RP-90-4

TOWARD ALTERNATIVE TRANSPORTATION FUELS

by

Daniel Sperling, Mark A. DeLuchi, and Quanlu Wang
Institute of Transportation Studies
University of California, Davis

for

California Policy Seminar

September 1990

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 this interest in transportation energy are urban air quality, energy security, and 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 and 34% of the carbon dioxide in California, and consumes almost 3/4 of all petroleum.

A Technical Fix Solution

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; indeed, they dangle the promise of never having to restrict motor vehicle use, because the vehicles could prove to be environmentally benign. Alternative fuels are attractive because they are less disruptive and politically and institutionally easier to implement than strategies based on reduced use of single-occupant autos and changes in land use.

Moreover, one may argue, using practically any set of conceivable assumptions, that 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.

Objectives

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

We conclude that definitive evidence cannot be marshalled to justify a massive near-term introduction of alternative fuels. But neither can definitive evidence be marshalled to justify the contrary. The problem is that many uncertainties remain -- future oil prices and supply, the rate and associated cost of technological improvements, the rate of climate change -- and social preferences shift. Which goal will dominate in ten years: Will it be air quality, energy security, or slowing climate change? The decision to emphasize one social goal over another dramatically alters the relative attractiveness of particular fuel options.

Nonetheless, robust qualitative judgements can be made regarding the relative merits and drawbacks of each option, and we make those judgements in this report. We conclude that no one fuel option emerges superior -- because of shifting values and goals and an uncertain future, large regional differences in the nature of the air pollution problem, and the existence of multiple social goals -- and argue that a flexible fuel-neutral policy framework that relies on incentives and not specific rules is most appropriate and desirable in guiding future energy choices.

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

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

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 (Burns, 1989; EIA, 1989). 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 $43 (1988 $), 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; NRC, 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 and gaseous fuels made from biomass. As indicated above, biomass fuels would cost about the same as coal-based fuels and be environmentally superior, although their production, especially in California, should probably be limited so as not to exacerbate soil erosion. The (private) production cost of hydrogen is currently much higher than that of other fuel options, but hydrogen does provide non-market benefits of much lower pollution.

The point is that the world is not in imminent danger of running out of energy and that with a well-functioning market system, energy prices will not increase dramatically in the foreseeable future.

But the international petroleum market is not a well-functioning market; it is erratic and politicized, distorting energy decisions through inappropriate price signals and uncertainty, and 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. 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 1989, U.S. crude oil production averaged 7.6 million barrels per day, the lowest in 26 years, a drop of 553,000 barrels per day from 1988. All projections indicate that domestic production will continue to drop; the U.S. DOE projects average annual declines of 350,000 barrels per day.

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

The transportation sector, unlike other energy-consuming sectors, has remained almost completely dependent on petroleum fuels. As a result, transportation has gradually increased its share of the petroleum market. In the U.S., transportation increased its share from 53% of petroleum consumption in 1977 to 63% in 1987 (EIA, 1988). In California, tranportation accounts for an even larger proportion of oil consumption, reaching 77%(??) in 1988.

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

It is unclear how important this import dependency problem is. 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? The cost of oil dependency is difficult to measure; it depends not only on determinations of the probability of the foregoing types of events occurring, but also on how the cost of military expenditures in the Middle East and other important supply regions are allocated, the cost of maintaining the Strategic Petroleum Reserve (now containing over 500 million barrels), the risk of supply disruptions, and losses in national income from contraction of demand for U.S. goods and services. The sum of these costs have been estimated at 21-125 billion dollars per year (DeLuchi et al., 1987).

Import dependency will probably not be a principal motivation for initiating a transition to alternative fuels in the near future unless an unexpected disruption or price escalation occurs. Nevertheless, oil-import dependency will continue to increase and therefore gain increasing political attention, resulting in the dependency issue becoming an increasingly important force in motivating an energy transition.

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

Price volatility creates uncertainty and distorts investment decisions, resulting in a preference for short term investments. Erratic and uncertain petroleum prices results 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, illustrated in Figure 1, 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 slower than otherwise. If oil importers wait for the higher prices, they will not be able to react with susbstituted 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.

<u>Greenhouse Effect</u>

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

The scientific community is in agreement that the globe's temperature will increase and climate patterns will change if emisssions of carbon dioxide and other greenhouse gases in the atmosphere continue to increase (Science, August 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, 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. Unfortunately, these climatic changes can not be predicted accurately with existing meteorological models. In any case, 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 the 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 California, politically the most potent: air pollution improvement. The use of petroleum for transportation results in large quantities of pollutant emissions from vehicles, refineries, and fuel stations. What makes the air pollution imperative most salient in the public policy arena is the existence of a set of institutions and rules for improving air quality.

Virtually all metropolitan areas of the country experience high levels of air pollution. Roughly 60 to 100 metropolitan areas (representing 80-130 million people) do not meet the statutory ambient air quality standards of the 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 were even more severe than had previously been thought, established more stringent ambient ozone standards than the federal government (0.09 vs 0.12 ppm over a one hour period, with no excedances allowed versus 3 excedances per 3 years allowed in the federal rules).

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

Table 1: Percent of Days Over State Standard, 1987 Summer and Winter Seasons

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

*Particulate matter less than 10 microns in diameter.

Source: California Air Resources Board (1988), California Air Quality Data: Summary of 1987 Air Quality Data. Sacramento, Calif., Vol. XIX.

The external (nonmarket) costs of this air pollution are huge: estimates for the U.S. range from 11-187 billion dollars 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 et al., 1987).

As an indication of how large the costs and benefits are, it is estimated that implementation of the Los Angeles area (South Coast) air quality plan will generate benefits of $1.5-7.4 billion per year in that region (Portney et al., 1989: 70).

Motor vehicles are a principal cause of urban air pollution. ARB 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. ARB estimates that over half the PM10 that is directly emitted from anthropogenic sources is dust kicked up by motor vehicle activity on roadways.)

One of the problems to keep in mind in the later evaluation of fuel alternatives is the uncertain nature of estimated air quality impacts. While it is certain that air quality benefits would occur with the use of natural gas, electricity and methanol, data and modelling results are not in agreement on how large those benefits would be, especially for ozone (Murrell and Piotrowski, 1987; Carter et al., 1986; Harris et al., 1988, DeLuchi et al., 1988).

It is difficult and misleading to specify precisely the differences in emissions and air quality impacts between different fuels, especially for ozone. First, emission rates are determined by tradeoffs between emissions, costs, performance, and driveability. If a particular fuel is less polluting, then engines will be 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. Second, pollutant production is sensitive to the air/fuel ratio of engines. If future engines are designed to run "lean" (high air/fuel ratio) to gain higher fuel efficiency, then NO_x levels would be relatively higher and CO and HC emissions and engine power would be lower than an engine operating at stoichiometric ratios, as are most of today's gasoline engines. Third, a distinction must be made between single-fuel optimized engines and retrofitted or bi-fuel engines.

