/85-22007, 1987), 3.

[16]Stanford Research Institute, Int., *Synthetic Liquid Fuels Development: Assessment of Critical Factors* (Washington, D.C.: Government Printing Office, ERDA 76-129/1, 1976), xii.

[17]Kant et al., *Feasibility Study of Alternative Fuels for Automotive Transport*; Stanford Research Institute, *Synthetic Liquid Fuels Development*; Purdue University, *Transportation Energy Futures: Paths of Transition* (West Lafayette, Ind.: Purdue University, 1981).

[18]H. Perry and H. Landsberg, "Factors in the Development of a Major U.S. Synthetic Fuels Industry," *Annual Review of Energy* 6: 248.

[19]Pace Company Consultants and Engineers, *Comparative Analysis of Coal Gasification and Liquefaction*, prepared for Acurex Corp., Denver, Colo., and California Energy Commission, 1981.

higher-polluting fuel, at additional cost. Methanol was a minor consideration well into the 1980s.

In the early 1980s, perceptions began to shift, motivated by two insights: First, the cost of manufacturing petroleumlike fuels was greater than had been anticipated and, second, petroleumlike synthetic fuels did not help to reduce persistent urban air pollution. The cost problem became salient as world petroleum prices stabilized and then dropped and as feasibility studies performed by project sponsors for the United States Synthetic Fuels Corporation began to indicate that the cost of producing refined shale oil and petroleumlike liquids from coal would be as much as $100 per oil-equivalent barrel in first-generation plants.[20]

The air pollution benefits of methanol first gained attention, although as a secondary issue, in the early 1980s. A study prepared for the California Energy Commission (CEC) played a key role, not because it gained wide circulation, but because it laid the basis for the commission's organizational commitment to methanol fuel.[21] This landmark study concluded that, given the state's severe air pollution problems, the most attractive use of coal for California was to convert it to methanol for the transportation and electric utility sectors. This study was important because the CEC proved to be the most influential advocate of methanol through the 1980s, their major justification for this advocacy being air quality.[22]

As the expensive synfuels projects floundered, attention began to shift toward methanol, at first because of the relatively advanced state of coal-to-methanol conversion technology, and shortly thereafter because of a growing realization that much more natural gas existed than had been recognized. Although estimates of domestic and worldwide natural gas reserves began to be revised sharply upward in 1979, this was not widely acknowledged until several years later. The changed perception of natural gas availability is crucial because methanol can be manufactured more cheaply and cleanly from natural gas than from coal.

Interest in methanol began to surge around 1985 as methanol proponents shifted their arguments away from energy security, a diminishing concern, to urban air quality, a stubborn problem for which most of the "easy" solutions had already been exhausted. Proponents, especially in California, argued that "the transition to neat methanol fuels for all motor vehicles represents the most significant opportunity for air quality progress which exists between now and the end of the 20th century."[23]

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[20]Synthetic Fuel Corp., *Comprehensive Strategy Report*, Appendixes (Washington, D.C., 1985), H-10.

[21]Acurex Corp., *Clean Coal Fuels: Alternate Fuel Strategies for Stationary and Mobil Engines* (Sacramento, Calif.: CEC, P500-82-020, 1982), Executive Summary.

[22]K. D. Smith et al., *Proceedings of International Alcohol Fuel Symposium on Alcohol Fuel Technology* (Ottawa, Canada, 1984), 2-373–2-383; Three-Agency Methanol Task Force, Report (Sacramento, Calif., prepared jointly by California Air Resources Board, California Energy Commission, and South Coast Air Quality Management District, 1986).

[23]Larry Berg (member of Executive Committee of South Coast Air Quality Management District), Testimony to U.S. Congress, House of Representatives Commission on Energy and Commerce, Subcommittee on Fossil and Synthetic Fuels, Methanol as Transportation Fuel, 98th Cong., 2d sess., April

That argument was overstated. It reflected a perception that gaseous fuels and electric vehicles are too different from liquid fuels, requiring too many costly changes in motor vehicles and the fuel distribution system and in consumer behavior to be a widely used fuel,[24] exactly the same argument that had been used against methanol ten years earlier.

In the late 1980s, as analysts began to scrutinize more carefully the relative costs and benefits to air quality, energy security, and the greenhouse effect of the alternative fuels, natural gas and electricity began to receive more attention. The perception that only a liquid fuel was acceptable slowly eroded as the natural gas and electric utility industries began to give more support to natural gas and electric vehicles. Methanol is still favored in many quarters, but less strongly than a few years ago.

4 and 25, 1984 (Washington, D.C.: Government Printing Office, 98-145, 1984), 26.

[24]California Energy Commission, *Energy Development Report* (Sacramento, Calif., 1986); California Energy Commission, *Biennial Fuels Report* (Sacramento, Calif., 1986); California Energy Commission, *Fuels Report* (Sacramento, Calif., 1987).

COMPARATIVE ANALYSIS OF ENERGY OPTIONS

Considerable space is devoted here to a comparative analysis to demonstrate the advantages and disadvantages of different options. Each of the fuel options analyzed here can be shown to be superior in some situation, but no one fuel can be identified as superior to all others in all situations. The transportation energy options analyzed here, as the most attractive near- and medium-term options, are biomass fuels, methanol made from natural gas and coal, natural gas vehicles, electricity, and hydrogen. Liquefied petroleum gases (LPG) and petroleumlike fuels made from coal, oil shale, and tar sands are not included in this report.

FUELS NOT CONSIDERED

Petroleumlike Fuels

Petroleumlike fuels are not considered further because they have large negative environmental impacts, including high levels of greenhouse gas emissions, large quantities of solid waste, large water needs, and the introduction of additional toxic materials into the ecosystem. The fuels would be considerably more expensive than compressed (or liquefied) natural gas and methanol made from natural gas, although proponents claim that their costs can be reduced significantly with intensified R&D efforts, perhaps to as low as $30 per barrel.[25] The final cost would be considerably higher for California and the United States, however, because of the large costs required to reformulate the fuel to meet future emission standards and to meet other increasingly stringent environmental restrictions, including likely restrictions on greenhouse gas emissions.

Reformulated Gasoline

Reformulated gasoline is also not analyzed here, principally because of insufficient data. Gasoline consists of a large number of different molecular compounds, ranging from very light, near-gaseous hydrocarbon molecules to heavy complex molecules. In practice, no two quantities of gasoline are identical; in fact, refiners purposefully create different gasolines for summer and winter and for certain regions of the country. Reformulated gasoline is gasoline that has been modified to have lower emissions of hydrocarbons, benzene, and other pollutants. Reformulated gasoline was first proposed as an alternative fuel in summer 1989 in response to the growing pressure for

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[25] R. E. Lumpkin, "Recent Progress in the Direct Liquefaction of Coal," *Science* 239 (1988): 873–77; National Research Council, *Fuels to Drive Our Future.*

cleaner-burning fuels, in particular the July proposal by President Bush to require the sale of alternative-fuel vehicles in the nine most polluted cities of the country. In fall 1989 in Southern California, ARCO became the first oil supplier to market a gasoline reformulated for lower emissions. The fuel they reformulated was leaded gasoline, in part by blending in MTBE, an oxygenated derivative of methanol. ARCO's self-reported cost differential for their limited production was 2 cents per gallon; tests indicate that hydrocarbon emissions from the tailpipe were reduced 4 percent and evaporative emissions (which account for much less than half the total hydrocarbon emissions) about 21 percent. Carbon monoxide emissions were reduced 9 percent and NO_x emissions about 5 percent. Preliminary experiments suggest that the cost of large-scale production of reformulated unleaded gasoline with a 20 percent reduction in hydrocarbon emissions and a substantial reduction in benzene would be 10 to 20 cents per gallon.[26]

Liquid Petroleum Gas

Liquid petroleum gas is the light part of crude oil and the heavy part of natural gas; it represents a small proportion of oil and gas reserves. It is attractive now because of its low price, but if demand increased in the transportation or other fuels markets, this price advantage would disappear. LPG is not considered as anything more than a niche fuel, even by the LPG industry itself.

BIOMASS FUELS

Biological matter (biomass) can be a feedstock for the production of a range of liquid and gaseous fuels. Although biomass has been used to manufacture transportation fuels since the nineteenth century, major biomass transportation fuel activities were not initiated until the late 1970s, when Brazil and the United States fermented sugar cane and corn, respectively, into ethanol. About 184,000 barrels per day of ethanol were produced as a transportation fuel in Brazil in 1987[27] and about 50,000 barrels per day in the United States. More than 90 percent of all Brazilian cars were designed to operate strictly on ethanol from 1983 to 1989. In the United States the ethanol is mixed in a 10/90 blend with gasoline so that it can be burned in conventional unmodified gasoline-powered vehicles. Various developing countries have experimented with biomass ethanol, but with much less success.

Biomass fuels are attractive because the feedstocks are renewable and domestically available, and therefore could permanently displace imported petroleum. The use of biofuels in transportation could result in no net CO_2 produced (because the CO_2 is in effect being recycled), provided that the energy used in the manufacture of the biofuels—

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[26]U.S. General Accounting Office, *Gasoline Marketing: Uncertainties Surround Reformulated Gasoline as a Motor Fuel* (Washington, D.C.: GAO/RCED-90, 1990), 153; Boekhaus et al., "Reformulated Gasoline for Clean Air: An ARCO Assessment," presented at Second Biennial UC Davis Conference on Alternative Transportation Fuels, July 11–13, 1990, Monterey, Calif.

[27]S. Trindade and A. Vieira de Carvalho, "Transportation Fuels Policy Issues and Options: The Case of Ethanol Fuels in Brazil," in *Alternative Transportation Fuels: An Environmental and Energy Solution*, edited by D. Sperling (Westport, Conn.: Quorum Books/Greenwood Press), 163–86.

by farm machinery and fuel conversion facilities, in the making of fertilizers, and so on—is also biomass fuel or non-CO_2 producing. On the other hand, the potential supply of biomass is limited, production of biofuels is costly, and environmental impacts can be considerable. These negative factors are exacerbated in California by the aridity in the valley areas and the steep gradients of forestland. As a result, biomass fuels are relatively unattractive in California, relative to other options and to the more attractive conditions elsewhere in the United States.

Feedstocks and Fuel Production

While virtually all current biomass transportation fuel activities involve the fermentation of crops and food wastes containing large amounts of starch and sugar, the more promising option is the use of lignocellulosic material, especially wood pulp. Lignocellulosic material is more abundant and generally less expensive than starch and sugar crops. The most promising processes for converting lignocellulose (hereafter referred to simply as cellulose) into high-quality transportation fuels are thermochemical conversion into methanol or hydrolytic conversion into ethanol. Biomass may also be thermochemically gasified and then cleaned and upgraded into a clean high-Btu gas. The production cost and environmental impacts are similar to those of methanol production and the end-use attributes are identical to those of compressed natural gas (CNG). For simplicity, this latter option is not explicitly treated here.

Unlike other alternative energy options, biomass could not or, more accurately, should not be depended on as the sole transportation energy source, except perhaps in land-rich Brazil. In the United States, for instance, even if all the wood pulp now harvested by the paper and wood products industries, including logging and mill residues, and all the harvested corn and wheat were used to make biomass fuels, there would not be enough to satisfy current U.S. transportation fuel demand. A biomass fuels industry using dedicated biomass energy plantations could increase current yields of wood pulp on forestland tenfold or more, but total production would still be dwarfed by transportation energy demand unless a large proportion of forestland were diverted to biomass energy plantations.

Sperling estimated the upper bound of biomass fuel potential in the United States, assuming no major disruption of existing agricultural and silvicultural markets and land management activities, to be about 1.8 million oil-equivalent barrels per day of fuel.[28] Most of this biomass energy was estimated to come from wood plantations, the remainder coming from wood and crop residues, grass crops, peat, and municipal solid waste. In the 1990s the U.S. Department of Energy has returned its attention to biomass fuel, successfully inserting a strong statement for biomass fuels in the president's 1991 National Energy Strategy. Using assumptions that are excessively optimistic, the Solar Energy Research Institute of the U.S. DOE and others[29] are now estimating ethanol

[28]Sperling, *New Transportation Fuels.*

[29]L. R. Lynd et al., "Fuel Ethanol from Cellulosic Biomass," *Science* 251: 1318–23.

fuel potential in the United States (from cellulosic sources) to be several times higher than Sperling's predictions.

In any case, only a tiny proportion of this fuel would be produced in California. High-yield energy plantations would have much higher costs than elsewhere in the country because most forestland has steep gradients, which increases the cost of harvesting the wood, a major component of the total costs. The steep gradients also increase the potential for soil erosion, requiring greater mitigation efforts than elsewhere, further increasing the costs. In addition, irrigation would be required, especially in the agricultural areas, because of the relatively light rainfall, greatly increasing the cost of growing these water-intensive energy crops. The most attractive sources of biomass fuel in California would be agricultural and food-processing wastes, plus wood and crop residues, but the size of these sources would be modest.

Production Costs

Biomass-derived alcohols now are much more expensive than gasoline on an energy-equivalent basis, and are expected to remain so for the foreseeable future. Ethanol fuel in Brazil is about as costly to manufacture, on an energy basis, as gasoline produced from oil priced at $30 to $35 per barrel;[30] in the United States the cost of ethanol made from corn or other fermentable materials is substantially higher.[31]

The cost of converting cellulose to ethanol or methanol cannot be specified as precisely since the technology has not been commercialized, but a reasonable estimate would be a cost similar to that of converting coal to methanol, ultimately $0.70 to $1.00 per gallon (see Table 2).[32] This plant-gate production cost is equivalent to a retail gasoline price of more than $2 per gallon, since methanol contains only half the energy per unit volume as gasoline. Correspondingly, the distribution and retailing cost per gasoline-equivalent gallon is at least twice that of gasoline. Recent evidence indicates that improvements in cellulose conversion technology may lower production costs,[33] but even so, biomass transportation fuels will not be competitive in price with gasoline until oil prices are at least $30 to $40 per barrel. In California, the break-even price for large-scale production would be even higher.

Ethanol fuel activities are thriving in the United States and Brazil, despite high production costs, because of the political and economic strength of the agricultural and food-processing industries. Blends containing 10 percent ethanol and 90 percent gasoline accounted for about 7 percent of all gasoline sales in the United States in 1988. Ethanol exists in the United States only because of generous federal subsidies of 60 cents per ethanol gallon (equivalent to 90 cents per gallon of gasoline on an energy basis) and

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[30]D. Sperling, "Brazil, Ethanol and the Process of System Change," *Energy* 12 (1987): 11–23; H. Geller, "Ethanol Fuel from Sugar Cane in Brazil," *Annual Review of Energy* 10 (1985): 135–64.

[31]U.S. Department of Energy, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector* (Washington, D.C.: DOE, DOE/S-0057, 1988).

[32]Lynd et al., "Fuel Ethanol from Cellulosic Biomass."

[33]J. D. Wright, "Ethanol from Biomass by Enzymatic Hydrolysis," *Chemical Engineering Progress* (August 1988): 62–74.

TABLE 2
LIFE-CYCLE BREAK-EVEN GASOLINE PRICES[a]
(1985$/Gallon)

Vehicle/Feedstock	*Low-High Feedstock or Fuel Cost*	*Extra Cost of Fuel Storage*	*Break-even Price Low*	*High*
CNG/domestic gas	$4-6/million Btu to station	$1000-$1100	0.50	1.90
LNG/domestic gas	$4-6/million Btu to station	$700-$1000	0.40	1.80
Methanol/remote gas	$0.30-0.65/gallon, California	$50	0.95	1.70
Methanol/domestic coal	$0.70-$1.00/gallon, plant gate	$50	1.60	2.30
Electric/—[c]	$0.05/kwh at the outlet	$3500-$7200	0.30	3.50
Electric/—[c]	$0.10/kwh at the outlet	$3500-$7200	0.20	4.10
Electric/—[c]	$0.15/kwh at the outlet	$3500-$7200	0.60	4.80
Hydride/solar power	$0.05-0.15/kwh on site[d]	$2000-$3200	3.00	12.40
Liquid hydrogen/ solar power	$0.05-0.15/kwh on site[d]	$900-$2000	2.80	13.50
Gasoline/domestic coal[e]	—	$0	1.40	2.30
Gasoline/oil shale[e]	—	$0	1.60	2.30

Notes: The important baseline assumptions used here are: 9 percent real interest rate for auto loans; 30 mpg, $11,500, 120,000-mile life baseline gasoline vehicle; range and fuel system assumptions as per Table 7; methanol vehicles assumed to have same maintenance costs and life as gasoline vehicles, electric vehicles assumed to have 25 to 100 percent longer life and 25 to 50 percent lower maintenance costs, NGVs assumed to have 0 to 20 percent longer life and 0 to 15 percent lower maintenance costs, hydrogen vehicles assumed to have plus or minus 10 percent of the maintenance costs and minus 5 percent to plus 20 percent of the life; all vehicles are assumed to be optimized for one fuel and produced in high volume. See M. A. Deluchi, R. A. Johnston, and D. Sperling, *Methanol Versus Natural Gas Vehicles: A Comparison of Resource Supply, Performance, Emissions, Fuel Storage, Safety, Costs, and Transitions* (Warrendale, Penn.: Society of Automobile Engineers, 1988); M. A. DeLuchi, "Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, Environmental Impacts, and Cost," *International Journal of Hydrogen Energy* 14 (1989): 81–130; and M. A. DeLuchi, Q. Wang, and D. Sperling, "Electric Vehicles: Performance, Lifecycle Costs, Emissions, and Recharging Requirements," *Transportation Research* 23A, no. 3 (1989): 255–78.

