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4 ALTERNATIVE TRANSPORTATION ENERGY

Daniel Sperling and Mark A. DeLuchi

INTRODUCTION

Transportation energy issues are moving to the forefront of the public consciousness in the U.S. and particularly California, and gaining increasing attention from legislators and regulators. The three principal concerns motivating interest in transportation energy are urban air quality, oil dependence, and the threat of global warming. Transportation fuels are a principal contributor to each of these. The transportation sector, mostly motor vehicles, contributes roughly half the urban air pollutants, almost one-third of the carbon dioxide, and consumes over 60% of all petroleum.

One promising strategy for resolving pollution and energy problems is the use of clean-burning alternative fuels. Alternative fuels are an appealing technical fix. They require 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

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politically and are institutionally easier to implement than strategies aimed at reducing the use of single-occupant autos and changing land use. Indeed, because they provide the promise of being environmentally benign, alternative fuels tantalize us with the prospect of never having to restrict motor vehicle use.

It can be argued, using practically any set of conceivable assumptions, that the use of large amounts of alternative fuels are inevitable. They are clearly an important part of any long-term solution to urban air pollution, global warming, and diminishing energy security.

But when, where, and to which fuels will this transition occur? The public debate over this transition question has been unusually muddled and distorted. Why is this?

One explanation for the muddled and distorted debate is that many powerful industry groups have a large vested interest in the success (or failure) of one or more options, including the auto and oil companies, petrochemical and coal companies, agribusiness, and the natural gas and electricity industries. All have a lot to lose, or gain. All have high-powered lobbyists and large public relations and advertising budgets. These vested interest groups, operating in the public arena, often exaggerate and spread half-truths, easy to do given the difficulty of evaluating advantages and disadvantages on a common scale. Exaggerations and half-truths are routine and, unfortunately, accepted behavior in public policy debates.

A second explanation is that numerous fuel options are available; each option has a very different set of advantages and disadvantages. No one option is obviously superior to all others. Comparing the different attributes is like comparing apples and oranges. Because these differences are market externalities or related to performance and ease of use, they are not easily converted to monetary terms and therefore not readily comparable. Some alternative fuels help reduce air pollution, some enhance energy security, and some reduce greenhouse gas emissions. Which goal is most important? Should we choose a particular fuel if it significantly reduces urban smog, but doesn't help the other problems? And at what cost? The selection of a particular energy option is based upon world views and fundamental values, as well as technical judgements.

These evaluation difficulties are aggravated by the fact that each option is at a different state of development. Cost, performance, and emission estimates for today's gasoline fuels and vehicles, which have undergone 100 years of intense development, should not be directly compared to cost, performance, and emission estimates of hydrogen fuels and vehicles, which are at a very early stage of development, or even to estimates of compressed natural gas vehicles, which have been retrofitted after-market for several decades but have received only minimal attention from the major auto-makers.

These evaluation difficulties result in technical studies of alternative fuels that often have widely varying conclusions regarding the relative merits of the fuel options.

The goal of this chapter is to untangle technical judgements from the influence of ideology, values, and economic interests. We place narrow findings in a broader systems context, and peel away the layers of self-interested "technical" findings; we specify core knowledge of the relative merits of the principal petroleum substitutes, acknowledging uncertainty where it exists.

The status of the leading alternative fuel candidates is presented in terms of technology, cost, environmental impacts, energy security, and safety implications. We explain why inconsistencies exist and disclose misconceptions.

Analytical Caveats

Where appropriate and unless otherwise specified, the attributes and drawbacks of alternative fuels and their associated technology are compared with unleaded gasoline used in new automobiles that meet current emission standards. A few problems inhibit this type of analysis.

First, there is little uniformity among gasoline blends sold throughout the U.S. and, because gasoline compositions vary considerably according to producer, locality, and time of year, there is no gasoline standard by which to compare alternative fuels. This problem is becoming more severe in the 1990s as oil refiners, responding to new air quality rules, introduce new formulations of gasolines and oxygenated fuel blends that vary from region to region.

Secondly, we must compare gasoline vehicles—a product that has benefitted from decades of research—to relatively new alternative fuel technologies. But even gasoline vehicles are not a fixed target; for instance, even though emissions of gasoline cars were reduced 90% or so from the mid-1960s to late 1980s, new rules in California call for roughly another 80% reduction by the early 21st century. Still, new technologies generally outpace more mature technologies (if sufficient resources are devoted to the task). Therefore, despite the fact that we can only *estimate the capabilities* of first generation mass-produced alternative fuel vehicles, technological advances for alternative fuels are likely to be swifter than those of conventional petroleum vehicles.

Finally, the scale and rate of alternative fuel implementation will define many of the important parameters discussed in this chapter. We do not discuss implementation strategies nor market potential here, but assume in the evaluation that demand will be sufficient to stimulate large-scale production of alternative fuels and wide-scale installation of refueling infrastructure.

The Non-Problem

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 (U.S. Department of Energy, 1992). If one were willing to rely on Persian Gulf countries for their oil supply, and if the Persian Gulf countries could be relied upon 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 begin to lag significantly behind consumption, there are many other energy resources that 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 $4 per barrel (1988 dollars), the prevailing price in 1981. At about that 1981 price, coal and biomass could be economically converted into methanol, substitute natural gas, and possibly petroleum-like liquids, and oil shale could be processed into gasoline and diesel fuel (Sperling, 1988; National Research Council, 1990). Since natural gas, coal, and oil shale are all available in larger quantities than petroleum, worldwide as well as in the U.S., that means sufficient energy resources are available at or near 1981 prices for at least another century.

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 fuels made from biomass. As indicated above, biomass fuels will probably cost about the same as coal-based fuels and be environmentally superior, although their production should probably be limited so as not to exacerbate soil erosion and other problems associated with intensive land use (such as loss of biodiversity, and use of fertilizers and water). The (private) production cost of hydrogen is currently much higher than that of other fuel options, but hydrogen does provide non-market benefits of much lower pollution, with good prospects for much lower hydrogen costs in the early part of the 21st century.

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; not only is it erratic and politicized, distorting energy decisions through inappropriate price signals and uncertainty, but it also does not account for large environmental impacts.

SOCIAL AND NON-MARKET COSTS

Design of a transportation fuel strategy should be predicated upon an understanding of the full range of private market costs as well as non-market social costs: private market costs because they are the criterion that industry and individuals use in deciding whether to invest in and purchase alternative fuels, and social costs because they are the justification for government intervention. In the following paragraphs, the importance of air quality, energy security, and reduced global warming are explored.

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 the 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 U.S. 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 1990, U.S. crude oil production averaged 7.35 million barrels per day, the lowest in several decades. The U.S. Department of Energy (DOE) projects in its mid-range scenario that domestic oil production will drop another 1.85 million barrels per day by 2010 (U.S. Department of Energy, 1992). At the same time, domestic oil consumption continues to increase, mostly due to increased diesel fuel and jet fuel use. The U.S. DOE forecasts a 3.2 million barrels per day increase in domestic consumption between 1990 and 2010.