Fourth, the fuel must be specified since, for instance, some methanol emission data are based on a fuel consisting of 100% methanol, while others mix 10% or 15% gasoline into the methanol; it becomes even more complicated for multifuel methanol/gasoline engines since they will operate on varying blends of methanol and gasoline. Fifth, the ozone formation process is highly complex and even the most sophisticated photochemical air quality models have large error margins of 30% or more (Tesche, 1984). Sixth, 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. Seventh, emission data for dedicated single-fuel CNG engines are much sparser and less accurate than for methanol engines.

The point we are making is that emission and air quality data for alternative fuels are highly 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 $2.00, 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 reducitons. For instance, if all light duty vehicles were switched from gasoline to electricity, hydrocarbon emissions would be reduced by about 1/3 (electric vehicle use results in about 98% less hydrocarbon emissions and gasoline-powered autos and light trucks emit about a third of total hydrocarbons). The use of methanol and compressed natural gas would provide substantially less hydrocarbon emission reduction, but the point is that the 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 disjoint and conservative nature of transportation energy systems, alternative fuels and increased vehicular efficiency are uneconomically delayed.

In summary, if market mechanisms were operating efficiently, then optimal consumption and production of oil would follow. But that is not the case. Efficiency improvements and alternative fuels are delayed beyond the time when they would otherwise be economically attractive by uncertain and low oil 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.

<u>The Recent History of Alternative Transportation Fuels</u>

Methanol has received more attention than other alternative fuels since the mid-1980s. 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 US; 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 interest in methanol is partly explained by historical circumstance. In the mid-1970s, just after the 1973 Arab oil embargo, nations began searching for ways to attain energy independence. The major 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. DOE, 1987:123).

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 liquids options because it would require major changes in motor vehicles and pipeline and fuel distribution systems and would not support existing investments in oil refineries (Kant et al, 1974). At a Fall 1973 conference on Project Independence sponsored by the U.S. Dept. of Interior, "oil and automotive industry representatives voiced sharp opposition to a national energy program emphasizing methanol rather than synthetic gasoline fuels" (Bechtold, 1987:3). A 1976 report by 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, 1976: 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 et al., 1974; SRI, 1976; Purdue, 1981). Public and private R&D was heavily weighted toward direct liquefaction of coal (Perry and Landsberg, 1981).

Indeed, as late as 1981, only 5 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 new 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 (SFC, 1985: H-10).

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 (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 et al., 1984; Three-Agency Methanol Task Force, 1986).

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

Interest in methanol began to surge around 1985 as methanol proponents shifted their arguments away from energy security, a diminishing concern, to urban air quality, a stubborn problem for which most of the "easy" solutions had already been exhausted. Proponents, especially in California, argued that "the transition to neat methanol fuels for all motor vehicles represents the most significant opportunity for air quality progress which exists between now and the end of the 20th century" (Berg, 1984).

That statement was overstated. It reflected a perception that gaseous fuels and electric vehicles are too different from liquid fuels, requiring too many costly changes in motor vehicles and the fuel distribution system and in consumer behavior to be a widely used fuel (CEC, 1986a, 1986b, 1987) -- exactly the same argument 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 electricity began to receive more attention. The perception that only a liquid fuel was acceptable slowly eroded as the natural gas and electric utility industries began to give more support to natural gas and electric vehicles. Methanol is still favored in many quarters, but less strongly than a few years previous.

COMPARATIVE ANALYSIS OF ENERGY OPTIONS

Considerable space is devoted to this 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 are not considered further 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. The fuels would be considerably more expensive than compressed (or liquefied) natural gas and methanol made from natural gas, although proponents claim that their costs can be reduced significantly with intensified R&D efforts, perhaps to as low as $30 per barrel (Lumpkin, ?; NRC, 1990). The final cost would be considerably higher for California and 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, including likely restrictions on greenhouse gas emissions.

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 9 most polluted cities of the country. In Fall 1989 in southern California, ARCO became the first oil supplier to market a gasoline reformulated for lower emissions. The fuel they reformulated was leaded gasoline, in part by blending in MTBE, an oxygenated derivative of methanol. Leaded gasoline is being phased out. ARCO's self-reported cost differential was 2 cents per gallon; tests indicate that hydrocarbon emissions from the tailpipe were reduced 4% and evaporative emissions (which account for much less than half the total hydrocarbon emissions) about 21%. Carbon monoxide emissions were reduced 9% and NO_x emissions about 5%. Preliminary experiments suggest that the cost of reducing hydrocarbon emissions from unleaded gasoline by about 20% and benzene some significant proportion, would be 10-20 cents per gallon (Townsend, 1990).

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 should not be considered as anything more than a niche fuel.

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 activites 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 Vieira de Carvalho, 1989) and about 50,000 barrels per day in the United States. More than 90% of all Brazilian cars have been designed to operate strictly on ethanol since about 1983. 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 -- also does not produce CO_2. On the other hand, the potential supply of biomass is limited, production of biofuels is costly, and environmental impacts can be considerable. As explained below, these negative factors are exacerbated in California by the aridity in the valley areas, and the steep gradients of forestland. As a result, biomass fuels are relatively unattractive in California, relative to other options, and relative to the more attractive conditions elsewhere in the U.S.

<u>Feedstocks and Fuel Production</u>

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

Unlike other alternative energy options, biomass could not or, more accurately, should not be depended on as the sole transportation energy source, except perhaps in land-rich Brazil. In the United States, for instance, even if all the wood pulp now harvested by the paper and wood products industries, including logging and mill residues, and all the harvested corn and wheat were used to make biomass fuels, there would not be enough to satisfy current 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.

An optimistic estimate of biomass fuel potential in the United States, assuming no major disruption of existing agricultural and silvicultural markets and land management activities, is a maximum of about 1.8 million oil-equivalent barrels per day of fuel could be produced in the United States; more than half this energy is contributed by wood plantations. The remainder comes from wood and crop residues, grass crops, peat, and municipal solid waste.

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

Production Costs

Biomass-derived alcohols now are much more expensive than gasoline on an energy-equivalent basis, and are expected to remain so for the foreseeable future. Ethanol fuel in Brazil is about as costly to manufacture, on an energy basis, as gasoline produced from oil priced at $30-35 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. DOE, 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 $0.70-1.00 per gallon (Table 2). This plant-gate production cost is equivalent to a retail gasoline price of more than $2 per gallon, since methanol contains only half the energy per unit volume as gasoline. Correspondingly, the distribution and retailing cost per gasoline-equivalent gallon is at least twice that of gasoline. Recent evidence indicates that improvements in cellulose conversion technology may lower production costs (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. In California, the break-even price for large scale production would be even higher.