[a]The break-even price of gasoline for a particular alternative is the retail gasoline price that equates the full life-cycle cost per mile of the alternative with the full cost per mile of a comparable baseline gasoline car. Includes 20-cents/gallon state and federal taxes.

[b]This is the cost of high-pressure gaseous-fuel tanks, cryogenic tanks, liquid alcohol tanks,

[c]Any feedstock from which electricity can be produced and distributed for between 5 and 15 cents/kWh.

[d]The estimated cost of photovoltaic electricity at the site of production.

[e]Based on D. Sperling, *New Transportation Fuels: A Strategic Approach to Technological Change* (Berkeley/London: University of California Press, 1988) and the National Research Council, *Fuels to Drive Our Future* (Washington D.C.: National Academy Press, 1990.

additional subsidies from many state governments. These huge subsidies benefit primarily ethanol manufacturers, but also gasohol blenders and corn farmers.

Environmental Impacts of Biomass Fuel Production

The introduction of biomass fuels has the potential of nearly eliminating greenhouse gas contributions by the transportation sector and of providing small improvements in air quality. On the negative side, increased biomass fuel production may increase soil erosion.

The combustion of biomass fuels would generate large amounts of carbon dioxide, but these emissions would roughly be offset by the carbon dioxide taken out of the air by the biomass plants via photosynthesis. As long as fossil fuels are not used for processing heat in the feedstock processing plant and in other steps of production and distribution, biomass fuels would be a highly attractive strategy for reducing global warming. In practice, though, as is currently the situation with ethanol made in the United States, nonbiomass fuels are used throughout the chain of activities. In fact, most ethanol production plants in the United States currently burn coal for processing heat.

The most troublesome environmental impact of biomass production is soil erosion. Although there is considerable controversy over the current extent of soil erosion, a conservative estimate is that half or more of U.S. cropland is suffering a net loss of soil. The Soil Conservation Service estimates that the average erosion on U.S. cropland due only to rainfall is 4.77 tons per acre per year,[34] while others estimate total annual erosion, including wind erosion, to be as high as 9 tons.[35] Since only about 1.5[36] to 5 tons of soil form per acre-year,[37] soil formation cannot keep pace with these losses.

New land brought into cultivation to produce biomass fuels will be at least as prone to erosion as existing land.[38] If marginal lands are brought into cultivation without careful soil management, comparatively large amounts of soil will be lost. In general, proper soil management can greatly reduce erosion, but in practice it is rare, because of ignorance, reluctance to change, and unwillingness to invest in techniques with long-term payoffs. Consequently, extensive cultivation of biofuels is likely to be economically and ecologically damaging, more so in California than elsewhere because of the steep gradients of most forestland.

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[34]Soil Conservation Service, *National Erosion Inventory Estimate* (Washington, D.C.: USDA, 1978).

[35]W. Larson, Crop Residues: "Energy Production or Erosion Control," *Journal of Soil and Water Conservation* 34 (1979): 74–76.

[36]D. Pimentel, "Biomass Energy from Crop and Forest Residues," *Science* 212 (1981): 1115.

[37]U.S. Office of Technology Assessment, *An Assessment of Oil Shale Technology* (Washington, D.C.: Government Printing Office, 1980), 71.

[38]U.S. Office of Technology Assessment, *An Assessment of Oil Shale Technology*, 71.

METHANOL FROM NATURAL GAS AND COAL

Methanol has been the most widely promoted alternative transportation fuel in the United States.[38] In this section, the salient aspects of methanol fuel are analyzed.

Feedstocks

At present, economic and environmental considerations favor natural gas over coal and biomass as a methanol feedstock. The production of methanol from natural gas is much less expensive (see Table 2) and produces much less pollution than coal-methanol processes. Emissions from NG-to-methanol plants are similar to those of petroleum refineries, while emissions from coal-to-methanol plants are much greater (see Table 3).

The least expensive natural gas is so-called remote natural gas (RNG), gas in foreign (usually third-world) countries remote from readily accessible markets and priced at about $1 per million Btu or less. Initially, methanol would be made in these low-cost, gas-rich countries, including many OPEC countries, and imported to the United States. Methanol imports would do little to enhance U.S. energy security, and in fact could weaken it, because foreign methanol suppliers might be no more secure than petroleum exporters, and because a drop in the price of oil, due to the substitution of methanol for some gasoline, would in some cases shut down high-cost domestic petroleum production. Methanol use would probably also increase U.S. payments to exporters for energy, which would add to the trade deficit.[39] However, as demand for methanol and for other uses of RNG grows, remote gas will become more valuable and its price will rise. Eventually, the price will be high enough to make domestic gas, and then coal and biomass, competitive as feedstocks.

Methanol made from natural gas could supplant petroleum fuels for several decades. The precise duration of a natural gas-to-methanol era would depend on natural gas use in other sectors, the number of vehicles switched to methanol, and the success of natural gas exploration and development efforts.

Environmental Impacts

Methanol from natural gas is not a permanently sustainable transportation option, nor is it dramatically cleaner than gasoline. It may, however, be enough cleaner to help some cities in air-quality nonattainment areas make small progress toward meeting national air quality standards. Methanol also will be much cleaner than diesel fuel, and may be an

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[38]C. Gray and J. Alson, *Moving America to Methanol: A Plan to Replace Oil Imports, Reduce Acid Rain, and Revitalize Our Domestic Economy* (Ann Arbor, Mich.: University of Michigan Press, 1985); U.S. Department of Energy, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector*; California Energy Commission, *Fuel Reports*, 1984–1988, Sacramento, Calif.; B. McNutt and E. E. Ecklund, *Is There a Government Role in Methanol Market Development?* (Society of Automotive Engineers, Warrendale, Penn.: SAE 861571, 1986).

[39]DeLuchi et al., *Methanol Versus Natural Gas Vehicles.*

TABLE 3:
COMPARISON OF AIR-POLLUTANT EMISSIONS FROM ENERGY CONVERSTION PROCESSES
(gm/million Btu of output, with controls)

			Emissions				
Product/process	*Feedstock*		*Particulates*	*SO_x*	*HC*	*NO_x*	*CO_2*
Syncrude/pyrolysis	Oil shale	1-35	3–16	3–15	50–150	3–16	55,000
yncrude/liquefaction[a]	Bituminous coal, 4% S	10-25	18–60	0.3–3	4–210	3–5	50,000
Ethanol/fermentation	Corn	45-370	37–1500	5–140	100–830	10–170	NA
Ethanol/hydrolysis	Crop residues	100–200	800–1100	NA	500–600	NA	NA
Methanol/gasification[b]	Subbit. & lignite coal, 0.5% S	1-25	30–200	100–500	15–150	NA	65,000–90,000
Methanol/Texaco gas.[c]	Coal	9	113	NA	82–276	13.7	125,000
Methanol/gasification	Wood	0–30	0	NA	10–200	NA	NA
SNG/coal gasification[d]	Bituminous coal	5.7	28	NA	82	NA	NA
SNG/coal gasification[e]	Lignite coal	11	108	no limit	63	no limit	no limit
Petroleum/refinery	Crude oil	2	11	10	9	NA	NA
Petroleum/refinery[f]	Crude oil	2.5	40;10	12;20	12;7	2;360	NA
Electricity/coal combustion[g]	Bitum. coal, 2% S	20	200–400	very low	very low	100–500	NA
Electricity/IGCC at Cool Water[h]	Various coals	2–4	8–34	NA	32–43	2	NA

Notes: Adapted from reports published from 1978 to 1983 by Pace Co., U.S. Office of Technology Assessment, Argonne National Laboratory, US DOE, and SRI International, except as noted below. For full citations, see Table 49 in D. Sperling, *New Transportation Fuels: A Strategic Approach to Technological Change* (Berkeley/London: University of California Press, 1988).

NA = not available.

[a]Based on Exxon Donor Solvent and Solvent Refined Coal II processes.

[b]Based on various gasifier technologies. The upper values refer to low-temperature Lurgi gasifiers.

[c]From a German study cited in M. J. Chadwick et al., *Environmental Impacts of Coal Mining and Utilization* (Oxford, Eng.: Pergamom, 1987), which did not specify the coal.

[d]American Gas Association, *The Gas Energy Supply Outlook Through 2010* (Arlington, Va., 1985).

[e]Emission rates established by air-quality permit for Great Plains SNG plant. Actual SOx emissions in 1986 were 360 gm/million Btu. "No limit" means that no emission limits were established in the permit.

[f]U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors*, Vol. 1, *Stationary Sources*, 4th ed. (Research Triangle Park, N.C., AP-42, 1985. First figure is for fluid catalytic cracking units with controls, second is for moving-bed catalytic cracking. We assume 0.05 million Btu of residual fuel oil per million Btu of output for process heat, a crude oil sulfur content of 2 percent by weight and energy content of 140,000 Btu/gallon. HC emissions includes fugitive emissions (12 gm/mmBtu).

[g]Based on New Source Performance Standards for new power plants.

[h]Integrated gasification combined-cycle power plant. From R. Wolk and N. Holt, *The Environmental Performance of Integrated Gasification Combined Cycle (IGCC) Systems* (Palo Alto, Calif.: Electric Power Resource Institute, 1988).

attractive strategy in some cases for meeting the stringent 1991-94 North American emission standards for heavy-duty engines.[40]

Unburned methanol emissions from methanol vehicles are generally less reactive than the hydrocarbon (HC) emissions from gasoline vehicles, and thus tend to produce less ozone. This promise of reduced ozone is the primary attraction of methanol vehicles; they are likely to have few other environmental benefits. Methanol may produce less CO or NO_x (but not both) than gasoline vehicles (see Table 4). The result will depend on the air-fuel ratio, the type of catalyst materials used in control devices, and the state of cold-start technology. Methanol production from natural gas is probably slightly cleaner than petroleum refining. Methanol from natural gas would not reduce emissions of greenhouse gases from the transportation sector, compared to gasoline and diesel-fuel use. Methanol from coal would cause a large increase in greenhouse gas emissions (see Table 5).

The magnitude of ozone reduction possible with methanol substitution is uncertain; many studies have been conducted, but the results are controversial and difficult to generalize. In the mid-1980s, several researchers concluded that the use of methanol in highway vehicles would reduce peak one-day ozone concentrations in urban areas by 10 to 30 percent.[41] In Los Angeles (and elsewhere), however, the worst smog episodes occur as pollution builds up over several days; in 1986 smog-chamber experiments indicated that methanol use may not be as beneficial in multiday ozone episodes.[42] Subsequent modeling studies at Carnegie-Mellon University found that in the Los Angeles area, the use of 85 percent methanol/15 percent gasoline (the most likely combination) in all mobile sources (vehicles) except motorcycles and planes would result in only a 6 percent reduction in peak ozone levels.[43]

If 100 percent methanol (M100) were used in advanced-technology engines with extremely low formaldehyde emissions, ozone would be reduced 9 percent compared to an advanced-technology gasoline engine. The 9 percent reduction with advanced-technology M100 represents 43 percent of the maximum ozone reduction attainable from motor vehicles; that is, if all vehicle emissions were eliminated, ozone would be reduced 21 percent.[44] A subsequent study questions these findings, arguing that methanol

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[40]D. Santini and J. J. Schiavone, "An Overview of Problems to Be Resolved When Meeting the 1991 Bus Particulate Emissions Standard," presented at the 67th Annual Meeting of the Transportation Research Board, January 11-15, Washington, D.C.

[41]Systems Application, Inc., *The Impact of Alcohol Fuels on Urban Air Pollution: Methanol Photochemistry Study* (Springfield, Va.: NTIS, DOE/CE/50036-1, 1984); Jet Propulsion Lab, *California Methanol Assessment* (Pasadena, Calif.: JPL, #83-14, 1983); R. J. Nichols and J. M. Norbeck, "Assessment of Emissions from Methanol-Fueled Vehicles: Implications for Ozone Air Quality," presented at Annual Meeting of Air Pollution Control Association, Detroit, Michigan, 1985.

[42]Carter et al., *Effects of Methanol Fuel Substitution on Multi-Day Air Pollution Episodes.*

[43]Harris et al., *Air Quality Implications of Methanol Fuel Utilization.*

[44]Harris et al., *Air Quality Implications of Methenol Fuel Utilization.*

TABLE 4
PERCENTAGE CHANGE IN EMISSIONS FROM
ALTERNATIVE-FUEL VEHICLES RELATIVE TO GASOLINE[a]

Fuel	NMHC	CO	NOx	O3	SOx	PM
Methanol (w/catalyst)	-50	0	0	-50	lower[b]	
CNG, LNG (w/catalyst)	-60	-50	0		lower[b]	
Hydrogen (no catalyst)	-95	-99	?	-95	lower[b]	
Electricity (nonfossil)[c]	-100	-100	-100	-100	-100	-100
Electricity/year 2010 mix[d]	-99	-98	-75	?	-50	+30

Notes: From data in M. A. DeLuchi, R. A. Johnston, and D. Sperling, *Methanol Versus Natural Gas Vehicles: A Comparison of Resource Supply, Performance, Emissions, Fuel Storage, Safety, Costs, and Transitions* (Warrendale, Penn.: Society of Automobile Engineers, 1988); Q. Wang, M. A. DeLuchi, and D. Sperling, "Emission Impacts of Electric Vehicles," *Journal of Air and Waste Management Asssociation* 40 (1990): 1275–84; and M. A. DeLuchi, "Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, Environmental Impacts, and Cost," International *Journal of Hydrogen Energy* 14 (1989): 81–130. These are rough estimates only, assuming advanced-technology, single-fuel cars, and emission controls and engine operation designed to meet an NO_x standard, which will be the most difficult standard to meet. Does not include evaporative emissions from vehicles, vehicle refueling, or emissions from petroleum refining and fuel manufacture. NMHCs = nonmethane hydrocarbons (total hydrocarbon emissions less methane, which is nonreactive and hence does not contribute to ozone formation). PM = particulate matter.

[a]Ethanol fuel is not included because of minimal experience and testing with controlled vehicles. In general, ethanol-powered vehicles will have similar emissions to methanol. One difference is in aldehyde emissions, which may lead to the increased formation of another oxidant, peroxyacetyl nitrate (PAN) with ethanol (R. A. Tanner et al., "Atmospheric Chemistry of Aldehydes: Enhanced Peroxyacetyl Nitrate Formation from Ethanol-fueled Vehicular Emissions," *Environmental Science and Technology* 22: (1988): 1026–34.

[b]SO_x emissions depend on the amount of sulfur in the fuel.

[c]Emissions from a fuel-cell vehicle using nonfossil hydrogen would be the same.

[d]See Q. Wang et al., "Emission Impacts of Electric Vehicles": 1275–84 for details. Based on forecasts and estimates for California of the energy mix for electricity generation, emission control technologies deployed on power plants, vehicle emission rates, and electricity consumption rates of electric vehicles.

vehicles would emit more NO_x than gasoline vehicles, more than is assumed by the Carnegie-Mellon researchers, thereby causing ozone levels to increase.[45]

In any case, the greatest potential ozone reductions with methanol require the use of M100 and very low formaldehyde emissions, two conditions that may not be attainable. We estimate that the substitution of methanol for gasoline in all motor vehicles would result in a maximum reduction in peak ozone levels of 0 to 15 percent in multiday smog episodes.

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[45]Sierra Research, Inc., *Potential Emissions and Air Quality Effects of Alternative Fuels* (Sacramento, Calif., SR88-11-02, 1988).

TABLE 5
EMISSIONS PER MILE OF A COMPOSITE MEASURE[a] OF GREENHOUSE GASES RELATIVE TO GASOLINE-POWERED INTERNAL COMBUSTION ENGINES[b]

Fuel/Feedstock	*Percent Change*
Fuel cells, hydrogen with solar power	-90 to -85
Ethanol from wood	-75 to -40
Hydrogen with nuclear	-70 to -10
EVs, natural gas plants	-50 to -25
LPG	-30 to -10
CNG from NG	-20 to 0
Methanol from NG	-10 to +8
EVs, current U.S. power mix	-20 to 0
Gasoline	—
EVs, new coal plant	0 to +10
Methanol from coal	+30 to +70

Source: M. A. DeLuchi, *State-of-the-art Assessment of Emissions of Greenhouse Gases from the Use of Fossil and Nonfossil Fuels, with Emphasis on Alternative Transportation Fuels* (Argonne, Ill.: Center for Transportation Research, Argonne National Laboratory, forthcoming.