As a result of these production and consumption trends, imports are expanding. In 1990, oil imports accounted for 42% of consumption, close to the peak of 47% recorded in 1977. DOE expects this percentage to increase to 53% to 68% by 2010.

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 U.S., transportation increased its share from 53% of petroleum consumption in 1977 to 64% in 1990 (*Ibid.*). In California, transportation accounts for about three-quarters of oil consumption (California Energy Commission, 1991).

Already, the U.S. transportation sector by itself consumes more petroleum than is produced in the entire country. This level of dependency is unlikely to remain acceptable politically and perhaps economically.

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 another war break out in the Persian Gulf area, and with what repercussions? 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 U.S. Strategic Petroleum Reserve (now containing over 500 million barrels), the risk of supply disruptions, and losses in national income from contraction of demand

for U.S. goods and services. The sum of these costs have been estimated to be as high as $21 to $125 billion per year (DeLuchi, Sperling, and Johnston, 1987).

Import dependency will probably not be the principal motivation for initiating a transition to alternative fuels in the near future, even with disruptions such as the August 1990 Iraqi takeover of Kuwait. Oil-import dependency is expected to grow, however, thereby attracting increasing political attention, and creating at least some pressure for the introduction of non-petroleum fuels.

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, 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 term as well as in response to rapid price escalations. Initial efforts at modelling 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 (Difiglio, 1989). Thus the price suppression benefit to the U.S. 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 more slowly 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 U.S. and other oil importers struggle to expedite the transition to non-petroleum 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

A second problem, global warming, is caused by emissions of carbon dioxide and other trace gases that create a greenhouse effect. It attracts more attention than energy security or indirect economic impacts, in part because the potential costs are much greater—though also more speculative.

The scientific community is in agreement that the globe's temperature will increase and climate patterns will change if emissions of carbon dioxide and other greenhouse gases in the atmosphere continue to increase (Science, 1990). 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, eventually causing melting of ice masses and increases in ocean levels. Gradual but ultimately dramatic changes could occur in local and regional climates. Rainfall would increase in some areas, decrease in others, and atmospheric temperatures would change, increasing in most but not all locations. Although these climatic changes can not be predicted accurately with existing meteorological models, it is clear that there is the potential 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% 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 reduced economically using control technologies on vehicles or refineries. The most effective strategies for reducing greenhouse gas emissions from transportation is reduced use of chlorofluorocarbons (CFCs) in air conditioners and less consumption of petroleum, either through fuel efficiency or the use of non-fossil fuels, including biomass, hydrogen made from water with non-fossil electricity, and electricity made from non-fossil fuels.

Air Pollution

The third imperative for introducing alternative transportation fuels is, in the U.S., 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 80–130 million people) do not meet the statutory ambient air quality standards of the U.S. 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 three excedances per three years allowed in the federal rules).

As shown in Table 4-1 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 U.S. 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 (DeLuchi, Sperling, and Johnston, 1987). Portney, Harrison, Krupnick, and Dowlatabadi (1989) es-

TABLE 4-1 Percent of Days Over State Standard, 1987 Summer and Winter Seasons.

Region	O_3 *1-hr, summer*	*CO 8-hr, winter*	*PM10*[a] *24-hr*
South Coast (LA)	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

SOURCE: California Air Resources Board (1988).
[a] Particulate matter less than 10 microns in diameter.

timated 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.

Motor vehicles are a principal cause of urban air pollution. The California Air Resources Board (CARB) (1990) estimates that cars and trucks contributed 43% of the hydrocarbons (also categorized as reactive organic gases), 57% of the nitrogen oxides, and 82% of the carbon monoxide emitted in the major urban areas of California in 1987. [Motor vehicles emit relatively little particulates from their exhaust, but airborne particulates (PM10) are composed of up to 35% aerosols, which are largely the result of atmospheric chemical reactions of the NO_x and hydrocarbons largely emitted by motor vehicles. CARB 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 modelling results are not in agreement on how large those benefits would be, especially for ozone (Murrell and Piotrowski, 1987; Carter, Atkinson, Long, Parker, and Dodd, 1986; Harris, Russell, and Milford, 1988; DeLuchi, Johnston, and Sperling, 1988; Office of Technology Assessment, 1990).

It is difficult and misleading to specify precisely the differences in emissions and air quality impacts between different fuels, especially for ozone. (1) Emission rates are determined by tradeoffs between emissions, ... of

mance, and driveability. If a particular fuel is less polluting, then engines will be 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 likely vary considerably across vehicle make and model. (2) 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 an engine operating at stoichiometric ratios, as are most of today's gasoline engines. (3) A distinction must be made between single-fuel optimized engines and retrofitted or bi-fuel engines.

(4) The fuel must be specified since, for instance, some methanol emission data are based on a fuel consisting of 100% methanol, while others assume 10% or 15% gasoline mixed into the methanol; it becomes even more complicated for multi-fuel methanol/gasoline engines since they will operate on varying blends of methanol and gasoline. (5) The ozone formation process is highly complex, and even the most sophisticated photochemical air quality models have error margins of 30% or more (Tesche, 1984). (6) Only in the Los Angeles areas has sufficient meteorological and spatial pollutant concentration data been collected to operate multi-day photochemical airshed models; results from Los Angeles are not generalizable to other regions.

(7) Emission data for dedicated single-fuel compressed natural gas (CNG), ethanol, propane, and hydrogen engines are much sparser and less accurate than for methanol engines. (8) Recent studies suggest for a variety of reasons related to the realism of emission test procedures and widespread engine tampering, that actual hydrocarbon and carbon monoxide emissions from gasoline vehicles are several times greater than tested emissions. For some fuel comparisons, these errors will not alter the relative ratings of the fuels, but for others, especially electric vehicles, where emissions are more accurately known, the huge underestimates of emissions from gasoline vehicles result in studies biased against the alternatives.

The point we are making 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.

Another factor to keep in mind, to illustrate the notion that it is easier and more effective to introduce the technical fix of alternative fuels, are the meager impacts projected for other urban air pollution control strategies. For instance, a current analysis of the emission impacts of various control strategies in the San Francisco Bay Area produced the following results (Harvey, 1990). Providing free mass transit to riders with income of less than $25,000, doubling transit service outside center cities, managing freeway traffic more intensely through use of metering lights, warning signs, and lane direction changes, imposing $1 daily parking surcharges in cities, increasing bridge tolls by $2, and charging a 2 cents per mile surcharge on vehicles, would each reduce hydrocarbon emissions by only 1% to 2.5%. Each of these strategies requires huge subsidies and/or would face major opposition, and yet provide minimal benefits. (It should noted that the emission and vehicle usage impacts of these transportation control strategies is small because of current dispersed land-use patterns. If land-use patterns were reorganized on a regional level to assure coodination in a transportation sense between housing, work, and services, then vehicle drivers would be much more responsive to incentives to share rides and shift to transit.)