Table 2: Life-cycle break-even gasoline prices[a], 1985$/gallon

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

Notes:

The important baseline assumptions used here are: 9% real interest rate for auto loans; 30 mpg, $11,500, 120,000-mile life baseline gasoline vehicle; range and fuel system assumptions as per Table 3; methanol vehicles assumed to have same maintenance costs and life as gasoline vehicles, electric vehicles assumed to have 25%-100% longer life and 25%-50% lower maintenance costs. NGVs assumed to have 0%-20% longer life and 0%-15% lower maintenance costs, hydrogen vehicles 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. See DeLuchi et al. (1988, 1989) and DeLuchi (1989) for details.

[a]The break-even price of gasoline for a particular alternative is the retail gasoline price that equates the full life-cycle cost per mile of the alternative with the full cost per mile of a comparable baseline gasoline car. Includes $0.20/gallon state and Federal taxes.

[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 3), less the cost of the gasoline tank in the baseline gasoline vehicle.

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

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

[e]Based on Sperling (1988) and NRC (1990).

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.

<u>Environmental Impacts of Biomass Fuel Production</u>

The introduction of biomass fuels has the potential to nearly eliminate 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.

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 US 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 (OTA, 1980:71), 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 (OTA, 1980:71). If marginal lands are brought into cultivation without very careful soil management, comparatively large amounts of soil will be lost. In general, proper soil management can greatly reduce erosion, but in practice it is rare, because of ignorance, reluctance to change, and unwillingness to invest in techniques with long-term payoffs. Consequently, extensive cultivation of biofuels is likely to be economically and ecologically damaging, more so in California than elsewhere because of the steep gradients of most forestland.

METHANOL FROM NATURAL GAS AND COAL

As indicated above, methanol has been the most widely promoted alternative transportation fuel in the United States (Gray and Alson, 1985; DOE, 1988; California Energy Commission, 1984-1988; 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 over coal and biomass as a methanol feedstock. The production of methanol from natural gas is much less expensive (see Table 2) and produces much less pollution than coal-methanol processes; emissions from NG-to-methanol plants are similar to those of petroleum refineries, while emissions from coal-to-methanol plants are much greater (Table 3). The least expensive natural gas is so-called "remote natural gas" (RNG), gas in foreign (usually third-world) countries remote from readily-accessible markets and priced at about $1.00 per million Btu or less. Initially, methanol would be made in these low-cost, gas-rich countries and imported to the United States. Methanol imports would do little to enhance US energy security, and in fact could weaken it because, on balance, foreign-made methanol would be replacing high-cost, domestic petroleum, and foreign methanol suppliers might be no more secure than petroleum exporters. Methanol use would probably also increase US payments to exporters for energy, which would add to the trade deficit (DeLuchi et al, 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.

Table 3: Comparison of air pollutant emissions from energy conversion processes, gm/million Btu of output, with controls

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

Notes:

Adapted from reports published from 1978 to 1983 by Pace Co., U.S. Office of Technology Assessment, Argonne National Laboratory, US DOE, and SRI International, except as noted below. See Sperling (1988), Table 49 for full citations.

NA = not available.

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

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

[c] From a German study cited in Chadwick et al. (1987) which did not specify the coal.

[d] AGA (1985).

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

[f] U. S. EPA (1985). First figure is for fluid catalytic cracking units with controls, second is for moving-bed catalytic cracking. We assume 0.05 million Btu of residual fuel oil per million Btu of output for process heat, a crude oil sulfur content of 2% by weight and energy content of 140,000 Btu/gallon. HC emissions includes fugitive emissions (12 gm/mmBtu).

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

[h] Integrated gasification combined-cycle power plant. From Wolk and Holt (1988).

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 cities in air-quality nonattainment areas make small progress toward meeting national air quality standards. Methanol also will be much cleaner than diesel fuel, and may be the best strategy for meeting the stringent 1991/94 North American 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; they are likely to have few other environmental benefits. Methanol may produce less CO or NO_x (but not both) than gasoline vehicles (Table 4); 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 5).

Table 4: Percentage change in emissions from alternative-fuel vehicles, relative to gasoline[a]

Fuel	NMHC	CO	NO_x	O_3	SO_x	PM
Methanol (w/catalyst)	-50	0	0	-50	lower[b]	
CNG, LNG (w/catalyst)	-60	-50	0	-60	lower[b]	
Hydrogen (no catalyst)	-95	-99	?	-95	lower[b]	
Electricity (nonfossil)[c]	-100	-100	-100	-100	-100	-100
Electricity/year 2010 mix[d]	-99	-98				

Notes:
From data in DeLuchi et al. (1988, 1989), and DeLuchi (1989). 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.

NMHCs = nonmethane hydrocarbons (total hydrocarbon emissions less methane, which is nonreactive and hence does not contribute to ozone formation). PM = particulate matter.

[a]Ethanol fuel is not included because of minimal experience and testing with controlled vehicles. In general, ethanol-powered vehicles will have similar emissions to methanol. One difference is in aldehyde emissions which may lead to the increased formation of another oxidant, peroxyacetyl nitrate (PAN) with ethanol (Tanner et al., 1988).

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

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

[d]See Wang et al., 1990 for details. Based on forecasts and estimates of energy mix for electricity generation forecasted for California, emission control technologies deployed on power plants, vehicle emission rates, and electricity consumption rates of electric vehicles.

Table 5. Emissions per mile of a composite measure[a] of greenhouse gases, relative to petroleum-powered internal combustion engines[b]

Fuel/Feedstock	Percent Change
EVs/nonfossil electricity	-100
EVs, natural gas plants	-50 to -25
CNG from NG	-20 to 0
Methanol from NG	-10 to +10
EVs, current power mix	- 5 to 0
Gasoline and diesel	--
EVs, new coal plant	0 to +10
Methanol from coal	+30 to +80

Source: DeLuchi, 1990.

[a]We converted CH_4 and N_2O mass emissions from vehicles 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 (we have chosen 125 years), where one degree-year is defined as an increased surface temperature of 1^oC for one year. In order to convert CH_4 emissions into CO_2 emissions having the equivalent temperature effect, one needs to know for both gases the relationship between: 1) equilibrium surface temperature and equilibrium atmospheric concentration of the gas; and 2) the increase in yearly emissions of the gas and the increase in the equilibrium atmospheric concentration (note that many "conversion factors" given in the literature ingore the second step, and hence cannot be applied to emissions). These relationships are derived in DeLuchi et al. (1987b). The result is that N_2O mass emissions multiplied by 175, and CH_4 emissions by 11.6, produce the mass of CO_2 emissions with the same temperature effect. The ranges in values in the table corrspond in part to a range in equivalency values between CH_4 and CO_2 of 10 to 40.