[a] CH_4 and N_2O mass emissions from vehicles were converted into the mass amount of CO_2 emissions with the same temperature effect where "same temperature effect" is defined as the same number of degree-years over a given time period (125 years was chosen), where "one degree-year" is defined as an increased surface temperature of 1°C for one year. In order to convert CH_4 emissions into CO_2 emissions having the equivalent temperature effect, one needs to know for both gases the relationship between: (1) equilibrium surface temperature and equilibrium atmospheric concentration of the gas and (2) the increase in yearly emissions of the gas and the increase in the equilibrium atmospheric concentration (note that many "conversion factors" given in the literature ignore the second step, and hence cannot be applied to emissions). These relationships are derived in M. A. DeLuchi et al., *A Comparative Analysis of Future Transportation Fuels* (Berkeley: Institute of Transportation Studies, UC, 1987). The result is that N_2O mass emissions multiplied by 175 and CH_4 emissions multiplied by 11.6 produce the mass of CO_2 emissions with the same temperature effect. The ranges in values in the table correspond in part to a range in equivalency values between CH_4 and CO_2 of 10 to 40.

[b] The analysis considered emissions of CH_4, N_2O, and CO_2 from the production and transportation of the primary resource (coal, natural gas, or crude oil), conversion of the primary resource to transporation energy (e.g., natural gas to methanol, or coal to electricity for battery-powered vehicles), distribution of the fuel to retail outlets, and combustion of the fuel in engines, except as noted. N_2O emissions from vehicle engines were not included (the estimate in M. A. DeLuchi, *State-of-the-art Assessment of Emissions of Greenhouse Gases from the Use of Fossil and Nonfossil Fuels, with Emphasis on Alternative Transportation Fuels* indicates that they are relatively unimportant). Emissions of ozone (O_3) precursors, CFCs from air conditioning systems, and H_2O were not considered (available data and models do not allow estimation of the greenhouse effect of emissions of ozone precursors; CFC emissions are independent of fuel use; and H_2O emissions from fossil fuel use worldwide are a negligible percentage of global evaporation).

[c] Hydrogen vehicles emit N_2O and H_2O; as noted above, H_2O emissions from the entire fuel cycle and N_2O emissions from vehicles were ignored.

[d] CNG and methanol vehicles emit N_2O, H_2O, ozone precursors, and CH_4. As noted above, vehicular emissions of N_2O and all emissions of H_2O and ozone precursors were ingored. The carbon in CH_4 emissions from biofuel vehicles originally comes from atmospheric CO_2, and since CH_4 is a more effective greenhouse gas than CO_2 per molecule of emissions, the transformation of CO_2 to CH_4 by the biofuel production and use cycle results in a slight increase in effective emissions of greenhouse gases.

Two cautionary notes: (1) ozone air quality models are subject to considerable uncertainty because of inadequate input data, especially outside Los Angeles, and (2) optimized single-fuel engines are much cleaner burning than multifuel engines.

This second point is critical because the preceding assessment of emission impacts of alternative fuels was based on the assumption that the engines were designed specifically for those fuels. Commercial versions of such optimized single-fuel engines do not yet exist. Indeed, there is relatively little experience with optimized alternative-fuel engines and catalyst technology. If a serious sustained effort were made to reduce emissions, similar to the 25-year history with gasoline engines, major emission reductions would be likely.

In contrast to the uncertainties surrounding the environmental benefits of substituting methanol for gasoline, there are several clear environmental advantages to using pure methanol in heavy-duty engines. Methanol produces essentially no particulates, smoke, SO_x, or unregulated pollutants. In addition, a methanol engine with an oxidation catalyst produces very little CO, HCs, and formaldehyde.[46]

In summary, methanol use would not reduce greenhouse gas emissions, but would provide some air-quality benefits when used in diesel engines; it may lead to a minor reduction in either NO_x or CO emissions in spark-ignition engines (and perhaps an increase in the other), and has the potential in some regions for achieving a part of the maximum ozone reduction attainable through changes in the transport sector. But the magnitude of these potential improvements is modest.

Safety and Toxicity

One of the primary arguments used against methanol has been its toxicity and safety. Methanol causes blindness if drunk, burns with an invisible flame (making it difficult to detect fires), and is highly soluble in water (making it difficult to contain a spill).

The first two of these problems are solved by adding 10 to 15 percent gasoline (or some other combustible denaturant) to the methanol, making the flame visible and giving the liquid a very unpalatable smell and taste. The third issue, solubility of methanol in water, is not necessarily a disadvantage; the greater solubility causes the methanol to quickly dissolve, thus not causing the long-lasting destruction typical of large oil spills. Overall, gasoline is a more threatening fuel than methanol: It is far more flammable and contains many carcinogens.

Cost

Methanol is more expensive than gasoline on an energy-equivalent basis, and will continue to be so for the foreseeable future. The most recent estimates are that very small amounts of methanol can be delivered to the United States for as little as 20 to 30

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[46]T. L. Ullman and C. T. Hare, *Emission Characterization of Spark-Ignited, Heavy-Duty, Direct-Injected Methanol Engine* (Ann Arbor, Mich.: U.S. Environmental Protection Agency, EPA 460/3-82-003, 1982); Jeff Alson, J. Adler, and T. Baines, "Motor Vehicle Emission Characteristics and Air Quality Impacts of Methanol and Compressed Natural Gas," In *Alternative Transportation Fuels: An Environmental and Energy Solution*, edited by D. Sperling (Westport, Conn.: Quorum Books/Greenwood Press, 1989).

cents per gallon if the RNG feedstock is virtually free and if costs sunk in methanol plants are ignored.[47] A more reasonable estimate, based on sustainable rate-of-return conditions and assuming competition for the RNG feedstock—including both domestic uses and other exporting possibilities—is 40 to 60 cents per gallon equivalent on an energy basis to 80 cents to $1.20 per gasoline gallon.[48] Methanol could be produced from coal in the United States for around $1 per gallon.[49] When transportation, storage, and retailing costs are considered, methanol from RNG would not be competitive with gasoline until gasoline sold for $1.10-1.70 per gallon, including taxes (and allowing for the fact that methanol is about 10 to 20 percent more efficient than gasoline in internal combustion engines). Methanol from coal would not be competitive until gasoline sold for at least $2 per gallon.

From a public-policy perspective, a more relevant analysis might be methanol's cost effectiveness in reducing ozone pollution relative to other pollution-reduction strategies. Such an analysis conducted by the Office of Technology Assessment (OTA)[50] came to a mixed conclusion. Their analysis assumed the following: an ozone-reduction potential of methanol relative to gasoline ranging from a low of 30 percent using M85 to as high as 90 percent for M100; a cost of 5 to 56 cents more per gasoline-equivalent gallon for methanol than gasoline; and an additional cost of $0 to $1000 for a methanol car over a gasoline car. OTA conducted the analysis for a vehicle that travels 26,000 miles per year, more than twice the national average. The result was that the use of M85 would cost $9,000 to $66,000 to eliminate 1 ton of "ozone-equivalent" hydrocarbon emissions; if M100 were used, assuming favorable ozone-reduction parameters, the cost would be $3,000 to $22,000 per ton.

A similar analysis conducted for California as part of the AB234 Advisory Board on Air Quality and Fuels estimated the cost effectiveness of M85 at $8,000 to $40,000 per ton,[51] and a study by Resources for the Future for the U.S. estimated the cost effectiveness for M85 in the year 2000 at $33,268 and for M100 in the year 2010 at $59,736.[52]

Most of the nonmethanol ozone-reduction strategies studied by OTA had cost-effectiveness reductions of $500 to $6000 per ton. Methanol, however, along with other alternative fuels, provides the potential for much larger ozone reductions than any other strategy.

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[47]U.S. Department of Energy, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector.*

[48]U.S. Department of Energy, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector.*

[49]Sperling, *New Transportation Fuels.*

[50]U.S. Office of Technology Assessment, *Catch our Breath: Next Steps for Reducing Urban Ozone* (Washington, D.C.: Government Printing Office, OTA-O-412, 1989).

[51]California Advisory Board on Air Quality and Fuels, "Report to the California Legislature," Vol. 1 (October 1989), Executive Summary.

[52]A. J. Krupnick and M. A. Walls, *The Cost-Effectiveness of Methanol for Reducing Motor Vehicle Emissions and Urban Ozone Levels* (Washington, D.C.: Resources for the Future, 1990).

The OTA estimates suggest that *multifuel* methanol cars are clearly not a cost-effective ozone-control strategy. Given the range of uncertainty in costs and emission reductions, a similarly definitive conclusion regarding optimized dedicated methanol cars is premature since these cost-effectiveness analyses are too narrow, too short sighted, and highly sensitive to several key parameters that cannot be accurately specified. Cost-effectiveness analysis will almost always advise not doing something new and unique, because it does not capture all the direct benefits, much less the secondary benefits. And it ignores the fact that with new technologies—such as computers, freeways, and recycled paper—investments, institutions, and behavior gradually shift to accommodate and support them, thereby gradually improving their apparent cost competitiveness.

In any case, if methanol fuel and vehicle prices are not too much higher than those for their gasoline counterpart, and if continued advances are made in emission controls of methanol vehicles, then dedicated methanol vehicles could be a cost-effective strategy for reducing ozone.

Opportunities for Methanol

An important first use of methanol (and natural gas) fuels in California and the U.S. may be in heavy-duty diesel engines. New emission standards requiring sharp reductions in particulate and NO_x emissions from heavy-duty diesel vehicles take effect in the United States and Canada in 1994 (1991 for transit buses). Meeting the standards by applying control technology to diesel combustion will be difficult; the vehicle capital costs may be less with a methanol (or natural gas) engine, although the methanol fuel costs will be greater. Several heavy-duty engine manufacturers are developing methanol (and natural gas) engines.

However, diesel-powered trucks consume only about 2 of the 15 quadrillion Btus of energy used annually on the highways in the United States,[53] although the proportion is increasing). If methanol is to replace a significant amount of petroleum transportation fuel and have a discernible impact on air quality, it must penetrate the market for light-duty (gasoline) vehicle fuels. A strategy to introduce methanol into this market must address the high cost of methanol fuel compared to gasoline, as well as the large initial costs both for manufacturing methanol fuel and methanol vehicles and for establishing a national methanol distribution network for light-duty vehicles. The large initial costs and uncertain market create a need for cooperation between fuel producers and vehicle manufacturers.

The problem of fuel cost is straightforward. Consumers will not use methanol and manufacturers will not make dedicated methanol vehicles unless methanol use is mandated or subsidized to bring its cost below that of premium gasoline. Government perhaps could justify subsidies or mandates on air quality grounds, but not on global-warming or energy-security grounds.

The problem of start-up costs is more complicated. Because of large start-up costs, manufacturers will not invest in the manufacture of methanol vehicles if methanol fuel

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[53]Oak Ridge National Laboratory, *Transportation Energy Data Book*, 9th ed. (Springfield, Va.: NTIS, ORNL-6325, 1987).

is not available, and fuel producers will not invest in the production and distribution of methanol, even when it is cheaper than gasoline, unless vehicles are available that can burn it. To use methanol, motor vehicles must be modified; the cost of building these modified vehicles will be large initially, since retooling and R&D costs must be spread over a relatively small number of vehicles, although at full production the cost of a methanol-powered vehicle is expected to be about the same as the cost of a comparable gasoline-powered vehicle. Similarly, establishing a methanol fuel-delivery infrastructure will be fairly expensive. The minimum cost approach for a large-scale effort would be to market the fuel only in and near ports with ocean access, obviating the need to modify the existing oil-product pipeline network or to build an entirely new one. Since methanol will be imported initially, a port-based distribution system will be adequate at first. The DOE estimates that the additional capital cost of building a national methanol distribution system to replace 1 million barrels per day of petroleum fuels, using only waterborne and truck transport, and with methanol marketed only within 100 miles of major river and ocean ports (reaching about 75 percent of the United States), would be $5 billion.[54]

The "chicken-and-egg" dilemma created by these large start-up costs could be resolved by coordinating vehicle manufacture, fuel distribution, and fuel production. Such coordination probably would be arranged by state or federal government. Incentives, not necessarily financial, would need to be offered to vehicle manufacturers to induce them to manufacture and market methanol vehicles, and financial subsidies would need to be offered to retail fuel stations and consumers, at least initially, to overcome the price disadvantage of methanol. (Note, however, that what government invokes it can revoke, and that even with incentives and subsidies, the private sector runs some risk. Relaxation of vehicle fuel-efficiency standards for manufacturers that market methanol vehicles, as provided for in the Alternative Motor Fuels Act of 1988 (PL 100-494), might be sufficient to induce manufacturers to produce methanol or other nonpetroleum vehicles. Retail fuel suppliers will require more direct subsidies, such as the $50,000 capital grants offered by the Canadian government to retail fuel stations to install facilities for compressed natural gas and the per-gallon subsidies provided by the California Energy Commission to methanol fuel suppliers. Ultimately, consumers would have to be subsidized to convince them to buy methanol, since methanol will cost more than gasoline until oil prices reach at least $30 per barrel on a sustained basis.

In summary, a long-lasting transition to methanol should occur only if reducing energy imports, slowing the greenhouse effect, and significantly improving air quality are not high priorities. Methanol offers modest environmental benefits at modest cost.

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[54]U.S. Department of Energy, *Vehicle and Fuel Distribution Requirements: Technical Report Four, Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector* (Washington, D.C.: DOE, 1990.

METHANE FUELS

Feedstocks

Natural gas, comprised mostly of methane, need not be made into methanol to be used as a transportation fuel; it can be stored onboard a vehicle, in compressed (CNG) or liquefied (LNG) form, and burned in the engine as a gas. Later, as the availability of natural gas diminishes and its cost increases, a substitute (synthetic) natural gas (SNG) could be produced from coal or perhaps biomass. The principal advantage of this methane path is lower fuel cost to the end user during the natural gas era, because it is cheaper to compress or liquefy natural gas than to convert it to methanol. Methane could remain as an important or even dominant fuel after natural gas supplies become scarce by converting coal to SNG (mostly methane); the cost for converting coal to methane would be about the same as converting it to methanol. The principal disadvantages of the CNG/LNG path are those associated with storing gaseous fuels in vehicles and establishing a network of retail fuel outlets.

In sum, RNG will not be a major feedstock for U.S. NG transportation fuels, unless the cost advantage of RNG feedstock increases or there is large demand for LNG by LNG vehicles. This contrasts with the methanol case, in which RNG will be a more economical feedstock than domestic gas. That it is more economical to make methanol from RNG than from domestic gas but more economical to make CNG from domestic gas than from RNG is due to the fact that in the methanol case the cost advantage of the cheaper RNG feedstock relative to domestic feedstock must compensate only for higher transporation costs, but in the CNG case must compensate for the cost of liquefaction and regasification as well as for higher transportation costs. There is, in other words, an extra step in the RNG-LNG-CNG route (namely, LNG), compared to RNG-methanol, and this extra step is costly enough to tip the economic balance away from RNG.

This difference—that methanol will be made initially from foreign gas, whereas CNG or LNG will be made from North American gas—may give CNG and LNG an edge in energy security. The total amount of fuel imports and the total risk of disruption and outflow of funds would be lower with NG fuels than with methanol.

Another resource consideration is that domestic natural gas resources will last somewhat longer if used as CNG or LNG than as methanol because conversion losses are much less. Energy losses were estimated during each of the following activities: recovery of natural gas (95 percent efficient), transmission and distribution of natural gas and finished product (95 percent efficient), reforming of NG to methanol (68 percent efficient), and NG liquefaction (80 percent efficient) or compression (94 percent efficient).[55] Based on these estimates, the overall energy efficiency of the NG-to-CNG chain is about 85 percent, compared to 61 percent for NG to methanol and 72 percent for NG to LNG.

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[55]DeLuchi et al., *Methanal Versus Natural Gas Vehicles.*

Natural Gas Vehicle Technology

Internal combustion engines may be readily adapted to operate on CNG. They may be retrofitted, as are all but about 30 of the 500,000 or so CNG vehicles currently operating worldwide, at a cost of about $1,500 to $2,000 per vehicle. The major change is the addition of one or more pressurized tanks for CNG storage, additional fuel lines for the gaseous fuel, and a gaseous fuel mixer in the engine. A far superior vehicle would be one designed specifically for natural gas and not burdened by redundant fuel systems. A vehicle dedicated to and optimized for natural gas would have generally lower emissions than gasoline vehicles and about 10 percent greater efficiency because of its higher octane and similar power. It would cost about $700 to $1,000 more because of the more costly fuel tanks, but would not have cold-start problems. It would also have a shorter driving range or reduced trunk space because of the much lower volumetric energy density of gaseous fuels (see Table 6).