As will be shown later, 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 95% less hydrocarbon emission 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 absence of substitute fuels. Because the price of petroleum does not take into account these social costs and economic losses, and because of the disjointed 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, as indicated later, 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 will be premised upon the public-good concerns listed above: the greenhouse effect, dependency on foreign oil supplies, economic benefits of lower energy prices, and urban air pollution.

Recent History of Alternative Transportation Fuels

Several transportation energy alternatives have emerged only to pushed from the public spotlight in recent years. In the 1970s and early 1980s, petroleum-like fuels from oil shale and coal dominated public policy and private investment; in the mid to latter part of the 1980s, methanol was the favorite, and in the early 1990s, electric vehicles moved to the forefront.

In the mid-1970s, just after the 1973 Arab oil embargo, nations began searching for ways to attain energy independence. The major non-petroleum domestic energy resources in the U.S. 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 U.S. 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 (U.S. Department of Energy, 1987, p. 123).

For the transportation sector, the most attractive options seemed to be petroleum-like 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 liquid 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 (Kant, Cohen, Cunningham, Farmer, and Herbst, 1974). At a Fall 1973 conference on Project Independence sponsored by the U.S. Department of Interior, "oil and automotive industry representatives voiced sharp opposition to a national energy program emphasizing methanol rather than synthetic gasoline fuels" (Bechtold, 1987, p. 3). A 1976 report by Stanford Research Institute (SRI) International prepared for the predecessor agency of DOE 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" (SRI International, 1976, p. xii).

Virtually all the major energy studies in the 1970s and early 1980s, as well as government energy policy, favored petroleum-like fuels from coal and oil shale (Kant, Cohen, Cunningham, Farmer, and Herbst, 1974; SRI International, 1976; Purdue, 1981). Public and private research and development was heavily weighted toward direct liquefaction of coal (Perry and Landsberg, 1981, p. 248).

Indeed, as late as 1981, only five of the 31 most advanced synthetic fuels projects in the U.S. intended to produce methanol as a primary product, and of those, several intended to co-produce high-Btu pipeline-quality substitute natural gas (Pace, 1981). 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, 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 petroleum-like fuels was greater than had been anticipated, and second, petroleum-like synthetic fuels did not help 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 U.S. Synthetic Fuels Corporation began to indicate that the cost of producing refined shale oil and petroleum-like liquids from coal would be as much as $100 per oil-equivalent barrel in first generation plants (U.S. Synthetic Fuels Corporation, 1985, p. H-10).

Attention began to shift toward methanol 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 (American Gas Association, 1985). 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 was crucial because methanol can be manufactured more cheaply and cleanly from natural gas than from coal.

Methanol received more attention than other alternative fuels from the mid-1980s until about 1990. The explanation for this attention is the following: Methanol can be made from a large number of materials, many of them available in abundance in the U.S.; it can be made less expensively than most other options; it emits less reactive air pollutants than petroleum fuels; and because it is a liquid and therefore more similar to gasoline and diesel fuel than other leading candidates, it requires less costly changes in motor vehicles and the fuel distribution system.

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) (Acurex, 1982) 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. 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 the air quality argument (Smith, Fong, Kondoleon, and Sullivan, 1984; Three-Agency Methanol Task Force, 1986).

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" (Berg, 1984).

That argument was overstated. It reflected a perception that gaseous fuels and electric vehicles were 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 (e.g., see California Energy Commission, 1986a, 1986b, 1987)—exactly the same argument that had been used against methanol 10 years earlier.

In the late 1980s, as analysts began to scrutinize more carefully the relative costs, and air quality, energy security, and greenhouse benefits of the alternative fuels, natural gas and especially electricity began to receive more attention. The perception that only a liquid fuel was acceptable slowly eroded. While methanol continues to retain substantial support, the early 1990s has seen the emergence of electric vehicles as an important if not leading option.

The dramatic emergence of electric vehicles was due to a realization that the air quality benefits of methanol were more modest than originally believed, and that electric vehicles provided the potential for much greater air quality improvements. The action that galvanized industry into action was a rule adopted in late 1990 by the California Air Resources Board, requiring that a growing percentage of each automaker's sales in California must be zero-emission vehicles (ZEVs); the percentage was set at 2% for 1998, increasing to 5% in 2001 and 10% in 2003.

A surge of investment in electric vehicles (EVs) was assured when General Motors announced in early 1991 that it had selected an assembly plant in Michigan for production of an electric vehicle (based on their Impact concept car) and expected to begin production in the mid-1990s. This announcement undermined tentative plans by other auto manufacturers, especially those based outside the U.S., to eliminate or water down the ZEV mandate. The commitment of automotive manufacturers to EV production was further enhanced by a growing perception worldwide that emission standards and rules adopted in California will eventually be adopted elsewhere. Manufacturers around the world began a crash EV development program, and in the U.S. an "Advanced Battery Consortium" was formed by the electric utilities, auto manufacturers, and U.S. government (DOE) to accelerate the development of advanced batteries.

COMPARATIVE ANALYSIS OF ENERGY OPTIONS

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

Petroleum-like Fuels

Petroleum-like fuels derived coal and oil shale are not considered further in this chapter because they have large negative environmental impacts, including higher levels of greenhouse gas emissions, large quantities of solid waste, large water needs, and introduction of additional toxic materials into the ecosystem (Chadwick, Highton, and Lindman, 1987). 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 research and development efforts, perhaps to as low as $30 per barrel (Lumpkin, 1988; National Research Council, 1990). The final cost would be considerably higher for the U.S., however, because of the large costs required to reformulate the fuel to meet future emission standards and to meet other increasingly stringent environmental restrictions.

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 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 the fall of 1989 in Southern California, ARCO became the first oil supplier to market a gasoline reformulated for lower emissions. They reformulated leaded gasoline, in part by blending in MTBE, an oxygenated derivative of methanol.

The U.S. Clean Air Act amendments of 1991 required reformulation of gasoline in the more polluted cities of the country, and the California Air Resources Board in late 1991 went one step further, with the encouragement of ARCO (and against the opposition of all other major oil companies), in requiring a much more stringent reformulation for gasoline sold in California beginning in 1996. It is claimed that reformulated gasoline will reduce ozone-causing emissions by 30% or so (and other pollutants by varying amounts) and to cost an extra 15 cents per gallon (U.S. General Accounting Office, 1990; Boekhaus, 1990).

Liquefied Petroleum Gases

LPG 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 19th 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 (Trindade and de Carvalho, 1989) and about 50,000 barrels per day in the United States. More than 90% 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—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.