[b]The analysis considered emissions of CH_4, N_2O, and CO_2 from the production and transportation of the primary resource (coal, natural gas, or crude oil), conversion of the primary resource to transporation energy (e.g., natural gas to methanol, or coal to electricity for battery-powered vehicles), distribution of the fuel to retail outlets, and combustion of the fuel in engines, except as noted. N_2O emissions from vehicle engines were not included (the preliminary estimate in DeLuchi et al. (1989) indicates that they are relatively unimportant). Emissions of ozone (O_3) precursors, CFCs from air conditioning systems, and H_2O were not considered (available data and models do not allow estimation of the greenhouse effect of emissions of ozone precursors; CFC emissions are independent of fuel-use; and H_2O emissions from fossil fuel use worldwide are a negligible percentage of global evaporation).

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

[d]CNG and methanol vehicles emit N_2O, H_2O, ozone precursors, and CH_4. As noted above, vehicular emissions of N_2O, and all emissions of H_2O and ozone precursors, were ingored. The carbon in CH_4 emissions from biofuel-vehicles originally comes from atmospheric CO_2, and since CH_4 is a more effective

greenhouse gas than CO_2 per molecule of emissions, the transformation of CO_2 to CH_4 by the biofuel production and use cycle results in a slight increase in effective emissions of greenhouse gases.

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 one-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 multiday ozone episodes (Carter et al, 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) except motorcycles and planes would result in only a 6% reduction in peak ozone levels (Harris et al, 1988).

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 et al, 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., 1988). In any case, the greatest potential ozone reductions with methanol require the use of M100 and very low formaldehydye emissions, two conditions that may not be attainable. We estimate that the substitution of methanol for gasoline in all motor vehicles would result in a maximum reduction in peak ozone levels of 0 to 15% in multiday smog episodes.

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

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

In contrast to the uncertainties surrounding the environmental benefits of substituting methanol for gasoline, there are several clear environmental advantages to using pure methanol in heavy-duty engines. Methanol produces essentially no particulates, smoke, SO_x, or unregulated pollutants. In addition, a methanol engine with an oxidation catalyst produces very little CO, HCs, and formaldehyde (Ullman and Hare, 1982; Alson et al, 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 for achieving a part of the maximum ozone reduction attainable through changes in the transport sector. But the magnitude of these potential improvements is modest.

Safety and Toxicity

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

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

Cost

Methanol is more expensive than gasoline on an energy-equivalent basis, and will continue to be so for the foreseeable future. The most recent estimates are that very small amounts of methanol can be delivered to the United States for as little as $0.20-$0.30 per gallon if the remote natural gas (RNG) feedstock is virtually free and sunk costs in the methanol plant are ignored (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) (Department of Energy, 1988). Methanol could be produced from coal in the United States for around $1.00 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 $1.10-1.70 per gallon, including taxes (and allowing for the fact that methanol is about 10-20% 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 $1000 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 85 would cost $9000 to $66,000 to eliminate one ton of "ozone-equivalent" hydrocarbon emissions; if M100 were used, assuming favorable ozone-reduction parameters, the cost would be $3000 to $22,000 per ton. The high estimates are probably overstated and are likely to be revised downward by OTA in the near future.

A similar analysis conducted for California as part of the AB234 Advisory Board on Air Quality and Fuels estimated the cost-effectiveness of M85 at $8000 to $40,000 per ton (California Advisory Board on Air Quality and Fuels (1989).

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

The OTA estimates suggest that multifuel methanol cars are clearly not a cost-effective ozone control strategy. Given the range of uncertainty in costs and emission reductions, a similarly definitive conclusion regarding optimized dedicated methanol cars is premature. Indeed, if methanol fuel and vehicles 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 in California and the U.S may be in heavy-duty diesel engines. New emission standards requiring sharp reductions in particulate and NO_x emissions from heavy-duty diesel vehicles take effect in the United States and Canada in 1994 (1991 for transit buses). Meeting the standards by applying control technology to diesel combustion will be difficult; the vehicle capital costs may be less with a methanol (or natural gas) engine, although the methanol fuel costs would be greater. Several heavy-duty engine manufacturers are developing methanol (and natural gas) engines.

However, diesel-powered trucks consume only about 2 of the 15 quadrillion Btus of energy used annually on the highways in the United States (ORNL, 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 R&D costs must be spread over a relatively small number of vehicles (although at full production the cost of a methanol-powered vehicle is expected to be about the same as the cost of a comparable gasoline-powered vehicle). Similarly, establishing a methanol fuel delivery infrastructure will be fairly expensive. The minimum cost approach for a large scale effort would be to market the fuel only in and near ports with ocean access, obviating the need to modify the existing oil product pipeline network or to build an entirely new pipeline network. (Since methanol will be imported initially, a port-based distribution system will be adequate at first.) DOE estimates that the capital cost of building a national methanol distribution system, using only waterborne and truck transport, with methanol marketed only within 100 miles of major river and ocean ports (reaching about 75% of the United States), would be $13 billion (McNutt et al., 1987).

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 nonpetroleum) vehicles. Retail fuel suppliers will require more direct subsidies, such as the $50,000 capital grants offered by the Canadian government to retail fuel stations to install facilities for compressed natural gas (CNG) and the per-gallon subsidies provided by the California Energy Commission to methanol fuel suppliers. Ultimately, consumers would have to be subsidized to convince them to buy methanol, since methanol will cost more than gasoline until oil prices reach $30 per barrel or more.

In summary, 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. Methanol offers modest environmental benefits at modest cost.

METHANE FUELS

Feedstocks

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

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

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

Another resource consideration is 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 et al., 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 $1500-2000 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 similar power; it would cost about $700 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 7).

Table 7: Characteristics of vehicular energy storage systems

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

Notes:

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

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

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

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

[d]Adapted from data in DeLuchi et al. (1988). Assumes fiberglass-wrapped aluminum CNG cylinders; 15% thermal efficiency advantage for CNG and LNG; weight penalty for CNG. LNG system size includes LNG pump.

[e]Adapted from data in DeLuchi (1989). Assumes 25% thermal efficiency advantage; weight penalty for hydride. LH_2 system size includes pump.

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

[g]35-kWh capacity, 120 Wh/l, 110 wh/kg, 4.4 mi/battery-kWh (DeLuchi et al., 1989).

[h]Fast electric vehicle charging is theoretically possible, but requires a very large current and is possible only with certain batteries. It has not been investigated.

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

Currently, large numbers of CNG vehicles are operating in Italy, New Zealand, Canada, and the Soviet Union (Sathaye et al., 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 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 stagnated at 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 announced the intention in 1988 of converting 500,000 to 1 million vehicles to CNG by 1995, most of them taxis and trucks.