Methane can be stored in carbon skeletal networks called adsorptents. The potential advantage of adsorption is that a given energy density can be attained at a pressure lower than that required to compress natural gas by itself to the same volumetric energy density. For example, an adsorptent at less than 1000 psi can attain the same volumetric energy density as CNG at over 1500 psi. This form of storage, although not yet commercially viable, may lower the cost and bulk of storing natural gas and may make low-pressure home compression viable. In the United States the Gas Research Institute is sponsoring R&D work aimed at commercializing adsorptents.

Currently, large numbers of CNG vehicles are operating in Italy, New Zealand, Canada, and the Soviet Union.[56] All are retrofitted gasoline-powered vehicles. About 300,000 vehicles have been operating since the 1950s in Italy, mostly in fleet use. Governments in the remaining three countries initiated major CNG programs in the 1980s. In New Zealand, about 110,000 vehicles were converted to CNG, representing roughly 10 percent of gasoline use. When the country shifted much of its economy from the public to the private sector in the late 1980s, the government withdrew the substantial subsidies it had offered to consumers, and market penetration dropped below the 10 percent level. The federal and provincial Canadian governments and local gas utilities offered major incentives to fuel suppliers and consumers beginning in the mid-1980s; by 1988 about 15,000 vehicles were operating on CNG, about half by households and half by fleet operators. The Soviet Union announced the intention in 1988 of converting 500,000 to 1 million vehicles to CNG by 1995, most of them taxis and trucks.

CNG has an extraordinary safety record in actual experience. In New Zealand, for instance, with over 100,000 vehicles in operation for almost ten years, there has been only one explosion or fire of a natural gas tank, and no one was hurt. The only danger is the accidental leakage of gas from CNG in an enclosed space (in an open space the gas xxxxxxx

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[56]J. Sathaye, B. Atkinson, and S. Myers, "Promoting Alternative Transportation Fuels: The Role of Government in New Zealand, Brazil, and Canada," in *Alternative Transportation Fuels: An Energy and Environmental Solution*, edited by D. Sperling (Westport, Conn.: Quorum Books/Greenwood Press, 1989).

TABLE 6
CHARACTERISTICS OF VEHICULAR ENERGY STORAGE SYSTEMS

Vehicle	*Range (miles)*	*Total Weight (full lbs.)*	*Total Size (gallons)*	*Fuel Dispensing (time, minutes)*
Gasoline[a]	300	80	11	2
Methanol[b]	300	135	17	3–4
Ethanol[c]	300	110	13.5	2–3
LNG[d]	300	130	27	2–4
CNG/3000 psi[d]	300	240	45	4–8
Liquid hydrogen[e]	300	100	72	3–4
Fe–Ti hydride[e]	150	640	37	5–20[f]
EV/Na–S[g]	150	700	77	20[h]–720

Notes: The baseline gasoline vehicle gets 30 mpg, lifetime average. Efficiency of other vehicles is referenced to this gasoline vehicle baseline. Na–S = sodium/sulfur couple; Fe–Ti = iron–titanium.

[a]23 lb. gasoline tank, 6.18 lbs.gal., 1.07 outer tank/inner displacement ratio.

[b]64,000 Btu/gal. (cf. 124,000 for gasoline), 6.6 lbs./gal., 15% thermal efficiency over gasoline, 37-lb. tank, 1.07:1 outer/inner ratio.

[c]84,600 Btu/gal. others as for methanol.

[d]Adapted from data in M. A. DeLuchi, R. A. Johnston, and D. Sperling, *Methanol Versus Natural Gas Vehicles: A Comparison of Resource Supply, Performance, Emissions, Fuel Storage, Safety;, Costs, and Transitions* (Warrendale, Penn.: Society of Automobile Engineers, 1988). Assumes fiberglass-wrapped aluminum CNG cylinders; 15% thermal efficiency advantage for CNG and LNG; weight penalty for CNG. LNG system size includes LNG pump.

[e]Adapted from data in M.A. DeLuchi, "Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, Environmental Impacts, and Cost," *International Journal of Hydrogen Energy* 14 (1989): 81–130.

[f]80% of hydride refilled in under 10 minutes.

[g]35-kWh capacity, 120 Wh/1, 110 wh/kg, 4.4 mi/battery-kWh (M. A. DeLuchi et al., Electric Vehicles: Performance, Lifecycle Costs, Emissions, and Recharging Requirements, *Transportation Research* 23A, No. 3 (1989): 255–78.

[h]Fast electric vehicle charging is theoretically possible, but requires a very large current and is possible only with certain batteries.

evaporates quickly causing no problems), but again the safety record of CNG in Italy, New Zealand, and Canada has been virtually unblemished. Liquefied natural gas use would be similarly safe since the gas evaporates quickly, unlike gasoline and LPG, minimizing the possibility of fire. LNG could be a problem in enclosed spaces, where leaking or intentionally boiled-off gas would collect, but boiled-off gas could be burned with a small pilot flame, as with a kitchen stove, and rules could be enforced requiring proper ventilation in enclosed garages.

Costs

CNG made from domestic natural gas will be less expensive than imported methanol made from RNG and much less expensive than methanol made from domestic NG. Imported methanol will cost between 40 and 50 cents per gallon, at relatively low levels of demand for the RNG feedstock, if the low production cost estimates prove correct. Transport, storage, and retail station costs will add at least 14 cents per gallon to the price, bringing the retail cost to at least $9 per million Btu (mmBtu) before taxes, assuming a landed cost of 45 cents per gallon. At the same time domestic gas will be delivered to stations for about $5 per mmBtu, according to price projections for commercial gas.[57] Based on an exhaustive review of the literature and a detailed accounting of all costs, including land, site preparation, hook-up to the gas main, energy needed to compress gas from pipeline pressure to 3000 psi, etc, the cost of compression and retailing is estimated to be about $3 per mmBtu.[58] B.C. Gas of Canada, a marketer of CNG, also estimates $3 per mmBtu.[59] Thus a midrange estimate of the cost of CNG is $8 per mmBtu before taxes; a low-end estimate for methanol is about $9 per mmBtu. LNG will cost about the same as CNG.

However, because of the high cost of high-pressure storage tanks for CNG, NG vehicles would cost about $1000 more than gasoline and methanol vehicles with the same range and performance. This higher upfront cost is partially compensated for by lower back-end costs: The storage systems will probably have a high salvage value, and the use of NG may increase the life of the engine and hence increase the resale value of the vehicle.

Ownership and operating costs can be combined and expressed as a total cost per mile over the life of a vehicle by amortizing the initial cost at an appropriate interest rate, adjusting for salvage values and vehicle life and adding periodic costs such as maintenance, fuel, insurance, and registration. Table 2 presents the life-cycle cost of various alternative-fuel vehicles relative to a comparable baseline gasoline vehicle. It shows the retail price per gallon of gasoline (including taxes) at which the life-cycle cost of the alternative-fuel vehicle and the comparable gasoline vehicle would be equal. This is called the "break-even" price of gasoline. As shown in Table 3, the total life-cycle cost of NG vehicles (using U.S. NG) will be close to the life-cycle cost of gasoline vehicles at pre-1990 gasoline prices, and may be less than the life-cycle cost of methanol vehicles (using remote natural gas), although the range of estimated costs overlap.

The analysis is conducted from the end-user's perspective, with these assumptions: The automobiles are optimized for methanol (M100), CNG, and electricity; the fuels are produced and used on a large scale; refueling station costs are fully incorporated; and costs are calculated on a per-mile basis to take into account differences in total life-cycle vehicle costs, including differences in thermal efficiency, maintenance, and engine life.[60]

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[57] U.S. Energy Information Administration, *Annual Energy Outlook 1987.*

[58] DeLuchi et al., *Methanol Versus Natural Gas Vehicles.*

[59] J. H. Cann, Presentation by B.C. Hydro of Canada to Gas Symposium, Washington, D.C., April 19, 1988.

[60] See DeLuchi et al., *Methanol Versus Natural Gas Vehicles.*

These assumptions are based on an exhaustive review of the literature, including experiences in Europe, Canada, New Zealand, and the United States and extensive discussions with vehicle and equipment manufacturers. The analysis is based on a near-term scenario for single-fuel vehicles optimized to run on their respective fuels. The costs associated with CNG vehicles are somewhat more uncertain than those for methanol since the development of CNG vehicle technology has lagged: Relatively little effort has gone into designing and testing an optimized-for-CNG vehicle, including the development of advanced storage tanks, and there is little reliable evidence from which to estimate the operating costs and life of such an optimized vehicle.

The baseline gasoline vehicle, against which the alternative-fuel vehicles are compared, has the following attributes: 35 mpg, 2,530 pounds, 262-mile range, and a vehicle life of 130,000 miles at 10,000 miles per year. It is assumed that a methanol car costs the same as a gasoline car and that a CNG car costs $700 to $800 more. The retail price of gasoline, including taxes, is assumed to be $1.15 per gallon, compared to an estimated 74 cents to $1.13 per gallon for methanol and $8.90 to $14.10 per 1,000 Btu for CNG. The cost parameters and vehicle attributes are listed in Table 7.[61]

The methanol and CNG cars are comparable to the baseline gasoline vehicle; they have the same size, range, and weight (excluding the extra weight for CNG tanks and methanol fuel), and similar power. They are assumed to be 10 to 20 percent and 10 to 25 percent, respectively, more fuel efficient than the baseline gasoline car.

The analysis shows that the life-cycle cost of a CNG auto tends to be less than for a methanol vehicle, although not for all assumed values. The ranges in values correspond to uncertainties in cost estimates and vehicle attributes, as presented in Table 7.

Similarly, NG vehicles are a more cost-effective strategy for reducing ozone than methanol.The OTA ozone report cited earlier in the cost-effectiveness analysis for methanol estimated that the cost effectiveness of reducing ozone using dedicated NG vehicles would be $0 to $1400 per ton—significantly lower than the $3200 to $22,000 estimated for comparable single-fuel methanol cars.

HYDROGEN AND CLEAN ELECTRICITY

Hydrogen and electric vehicles are linked here because they both are part of a potentially sustainable and very clean energy path and both can use the same clean sources of energy. Battery-powered (or roadway-powered) electric vehicles can use electricity made with solar or nuclear power (from fission or fusion reactors), and hydrogen-powered vehicles can use solar or nuclear power to split water to make hydrogen. This path would be followed if great emphasis were placed on reducing environmental pollution and global warming and on creating a permanently sustainable energy supply system.

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[61]For full documentation, see DeLuchi et al., *A Comparative Analysis of Future Transportation Fuels* and DeLuchi et al., *Methanol Versus Natural Gas Vehicles.*

TABLE 7
COST PARAMETERS AND VEHICLE ATTRIBUTES USED IN COST ANALYSIS

Description	*Gasoline*	*Methanol*	*CNG*
Retail price of gasoline, $/gallon, excluding taxes	0.95	—	—
Methanol price, $/gallon, plantgate or port	—	.50–.80	—
Domestic transportation cost and retail mark-up	—	.14–.23	—
Cost of gas to station, $/mmBtu	—	—	5–8
Station mark-up, $/mmBtu	—	—	2.3–4.5
Fuel taxes	0.20	0.10	1.60
Lifetime vehicle fuel efficiency, mpg	3.5	—	—
Thermal efficiency, relative to gasoline car, %	—	+10–20	+10–25
Vehicle price, thousand $	9.5	9.5	10.2–10.3
Life of vehicle, thousand miles	130	130	130–160
Weight of vehicle, lbs.	2535	2535	2635
Real interest rate for car loan, %	9	9	9
Maintenance costs, $/year	400	400	300–400

Note: Station costs for CNG were calculated independently, taking into account 15 different cost and operations factors. For details, see M. A. DeLuchi, R. A. Johnston, and D. Sperling, *Methanol Versus Natural Gas Vehicles: A Comparison of Resource Supply, Performance, Emissions, Fuel Storage, Safety, Costs,and Transitions* (Warrendale, Penn.: Society of Automobile Engineers, 1988).

Hydrogen

Hydrogen is an attractive transportation fuel in two important ways: It is the least polluting fuel that can be used in an internal combustion engine and it is potentially available wherever there is water and a clean source of power. The prospect of a clean, widely available transportation fuel has motivated much of the research on hydrogen fuels. The technology for cleanly producing, storing, and combusting hydrogen is far from commercialization, and thus a large range of technology options is explored in this section.

Production

Hydrogen can be produced from water or fossil fuels. Fossil fuels consist of hydrocarbon molecules that can be reformed, cracked, oxidized, or gasified to produce hydrogen. Coal is relatively abundant and could provide a low-cost feedstock for hydrogen for many decades, but if coal or other fossil fuels are to be used, it would be more attractive to convert them to liquid or gaseous fuels with a higher volumetric energy density. In addition, the conversion of fossil energy to hydrogen fuels would cause major environmental impacts and would not be a renewable energy path. Most of the hydrogen research community agrees that if hydrogen is to be used as a fuel, the most attractive source is water.[62]

There are several methods for splitting water to produce hydrogen: thermal and thermochemical conversion, photolysis, and electrolysis. Electrolysis—the use of electricity to split water into hydrogen and oxygen—is the most developed method. The cost and environmental impact of producing hydrogen from water depend on the primary energy used to generate the electricity to split the water. Fossil fuels would not be used as the source of electric power because it would be cheaper and more efficient and would generate less carbon dioxide to make the hydrogen directly from the fossil fuels. Hence, nonfossil feedstocks such as solar, geothermal, wind, hydro, and nuclear energy would be used to generate electricity for the electrolysis process. Of these, solar energy and nuclear energy (from breeder reactors or possibly fusion plants) will potentially be available in the greatest quantities for the long term.

Vehicular Fuel Storage

The principal obstacle, other than costs, to using hydrogen in vehicles is hydrogen's very low volumetric energy density as a gas at ambient temperature and pressure. Hydrogen's density may be increased by storing it on board a vehicle as a gas bound with certain metals (hydrides), as a liquid in cryogenic containers, as a highly compressed gas (up to 10,000 psi) in ultra-high-pressure vessels, as a liquid hydride, and in other forms.Most research has focused on hydride and liquid hydrogen storage.

Hydride storage units, which include housings for the hydrides and the coolant systems, are very large, from 25 to over 80 gallons, and quite heavy, 250 to 1,000 lbs (see Table 6). Barring major improvements in vehicular fuel efficiency, hydride vehicles would be limited by storage weight to a range of about 100 to 200 miles. Liquid hydrogen must be stored in double-walled, superinsulated vessels designed to minimize heat transfer and the boil off of liquid hydrogen. Liquid hydrogen systems are much lighter and often more compact than hydride systems providing an equal range. In fact, liquid hydrogen storage is not significantly heavier than gasoline storage, on an equal-range basis, although it is about six times bulkier (see Table 6).

In summary, all hydrogen storage systems systems are bulky and costly and will remain so, even with the major advances that are likely to occur with expanded R&D efforts. Hydrogen vehicles will be successfully introduced only if users are willing to accept vehicles with much larger fuel tanks and shorter ranges than other vehicles—which is quite possible if strong incentives and social messages are given for environmentally benign and sustainable fuels.

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[62]J. Bockris et al., "On the Splitting of Water," *International Journal of Hydrogen Energy* 10, no. 3 (1985): 179–201.

Environmental Impacts of Hydrogen Vehicles

The attraction of hydrogen is nearly pollution-free combustion. While many undesirable compounds are emitted by gasoline and diesel-fuel vehicles or formed from their emissions, the main combustion product of hydrogen is water. Hydrogen vehicles would not produce significant amounts of CO, HCs (only small amounts from the combustion of lubricating oil), particulates, SO_x, ozone, lead, smoke, benzene, or CO_2 or other greenhouse gases (see Tables 4 and 5). If hydrogen is made from water using a clean power source, then hydrogen production and distribution will be pollution free.

The only pollutant of concern would be NO_x, which is formed, as in all internal combustion engines, from nitrogen taken from the air during combustion. With lean operation and some form of combustion cooling such as exhaust gas recirculation, water injection, or the use of very cold fuel (i.e., liquid hydrogen), but with no catalytic control equipment on the engine, an optimized hydrogen vehicle probably could meet the current U.S. NO_x standard and probably have lower lifetime average NO_x emissions than a current-model catalyst-equipped gasoline vehicle.[63]

The use of hydrogen made from nonfossil electricity and water is one of the most effective ways to reduce anthropogenic emissions of greenhouse gases. Highway vehicles burning hydrogen would emit essentially no CO_2 or CH_4, and because they would emit no reactive hydrocarbons (precursors to ozone formation in the troposphere), would help to reduce ozone (see Table 4).