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 upon 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 United States transportation fuel demand. A biomass fuels industry using dedicated biomass energy plantations could increase current yields of wood pulp on forest land tenfold or more, but total production would still be dwarfed by transportation energy demand unless a large proportion of forest land were diverted to biomass energy plantations (or vehicular energy efficiencies were greatly improved).

Sperling (1988) 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. Most of this biomass energy was estimated to come from wood plantations; the remainder would come from wood and crop residues, grass crops, peat, and municipal solid waste. The U.S. Department of Energy around 1990 returned its attention to biomass fuel and successfully inserted a strong statement for biomass fuels in the President's 1991 National Energy Strategy. Using optimistic assumptions, the Solar Energy Research Institute of the U.S. DOE and others (Lynd, Cushman, Nichols, and Wyman, 1991) are now estimating ethanol fuel potential in the U.S. (from cellulosic sources) to be several times higher than those of Sperling (1988).

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 (Sperling, 1987; Geller, 1985); in the United States the cost of ethanol made from corn or other fermentable materials is substantially higher (U.S. Department of Energy, 1988).

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 $0.65 to $1 per gallon (Lynd, Cushman, Nichols, and Wyman, 1991; see Table 4-5). This plant-gate production cost is equivalent to a retail gasoline price approaching $2 per gallon, since methanol contains only one-half the energy per unit volume as gasoline (two-thirds for ethanol), and the distribution and retailing cost per gasoline-equivalent gallon of ethanol and methanol are about twice that of gasoline. Recent evidence indicates that improvements in cellulose conversion technology may lower production costs (Wright, 1988), 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.

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% ethanol and 90% gasoline accounted for about 7% of all gasoline sales in the United States in 1988. Ethanol exists in the U.S only because of generous federal subsidies of $0.60 per ethanol gallon (equivalent to $0.90 per gallon of gasoline on an energy basis) and 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 to sharply reduce greenhouse gas contributions by the transportation sector and to provide small improvements in air quality. On the negative side, increased biomass fuel production may increase soil erosion, reduce biodiversity, and require large amounts of water, fertilizer and herbicides.

The combustion of biomass fuels would generate large amounts of carbon dioxide, but these emissions would be roughly 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 process 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 U.S., non-biomass fuels are used throughout the chain of activities. In fact, most ethanol production plants in the U.S. currently burn coal for process heat.

The most troublesome environmental impact of biomass production will be soil erosion. Although there is considerable controversy over the 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 average erosion on United States cropland due only to rainfall is 4.77 tons per acre per year (Soil Conservation Service, 1978), while others estimate total annual erosion, including wind erosion, to be as high as 9 tons (Larson, 1979). Since only about 1.5 (Pimentel, 1981) to 5 tons of soil form per acre-year (Office of Technology Assessment, 1980, p. 71), 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 (*Ibid.*). 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 threatens to be economically and ecologically damaging.

METHANOL FROM NATURAL GAS AND COAL

As indicated above, methanol was the most widely promoted alternative transportation fuel in the United States during the late 1980s (Gray and Alson, 1985, 1989; U.S. Department of Energy, 1988; California Energy Commission, 1986a, 1986b, 1987; McNutt and Ecklund, 1986). In this section, the salient aspects of methanol fuel are analyzed.

Feedstocks

At present, economic and environmental considerations favor natural gas (NG) over coal and biomass as a methanol feedstock. The production of methanol from natural gas is much less expensive 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 (Sperling, 1988, pp. 316–17). 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 available 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 (DeLuchi, Johnston, and Sperling, 1988). 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 progress toward meeting national air quality standards. Methanol also will be much cleaner than diesel fuel, and may be an attractive strategy in some cases for meeting the stringent 1993–94 emission standards for heavy-duty engines (Santini and Schiavone, 1988).

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; the only other important environmental benefit is likely to be lower emissions of toxic pollutants. Methanol may produce less CO or NO_x (but not both) than gasoline vehicles (Table 4-2); the result will depend on the air/fuel ratio, the type of catalyst materials used in control devices, and 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 (Table 4-3).

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 all highway vehicles would reduce peak 1-day ozone concentrations in urban areas by 10% to 30% (Systems Application, Inc., 1984; Jet Propulsion Lab, 1983; Nichols and Norbeck, 1985). 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 multi-day ozone episodes (Carter, Atkinson, Long, Parker, and Dodd, 1986). Subsequent modeling studies at Carnegie-Mellon University found that in the Los Angeles area, the use of 85% methanol/15% gasoline (the most likely combination) in all mobile sources (vehicles)

TABLE 4-2 Percentage Change in Emissions from Alternative Fuel Vehicles, Relative to Gasoline.[a]

Fuel	*NMHC*[b]	*CO*	NO_x	O_3	SO_x	*PM*[c]
Methanol (w/catalyst)	–50	0	0	–50	lower[d]	
CNG, LNG (w/catalyst)	–70	–50	0	–70	lower[d]	
Hydrogen (no catalyst)	–95	–99	?	–95	lower[d]	
Electricity/yr 2010 mix[e]	–99	–98	–75	?	–50	+30

SOURCES: From data in DeLuchi, Johnston, and Sperling (1988), DeLuchi (1989), and Wang, DeLuchi, and Sperling (1990).
[a] These are rough estimates only, assuming advanced-technology, single-fuel cars, and emission control and engine operation designed to meet a NO_x standard, which will be the most difficult standard to meet. Does not include evaporative emissions from vehicle or vehicle refuelling, or emissions from petroleum refining and fuel manufacture. 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 (Tanner, Miguel, de Andrade, Gaffney, and Streit, 1988).
[b] NMHC = nonmethane hydrocarbons (total hydrocarbon emissions less methane, which is nonreactive and hence does not contribute to ozone formation).
[c] PM = particulate matter.
[d] SO_x emissions depend on the amount of sulfur in the fuel.
[e] See Wang, DeLuchi, and Sperling (1990) for details. Based on forecasts and.estimates for California of energy mix for electricity generation, emission control technologies deployed on power plants, vehicle emission rates, and electricity consumption rates of electric vehicles.

except motorcycles and planes would result in only a 6% reduction in peak ozone levels (Harris, Russell, and Milford, 1988; Russell, 1987).

If 100% methanol (M100) were used in advanced technology engines with extremely low formaldehyde emissions, ozone would be reduced 9%, compared to an advanced-technology gasoline engine. The 9% reduction with advanced-technology M100 represents 43% of the maximum ozone reduction attainable from motor vehicles; that is, if all vehicle emissions were eliminated, ozone would be reduced 21% (Harris, Russell, and Milford, 1988). A subsequent study questions these findings, arguing that methanol vehicles would emit more NO_x than gasoline vehicles, and more than is assumed by the Carnegie-Mellon researchers, thereby causing ozone levels to increase (Sierra Research, Inc. 1988a, 1988b). In any case, the greatest potential ozone reductions with methanol require the use of M100 and very low formaldehyde emissions. We estimate that the substitution of methanol for gasoline in all motor vehicles

TABLE 4-3 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: DeLuchi (1991).
[a] CH_4, N_2O, NO_x and NMHC mass emissions from vehicles are 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. See DeLuchi (1991) for details.
[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, combustion of the fuel in engines, and the manufacture of the vehicles.

would result in a maximum reduction in peak ozone levels of 0% to 15% in multi-day smog episodes.