CNG has an extraordinary safety record in actual experience. In New Zealand, for instance, with over 100,000 vehicles in operation for almost 10 years, there has been only one explosion or fire of a natural gas tank, and no one was hurt. The only danger is the accidental leakage of gas from CNG in an enclosed space (in an open space the gas 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.

<u>Costs</u>

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 RNG 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 (mmBtu) 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 mmBtu, according to price projections for commercial gas (EIA, 1988). Based on an exhaustive review of the literature, and a detailed accounting of all costs, including land, site preparation, hook-up to the gas main, energy needed to compress gas from pipeline pressure to 3000 psi, etc, we estimate that the cost of compression and retailing is about $3 per mmBtu (DeLuchi et al., 1988). B.C. Gas of Canada, a marketer of CNG, also estimates $3 per mmBtu (Cann, 1988). Thus a midrange estimate of the cost of CNG is $8 per mmBtu before taxes; a low-end estimate for methanol is about $9 per mmBtu. LNG will cost about the same as CNG.

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

Ownership and operating costs can be combined and expressed as a total cost per mile over the life of a vehicle, by amortizing the initial cost at an appropriate interest rate, adjusting for salvage values and vehicle life, and adding periodic costs such as maintenance, fuel, insurance, and registration. Table 8 presents the life-cycle cost of various alternative-fuel vehicles relative to a comparable, baseline gasoline vehicle. It shows the retail price per gallon of gasoline (including taxes) at which the life-cycle cost of the alternative-fuel vehicle and the comparable gasoline vehicle would be equal. This is called the "break-even" price of gasoline. As shown earlier in Table 3, the total life-cycle cost of NG vehicles (using US NG) will be close to the life-cycle cost of gasoline vehicles at current gasoline prices, and may be less than the life-cycle cost of methanol vehicles (using remote natural gas), although the range of estimated costs overlap.

The analysis is conducted from the end-user's perspective. 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, Sperling, and Johnston (1988).

The assumptions are based on an exhaustive 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 an optimized for-CNG vehicle, including the development of advanced storage tanks, and there is little reliable evidence from which to estimate the operating costs and life of such an optimized vehicle.

The baseline gasoline vehicle, against which the alternative fuel vehicles are compared, has the following attributes: 35 mpg, 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 $700 to $800 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 thousand Btu for CNG. The cost parameters and vehicle attributes are listed in the appendix (Table A-1) and fully documented in DeLuchi et al. (1987, 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 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 analysis shows that 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 as presented in Table A-1.

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

HYDROGEN AND CLEAN ELECTRICITY

Hydrogen and electric vehicles are linked here because they both are part of a potentially sustainable and very clean energy path and both 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 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 et al., 1985:179-201).

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

Vehicular Fuel Storage

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

Hydride storage units, which include housings for the hydrides and the coolant systems, are very large, from 25 to over 80 gallons, and quite heavy, 250 to 1000 lbs (Table 7). 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 7).

In summary, all hydrogen storage systems systems are bulky and costly and will remain so, even with major advances. 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.

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 and 5). If hydrogen is made from water using a clean power source, then hydrogen production and distribution will be pollution-free.

The only pollutant of concern would be NO_x, which is formed, as in all internal-combustion engines, from nitrogen taken from the air during combustion. With lean operation, and some form of combustion cooling such as exhaust gas recirculation, water injection or the use of very cold fuel (i.e., liquid hydrogen), but with no catalytic control equipment on the engine, an optimized hydrogen vehicle probably could meet the current US NO_x standard, and probably have lower lifetime average NO_x emissions than a current-model catalyst-equipped gasoline vehicle (DeLuchi, 1989).

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

<u>Nuclear</u> <u>Versus</u> <u>Solar</u>

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 slightly <u>less</u> acreage per unit of energy produced than nuclear power generation, when mining, transportation, and waste disposal are considered (ref 93c??). In the hydrogen vehicle cost analyses below, we consider solar photovoltaic energy as the primary energy source.

<u>Cost</u>

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 5-25% 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 8 shows the price of gasoline that would be required to make the life-cycle cost of a gasoline and hydrogen vehicle equal (the other assumptions are discussed in the notes to Table 8). 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 $3.00 per gallon; in other words, gasoline would have to sell for more than $3.00 per gallon for hydrogen vehicles (using hydrogen made from water with solar power) to be economically competitive. Thus, it appears that hydrogen vehicles will be cost-competitive in the middle term only if the most optimistic cost projections are realized <u>and</u> the price of gasoline at least triples.

<u>Opportunities for Hydrogen</u>

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

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

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

<u>Electric Vehicles</u>

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.

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

Performance of EVs

Electric vehicles were commonplace in the United States at the turn of the century. However, by 1920 improvements in EV technology had lagged so far behind the development of the internal combustion engine that EVs became practically extinct (Hamilton, 1980a). 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. Several major auto manufacturers expect to mass-produce EVs with ac power trains and sodium/sulfur batteries in the 1990s (Mader and Bevilacqua, 1989).

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. 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. With these characteristics, EVs would be attractive as second vehicles in most multicar households (Lunde, 1980:361-377; Horowitz and Hummon, 1987:17-26) and as vans in most urban fleets (Berg, 1985; Brunner and Wood, 1988). As personal vehicles become more specialized and expectations regarding multipurpose usage of vehicles continue to diminish, EVs may even become acceptable as primary commuter cars. Exotic batteries under development, such as the aluminum-air battery, that promise even longer ranges and faster recharging, could eventually make EVs the vehicle of choice in a world of high energy prices and heightened environmental concern.

Cost

If the most optimistic cost conditions are satisfied -- high vehicle efficiency, high battery energy density, low-cost off-peak power, low initial battery cost, long battery cycle-life, long EV life, and low maintenance costs -- then EVs will have much lower life-cycle costs than comparable gasoline vehicles and will be economically competitive even if gasoline is free (Table 8). However, under high-cost conditions, EVs will not be cost-competitive until gasoline sells for $3-4 per gallon (Table 8). If electricity is more expensive, in the range of 10 to 15¢ per kwh, the breakeven price is about $4-5 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.

<u>Environmental Impacts</u>

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 (DeLuchi et al., 1989; Wang et al., 1989; see Table 5).

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

The impact of EV use on greenhouse gas emissions is more mixed and much 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 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 mix of electricity sources existing in the United States in 1985, then about the same quantity of greenhouse gases will be emitted as was emitted by the use of gasoline and diesel fuel vehicles in 1985. If nonfossil fuels (nuclear, solar, hydroelectric power, or biomass fuels) are used in all engines, there will be essentially zero emissions of greenhouse gases.