Nuclear Versus Solar

Solar electrolytic hydrogen is environmentally and politically preferable to nuclear electrolytic hydrogen, for several reasons. First, although the nuclear power industry is developing "passively safe" reactors, such as the high-temperature, gas-cooled reactor, which relies on physical laws rather than human corrective action to safely resolve emergencies,[64] it is not clear if the public, regulatory agencies and financial backers will be convinced that they are safe enough to warrant a large expansion of nuclear power. Second, if nuclear power was aggressively developed, the reprocessing of spent nuclear fuel and reprocessing of plutonium for breeder reactors would circulate large amounts of weapons-grade nuclear material.[65] Third, and perhaps most importantly, long-term underground disposal of nuclear wastes remains environmentally controversial.

Solar-power production is much less risky environmentally and politically; even concern over the amount of land devoted to photovoltaic (PV) systems may be misplaced, as it has been estimated that PV power generation (assuming 15 percent efficiency) requires only three times more acreage per unit of energy produced than

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[63] M. A. DeLuchi, "Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, Environmental Impacts, and Cost," *International Journal of Hydrogen Energy* 14 (1989): 81–130.

[64] J. J. Taylor, "Improved and Safer Nuclear Power," *Science* 244 (1989): 318–25.

[65] J. M. Ogden and R. H. Williams, *Hydrogen and the Revolution in Amorphous Silicon Solar Cell Technology* (Princeton, N.J.: Center for Energy and Environmental Studies, Princeton University, PU/CEES Report No. 231, February 15, 1989).

nuclear power generation when mining, transportation, and waste disposal are considered.[66] In the hydrogen vehicle cost analyses that follow, solar photovoltaic energy is considered the primary energy source.

Cost

Hydrogen's environmental advantages must compensate for the very high cost of hydrogen fuel and the high cost of hydrogen storage systems. Hydrogen fuel is expensive primarily because electricity is relatively expensive (and 5 to 25 percent of the energy in the electricity is lost in the electrolysis process). We assume that hydrogen is produced from photovoltaic power costing between 5 and 15 cents per kwh at the generation site.[67] With this assumption, Table 2 shows the price of gasoline that would be required to make the life-cycle cost of a gasoline and hydrogen vehicle equal. In the high-cost cases, both hydride and liquid hydrogen vehicles are prohibitively expensive compared to gasoline vehicles. Even in the low-cost case, the low break-even price is about $3 per gallon. In other words, gasoline would have to sell for more than $3 per gallon for hydrogen vehicles (using hydrogen made from water with solar power) to be economically competitive. Thus, it appears that hydrogen vehicles will be cost competitive in the middle term only if the most optimistic cost projections are realized *and* the price of gasoline at least triples.

Opportunities for Hydrogen

The attractiveness of hydrogen vehicles hinges on technological progress in three areas. First, in order to increase hydride vehicle range and performance, hydrides with high mass-energy density, low dissociation temperature, and relatively low susceptibility to degradation by gas impurities must be found. At present, the probability of hydride vehicles achieving performance and range parity with gasoline vehicles seems low. Second, the loss of trunk space to bulky hydrogen storage systems needs to be minimized. Hydrogen storage systems are many times larger than gasoline tanks of equal range. Barring dramatic advances in technology, this disparity is not likely to change. Third, reliable, low-cost boil-off control devices must be developed for liquid hydrogen vehicles so that the vehicles can be left for a week or more in enclosed areas without creating safety hazards.

The most attractive feature of hydrogen is its very low pollutant emissions, including greenhouse gases. The most fundamental barrier is cost. Therefore, if hydrogen is to be introduced as a transportation fuel, optimistic projections of the cost of hydrogen vehicles and hydrogen fuel must be realized and a relatively high value must be placed on reducing air pollution, avoiding greenhouse warming, and reducing dependence on finite and imported energy resources.

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[66]Merid Corp., *Energy Systems Emissions and Material Requirements*, prepared for U.S. DOE, 1989. The land estimate for nuclear energy appears to have been misrepresented in Hubbard, "Photovoltaics Today and Tomorrow" (see footnote following).

[67]H. M. Hubbard, "Photovoltaics Today and Tomorrow," *Science* 244 (1989): 297–304.

In conclusion, while hydrogen fuel is not a near-term option, it is also not strictly an exotic, distant-future possibility. Although all hydrogen vehicles have serious shortcomings, none of the problems are necessarily insurmountable. With a strong R&D effort, normal technological progress, and continuing reductions in the cost of solar electricity, hydrogen vehicles could be cost competitive on a social-cost basis, taking into consideration air pollution, energy security, global warming, etc., within perhaps 30 years.

Electric Vehicles

A cost-effective, high-performance electric vehicle (EV), recharged quickly by solar (or perhaps nuclear) power using widely available battery materials, would be an attractive transportation machine. Progress over the last ten years has brought this ideal closer to reality.

Although most reports and statements in the United States emphasize methanol as a replacement for gasoline and diesel fuel, there is increasing awareness of the potential for advanced EVs with acceptable performance to provide substantial air quality and petroleum conservation benefits at comparatively low cost.

Performance of EVs

Electric vehicles were commonplace in the United States at the turn of the century. However, by 1920 improvements in EV technology had lagged so far behind the development of the internal combustion engine that EVs became practically extinct.[68] With the resurgence of interest in EVs in the 1960s came promises of breakthroughs that were to make EVs as economical and high performing as internal combustion engine vehicles. But a decade later the promised EV had still not materialized.

The efforts of the past decade have not produced any dramatic breakthroughs. However, over that period the technology of EV batteries and power trains has developed incrementally and the cumulative result is substantial. For example, advances in microelectronics have resulted in low-cost, light-weight dc-to-ac inverters, which make it attractive to use ac rather than dc motors. With the improved inverters the entire ac system is cheaper, more compact, more reliable, easier to maintain, more efficient, and more adaptable to regenerative braking than the dc systems that have been used in virtually all EVs to date. Similarly, the development of advanced batteries, particularly the high-temperature sodium/sulfur battery, has progressed to the point at which successful commercialization does not depend on major technical breakthroughs but on the resolution of manufacturing and quality-control problems. Several major auto manufacturers expect to mass-produce EVs with ac power trains and sodium/sulfur batteries in the 1990s.[69]

Advanced EVs now under development and projected to be commercially available within a decade are expected to offer considerably better range and performance than

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[68] W. Hamilton, *Electric Automobiles* (New York: McGraw-Hill, 1980).

[69] G. Mader and O. M. Bevilacqua, "Electric Vehicle Commercialization," in *Alternative Transportation Fuels: An Energy and Environmental Solution*, edited by D. Sperling (Westport, Conn.: Quorum Books/Greenwood Press, 1989).

the state-of-the art EVs of ten years ago. The first mass-produced commercial EV is likely to be a variation of General Motors' "Impact," unveiled in early 1990 and expected to be for sale around 1995. (In early 1991, GM announced that it was converting one of its factories with a capacity of about 25,000 vehicles per year to EV production.) The Impact uses advanced electric motor technology—two ac motors, one over each wheel, and a compact, efficient inverter—and an ultra-high-efficiency design to achieve a reported 120-mile range (at constant speed and under other artificial conditions) and performance equal to or better than that of comparable internal combustion EVs (ICEVs).

Without sacrificing seating or cargo capacity, passenger vehicles and vans are projected to have urban ranges of about 150 miles, high top speeds and acceptable acceleration, and low energy consumption by the turn of the century. With these characteristics, EVs would be attractive as second vehicles in most multicar households[70] and as vans in most urban fleets.[71] As personal vehicles become more specialized and expectations about the multipurpose usage of vehicles continue to diminish, EVs may become acceptable as primary commuter cars. Exotic batteries under development, such as the aluminum-air battery, that promise even longer ranges and faster recharging, could eventually make EVs the vehicle of choice in a world of high energy prices and heightened environmental concern.

Cost

If the most optimistic cost conditions are satisfied—high vehicle efficiency, high battery-energy density, low-cost off-peak power, low initial battery cost, long battery cycle life, long EV life, and low maintenance costs—then EVs will have much lower life-cycle costs than comparable gasoline vehicles and will be economically competitive even if gasoline is free (Table 2). However, under high-cost conditions, EVs will not be cost competitive until gasoline sells for $3 to $4 per gallon (see Table 2). If electricity is more expensive, in the range of 10 to 15 cents per kwh, the breakeven price is about $4 to $5 per gallon in the high-cost case. The great difference between the high and low break-even gasoline prices is due primarily to uncertainty about the cost of batteries and the life of EVs relative to the life of internal combustion engine vehicles.

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[70] L. G. Lunde, "Some Potential Impacts on Travel of Alternative Assumptions on the State of Electric Vehicle Technology," *Transport Policy and Decision Making* 1 (1980): 361–77; A. Horowitz and N. P. Hummon, "Exploring Potential Electric Vehicle Utilization: A Computer Simulation," *Transportation Research* 21A (1987): 17–26.

[71] M. Berg, "The Potential Market for Electric Vehicles: Results from a National Survey of Commercial Fleet Operators," *Transportation Research Record* 1049 (1985): 70–78; J. Brunner and D. Wood, "Assessment of U.S. Market for Electric Vans," Proceedings of Ninth International Electric Vehicle Symposium, Toronto, Canada, November 13–16, 1988 (Mississauga, Canada: Kerwill Publications, EVS88-072, 1988).

Environmental Impacts

A principal attraction of electric vehicles is the promise of improved urban air quality. If EVs use solar power, then they will be essentially nonpolluting. But even if they were to consume electricity generated in a combination of power plants using coal, natural gas, oil, hydroelectric power, nuclear power, and solar power, they would still provide a major reduction in emissions[72] (see Table 4).

Regardless of the type of power plant, fuel, and emission controls employed, EV use will practically eliminate CO and HC emissions on a per-mile basis, relative to gasoline vehicles meeting future stringent emission standards. NO_x and particulate emissions will be reduced with EV use if at least moderate controls are used. SO_x emissions will be practically eliminated if natural gas is used to generate electricity, but will increase if coal is used—by several fold in the case of uncontrolled or moderately controlled coal steam plants. It should be noted that the light-duty transportation sector is now a major source of HC, CO, and NO_x emissions but a very minor source of SO_x and particulates, and that CO and ozone are the major urban air pollution problems. Thus, a large decrease in HC, CO, and NO_x emissions from light-duty highway vehicles would have a greater impact on urban ambient air quality than would a moderate increase in SO_x emissions. As a result, regardless of the feedstock used for electricity generation, EVs will tend to improve urban air quality significantly.

The impact of EV use on greenhouse gas emissions is more mixed and more sensitive to the type of electricity feedstock used. Fossil-fuel-burning power plants emit several greenhouse gases, as well as the regulated pollutants discussed. Table 5 shows the results of substituting EVs for internal combustion engine vehicles, expressed as percent change per mile in emissions of a composite greenhouse gas (CO_2 equivalents). On a per-mile basis, the use of coal-fired power by EVs will cause a moderate increase in emissions of all greenhouse gases, relative to current emissions associated with the use of gasoline and diesel fuel. If natural gas is used, there will be a moderate decrease in emissions of greenhouse gases, mainly because of the low carbon-to-hydrogen ratio of natural gas. If EVs are powered by the mix of electricity sources existing in the United States in 1985, then about the same quantity of greenhouse gases will be emitted as was emitted by the use of gasoline and diesel fuel vehicles in 1985. If nonfossil fuels (nuclear, solar, hydroelectric power, or biomass fuels) are used in all engines, there will be essentially zero emissions of greenhouse gases.

Opportunities for EVs

EVs will gain strong support from industry for three reasons. First, utilities generally support the use of EVs because they expect EVs to draw power from otherwise idle capacity and not to require the construction of new plants. Given appropriate time-of-use rates (or other load management), most recharging of EVs will be postponed until evening, when electric utilities have ample capacity available and the use of oil, which is generally a peaking fuel, is at a minimum. Studies of the impact of EV use on utility

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[72]Q. Wang, M. A. DeLuchi, and D. Sperling, "Emission Impacts of Electric Vehicles," *Journal of Air and Waste Management Association* 40 (1990): 1275–84.

energy supply have shown consistently that California utilities have sufficient capacity in place to support perhaps millions of electric vehicles, charging off peak.[73]

Second, the life-cycle cost of advanced, mass-produced EVs, using cheap off-peak power, probably will be low enough to induce some fleet operators and homeowners to purchase those vehicles. Third, vehicle sales will not be hindered initially as much as methanol and CNG vehicles by the absence of a fuel distribution network because one already is in place. Electricity is available virtually everywhere, and most homes and businesses can set up an EV charging station for well under $1,000.[74] These relatively small cost and start-up barriers (the "chicken-and-egg" problem) means that the market penetration of EVs can proceed, to a point, largely by market forces. (The Electric Vehicle Development Corporation, a private group supported by electric utilities, battery manufacturers, and auto manufacturers, is developing markets and service infrastructure for EVs.)[75]

The degree of market penetration by EVs will depend initially on their range, performance, and life-cycle cost. In the near future, EVs will be attractive in some urban fleets; as the technology improves and vehicles are produced in large quantities, EVs may be attractive as commuter vehicles. However, even if advanced EVs prove to be as high performing and economical as is hoped and are favored for their environmental benefits, there will still be one significant obstacle to widespread consumer acceptance: the long recharging time. If it takes eight hours to recharge an EV, most households will want at least one nonelectric vehicle and EVs will be limited to the role of second car in some multicar, home-owning households. However, if EVs can be charged in under 30 minutes, they may be able to displace gasoline vehicles in many applications and gain a large share of the vehicle market: They may be suitable for all applications except those requiring more power than even advanced batteries can provide.

There are several ways of quickly recharging EVs, including swapping discharged batteries for previously fully charged ones, using mechanically rechargeable batteries, and using ultra-high-current recharging. None of these methods has been demonstrated, however, and all are likely to be expensive. Much more work is needed in this area.

The successful completion of advanced EV development programs and the development of a means of quickly recharging EVs would make the EV a competitive alternative to internal combustion vehicles. The combination of large environmental benefits and potentially low private cost in the near term, along with the prospect of a pollution-free feedstock in the long run, may well make EVs the option with the lowest social cost. In the meantime, though, EVs may be economical, on a private-cost basis, in some applications today.

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[73]E. P. Marfisi et al., *The Impacts of Electric Passenger Automobiles on Utility System Loads, 1985–2000* (Palo Alto, Calif.: Electric Power Research Institute, EA-623, 1978).

[74]W. Hamilton, *Electric and Hybrid Vehicles*, technical background report for the U.S. DOE Flexible and Alternative Fuels Study, prepared for the U.S. Department of Energy, 1988.

[75]G. Mader and O. M. Bevilacqua, "Electric Vehicle Commercialization," in *Alternative Transportation Fuels: An Energy and Environmental Solution*, edited by D. Sperling (Westport, Conn.: Quorum Books/Greenwood Press, 1989).

In summary, EVs and hydrogen vehicles require substantial improvements before they become attractive as the dominant transportation technology. For that to happen, R&D investments must be expanded greatly. A clean electricity and hydrogen path will come into being in a timely manner only if society places much greater emphasis on the need to reduce air pollution and slow the greenhouse effect.

SHORT- VERSUS LONG-TERM CONSIDERATIONS

WHY HAS METHANOL DOMINATED THE DEBATE?

If natural gas and electric vehicles are likely to be less expensive and have larger social benefits than methanol, then why has methanol dominated the debate? The answer is simple: The auto industry, with a short-term focus, prefers methanol because it is physically and chemically more similar to gasoline than electricity and natural gas and is more compatible with gasoline in multifuel engines. Switching to methanol would require less modification to current gasoline vehicles than would gaseous or electric-powered vehicles, and less change in driver behavior. There would be less cost and less market risk. Government regulators, concerned with quick impacts, have accepted auto-industry thinking and concerns.

This focus on methanol began to diminish about 1989 when the natural gas and electric utility industries began to significantly increase their lobbying efforts in response to proposals to amend the national Clean Air Act and to lower California vehicle emission standards.

Nevertheless, the auto industry in general continues to prefer methanol, fearing that consumers will be unwilling to accept the shorter driving range of natural gas and, especially, electric vehicles. Current EVs travel only about 60 miles per charge. Advanced EVs likely to be available in the late 1990s will probably have a range of 100 to 150 miles, but even this is much less than for gasoline vehicles. Natural gas vehicles (NGVs) have a less severe range problem; assuming that future vehicles will be somewhat more energy efficient than today's vehicles and that auto engineers would slightly redesign an NGV in order to fit more tank capacity into a vehicle, then a future NGV is likely to have a range of about 200 to 250 miles, still somewhat less than today's gasoline vehicles.