Two cautionary notes in interpreting these air quality analyses. One, ozone air quality models are subject to considerable uncertainty because of inadequate input data, especially outside Los Angeles, and two, optimized single-fuel engines are much cleaner-burning than multi-fuel 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, an M100 methanol engine with an oxidation catalyst produces very little CO, HCs, and formaldehyde (Ullman and Hare, 1982; Alson, Adler, and Baines, 1989).

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 concerns about 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% gasoline (or some other combustible denaturant) to the methanol, making the flame visible and giving the liquid a very unpalatable smell and taste—although this reduces methanol's air quality advantages. 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.

Costs

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 $0.20 to $0.30 per gallon if the remote natural gas (RNG) feedstock is virtually free and sunk costs in the methanol plant are ignored (U.S. Department of Energy, 1988). 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 $0.40 to $0.60 per gallon (equivalent on an energy basis to $0.80 to $1.20 per gasoline gallon) (*Ibid.*). Methanol could be produced from coal in the United States for around $1 per gallon (Sperling, 1988). When transportation, storage, and retailing costs are considered, methanol from RNG would not be competitive with gasoline until gasoline sold for $1.10 to $1.70 per gallon, including taxes (and allowing for the fact that methanol is about 10% to 20% 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 (1989) 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% using M85 to as high as 90% for M100; a cost of $0.05 to $0.56 more per gasoline-equivalent gallon for methanol than gasoline; and an additional cost of zero to $1,000 for a methanol car over a gasoline car. They 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 under the auspices of a blue-ribbon advisory board estimated the cost-effectiveness of M85 at $8,000 to $40,000 per ton (California Advisory Board on Air Quality and Fuels, 1989); and a study by Resources for the Future (Krupnick and Walls, 1992) for the U.S. estimated the cost-effectiveness for M85 in 2000 at $33,268 and for M100 in 2010 at $59,736.

Most of the non-methanol ozone-reduction strategies studied by OTA had cost-effectiveness reductions of $500 to $6,000 per ton. While methanol may be less cost-effective than other options it, along with other alternative fuels, nonetheless provides the potential for much larger ozone reductions than any other strategy.

The OTA estimates suggest that *multi-fuel* 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 tell you not to do 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, recycled paper—we gradually shift our investments and institutions and behavior to accommodate and support those new technologies, and thereby gradually improve 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 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 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 in 1994 (1993 for transit buses). Meeting the standards by applying control technology to diesel combustion is expensive, though probably no more so on a lifecycle cost basis than using methanol or natural gas. Several heavy-duty engine manufacturers are developing methanol (and natural gas) engines. These engines have potentially lower particulate and NO_X emissions than controlled diesel engines and will probably be used mostly in those areas with more severe air pollution and/or where regulators and legislators mandate their usage.

However, diesel-powered trucks and buses consume only about two of the 15 quadrillion Btus of energy used annually on the highways in the United States (Holcomb, Floyd, and Cagle, 1987) (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 in this market must address the high cost of methanol fuel compared to gasoline and

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, nor manufacturers 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, as noted above, 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 the methanol fuel is not available, and fuel producers will not invest in the production and distribution of methanol, even when it is cheaper than gasoline, unless there are vehicles 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 research and development 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 pipeline network. (Since methanol will be imported initially, a port-based distribution system will be adequate at first.) 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% of the United States), would be $5 billion (U.S. Department of Energy, 1990).

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. (We 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 non-petroleum) 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 (CNG) and the per-gallon subsidies provided by the California Energy Commission to methanol fuel suppliers.

The combination of subsidies to gasoline marketers to sell methanol, incentives to manufacturers to sell fuel-flexible (as well as dedicated) methanol vehicles, and subsidies to vehicle owners to purchase methanol cars, as has been occurring in California in the early 1990s, may prove effective in overcoming the "chicken-and-egg" dilemma. Ultimately, though, methanol fuel itself would have to be subsidized to convince consumers to buy methanol, since methanol will cost more than gasoline until oil prices reach at least $30 per barrel on a sustained basis. Even with subsidies, oil marketers will be reluctant to provide methanol pumps if fuel-flexible vehicle owners purchase only gasoline—and, of course, at some point it will become politically untenable to subsidize oil companies if they are not selling much methanol.

In summary, because methanol offers modest environmental benefits at modest cost, a long-lasting transition to methanol will occur only if reducing energy imports, slowing the greenhouse effect, and significantly improving air quality are not high priorities. Other options provide greater non-market social benefits.

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 on board a vehicle in compressed (CNG) or liquefied (LNG) form and used in the engine

Later, as the availability of natural gas diminishes and its cost increases, a substitute ("synthetic") natural gas 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, as explained below, 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 substitute natural gas (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 the U.S. remote natural gas (RNG), unlike methanol, will not be a major feedstock for NG transportation fuels, unless the cost advantage of remote natural gas feedstock increases, or there is large demand for LNG by LNG vehicles. This contrasts with the methanol case, in which remote natural gas will be a more economical feedstock than domestic gas. (That it is more economical to make methanol from remote than from domestic gas, but more economical to make CNG from domestic gas than from remote gas, is due to the fact that in the methanol case the cost advantage of the cheaper remote feedstock relative to domestic feedstock must compensate only for higher transportation 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 natural gas 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. We estimated energy losses during each of the following activities: recovery of natural gas (95% efficient), transmission and distribution of natural gas and finished product (95% efficient), reforming of NG to methanol (68% efficient), and NG liquefaction (80% efficient) or compression (94% efficient) (DeLuchi, Johnston, and Sperling, 1988). Based on these estimates, the overall energy efficiency of the NG-to-CNG chain is about 85%, compared to 61% for NG to methanol, and 72% for NG to LNG.

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 $2,500 per vehicle. The major change is the addition of one or more pressurized tanks for compressed natural gas (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, about 10% greater efficiency because of its higher octane and power, and 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 4-4).

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 research and development work aimed at commercializing adsorptents.

Currently, large numbers of CNG vehicles are operating in Italy, New Zealand, Canada, and the former Soviet Union countries (Sathaye, Atkinson, and Myers, 1989). 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 at its peak roughly 10% of gasoline use. When the country shifted much of its economy from the public to private sector in the late 1980s, the government withdrew the substantial subsidies it had offered to consumers, and market penetration dropped below the 10% 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 had announced the intention in 1988 of converting 500,000 to one million vehicles to CNG by 1995, most of them taxis and trucks, although this plan has apparently been abandoned or dramatically curtailed.