<u>Opportunities for EVS</u>

EVs probably will be introduced with relatively little government involvement, 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 late at 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 California utilities have sufficient capacity in place to support perhaps millions of electric vehicles, charging off-peak (Mathtech, 1978).

Second, the life-cycle cost of advanced, mass-produced EVs, using cheap off-peak power, probably will be low enough to induce some fleet operators and home owners to purchasease 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 $1000 (Hamilton, 1988). These relatively small cost and start-up barriers (the "chicken-and-the-egg" problem) means that the market penetration of EVs can proceed, to a point, largely by market forces. (The Electric Vehicle Development Corporation, a private group supported by electric utilities, battery manufacturers, and auto manufacturers, is developing markets and service infrastructure for EVs (Mader et al., 1988).) The most important role of government may be to coordinate or make large purchases of EVs, allowing manufacturers to achieve economies of scale in production. The government could justify this modest role on environmental grounds.

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 eight hours to recharge an EV, most households will want at least one nonelectric vehicle, and EVs will be limited to the role of second car in some multicar, home-owning households. However, if EVs can be charged in under 30 minutes, they may be able to displace gasoline vehicles in many 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 demonstrated, however, and all are likely to be expensive. Much more work is needed in this area.

The successful completion of advanced EV development programs, and the development of means of quickly recharging EVs, would make the EV a competitive alternative to internal combustion vehicles. The combination of large environmental benefits and potentially low private cost in the near term, 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 today.

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

Why Has Methanol Dominated the Debate: Short vs Long Term Considerations

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

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

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

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

It may also be that consumers are not as conservative and unchanging in their vehicle purchasing preferences as is commonly assumed; or, more accurately, there may be various groups of buyers who are willing to accept the shorter driving range of EVs and NGVs and the long recharging time of EVs in exchange for their environmental superiority (Sperling et al, 1990). Recent indications of this interest, especially in EVs, is the unexpectedly enthusiastic response General Motors reportedly received to the unveiling of their EV prototype in early 1990(?), and a disproportionate interest evinced in August 1990 focus group interviews in the Los Angeles area. In untargeted discussions of alternative fuels, participants mentioned electric vehicles 34 times, compared to 9 for propane, 6 each for methanol and alcohols, 4 each for CNG and hydrogen, and 5 for reformulated gasoline (Turrentine, 1990).

While these observations are not definitive evidence, they suggest a yearning for a "green" car. If battery and EV technology continues to be improved, resulting in lifecycle costs similar to those for gasoline-powered vehicles, a not implausible expectation (DeLuchi et al, 1989), then we believe it is likely that EVs can gain significant market penetration. A similar case can be made for natural gas vehicles, since they can also be marketed as a "green" product.

Experiences in Brazil and New Zealand lend further support to the hypothesis that consumers are likely to modify their behavior to accept range and recharging disadvantages, if given a good reason to do so (Sperling, 1987; Kurani, 1990). The reasons in these two cases were part nationalism, part economic, and part risk aversion. In Brazil, in particular, consumers were convinced by government actions and proclamations that ethanol was the fuel of the future, not gasoline, and therefore that they would have a better chance of retaining access to fuel in the future and of retaining the resale value of their vehicles if they purchased an ethanol-powered vehicle. As a result, ethanol cars accounted for over 95% of new car sales in Brazil through the mid 1980s; in New Zealand, about 10% of all cars were converted to CNG during the same time period.

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

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

THE IMPOSSIBLE ANALYSIS

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

Still greater uncertainty exists on the benefit side of the equation regarding emission characteristics, relationships between emissions and air quality, emissions and global warming, magnitude of safety and toxicity impacts, and impact on energy security. Consider, for instance, the calculations by OTA (1989) and the California Advisory Board (1989) reported earlier in the text of the cost-effectiveness of methanol and CNG as ozone reduction strategies. They included only two important factors: fuel/vehicle cost and ozone impact, excluding other social benefits. But even these two factors include considerable uncertainty and unverifiable assumptions, and produced results with a very broad range.

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

The choice of transportation energy futures should be open-minded and flexible. There is not one optimal choice for everyone, or every region; the era of one (or two) uniform transportation fuels may be over. This prospective multiplicity of fuel options presents a challenge for business and government. Because many of the benefits resulting from initial alternative-fuel investments do not accrue to the private sector supplier of the fuel, government must take much of the initiative.

Facts, Beliefs, and Values

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

The choice of transportation energy paths should focus on values and goals, rather than on projections of market costs, especially when projected costs do not differ much between energy options or are based on technologies that are still far from commercialization (and likely to become much less expensive with learning curve improvements). Current and projected market prices can be poor criteria for long-term energy choices. Shifting societal goals, values, and preferences will result in redirected government initiatives that will change relative energy prices, while the long-term replacement of today's sunk investments will also cause a shift in long-term energy prices. We should therefore take care not to allow current and extrapolated energy prices to overly influence transition strategies. In the words of Herman Daly, "the choice between... energy futures is price determining, not price-determined" (Daly, 1976:68).

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

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

If economic efficiency, measured by conventional market indicators, is the dominating value, then hydrogen would be discarded as an option. Electric vehicles would be competitive in some applications if optimistic battery 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 environmental quality and sustainability takes precedence, then hydrogen and electric vehicles, using clean and renewable energy (probably solar power), would be preferred. Methanol and NG vehicles, regardless of the feedstocks, would be deployed as transitional options only, if at all.

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

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

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

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

MOVING TOWARD A MORE EFFICIENT AND FLEXIBLE REGULATORY SYSTEM

Current regulatory initiatives to introduce alternative fuels on the national level are based on vehicle emission standards and mandated use of alternative fuels. They are part of a first generation regulatory framework that is not suited to the changing circumstances of the future: they do not reflect multiple social goals, are not flexible in responding to changing economic and technological conditions, are insensitive to regional differences, and do not acknowledge the likelihood of shifting social priorities. There are good reasons for the simplistic inflexibility of past and current approaches -- mostly associated with ease of implementation -- but they are becoming increasingly inefficient and inappropriate.

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

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

Continued reliance on the current command-and-control approach implies the use of specific rules, standards, mandates and subsidies to place direct controls on individual and industry behavior. Current initiatives, reflecting this command-and-control style, are proposals that fuels be required to contain a certain percentage of oxygenates and that certain vehicle fleets convert to alternative fuels. This approach requires that government administrators have the foresight to be able to orchestrate which fuels and vehicles should be introduced where and when. Given the uncertainty about the relative attractions of alternative fuels and the best way to introduce new fuels and vehicles, and given the uncertainty about the future, a more efficient and resilient approach would be to offer incentives to industry and consumers that push them in the correct direction -- toward lower air pollution, reduced greenhouse gases, and perhaps even domestic resources. This approach is fundamentally more efficient. This approach seeks to alter the behavior of individual and industry by restructuring rather than overtly limiting the choice environment. It does not rely on omniscient government bureaucrats to prognosticate; rather, it relies on bureaucrats to do what they do best -- administrate.