A broader, longer-term view suggests that EVs and NGVs may be successful in the future, possibly more so than methanol, as utilities continue to be deregulated and slowly emerge from their lethargy—becoming more aggressive marketers and lobbyists for EVs and NGVs.

It may also be that consumers are not as conservative and unchanging in their vehicle purchasing preferences as is commonly assumed. More accurately, there may be various groups of buyers who are willing to accept the shorter driving range of EVs and NGVs and the long recharging time of EVs in exchange for their environmental superiority.[76] Recent indications of this interest, especially in EVs, is the unexpectedly enthusiastic response General Motors reportedly received to the unveiling of their EV prototype in

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[76] D. Sperling, D. Hungerford, and K. Kurani, "Consumer Demand for Methanol," in *Methanol as an Alternative Fuel Choice: An Assessment*, edited by W. Kohl (Washington, D.C.: International Energy Program, Johns Hopkins University, 359–77.

early 1990, and a disproportionate interest evinced in EVs in August 1990 focus group interviews in the Los Angeles area. In untargeted discussions of alternative fuels, participants mentioned electric vehicles 34 times, compared to 9 for propane, 6 each for methanol and alcohols, 4 each for CNG and hydrogen, and 5 for reformulated gasoline.[77]

While these observations are not definitive evidence, they suggest a yearning for a "green" car. If battery and EV technology continues to be improved, resulting in life-cycle costs similar to those for gasoline-powered vehicles, a plausible expectation,[78] then we believe it is likely that EVs can gain significant market penetration. A similar case can be made for natural gas vehicles, since they can also be marketed as a "green" product.

Experiences in Brazil and New Zealand lend further support to the hypothesis that consumers are likely to modify their behavior to accept range and recharging disadvantages, if given a good reason to do so.[79] The reasons in these two cases were part nationalism, part economic, and part risk aversion. In Brazil, in particular, consumers were convinced by government actions and proclamations that ethanol, not gasoline, was the fuel of the future, and therefore that they would have a better chance of retaining access to fuel in the future and of retaining the resale value of their vehicles if they purchased an ethanol-powered vehicle. As a result, ethanol cars accounted for over 95 percent of new car sales in Brazil through the mid-1980s: In New Zealand, about 10 percent of all cars were converted to CNG during the same time period.

In conclusion, while it is true that consumers would be reluctant to purchase electric or natural gas vehicles, we believe that with intensified marketing and credible signals that government and industry are fully behind these technologies, significant numbers of consumers, especially in environmentally conscious California, would be willing to purchase those vehicles. Vehicle and fuel suppliers might even find that the possibility of refueling an NGV and recharging an EV at home prove to be marketing advantages with those many individuals who dislike refueling at retail stations.

The reality is that industry is conservative and adverse to risk and, all else being equal, would naturally prefer the least risky path. That is not an indictment, or even a criticism; it is the nature of our economic system. While this risk adverseness favors methanol in the case of the auto industry, the attractions of NGVs and EVs, the growing aggressiveness of gas and electric utilities, and the absence of a domestic economic constituency for methanol may eventually lead to the emergence of NGVs and EVs as leading transportation energy options. The challenge for government is to distinguish between short-term, ease-of-implementation preferences and more substantive, longer-term social benefits.

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[77]T. Turrentine, Memorandum, August 23, 1990, in study being conducted by U.C. Institute of Transportation Studies for California Energy Commission.

[78]DeLuchi, *Hydrogen Vehicles*.

[79]Sperling, "Brazil, Ethanol and the Process of System Change"; K. Kurani, *CNG in New Zealand: A Case Study*, manuscript in preparation, based on series of consumer surveys in New Zealand, 1991.

FACTS, BELIEFS, AND VALUES

To determine which fuel or fuels government should promote and to what extent, analysts ideally would calculate the cost effectiveness of each fuel option in reducing air pollution and greenhouse gases, plus reducing energy security and safety, and compare this rating to other strategies. In other words, they would synthesize all the information presented to this point in a single measure. Unfortunately, such an analysis is impossible to conduct with accuracy and precision at this time, in part because of uncertainty about vehicle and infrastructure costs, engine life, maintenance costs, and future energy prices.

Still greater uncertainty exists on the benefit side of the equation regarding emission characteristics, relationships between emissions and air quality, emissions and global warming, magnitude of safety and toxicity impacts, and impact on energy security. Consider, for instance, the calculations by The Office of Technology Assessment[80] and the California Advisory Board,[81] reported earlier in the text, of the cost effectiveness of methanol and CNG as ozone reduction strategies. They were based on only two important factors: fuel/vehicle cost and ozone impact, excluding other social benefits. But even these two factors included considerable uncertainty and unverifiable assumptions and produced results with a very broad range.

Even more daunting than calculating cost-effectiveness measures for particular impacts is the issue of how to weight the relative values of improved air quality and safety, reduced global warming, and greater energy security. How much is a 10 percent reduction in greenhouse gases worth? Is it worth more than a 10 percent reduction in hydrocarbon gases?

How, when, and where should there be a transition to alternative transportation fuels? There is no obvious answer and no consensus. The price of petroleum cannot be predicted, and many of the costs and benefits of alternative fuels are difficult to quantify. Different groups place different values on the important (nonmarket) concerns: energy security, air quality, global warming, and the ease and convenience of a transition. In short, different beliefs and values and familiarity with different facts lead individuals and organizations to different conclusions about the most desirable path.

The choice of transportation energy paths should focus on values and goals, rather than on projections of market costs, especially when projected costs do not differ much between energy options or are based on technologies that are still far from commercialization (and likely to become much less expensive with learning-curve improvements). Current and projected market prices can be poor criteria for long-term energy choices. Shifting social goals, values, and preferences will result in redirected government initiatives that will change relative energy prices, while the long-term replacement of today's sunk investments will also cause a shift in long-term energy prices. We should therefore take care not to allow current and extrapolated energy prices to overly

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[80]U.S. Office of Technology Assessment, *Catch Our Breath.*

[81]California Advisory Board on Air Quality and Fuels, *Report to the California Legislature,* Vol 1, Executive Summary, October 1989.

influence transition strategies. In the words of Herman Daly, "the choice between . . . energy futures is price determining, not price determined."[82]

The choice of transportation energy paths should also be open minded and flexible. There is no one optimal choice for everyone or every region; the era of one (or two) uniform transportation fuels may be over. This prospective multiplicity of fuel options presents a challenge for business and government. Because many of the benefits resulting from initial alternative-fuel investments do not accrue to the private-sector supplier of the fuel, government must take much of the initiative. But which fuels should it choose and how fast should it introduce them?

If concerns for self-sufficiency and energy independence were to dominate, then California should prefer energy options based on abundant domestic resources: fuels from coal and oil shale, domestic natural gas, and domestic electricity. Remote natural gas, imported as LNG or methanol, would be deemphasized.

If economic efficiency, measured by conventional market indicators, is the dominating value, then NGVs would be preferred, as would methanol if low-cost methanol production estimates prove accurate, while hydrogen would be discarded as an option. Electric vehicles would be competitive in some applications if optimistic battery cost and performance goals were met.

If environmental quality and sustainability takes precedence, then hydrogen and electric vehicles, using clean and renewable energy (probably solar power), would be preferred. Methanol and NG vehicles, regardless of the feedstocks, would be deployed as transitional options only, if at all.

If the abiding objective is to make the transition with as little disruption as possible, then petroleum fuels would be retained as long as possible by increasing oil imports and by reformulating gasoline and diesel fuel to be more environmentally acceptable.

A transition to methanol would require modifications to vehicles, storage tanks, and delivery systems, but would be less difficult than a transition to gaseous fuels. A transition to EVs would be relatively easy from an infrastructure standpoint, assuming that the cost and difficulty of establishing home recharging stations would not be great. However, the potential for EVs is limited by the weight and low-energy density of batteries and the long recharging time.

If the most important concern is to avoid a greenhouse warming, EVs using nonfossil power may be the best choice because they offer the best opportunity to immediately reduce emissions of greenhouse gases from the highway sector. Internal combustion engine vehicles using hydrogen made from water with nonfossil power would also emit only negligible amounts of greenhouse gases, but hydrogen vehicles are not likely to be commercially available as soon as EVs. Internal combustion engines using methanol or gas derived from biomass likewise would emit only small amounts of greenhouse gases, but the biomass resource base is limited, the use of these biomass fuels is much more polluting than the use of clean power by EVs, and biomass cultivation demands careful soil management.

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[82]H. Daly (1976), cited in A. Lovins, *Soft Energy Paths: Toward a Durable Peace* (New York: Harper & Row, 1977), 68.

Other values and goals could and should play instrumental roles—equity and distribution of power and wealth, growth versus stability, free enterprise, individual initiative, and public health—but the issues discussed here of environmetal quality, greenhouse effects, sunk investment, compatibility, and energy security have come to dominate the public debate.

MOVING TOWARD A MORE EFFICIENT AND FLEXIBLE REGULATORY SYSTEM

Current regulatory initiatives to introduce alternative fuels on the national level include a subsidy for ethanol-gasoline blends (excise tax exemption), preferential treatment of CNG and methanol in CAFE regulation, and mandated use of alternative fuels. The 1990 amendments to the U.S. Clean Air Act mandate the use of reformulated gasoline (which is expected to include varying amounts of methanol and ethanol) in severe nonattainment areas and the sale of alternative fuel vehicles in California, and virtually mandate (through stringent emission standards) the use of alternative fuels in some fleet vehicles. There is no coherent framework for guiding a transition to alternative fuels. The current approach is the vestige of a first-generation regulatory framework that is not suited to the changing circumstances of the future: It does not reflect multiple social goals, is not flexible in responding to changing economic and technological conditions, is insensitive to regional differences, and does not acknowledge the likelihood of shifting social priorities. There are good reasons for the simplistic inflexibility of past and current approaches—mostly associated with ease of implementation—but they are becoming increasingly inefficient and inappropriate.

Current federal government initiatives to reduce vehicular emissions and introduce alternative fuels are a continuation of the 1960's command-and-control style of social regulation, an innovation of lawyers and engineers[83] whose disciplinary paradigm is one of right and wrong and highly specific rules of conduct and design. Automotive emissions are currently regulated by requiring every vehicle to meet the same uniform standard, regardless of whether it costs less to reduce the emissions in some vehicles than others and regardless of whether there is an air pollution problem where the vehicle is sold and used.

This regulatory approach, unchanged by the 1990 amendments to the U.S. Clean Air Act, in which every vehicle is required to meet the same uniform emission standard, provides manufacturers with no incentive to do better than the standard. For instance, if an auto exceeds the standard, the company removes the valuable excess catalyst metals from the catalytic converters, reducing costs and allowing emissions to increase. This illustrates the flaw of uniform standards: They are not sensitive to differences in the cost of reducing emissions from one vehicle to another. Uniform emission standards are not only an economically inefficient method for reducing emissions, but also they provide no incentive to reduce emissions below the standard and therefore no incentive to introduce cleaner-burning alternative fuels.

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[83]B. Cook, *Bureaucratic Politics and Regulatory Reform: The EPA and Emissions Trading* (Westport, Conn.: Greenwood Press, 1988).

Continued reliance on the current inflexible and narrow approach to vehicle and fuel regulation implies the use of specific rules, standards, mandates, and subsidies to place direct controls on individual and industry behavior. It requires that government administrators have the foresight to be able to orchestrate which fuels and vehicles should be introduced where and when.

Given the uncertainty about the relative attractions of alternative fuels and the best way to introduce new fuels and vehicles, and given the uncertainty about the future, a more efficient and resilient approach would be to offer incentives to industry and consumers that push them in the correct direction—toward lower air pollution, reduced greenhouse gases, and perhaps even domestic resources. By utilizing principles of marginal cost, this approach becomes fundamentally more economically efficient. This incentive-based approach seeks to alter the behavior of individuals and industry by restructuring rather than overtly limiting the choice environment. It does not rely on omniscient government bureaucrats.

Before laying out the philosophy and concept of incentive-based regulatory approaches, it should be emphasized that the authors are not ideologically committed to any one approach, and that in practice vehicle and fuels regulation is not now based on a purely command-and-control approach. Moreover, incentive-based regulation would undoubtedly contain elements of command-and-control rules and might require an even larger governmental presence. This said, the case for moving toward a more incentive-based approach for reducing emissions and introducing alternative fuels is compelling. Indeed, the California Air Resources Board has already implicitly accepted this notion and is moving aggressively in that direction.

Incentive-based Approaches

Two different types of incentive-based approaches can be pursued. One is to make existing market arrangements operate better by manipulating key attributes of the market, particularly prices and information. The second is to create marketlike arrangements that mimic real markets in the way they generate incentives. The emphasis of both approaches is on decentralized decision making driven by self-interest but guided by the regulating body through its structuring of incentives.

The first approach, using existing markets better, typically involves the use of taxes, fees, and subsidies. One outstanding example is Senate Bill 1905, submitted by Gary Hart (based on the DRIVE+ proposal developed at Lawrence Berkeley Laboratory and the UC Berkeley School of Public Policy). That bill, which passed both houses of the California legislature but was vetoed by the governor in late September 1990, established a rebate-and-fee schedule for new car sales. Buyers would receive a rebate if the car they purchased had lower emissions and better fuel efficiency than average, or would pay a fee if the vehicle emitted more pollution or used more fuel than average. The size of the fee and rebate was proportional to how far the vehicle was above or below average. The effect of this fee-rebate proposal was to provide an incentive for individuals and organizations to purchase cleaner-burning and more fuel-efficient vehicles (including alternative-fuel vehicles) and for vehicle manufacturers to develop and sell such vehicles. It was an attempt to make the market system work. The principal challenge for regulators for this type of proposal is to determine the appropriate magnitude of fees and rebates to elicit the desired improvements.

Other conceptually similar but more limited proposals in California include providing tax credits for vehicles converted to "low-emitting" alternative fuels and reductions in vehicle license fees for specified low-emission vehicles.

These proposals to make the system work better (that is, to incorporate externalities) are conceptually attractive and potentially highly effective at responding to the concerns expressed earlier, especially when packaged in the form of comprehensive initiatives such as that of Senator Hart. But legislators and regulators are wary of these proposals.Legislators are reluctant to impose direct financial transfers on consumers, particularly when these transfers can be labeled as taxes. Regulators are reluctant to introduce these proposals because they would have to seek new authority and because very large financial transfers (or taxes) would be needed to compel changes of the magnitude sought by the regulators.[84]

The second incentive-based approach, creating new marketlike arrangements, includes the use of pollution licenses and permits and marketable credits. Licenses and permits tend to discourage entry into the market by newcomers; are difficult to adjust to new information and shifting economic, technological, and political conditions, and are difficult to assign in an equitable manner. Marketable credits, however, show great promise.

Marketable credits are created by setting standards, as is now done with vehicle-emission standards. Vehicle suppliers (or fuel suppliers in the case of fuel standards) would be allowed to average around the standard; if they do better than the standard, then they are allowed to bank and trade those excess credits, thus creating a market—with marketable credits as the currency—for whatever attribute is being regulated.

Averaging and Banking

The averaging and banking of attributes are not essential components of marketable credits, but they provide much more flexibility and lead to much greater efficiency in attaining standards. Banking and averaging procedures could be applied to uniform performance standards, such as those for vehicle emissions, in the absence of marketable credits (trading). But averaging and banking are especially important in creating a workable and efficient marketable credits system.

Consider the case of motor-vehicle emissions. With averaging, an emission standard would be established, as has been done for the last 20 years, but in this case vehicle manufacturers would have the flexibility to average emissions across their fleet of vehicles. Vehicle suppliers could reduce emissions to a lower level in those vehicles in which the cost of reducing emissions is less, and not reduce emissions as much in those vehicles in which the cost would be greater, as long as the average for all vehicles was below the standard. As the emission standard is lowered, resulting in an increasing cost

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[84]California Air Resources Board, *Proposed Regulations for Low-Emission Vehicles and Clean Fuels* (Sacramento, Calif., staff report, August 13, 1990), 57.

for emission reductions, there would be an incentive for automakers to market vehicles that operate on cleaner-burning alternative fuels.

The new averaging standard would need to be lower than an unaveraged uniform standard in order to gain the same net reduction; because the unaveraged standard is a ceiling and thus all vehicles emit under that standard, the result is an average emission rate that is actually considerably lower than the standard.

This averaging approach is not revolutionary. The same concept is used to regulate automotive fuel efficiency; it is not required that every vehicle meet the 27.5 mile per gallon CAFE standard, only that the average for each vehicle manufacturer be 27.5 or greater.