CNG has an extraordinary safety record in actual experience. In New Zealand, for instance, with over 100,000 vehicles in operation for almost 10 years, there has reportedly been only one explosion or fire of a natural gas tank, and

TABLE 4-4 Characteristics of Vehicular Energy Storage Systems.

Vehicle[a]	*Range (miles)*	*Total wt. (pounds)*	*Total size (gallons)*	*Fuel dispensing time (minutes)*
Gasoline[b]	300	80	11	2
Methanol[c]	300	135	17	3–4
Ethanol[d]	300	110	13.5	2-3
LNG[e]	300	130	27	2–4
CNG/3000 psi[e]	300	240	45	4–8
Liquid hydrogen[f]	300	100	72	3–4
Fe-Ti hydride[f]	150	640	37	5–20[g]
EV/Na-S[h]	150	7000	77	20[i]–720
EV/fuel cell[j]	250	200	80	2–4

[a] The baseline gasoline vehicle gets 30 mpg, lifetime average. Efficiency of other vehicles is referenced to this gasoline vehicle baseline.
[b] 23 lb. gasoline tank, 6.18 lbs./gal., 1.07 outer tank/inner displacement ratio.
[c] 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.
[d] 84,600 Btu/gal., others as for methanol.
[e] Adapted from data in DeLuchi, Johnston, and Sperling (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.
[f] Adapted from data in DeLuchi (1989). Assumes 25% thermal efficiency advantage; weight penalty for hydride. LH2 system size includes pump. Fe-Ti = iron-titanium.
[g] 80% of hydride refilled in under 10 minutes.
[h] 35-kwh capacity, 120 wh/l, 110 wh/kg, 4.4 mi/battery-kwh (DeLuchi, Wang, and Sperling, 1989). Na-S = sodium/sulfur couple.
[i] Although fast electric vehicle charging is possible, requiring a very large current, it is possible only with certain batteries; development efforts are very preliminary.
[j] DeLuchi, Larson, and Williams (1991).

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 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. Landed methanol will cost between $0.40 and $0.50 per gallon, at relatively low levels of demand for the remote NG feedstock, if the low production-cost estimates prove correct. Transport, storage, and retail station costs will add at least $0.14 per gallon to the price, bringing the retail cost to at least $9 per million Btu before taxes, assuming a landed cost of $0.45 per gallon. At the same time domestic gas will be delivered to stations for about $5 per million Btu, according to price projections for commercial gas (U.S. Department of Energy, 1991).

Based on a 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 compressing and retailing CNG is estimated at about $3 per million Btu (DeLuchi, Johnston, and Sperling, 1988; Cann, 1988). Thus a mid-range estimate of the cost of CNG is $8 per million Btu before taxes; a low-end estimate for methanol is about $9 per million Btu. LNG will cost about the same as CNG.

However, because of the high cost of high-pressure storage tanks for CNG, natural gas vehicles would cost about $1,000 more than gasoline and methanol vehicles with the same range and performance. This higher up-front cost is partially compensated by lower back-end costs—the higher salvage value of the storage systems and the probably longer life due to CNG use—thereby 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

propriate interest rate, adjusting for salvage values and vehicle life, and adding periodic costs such as maintenance, fuel, insurance, and registration. Table 4-5 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.

The analysis in Table 4-5 is conducted from the end-user's perspective. The following assumptions are made: 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. For specific assumptions and documentation, see DeLuchi, Johnston, and Sperling (1988).

The assumptions are based on a review of the literature, including experiences in Europe, Canada, New Zealand, and the U.S., 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 a vehicle optimized for CNG, 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, 2530 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 $1,000 more. The retail price of gasoline, including taxes, is assumed to be $1.15 per gallon, compared to an estimated $0.74 to $1.13 per gallon for methanol and $8.90 to $14.10 per million Btu for CNG. The cost parameters and vehicle attributes are fully documented in DeLuchi, Sperling, and Johnston (1987) and DeLuchi, Johnston, and Sperling (1988).

The methanol and CNG cars are comparable to the baseline gasoline vehicle: they have the same size, range, and weight (excluding the extra weight

TABLE 4-5 Life-Cycle Break-Even Gasoline Prices.[a] (1985 dollars per gallon)

Vehicle/ Feedstock	Fuel Cost	Extra Cost of Fuel Storage[b] ($)	Lifecycle Cost ($)
CNG/ domestic gas	\$4–6/mmBtu at station	1000	0.50–1.90
LNG/ domestic gas	\$4–6/mmBtu at station	850	0.40–1.80
Methanol/ remote gas	\$0.30–0.65/gallon, Calif.	50	0.95–1.70
Methanol/ coal	\$0.70–1.00/gallon	50	1.60–2.30
Electric[c]	\$0.05/kWh at outlet	7500	0.50–3.50
Electric[c]	\$0.10/kWh at outlet	7500	1.00–4.10
Electric[c]	\$0.15/kWh at outlet	7500	1.20–4.80
Hydrogen/ fuel cell[d]	\$0.05–0.15/kWh on site[e]	2500	1.40–3.20
Hydride/ solar	\$0.05–0.15/kWh on site[e]	2600	3.00–12.40
Liquid H_2/ solar	\$0.05–0.15/kWh on site[e]	1450	2.80–13.50
Gasoline/ coal[f]		0	1.40–2.30
Gasoline/ oil shale[f]		0	1.60–2.30

[a] The important baseline assumptions used here are: 9% real interest rate for auto loans, 30 MPG, \$11,500, 120,000-mile life baseline gasoline vehicle; range and fuel system assumptions consistent with Table 4-4; a range of fuel storage costs are used for each option; methanol vehicles are assumed to have same maintenance costs and life as gasoline vehicles; electric vehicles are assumed to have 25–100% longer life and 25–50% lower maintenance costs; natural gas vehicles are assumed to have 0–20% longer life and 0–15% lower maintenance costs; hydrogen vehicles are assumed to have plus or minus 10% of the maintenance costs and minus 5% to plus 20% of the life; all vehicles are assumed to be optimized for one fuel and produced in high volume. 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. Taxes are included. See DeLuchi, Johnston, and Sperling (1988); DeLuchi, Wang, and Sperling (1989); and DeLuchi (1989) for details.

TABLE 4-5 (continued)

[b] This is the cost of high-pressure gaseous-fuel tanks, cryogenic tanks, liquid alcohol tanks, batteries, or hydrides (for systems with attributes as in Table 4-4), less the cost of the gasoline tank in the baseline gasoline vehicle. A wide range of cost estimates were used for the lifecycle cost calculations. The battery costs have been updated (increased) from the original published estimates.
[c] Any feedstock from which electricty can be produced and distributed for between 5 and 15 cents/kWh.
[d] Based on DeLuchi and Ogden (1992).
[e] Estimated cost of photovoltaic electricity at production site.
[f] Based on Sperling (1988) and National Research Council (1990).

for CNG tanks and methanol fuel), and similar power. They are assumed to be 10% to 20% and 10% to 25%, respectively, more fuel efficient than the baseline gasoline car.