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

Incentive-Based Approaches

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

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

Other conceptually similar but more limited proposals in California include providing tax credits for vehicles converted to "low-emitting" alternative fuels (SB 2600) and reductions in vehicle license fees for specified low-emission vehicles (SB 907).

These proposals to make the system work better (that is, to incorporate externalities) are conceptually attractive and potentially highly effective at responding to the concerns expressed earlier, especially in the form of more comprehensive initiatives such as that of Senator Hart. These proposals do not seem to be popular with legislators or regualtors. Legislators seem reluctant to vote for proposals such as Senator Hart's, possibly because of a desire to avoid direct financial transfers to and from consumers, particularly when these transfers can be labeled as taxes. Regulators are reluctant to introduce these proposals because they would have to seek new authority and because very large financial transfers (or taxes) would be needed to compel changes of the order sought by the regulators (CARB, 1990, p.57).

The second incentive-based approach, creating new market-like arrangements, includes the use of pollution licenses and permits, and marketable credits. Licenses and permits may work well with a limited number of sources, as with most stationary sources, but not with the hundreds of millions of vehicles. Marketable credits, however, show great promise.

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

Averaging and Banking

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

Consider the case of motor vehicle emissions. With averaging, an emission standard would be established, as has been done for the last 20 years, but in this case vehicle manufacturers would have the flexibility to average emissions across their fleet of vehicles. Vehicle suppliers could reduce emissions to a lower level in those vehicles where the cost of reducing emissions is less and not reduce emissions as much in other vehicles where the cost would be greater, as long as the average for all vehicles was below the standard. As the emission standard is lowered, resulting in an increasing cost for emission reductions, there will be an incentive for automakers to market vehicles that operate on cleaner-burning alternative fuels.

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

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

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

Marketable Credits

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

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

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

The calculations were made using 1981 emission standards, forecasted vehicles sales for 1984-90, the vehicle and market mix prevailing in 1981, and based on a set of control cost functions derived from a statistical analysis of 1979-82 certification data and unreported estimated cost functions. The analysis is simplistic, perhaps out-of-date, relies on a poor data base, and uses aggregated data in a manner that underestimates the cost savings. Our sense is that with the vehicle technology, tighter standards and higher marginal costs of the 1990s, that cost savings would be much greater.

Nonetheless, if we use this low 25% estimate, and estimates that the current marginal cost for emission control is about $400 per vehicle, then we find that emission averaging and trading would generate cost savings of over $100 million per year in California and over a billion dollars for the U.S.

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

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

Averaging, trading, and banking of vehicle emissions are only one component of an incentive-based approach to the regulation of vehicles and fuels. By themselves, they provide greater efficiency and are fuel-neutral, but they do not allow for the design of region-specific strategies, because vehicles can be easily moved from one region to another, and do not incorporate other social goals. A more sophisticated and expanded framework is needed.

<u>Fuel Supply Regulation</u>

To incorporate a geographical element into the regulatory system it is necessary to involve fuel suppliers -- to allow fuel suppliers also to average, bank and trade emission reduction credits. The successful regulation of lead in gasoline since the 1970s (Hahn, 1989; Hahn and Hester, 1990; Nussbaum, 1990) is an indication that expanded regulation of fuels is feasible.

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

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

The administration of a fuels regulation program would be more difficult than a comparable program for automotive emissions, principally because there are many more fuel suppliers than vehicle suppliers and because of the multiple fuel supply industries. There is also less experience with fuels regulation. The only current regulation of fuels is through spot checks of vapor pressure, lead content, and the use of oxygenated blends (e.g. ethanol in Denver to reduce wintertime carbon monoxide) in some areas. Nonetheless, the successful experience with lead banking and trading rules in the 1980s (Hahn, 1989), in which administrative expenses were minimal (Nussbaum, 1990), suggest that fuels regulation will not be an onerous burden on companies or regulators.

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

Since each type fuel emits differing quantities and types of pollutants, the regulation of fuels as well as vehicle emissions would require that ratings be developed for each fuel that indicate the relative harm of pollutants associated with each fuel. Emission equivalency values would be assigned to the different fuels. Ozone reactivity ratings have already been developed for comparing the relative contribution of each type of fuel to ozone formation. In the case of fuels, a rating would be assigned to each carefully specified fuel. For instance, gasoline might be rated 1.0, "reformulated" gasoline 0.9, methanol 0.8, natural gas 0.7, and electricity 0.4. Each fuel supplier would be required physically, or via purchased or banked credits, to supply a slate of fuels that on average meets a rating established by the regional or state air quality regulator.

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

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

Table 8. Sample Regulatory Fuel Indices and Implementation Schedules

	City A	City B
Gasoline	1.0	1.0
Reform. gasoline	0.9	0.9
Methanol	0.7	0.9
Natural gas	0.5	0.8
Electricity	0.3	0.7
Sample Implementation Schedule		
1996	0.9	1.0
1998	0.8	0.9
2000	0.7	0.9
2005	0.6	0.9

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

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

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

The incentive-based regulatory concept presented here is not new or unknown to government. It has been slowly introduced over the past decade to control emissions from stationary sources such as powerplants and factories (Cook, 1988), and is an important part of EPA efforts to reduce sulfur oxide emissions and acid rain -- but it is new to vehicles and vehicular fuels.

It is a concept that is gaining increasing acceptance not only with researchers but also with policymakers. President Bush, for instance, in his mid-1989 Clean Air Act proposals, though vague in details, endorsed the concept of an incentive-based approach for regulating vehiclular emissions. Also, a blue ribbon advisory board composed of high level government and industry representatives, established by the California legislature to advise it on the introduction of alternative fuels, recommended in its October 1989 final report that a fuel regulation program be established similar to that described above (California Advisory Board, 1989). Labelled "fuel-pool averaging," the intent was to propose a program that was fuel-neutral. Details were never provided.

CARB's Bold Fuel and Vehicle Proposal

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

The new-vehicle emission standards are the heart of the CARB proposal. Tailpipe standards for hydrocarbon emissions (expressed as non-methane organic gases) measured at 50,000 miles would drop from today's 0.39 grams per mile to 0.25 in 1994 and then gradually down to 0.062 in 2003. The corresponding reduction in emissions for light duty trucks (under 3750 pounds) would be from 0.32 to .093 g/mi between 1994 and 2003. Reductions in standards are also proposed for nitrogen oxides, carbon monoxide, formaldehyde (methanol vehicles only), and particulates (diesel cars only).