Emission banking would allow manufacturers to bank emissions from years when they outperform the average for use in years when they fall short. Banking is especially critical to the success of schemes for trading emissions (or other attributes). Banking rules allow trades to occur when and where they are needed and desired. Emission banking also provides an incentive to introduce new technologies and products sooner in anticipation of continuing tightening of emission standards.

Marketable Credits

The heart of a marketable credits scheme is the trading of attributes (excess credits). It allows those manufacturers who prefer to focus on large engines, jeeps, and other types of vehicles that tend to produce more emissions to continue to do so—but to do so they would have to buy emission reduction credits from manufacturers who sell low-emitting vehicles that better the standard.

Through emissions averaging, banking, and trading, emission reductions would be achieved less expensively, since industry would have the flexibility and incentive to reduce emissions in the most cost-effective manner possible.

Unfortunately, no up-to-date reliable estimates have been calculated of the economic benefits of marketable credits. The only known study was conducted for the U.S. Environmental Protection Agency in 1984; it estimated the cost savings associated with emission averaging and trading, but not banking.[85] The EPA calculated that the differences in emission-control costs to automakers, between a regime of uniform emission standards and a regime allowing emission averaging and trading between companies, for equivalent reductions in total emissions was 25 percent. That is, if the four U.S. and four major foreign automakers had been allowed to use averaging and trading to meet emission reduction requirements, their costs for doing so would have been 25 percent less.

The calculations were made using 1981 emission standards, forecasted vehicles sales for 1984-90, the vehicle and market mix prevailing in 1981, and a set of control cost functions derived from a statistical analysis of 1979-82 certification data and unreported estimated cost functions. The analysis is simplistic and out of date, relies on a poor database, and uses aggregated data in a manner that underestimates the cost savings.

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[85]Katherine M. McElroy, "Cost Savings from Emission Averaging for Automobiles," Proceedings of APCA Specialty Conference on Mobile Source Issues in the 1980s, 1984, 73–84.

With the vehicle technology, tighter standards, and higher marginal costs of the 1990s, cost savings for emission trading and averaging would probalby be much greater.

Nonetheless, by using this low 25 percent estimate, and an estimate that the current marginal cost for emission control is as much as $946 per vehicle in 1985 dollars,[86] then emission averaging and trading would generate cost savings of $300 million per year in California and $3 billion for the U.S.[87] If fuel efficiency, air toxics, and energy security attributes were also incorporated to create a more comprehensive attribute-trading regulatory program, then the cost savings would be even greater.

Unfortunately, the incentive-based concept was tarnished by the handling of an emissions averaging provision in the mid-1989 Bush administration proposal for amending the Clean Air Act; the administration proposed an averaging standard that was not low enough to gain a net reduction in emissions compared to a nonaveraged uniform standard. Environmentalists objected vociferously, and appropriately so. This averaging provision apparently had been part of a compromise in which automakers had accepted the alternative-fuel mandates of the overall proposal in return for this softened averaging standard.

Emissions averaging, banking, and trading constitute the rudiments of a framework for guiding the transition to alternative fuels. Emissions averaging and trading provide the incentive to automakers to develop and market very clean-burning vehicles, whenever the additional cost for doing so is less than the additional cost of reducing emissions from their gasoline vehicles. As emission standards continue to be ratcheted down, the marginal cost of marketing alternative-fuel vehicles will eventually drop below that of gasoline vehicles. Emissions averaging would provide the incentive for automakers to gradually phase in clean-burning alternative-fuel vehicles by manufacturing them or, through emissions trading, by buying credits or vehicles from electric, natural gas, or methanol vehicle suppliers so that they could continue to sell mostly gasoline vehicles. The result would be an incentive-driven transition to clean-burning alternative fuels.

Averaging, trading, and banking of vehicle emissions are only one component of an incentive-based approach to the regulation of vehicles and fuels. The use of incentives that directly alter price signals to reflect the cost of externalites, including fees and rebates on vehicle prices and differential fuel taxes, are important complements to vehicle marketable credit schemes. Together, they provide greater economic efficiency and are fuel neutral. But an even more effective regulatory framework—especially in terms of designing region-specific strategies and incorporating multiple social goals—would specifically incorporate fuels.

Fuel Supply Regulation

To incorporate a geographical element into the regulatory system it is necessary to allow fuel suppliers also to average, bank, and trade emission reduction credits and other

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[86]F. G. Kappler and G. L. Rutledge, "Expenditures for Abating Pollutant Emissions from Motor Vehicles, 1968–84," *Survey of Current Business* (July 1985): 29–35.

[87]A research project at U.C. Davis, funded by the California Institute for Energy Efficiency and begun in late 1990, will be specifying these cost savings more accurately.)

fuel attributes. The successful regulation of lead in gasoline since the 1970s[88] is an indication that the expanded regulation of fuels is feasible.

Region-specific strategies are desirable because the magnitude and nature of the pollution problem varies greatly from one region to another. For instance, some regions have major pollution problems while others do not. In some cities, the most serious air pollution problem is a high concentration of carbon monoxide, while in others the more critical problem is ozone. Even for those cities with ozone problems, the controlling constituent in some is hydrocarbons, while in others it is nitrogen oxides.

Region-specific strategies are possible with fuels regulation because virtually all the fuel purchased within a region is consumed within that same region. Vehicles purchased within a region, in contrast, can be readily sold or transferred to another region, a right that government is unlikely to restrict. Thus fuels-based regulations are amenable to region-specific strategies, whereas vehicle-based regulations are not.

The administration of a fuels regulation program would be more difficult than a comparable program for automotive emissions, principally because there are many more fuel suppliers than vehicle suppliers and because of the multiple fuel-supply industries. There is also less experience with fuels regulation. The only current regulation of fuels is for vapor pressure, lead content, sulfur content (diesel fuel), and the use of oxygenated blends in some non-California cities to reduce wintertime carbon monoxide. Enforcement is by spot checks. Despite minimal regulatory attention to fuel quality, the successful experience with lead banking and trading rules in the 1980s[89] in which administrative expenses were minimal[90] suggest that fuels regulation will not be an onerous burden on companies or regulators.

Fuel regulation would involve hundreds of fuel marketers, and include not only petroleum marketers (who probably would also market some or all of the alternative fuels), but also distributors of natural gas and electricity. Fuel regulation would presumably occur at the bulk distribution terminals in the case of liquid fuels, which is the point at which excise and sales taxes on gasoline and diesel fuel are currently collected. Natural gas and electricity regulation would be much simpler because only one supplier operates in any geographical region (they are regulated monopolies) and because the activities of these companies are already heavily regulated and closely monitored.

Since each type of fuel emits differing quantities and types of pollutants, the regulation of fuels could be accomplished in either a dissagregate or aggregate fashion.

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[88]Robert W. Hahn, "Economic Prescriptions for Environmental Problems: How the Patient Followed the Doctor's Orders," *Journal of Economic Perspectives* 3, no. 2 (1989): 95–114; Robert W. Hahn and Gordon L. Hester, "Marketable Permits: Lessons for Theory and Practice," *Ecology Law Quarterly* 16 (1990): 361–406; Barry D. Nussbaum, "Unleaded Gasoline Transition in the U.S.—the Use of Mandates and Incentives," presented at Second Biennial U.C. Davis Conference on Alternative Transportation Fuels, Asilomar, Calif., July 11–13, 1990.

[89]Hahn, "Economic Prescriptons for Environmental Problems."

[90]Nussbaum, "Unleaded Gasoline Transition in the U.S.—the Use of Mandates and Incentives."

Disaggregated regulation would involve the establishment of standards for each attribute of concern for each fuel. A simpler aggregate approach would be to assign ratings to each fuel to reflect in an aggregate manner the relative harm associated with the use of that fuel.

The use of attribute-specific rules would be conceptually cleaner but would be much more difficult to administer and enforce because of the complexity involved. Broader fuel-specific ratings would be simpler and easier to implement, and is therefore probably the preferred approach. In both cases, either implicitly or explicitly, emission equivalency values would be developed for the different fuels. Ozone reactivity ratings have already been developed for comparing the relative contribution of each type of fuel to ozone formation.

In the case of broader fuel-specific regulation, a rating would be assigned to each carefully specified fuel. For instance, gasoline might be rated 1.0, "reformulated" gasoline, 0.9, methanol, 0.8, natural gas, 0.7, and electricity, 0.4. Each fuel supplier would be required either physically or via purchased or banked credits, to supply a slate of fuels that on average meets a rating established by the regional or state regulator.

This regulation of fuels creates (as shown in Table 8) the opportunity to develop region-specific strategies in two ways: The equivalency values can be adjusted to reflect the unique aspects of pollution in that area, and the average rating required of each fuel supplier can be raised or lowered depending upon the severity of the problem in that area.

TABLE 8
SAMPLE REGULATORY FUEL INDICES
AND IMPLEMENTATION SCHEDULES

	City A	*City B*
Gasoline	1.0	1.0
Reform. gasoline	0.9	0.9
Methanol	0.7	0.9
Natural gas	0.50	0.8
Electricity	0.3	0.7
Sample Implementation Schedule		
1996	0.9	1.0
1998	0.8	0.9
2000	0.7	0.9
2005	0.6	0.9

Thus, in Los Angeles the average rating imposed on each fuel supplier might be 0.7 by the year 2005, while in San Francisco it might be 0.9. Similarly, the rating asigned to methanol might be lower in NO_x-rich Los Angeles than other hydrocarbon-rich regions (e.g. 0.7 versus 0.8) because methanol is relatively more effective at reducing ozone in NO_x-rich atmospheres than in hydrocarbon-rich atmospheres. Or natural gas might be given a low rating in a region with serious carbon-monoxide problems, say 0.5, because natural gas vehicles emit very low levels of carbon monoxide.

In fuel-based regulation, each fuel supplier would determine the most cost-effective manner for meeting the specified *average* rating. If it is expensive for an oil refiner to reformulate gasoline to reduce its emissions, say, because of the design of its refineries, or if the average rating is set lower than what is achievable with reformulated gasoline, then credits could be purchased from another company that can meet the required rating at less cost. Or the oil refiner might choose to sell natural gas or even electricity itself at its own stations.

Over time, the standards would be gradually tightened on a predetermined schedule (with periodic midcourse adjustments). Fuel suppliers could plan their investments with this schedule in mind; smaller refiners less willing or able to invest in refinery modifications might move more quickly toward alternative fuels and sell their emission credits to larger refiners who might prefer to focus on reformulated gasoline. Likewise, some automakers might prefer to stick with improving gasoline-engine technology, including multifuel engines; they would buy emission credits from other companies that sell much lower-emitting EVs and single-fuel natural gas and methanol vehicles.

One last, but important refinement would be to design the fuel rating to incorporate other social goals, such as reduced emissions of greenhouse and toxic gases and greater energy security. This could be accomplished by converting the emission rating for each fuel into a social index; for instance, the rating for domestically supplied natural gas would be set at 0.4 instead of 0.6 because natural gas vehicles emit fewer greenhouse gases and the gas is domestically produced.

The incentive-based regulatory concept presented here is not new or unknown to government. It has been slowly introduced over the past decade to control emissions from stationary sources such as powerplants and factories,[91] and is an important part of EPA efforts to reduce sulfur-oxide emissions and acid rain—but it is new to vehicles and vehicular fuels.

It is a concept that is gaining increasing acceptance, not only by researchers but also by policymakers. President Bush, for example, in his mid-1989 Clean Air Act proposals, though vague in details, endorsed the concept of an incentive-based approach for regulating vehicular emissions (as well as acid-rain emissions from stationary sources). Also, a blue-ribbon advisory board composed of high-level government and industry representatives, established by the California legislature to advise it on the introduction of alternative fuels, recommended in its October 1989 final report that a fuel regulation

[91] Cook, *Bureaucratic Politics and Regulatory Reform.*

program be established similar to the one described above.[92] Labeled "fuel-pool averaging," the intent was to propose a program that was fuel neutral. Details were not provided.

CARB's Bold Fuel and Vehicle Proposal

An extremely important proposal was adopted by the California Air Resources Board (CARB) on September 28, 1990.[93] It is based on a marketable credits scheme, allowing for limited averaging, trading, and banking of both fuels *and* vehicle emissions for light- and medium-duty vehicles. It would affect all vehicle marketers and gasoline refiners in California. The proposal establishes equivalency factors between different fuels and vehicles. Although it falls short of a full-fledged marketable credits regulatory program, it represents a major break from the past and from the continuing national EPA approach of uniform emission standards.

The new-vehicle emission standards are the heart of the CARB initiative. Tailpipe standards for hydrocarbon emissions (expressed as nonmethane organic gases) measured at 50,000 miles would drop from today's 0.39 grams per mile (g/mi) to 0.25 in 1994 and then gradually down to 0.062 in 2003. The corresponding reduction in emissions for light-duty trucks (under 3,750 pounds) would be from 0.32 to .093 g/mi between 1994 and 2003. Reductions in standards are also proposed for nitrogen oxides, carbon monoxide, formaldehyde (methanol vehicles only), and particulates (diesel cars only).

Manufacturers would be allowed to average emissions across their vehicle fleet to meet the average, to bank emission credits when they beat the standard, and to sell (trade) excess emission credits to other manufacturers who are not meeting the standards.

However, the averaging, banking, and trading rules are constrained. First, the vehicles are certified as falling into one of five categories—zero emission, under 0.04 g/mi, under 0.075, under 0.125, and under 0.25—and emissions averaging is based on the upper-bound emission number in that category (i.e., 0, 0.4, 0.075, 0.125, and 0.25). The only effect is that actual emissions will be somewhat less than reported "average" emissions. Another restriction imposed for the sake of simplicity is that each hydrocarbon emission category has a nitrogen oxide, a carbon monoxide, and a formaldehyde standard assigned to it. The formaldehyde standard applies only to methanol vehicles. The effect is to constrain the flexiblity of auto suppliers.

A second constraint is that emission credits will lose their value over time when they are banked: They will lose 50 percent of their value at the end of the following model year, another 25 percent after another model year, and all of their value after yet another year. This constraint is well justified by the fact that standards are being continually tightened, and it would be counterproductive to allow vehicle suppliers to bank credits when emissions are less stringent for use at a later date when emissions are more stringent.

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[92]California Advisory Board on Air Quality and Fuels, Report fo the California Legislature.

[93]The California Air Resources Board staff proposal, *Proposed Regulations for Low-Emission Vehicles and Clean Fuels,* was slightly modified before being adopted.

A third and important constraint is that 2 percent of all vehicles supplied by major manufacturers to California must have zero emissions in 1998, with that proportion increasing steadily to 10 percent in the year 2003. The motivation behind this rule is to make certain that vehicle manufacturers make progress in designing electric, hydrogen, or fuel-cell vehicles, assuring that the South Coast (Los Angeles area) Air Quality Management District's goal of making the transition to zero-emitting vehicles is attainable in a timely manner.

Fourth, emission averaging would not be allowed for medium-duty vehicles. Instead, a specified percentage of each manufacturer's vehicles would have to meet a set of categorical standards; trading of credits for vehicles in each category would be allowed within and between companies.

On the fuel side, CARB proposes, beginning in 1994 in the Los Angeles area and in 1997 statewide, that gasoline suppliers be required to make available clean alternative fuels—defined to include alcohols, LPG, and CNG—at a specified number of fuel stations. The total number of retail fuel outlets required will be determined with respect to the number of alternative-fuel vehicles being sold. The minimum required in the Los Angeles area for each liquid fuel will be 90 in 1994, 200 in 1995, and 400 in 1996, and for the rest of the state the minimum required will be 400 in 1997. The required number of compressed natural gas stations will be determined strictly by formula, based on the number of CNG vehicles sold. The total number of retail fuel stations in California is about 15,000.

As initially proposed, gasoline suppliers were to be mandated to sell a specified amount of methanol and LPG, with the mandated quantities based on the sales of alternatively fueled vehicles in the previous time period and on suppliers' share of total fuel sales. Refiners were to be allowed to satisfy the clean liquid-fuel requirement by either selling those fuels directly or by buying credits from other suppliers who had sold clean liquid fuels in excess of their requirements. Banking of credits was to be allowed, with sharp discounts over time, and up to 10 percent of the fuel sale requirement could have been met by CNG or electricity sales to motor vehicles (for electricity, credits were to be allowed only for electricity sales beyond those required by the mandated 2 to 10 percent zero-emission vehicle sales). This mandated sales requirement was not adopted by the board because of opposition by oil refiners, who claimed that they could not guarantee that consumers would actually purchase methanol and LPG; the weaker "fuel availability" provision was adopted instead.

While the CARB initiative is revolutionary, it came about not for ideological reasons but because CARB found that marketable credits were a means to ease opposition from the automobile industry to the stringent emission standards they were proposing. CARB found, via a year-long series of workshops and public hearings, that the flexibility inherent in emission credits was attractive to an industry that until now has been forced to accept uniform emission standards. This new marketable credits program creates, for the first time anywhere in the world, a market for emission reductions from motor vehicles.