The lifecycle 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.

Similarly, CNG vehicles will probably prove to be a more cost-effective strategy for reducing ozone than methanol. The Office of Technology Assessment (1989) report cited earlier estimates that the cost-effectiveness of reducing ozone using dedicated NGVs would be \$0 to \$1,400 per ton—significantly lower than the \$3,200 to \$22,000 estimated for comparable single-fuel methanol cars.

Opportunities for Natural Gas Vehicles

Natural gas vehicles have lower fuel costs (per mile), but higher initial cost, than methanol and gasoline, and their refueling facilities are much more expensive than methanol and gasoline fueling facilities. For these reasons, the initial market for natural gas vehicles consists of large fleets with central fueling facilities that use their vehicles intensively. Intensive use is attractive because it takes advantage of the low fuel cost; large centrally fueled fleets are attractive because of the large investment in refueling facilities and the initial absence of a network of public refueling stations.

Beyond this niche, the success of natural gas vehicles depends upon automotive manufacturers participating in their production. Through the early 1990s, all but a handful of the 500,000 CNG vehicles in the world were gasoline vehicles that had been retrofitted to natural gas use. The conversion is expensive, and the resulting fuel efficiency, performance, and emission rates are inferior to those of a vehicle designed specifically for natural gas. Initial efforts by the natural gas industry in the early 1990s to put together an order of several thousand CNG vehicles for General Motors could be the important first step in eliciting manufacturer participation.

The "chicken-and-egg" start-up problem is more difficult for CNG than methanol for two reasons. First, fuel-flexible natural gas vehicles will be considerably more expensive than fuel-flexible methanol vehicles, due to the larger on-board energy storage cost (for that reason, automotive manufacturers are more willing to market a methanol vehicle than CNG vehicle); second, fuel suppliers are reluctant to invest in refueling facilities because of their high cost.

On the other hand, compared to methanol, CNG has the advantage of somewhat greater air quality benefits, lower fuel cost, a ubiquitous network of natural gas pipelines, and a large industry supporting it. The greater air quality benefit means that governments are more likely to be supportive. The low fuel cost means that once a fuel-flexible vehicle is sold, it would almost always use CNG—unlike fuel-flexible methanol vehicle owners—assuring market demand for CNG suppliers. And the existence of a large natural gas industry implies strong economic and political support for CNG.

In summary, CNG is somewhat more attractive than methanol from an environmental perspective, but faces more substantial start-up barriers. CNG will play a large role if the natural gas industry more actively supports its use, and if electric vehicles, an environmentally superior option, fail in the marketplace.

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 could 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 with internal combustion engines or fuel cells could use solar or nuclear power to split water to make hydrogen. This path would be followed if great emphasis is placed on reducing environmental pollution and global warming and on creating a permanently sustainable energy supply system.

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 we explore a larger range of technology options 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 (Bockris, Dandapani, Cocke, and Ghoroghchian, 1985).

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 non-fossil feedstocks, such as solar, geothermal, wind, hydro, and nuclear energy, would be used to generate electricity for the electrolysis process. Of these, solar energy appears to have the potential to 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 tainers, 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 1000 lbs. (Table 4-4). 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 (Table 4-4).

In summary, all hydrogen storage systems are bulky and costly and will remain so, barring major advances that might occur with expanded research and development 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, as indicated later, we believe some will do, if strong incentives and social messages are given for environmentally benign and sustainable fuels.

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 or HCs (only small amounts from the combustion of lubricating oil), particulates, SO_x, ozone, lead, smoke, benzene, or CO_2 or other greenhouse gases (tables 4-2 and 4-3). 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 in internal combustion engines (ICEs) would be NO_x, which is formed, as in all ICEs, 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 (DeLuchi, 1989). And if hydrogen were used in fuel cell vehicles, there would be no NO_x emissions—in fact, no emissions of any pollutant.

The use of hydrogen made from non-fossil 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 reduce ozone (Table 4-2).

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 rely on physical laws rather than human corrective action to safely resolve emergencies (Taylor, 1989), it is not clear if the public, regulatory agencies, and financial backers will be convinced that these are safe enough to warrant a large expansion of nuclear power. Second, if nuclear power were aggressively developed, the reprocessing of spent nuclear fuel and reprocessing of plutonium for breeder reactors would circulate large amounts of weapons-grade nuclear material (Ogden and Williams, 1989). 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% efficiency) requires only three times more acreage per unit of energy produced than nuclear power generation, when mining, transportation, and waste disposal are considered (Meridian, 1989).[1] In the hydrogen vehicle cost analyses below, we consider solar photovoltaic energy as the primary energy source.

1 The land usage for nuclear energy estimated in Hubbard (1989) appears to have been misrepresented.

Costs

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% 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 (Hubbard, 1989). With this assumption, Table 4-5 shows the price of gasoline that would be required to make the life-cycle cost of a gasoline and hydrogen ICE 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 ICE 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.

A more economical, as well as more environmentally sound, option for using hydrogen is in a fuel cell vehicle. Fuel cell vehicles are two to three times more efficient than ICE vehicles, thus reducing the cost of fuel per mile and the storage needed to attain a given range. Moreover, the electric drive system on the fuel cell vehicle would be much cheaper and longer-lasting than the power-train system for an ICE vehicle. The result, as shown in Table 4-5, is that hydrogen fuel cell vehicles can be expected to have a lower life-cycle cost than hydrogen ICE vehicles. Fuel cell vehicles represent the best long-term opportunity for hydrogen.

Opportunities for Hydrogen

The attractiveness of hydrogen vehicles hinges on technological progress in four areas. (1) 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. (2) 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 ad-

vances in technology, this disparity is not likely to change. (3) The cost of hydrogen storage must be reduced greatly. Recent developments indicate that this may be possible (see DeLuchi and Ogden, 1992). (4) Fuel cell vehicles must be successfully developed, because fuel cells represent the most promising use of hydrogen. Rapid progress is being made in reducing the cost and bulk of fuel cells (Journal of Power Sources, 1992).

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.

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 shortcomings, none of the problems are necessarily insurmountable. With a strong research and development 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.) by the early years of the 21st century.

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 10 years has brought this ideal closer to reality. EVs have the potential to provide substantial air quality and petroleum conservation benefits, at comparatively low cost with acceptable performance.

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 (Hamilton, 1980). 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 where successful commercialization does not depend on major technical breakthroughs, but on the resolution of manufacturing and quality control problems.

Advanced EVs now under development, and projected to be commercially available within a decade, are expected to offer considerably better range and performance than state-of-the art EVs of 10 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 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 around the turn of the century. With these characteristics, EVs would be attractive as second vehicles in most multi-car households (Lunde, 1980; Horowitz and Hummon, 1987; Turrentine, Sperling, and Kurani, 1992) and as vans in most urban fleets (Berg, 1985). As personal vehicles become more specialized and expectations regarding multi-purpose usage of vehicles continue to diminish, EVs may become acceptable as primary commuter cars. Exotic batteries under development, such as the zinc/air and lithium/iron sulfide battery, which 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.

Costs

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 life-cycle costs comparable to those of gasoline vehicles. However, under high-cost conditions, EVs will not be cost-competitive until gasoline sells for \$3 to \$4 per gallon (Table 4-5). If electricity is more expensive, in the range of 10 to 15 cents per kWh, the break-even 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.

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 (Wang, DeLuchi, and Sperling, 1990; see Table 4-2).

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 light-duty vehicles are 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 above. Table 4-3 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, as explained above). 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 marginal mix of electricity sources projected for the United States in 2000, then slightly less greenhouse gases would be emitted than will be emitted by gasoline vehicles in the year 2000. If non-fossil 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 the electricity industry, and perhaps eventually from the automotive 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 the night, 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 energy supply have shown consistently that utilities have sufficient capacity in place to support large numbers of electric vehicles. A detailed study of the Los Angeles area indicates that up to two million electric vehicles could be supplied with electricity without adding new generating capacity if most of the recharging took place in the evening or night (Ford, 1992).

Second, the life-cycle cost of advanced, mass-produced EVs, using cheap off-peak power, might be low enough to induce some fleet operators and home owners 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 (Hamilton, 1988; Nesbitt, Kurani, and DeLuchi, 1992). 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 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 can be hoped, and are favored by public policy for their environmental benefits, there still will be one significant obstacle to widespread consumer acceptance: the long recharging time. If it takes 8 hours to recharge an EV, most households will want at least one non-electric vehicle, and EVs will be limited to the role of second car in some multi-car, home-owning households. However, if EVs can be charged in under 30 minutes, they may be able to displace gasoline vehicles in many more 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 adequately demonstrated, however, and all are likely to be expensive. The successful development of fuel cell electric vehicles, though, could obviate the problem of recharging time because fuel cells can be "recharged" (refueled) in the same way as a methanol or hydrogen ICE vehicle.

Continued improvements in advanced batteries and fuel cells and a means for 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, and 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 in the very near future.

In summary, EVs and hydrogen vehicles require substantial improvements before they become attractive as the dominant transportation technology. For that to happen, research and development 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.

CONCLUSIONS AND RECOMMENDATIONS

No analytical basis exists for definitively determining which fuel is superior and when it should be introduced. The price of petroleum cannot be predicted, and many of the costs and benefits of alternative fuels are difficult to quantify.

Moreover, different regions and groups of people place differing 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 different values, and familiarity with different facts, lead individuals and organizations to different conclusions about the most desirable path.

There is no one optimal choice; the era of one (or two) uniform transportation fuels is nearing an end. 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 dominate, then the United States would favor fuels from biomass, coal, oil shale, and domestic natural gas, as well as electric vehicles.

If economic efficiency, measured by conventional market indicators, is the dominating value, then hydrogen ICE vehicles would be discarded as an option, while electric and hydrogen fuel cell vehicles would be competitive in some applications if optimistic battery and fuel cell cost and performance goals were met. For the larger passenger and heavy-duty vehicle markets, natural gas vehicles probably would be favored, as would methanol if low-cost methanol production estimates prove accurate.

If the overriding objective is to make the transition to new fuels with as little disruption as possible, then reformulated gasoline (and diesel) fuel should

be pursued in the very near term, followed by petroleum-like fuels and alcohol fuels. A transition to petroleum-like fuels would require no significant changes to vehicles and fuel distribution systems, but would be the least attractive environmentally and among the more expensive options. A transition to methanol would be more difficult than a transition to petroleum-like fuels, requiring modifications to vehicles, storage tanks, and delivery systems, but it would be less difficult than a transition to gaseous fuels. A transition to EVs would be relatively easy from an infrastructure standpoint, but not from a consumer acceptance perspective because of the weight and low energy density of batteries and the long recharging time.

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

If the most important concern is to avoid a greenhouse warming, battery- or fuel cell-powered electric vehicles, relying ultimately on non-fossil energy, are the best choice, because they completely eliminate fuel-cycle emissions of greenhouse gases. ICE vehicles using hydrogen made from water with non-fossil power would also emit only negligible amounts of greenhouse gases, but hydrogen ICE vehicles are not likely to be commercially available as soon as electric vehicles. ICEVs using methanol or gas derived from woody biomass 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.

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 environmental quality, greenhouse effects, sunk investment, compatibility, and energy security have come to dominate the public debate.

The rational analyst despairs of making choices in this context of competing goals and values, and with incomplete knowledge and limited foresight. Nonetheless, choices must be made. Based on a belief that a transition to alternative fuels is important but not extremely urgent at this time and that pollution and environmental damage should weigh heavily in decision-making, we suggest the following:

In the near term, CNG and EVs should be aggressively promoted so as to expand their use in market niches where they are economically attractive. The cost of electric vehicles, in particular, will drop sharply as technology development efforts are accelerated and economies of scale are realized. Natural gas and electric vehicles are the only options that (in the best case) can compete with gasoline when oil is in the range of $20 per barrel. They should especially be supported in areas with CO and ozone problems.

In the near term, in most regions, government should give priority to the introduction of electric, natural gas and methanol fuel—in that order. Methanol offers only limited air quality and energy security benefits, and no greenhouse benefits and, unlike CNG and EVs, is not attractive in any market niches. Perhaps methanol is best treated as a transitional "filler," along with natural gas vehicles, after CNG and EV niche markets are saturated and oil prices rise on a sustained basis to perhaps $30 per barrel.

The long-term and possibly permanent transportation fuels will probably be a mix of electricity, hydrogen, and biomass fuels used in battery-powered and fuel cell vehicles. These fuels produce much fewer greenhouse gas emissions, are more environmentally benign than other options, and can be supplied on a permanently sustainable basis. Since they provide large social benefits that are mostly ignored by the marketplace, they merit the most attention from government.

The worldwide petroleum-based transportation energy system now in place has served us well. But it will not serve us well in the future. The skewed distribution of petroleum reserves, the rapid worldwide growth of motor vehicles, the increasing concentration of greenhouse gases in the atmosphere, and persistent local air pollution problems, together are creating ever greater political and environmental stresses. Government policies and initiatives should be restructured so as to provide a framework for guiding private investments and consumer choices toward the options that can really make a difference. New transportation energy options should not be treated as second- best alternatives to petroleum but as opportunities to make a better world.

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