Nonetheless, it still falls short of the comprehensive incentive-based approach outlined here. The CARB proposal does not establish a mechanism that allows the development of region-specific strategies or the incorporation of nonozone goals. Nor does it provide an incentive-based mechanism for fuel suppliers or for trading between vehicle and fuel suppliers. The concern is not so much the absence of a mechanism to allow trading between vehicle and fuel suppliers. That is a logical step that can implemented as experience is gained in designing, administering, and enforcing incentive-based systems. As more is learned about how best to create such a system, the procedures and mechanisms can be developed. Of more concern is the need to be truly fuel neutral, to create the opportunity for region-specific flexible strategies, and to integrate multiple social goals into the system.

In CARB's case, the agency is reluctant to take on greenhouse gas reduction responsibilites and does not have the authoriy to deal with energy-security issues. The same division of responsibilities exists on the national level. Political leadership and analytical creativity are needed to bring these other closely related social concerns together with air pollution regulatory responsibilities. This division of responsibilities can be crippling in developing a coherent and rational strategy.

Consider the CARB situation: There is a chance that automakers, in conjunction with oil refiners, will devise emission-control techniques for gasoline-powered vehicles to meet all but the zero-emission standards. Indeed, CARB has conducted tests in which new cars equipped with "green" electrically heated catalysts emit as little as 0.03 grams per mile at low mileage.[94] Whether those catalysts will perform well as they age and be able to meet the 0.04 standard at 50,000 miles is still unknown.

If gasoline cars can meet the standard, it will be an impressive achievement. But at what cost? Would society be better off if automakers and fuel suppliers instead shifted to alternative fuels? The market cost for gasoline vehicles to meet the 0.04 standard is estimated to be around $200 per vehicle, plus up to $0.20 per gallon for the reformulated gasoline.[95] It would probably be cheaper in the long run to shift to inherently cleaner alternative fuels to meet the standard. But even if it were not cheaper to do so, it is still probably wiser to shift to alternative fuels, since the alternative fuels provide other benefits: They reduce carbon monoxide, airborne toxics, greenhouse gases, and energy dependency, in some cases spectacularly so.

But when automakers and oil companies are only forced to incorporate air pollution externalites into their decision-making process, and not other important externalities, then they will prolong their commitment to gasoline beyond the time when it would be otherwise rational. By ignoring the other important nonmarket attributes of fuel options, CARB is not acting in our best interests. A regulatory process needs to be developed that is not so narrowly mission oriented.

In all fairness, CARB has taken a huge first step away from command-and-control rules toward an incentive-based approach. CARB is to be commended for its considerable creativity and perseverance, especially when viewed in terms of the lack of

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[94]California Air Resources Board, *Proposed Regulations for Low-Emission Vehicles and Clean Fuels.*

[95]Boekhaus et al., "Reformulated Gasoline for Clean Air."

innovation and change at the national level and elsewhere in the world.[96] Considerable progress still needs to be made, however.

While it is argued strongly in this report that a more rational and efficient regulatory process would be based on incentives, it is also recognized that there is a role for prescriptive rules and sales mandates—for instance, where administration and enforcement difficulties prove especially great and there is a great urgency in initiating industry activities—but a command-and-control approach is best seen as temporary and complementary to an incentive-based regulatory program. The zero-emission sales mandate of CARB is a good example of where a mandate is probably appropriate, but this mandate should be seen as temporary and eventually be phased out in favor of strengthened incentives for environmentally benign and secure energy sources.

It should be recognized that various incentives for alternative fuels already exist, such as the large 60 cents per gallon subsidy for ethanol used in gasohol (10/90 blend of ethanol and gasoline) and the CAFE credits for CNG and methanol (whereby automakers are assigned an artificially high CAFE rating to vehicles that operate on CNG and methanol). But these two examples also illustrate how the current fragmented approach is inefficient and with uncertain benefits. The special subsidy for gasohol is indefensible on economic grounds in that it provides a massive subsidy to one of the least attractive options, and the CAFE benefit encourages automakers to manufacture less energy-efficient vehicles. These examples indicate the need to develop a comprehensive incentive-based system; marketable credits combined with a comprehensive system of fuel-neutral taxes and fees are the components of such a system.

INDUSTRY CONCERNS

For an incentive-based program to be implemented successfully, it must balance the concerns and interests of fuel and vehicle suppliers with the overall social good. Automakers are concerned that consumers will not buy a vehicle that differs from a conventional gasoline vehicle. As a result they prefer liquid-fuel vehicles; they hope to meet their alternative-fuel responsibilities relatively easily and inexpensively by building multifuel vehicles that operate on methanol and gasoline. Once purchased, these vehicles may be used as conventional gasoline vehicles, thereby presenting no marketing risk to automakers. While incentives must therefore be designed to encourage the use of multifuel vehicles, from a social perspective it is even more critical that the incentives be designed to expedite the transition to cleaner, more energy-efficient, and less costly single-fuel vehicles by heavily favoring single-fuel vehicles in the equivalency ratings and indices.

Oil companies, facing the greatest risk, have campaigned hard against alternative fuels, even as they hedge their bets by participating in government methanol programs in California and elsewhere. Mobil Oil, historically the most outspoken of the oil companies, mounted a national media campaign in August and September 1989 with large ads in *Time* magazine, the *New York Times*, and other influential publications that

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[96]Organisation for Economic Co-operation and Development, *Economic Instruments for Environmental Protection* (Paris, France, 1990).

opposed and even ridiculed the proposal to mandate alternative fuels. It argued that methanol was toxic, did not improve air quality, worsened the trade deficit, and was expensive.

The oil industry quickly moved beyond this initial tirade to embrace a proposal first introduced commercially by ARCO. ARCO, with its prime market in Southern California where the pressure to reduce air pollution is strongest, was more subtle and more effective in its opposition. It argued, again in a national media blitz, that alternative fuels were unnecessary since gasoline could be reformulated to emit fewer pollutants. In September 1989 it introduced a reformulated gasoline fuel, but only in Southern California and only as a replacement for leaded gasoline, a far simpler and cheaper task than reformulating unleaded gasoline. Indeed, ARCO and the oil industry in general have argued on behalf of reformulated gasoline as a superior "alternative" fuel, but have been evasive about the emission characteristics and costs of reformulated unleaded gasoline, saying they are studying the problem. (One is left to muse why it took them 20 years to initiate such a study.) This attempt to characterize reformulated gasoline as an alternative fuel must be acknowledged in the development of ratings and indices, but again care must be taken to assure that the fuel ratings and indices appropriately reward the much greater social benefits of nonpetroleum alternative fuels.

The central industry concern, underlying the auto industry preference for methanol and the oil industry preference for reformulated gasoline, is the very real lack of coordination between the two industries. Would fuel be available if the auto industry were to sell natural gas and methanol vehicles? Would vehicles be available to consume natural gas or methanol if investments were made to sell those fuels? This uncertainty about the other's marketing plans creates huge risks.

In theory, an incentive-based regulatory program would resolve this uncertainty via the workings of the markets (artificial markets in the case of marketable credits). For instance, if the market value of permits for natural gas fuels drops because natural gas vehicles are not being manufactured and there is no market for the fuel, then there would be an incentive for an entrepreneurial oil or automotive company to buy up those credits and to subsidize the manufacture of natural gas vehicles. In practice, it may be necessary initially for the administrative agency temporarily to use command-and-control rules to assure adequate matching supplies of fuels and vehicles. Indeed, this is what CARB staff had initially proposed to do.

The initially high level of uncertainty associated with alternative fuels for both fuel and vehicle suppliers will undoubtedly cause auto and oil companies to focus initially on improving existing engines and fuels. That's fine. But it would be desirable for government to create a system that encourages companies and individuals to pursue the most cost-effective path and local priorities, which will differ for each company and perhaps for each region, in moving toward cleaner burning, more socially desirable nonpetroleum fuels.

CONCLUSIONS AND RECOMMENDATIONS

There is no analytical basis for definitively determining which fuel is superior and when it should be introduced. The choice depends on one's values, increased knowledge about the greenhouse effect, and forecasts of future energy prices, future political events, and technological advances. The recommendations that follow are based on the authors' values and vision of the future.

Efforts to introduce methanol and CNG fuel should continue, with the recognition that they are not long-term solutions, though they may prove to be the preferred fuels in the first half of the twenty-first century. The long-term and possibly permanent transportation fuels for California will probably be a mix of electricity and hydrogen. These fuels provide the potential for a qualitatively superior and sustainable future. With this in mind, action needs to be taken to update R&D strategies and reorganize fuel and air quality regulatory structures.

Realizing that other competing views and values exist and have equal validity, and acknowledging limited knowledge and foresight, it is strongly recommended that the focus of government efforts be on providing incentives to push industry and consumers in the correct direction: the production and use of vehicles and fuels that are more environmentally benign, safer, and less threatening to our national security than what is currently in use.Midcourse corrections can be made over time.

What is needed, and what will best serve in the long run, is the establishment of an institutional framework that is flexible in responding to new information and shifting values and beliefs, that incorporates multiple social goals, and that is amenable to region-specific initiatives. The two types of incentive-based regulatory approaches addressed in this report—creating marketable credits and altering price signals with fees, credits, and taxes—respond to these needs. They also preclude government from mandating which fuels should be introduced and when, thereby eliminating the likelihood of expensive mistakes. This call for a more flexible, incentive-based framework does not preclude the use of command-and-control type rules; indeed, such rules are effective at "jump-starting" new initiatives, such as the 2 percent mandate for zero-emitting vehicles. Rather, they should be seen increasingly as a complement to, not a substitute for, incentive-based regulation.

Since the U.S. dramatically expanded its commitment to social-style regulation of pollution, safety, and other activities in the 1960s, legislators have become much more sophisticated and experienced at how best to regulate the manufacture and use of goods. The time has come to make use of that knowledge and experience to move beyond simplistic, fragmented efforts at regulation.

With a flexible regulatory framework in place, legislators and regulators could make modifications over time. For instance, with a marketable credits approach similar to but broader than what CARB has adopted, greenhouse gases could be weighed more heavily and incentives for energy security could be modified in accordance with prevailing perceptions of vulnerability. Either independently—but preferably in concert—fees, credits, and taxes could be instituted to alter price signals for fuels and vehicles, again to alter consumer and industry decisions. The specification of fuel indices, emission standards, and fees, credits, and taxes will not be straightforward and will be the focus of considerable debate. A powerful advantage of the marketable credits approach is that the debate is highly focused and directly addresses specific tradeoffs. Without this structure, working only with a system of uniform emission standards coupled with a potpourri of policy instruments that influence the introduction of one or more alternative fuels, the debate undoubtedly will continue to degenerate into a cocaphony of self-serving interest group arguments.

In a larger sense, we have come to a crossroads in dealing with pollution and energy use in the transportation sector. We must acknowledge the shortcomings of the narrow and relatively inflexible approach of social regulation that emerged in the late 1960s and 1970s and has dominated pollution-control efforts since. While industry, government regulators, and even environmental groups have become accustomed to the certainty that that system provides, it is unsuited to the needs of the 1990s and beyond. Although the move away from uniform emission standards will be unnerving to those involved, it should be done—gently, but decisively.

R&D RECOMMENDATIONS

To expand the body of knowledge about alternative fuels, their impacts, and strategies for introducing them, and to inform the decision-making process, it is recommended that priority be given to the following research areas:

1. Considerably more resources should be devoted to learning about environmental externalities, especially air pollution, the primary motivation driving the introduction of alternative fuels at this time. In particular, it is critical that emissions and ozone formation be tested and mathematically modeled under the same set of technological and operating conditions for all alternative fuels for different air basins. CARB has initiated this activity; it should be expanded and accelerated.

2. The automotive industry should be directing much more basic R&D toward the design of engines and fuel storage systems optimized for methanol and natural gas. No vehicular engine optimized in all respects for these fuels is known to exist. It appears that most automotive industry research is now devoted to fuel-flexible alcohol-gasoline engines, not optimized methanol and natural gas vehicles or other environmentally superior options. Engines optimized with respect to performance and emission parameters, for given engine costs, should be built and evaluated for each fuel type. The state of California should investigate options to accelerate these activities.

3. California should encourage auto manufacturers to increase the R&D of electric and hydrogen vehicles and batteries, and increase government participation in these activities. Key areas to target for technological improvement of vehicles are the

recharging time of advanced batteries, the further development of reliable and cost-effective control of gases boiled off from cryogenic fuels, improvements in the mass-energy density and desorption temperatures of metal hydrides, and the development of fuel cells suited to motor vehicles. The first major use of electric and hydrogen vehicles will undoubtedly be in the Los Angeles area. Yet R&D on electric and hydrogen vehicles at the major automakers has languished. The CARB requirement for zero-emission vehicles beginning in 1998 has stimulated General Motors to greatly expand its EV effort; GM's apparent good-faith effort to meet the requirements will discourage its competitors from fighting the requirement and should lead to renewed R&D by all automakers selling in the U.S. market. The CEC, South Coast AQMD, and CARB have directed minimal resources at EV, hydrogen, and fuel-cell technologies; they should dramatically increase their R&D support for these promising options. The proposals by Los Angeles to purchase 10,000 electric vehicles and by CARB to require that 10 percent of vehicles by the year 2003 be zero emitting send the correct signal. Expanded initiatives would be desirable.

4. Given that clean electricity should figure prominently in our transportation future to power electric vehicles or split water to make hydrogen, research and development of sustainable, pollution-free electricity-generating technologies, especially photovoltaics, should be a high priority of state and national energy policy. Solar energy should prove to be the most cost-effective source of renewable, clean, non-CO_2-producing energy available. The California Energy Commission has provided initial support for photovoltaic technology. This level of support should be dramatically increased.

5. Given that future fuels and vehicles will have different attributes and be used differently than today's gasoline-powered vehicles, consumer reaction to large batteries and fuel storage tanks, longer refueling times, reduced vehicle range, and cryogenic boil-off should be studied carefully. These are important aspects of the attractiveness of hydrogen and electric vehicles and, to a lesser extent, natural gas and methanol vehicles. California agencies have invested practically no effort in understanding consumer preferences and purchase behavior. New and more creative survey research is needed that acknowledges the changeability of consumer behavior and attitudes and the reality that current behavior and attitudes simply reflect today's choices and experiences and are not necessarily good predictors of future fuel and vehicle purchasing behavior. A new approach to consumer behavior research is critical to developing R&D priorities and designing effective and efficient incentives.

6. Investigations of alternative designs of incentive-based regulation of fuels and vehicles need to be greatly expanded. Scarcely any effort has been made to answer questions regarding the use of incentive-based regulatory programs in the transportation sector. Much more progress has been made in understanding and implementing incentive-based programs in other energy-consuming sectors of the economy. In this report, we have applied our insights and knowledge about the transportation and energy sectors in recommending a shift toward incentive-based regulation—using marketable credits for both fuel and vehicle regulation, and adjusting price signals to incorporate air pollution, global warming, and energy-security externalities. The authors are convinced xxxxx

this is the correct path to be following and that immediate efforts should be made to incorporate these general principles and strategies. Further research is needed to provide more specific guidance.

GLOSSARY

bifuel engine Engine that may operate on either of two different fuels
biomass biological matter
Btu British thermal unit
CAFE standards Corporate Average Fuel Economy Standards
CARB California Air Resources Board
CFCs chlorofluorocarbons
CH_4 methane
CNG compressed natural gas
CO carbon monoxide
CO_2 carbon dioxide
cryogenic relating to very low temperatures
ethanol ethyl alcohol, C_2H_5OH
EVs electric vehicles
fuel-flexible vehicle multifuel methanol vehicle
HC hydrocarbon
H_2O water
ICEVs internal combustion engine vehicles
LNG liquefied natural gas
LPG liquefied petroleum gas
methanol methyl alcohol, CH_3OH
mmBtu million Btu
M100/M85 100 percent/85 percent methanol
MTBE oxygenated derivative of methanol
NG natural gas
NGVs natural gas vehicles
NMHCs nonmethane hydrocarbons—total hydrocarbon emissions less methane, which is nonreactive and hence does not contribute to ozone formation
N_2O nitrous oxide, greenhouse gas
NO_x nitrous oxides, ozone precursor
O_3 ozone
OPEC Organization of Petroleum Exporting Counties
OTA Office of Technology Assessment, U.S. Congress
PAN peroxyacetyl nitrate, an oxidant
photochemical model mathematical model of ozone formation
plant-gate costs costs after production and before transport to end-use buyer
PM10 particulate matter 10 microns or less in diameter

PV systems photovoltaic systems
RNG remote natural gas
synfuels synthetic fuels
synthetic gasoline gasolinelike fuel made from nonpetroleum material

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