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

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

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

A third and very important constraint is that 2% of all vehicles supplied by major manufacturers to California must have zero emissions in 1998, with that proportion increasing steadily to 10% in 2003. The motivation behind this rule is to make certain that vehicle manufacturers make progress in designing electric, hydrogen, and/or fuel cell vehicles, assuring that the Los Angeles area's goal of transitioning to zero emitting vehicles is attainable in a more timely manner.

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

On the fuel side, CARB proposes, beginning in 1994 in the Los Angeles area and in 1997 statewide, that gasoline suppliers be required to supply alternative <u>liquid</u> clean fuels -- defined to include alcohols and LPG. The total quantity of mandated sales would be determined so as to be sufficient to meet the needs of alternative fuel vehicles; this quantity would be estimated based on the number of vehicles certified to operate on that fuel in the preceeding time period. The specified requirement for each company would be based on that company's share of the total gasoline market. Additional rules will be promulgated later to mandate the outfitting of retail fuel stations for alternative fuels.

A gasoline supplier could satisfy the clean liquid fuel requirement by either selling those fuels directly, or by buying credits from other suppliers who have sold clean liquid fuels in excess of their requirements. Banking of credits is allowed, but the credits lose their value after 2 years, and not more than 20% of their clean fuel sales can be banked in any 3 month period.

Although CNG and electricity are specifically excluded from the clean fuel requirement, a provision is made for gasoline suppliers to satisfy up to 10% of their requirement with credits purchased from electric and natural gas utilities. The utilities earn the credits by selling CNG and electricity directly to vehicles (for electricity, credits can only be earned for electricity sales beyond those required by the mandated 2-10% zero emission vehicle sales).

The rules constraining participation by CNG and EVs is justified by CARB on the premise that enough incentive already exists to encourage natural gas and electric vehicles, and that refiners' facilities are not suited to selling non-liquid fuels.

The CARB initiative is bold and innovative, but still falls short of the comprehensive incentive-based approach outlined above. The CARB proposal creates artificial preferences for liquid fuels, does not establish a mechanism that allows the development of region-specific strategies or the incorporation of non-ozone goals, and does not provide a mechanism for trading between vehicle and fuel suppliers.

We are not so concerned by the absence of a mechanism to allow trading between vehicle and fuel suppliers. That is a logical next step that can follow as experience is gained in designing, administering and enforcing incentive-based systems. As we learn more about how best to create such a system, the procedures and mechanisms can be developed.

Of much more concern to us is the need to be truly fuel-neutral and to integrate multiple social goals into the system.

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

Consider the CARB situation: there is a chance that automakers, in conjunction with oil refiners, will devise a method to meet all but the zero emission standards with gasoline-powered vehicles. Indeed, CARB has conducted tests in which new cars equipped with "green" electrically heated catalysts emit as little as 0.03 g/mi at low-mileage (CARB, 1990). Whether those catalysts will perform well as they age and be able to meet the 0.04 standard at 50,000 miles is still unknown.

If gasoline cars can meet the standard, it is an impressive achievement. But at what cost? Would society be better off if the automakers and fuel suppliers instead shifted to alternative fuels? The market cost for gasoline vehicles to meet the standard is estimated to be near $200 per vehicle, plus up to $0.20 per gallon for the reformulated gasoline (Townsend, 1990). It probably would be cheaper in the long run to shift to inherently cleaner alternative fuels to meet the standard. But even if it were not cheaper to do so, it still is probably wiser to shift to alternative fuels, since the alternative fuels provide other benefits: they reduce carbon monoxide, airborne toxics, greenhouse gases, and energy dependency, in some cases spectacularly so.

But when automakers and oil companies are only forced to incorporate air pollution externalites into their decisionmaking process, and not other important externalities, then they will, as explained below, prolong their commitment to gasoline beyond the time when it would be otherwise rational.

By ignoring the other important non-market attributes of fuel options, CARB is not acting in our best interests. A regulatory process needs to be developed that is not so narrowly mission-oriented.

In all fairness, CARB has taken a huge first step away from command-and-control rules toward an incentive-based approach. CARB is to be commended for its considerable creativity and perseverance, especially when viewed in terms of the lack of innovation and change at the national level and elsewhere in the world (OECD, 1989). Considerable progress still remains, however.

INDUSTRY CONCERNS

For an incentive-based program to be implemented successfully, it must balance the concerns and interests of fuel and vehicle suppliers with the overall societal good. Some of those concerns and interests, and possible responses to them are discussed below.

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

Oil companies, facing the greatest risk, have campaigned hard against alternative fuels, even as they hedge their bets by participating in government methanol programs in California and elsewhere. Mobil Oil, historically the most outspoken of the oil companies, mounted a national media campaign in August and September 1989 with large ads in Time magazine, the New York Times and other influential publications opposing and even ridiculing the proposal to mandate alternative fuels. It argued that methanol was toxic, did not improve air quality, worsened the trade deficit, and was expensive.

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

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

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

The initially high level of uncertainty associated with alternative fuels for both fuel and vehicle suppliers will undoubtedly cause auto and oil companies to focus initially on improving existing engines and fuels; that's fine. But gradually, following the most cost-effective path and local priorities, which will differ for each company and perhaps for each region, they will move toward cleaner-burning, more socially desirable non-petroleum fuels.

CONCLUSIONS AND POLICY RECOMMENDATIONS

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

Efforts to introduce methanol and CNG fuel should continue, but it should be recognized that they are not long-term solutions, though they may prove to be the preferred fuels in the first half of the 21st century. The long-term and possibly permanent transportation fuels for California will probably be a mix of electricity and hydrogen. These fuels provide the potential for a qualitatively superior and sustainable future. With this in mind we should act now, in particular by updating R&D strategies and reorganizing the fuels and air quality regulatory structures.

Realizing that other competing views and values exist and have equal validity, and acknowledging limited knowledge and foresight, we strongly believe that the focus of government efforts should be on providing incentives to push industry and consumers in the correct direction -- the production and use of vehicles and fuels that are more environmentally benign, safer, and less threatening to our national security. Mid-course corrections can be made over time.

What is needed, and what will best serve us in the long run, is the establishment of an institutional framework that is flexible in responding to new information, shifting values and beliefs, that incorporates multiple social goals and that is amenable to region-specific initiatives. The two types of incentive-based regulatory approaches addressed in this report -- creating marketable credits, and altering price signals with fees, credits and taxes -- respond to these needs. They also preclude government from mandating which fuels should be introduced and when, thereby eliminating the likelihood of expensive mistakes.

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

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

In a larger sense, we have come to a crossroad in dealing with pollution and energy use in the transportation sector. We must acknowledge the shortcomings of the narrow and relatively inflexible approach of social regulation that emerged in the late 1960s and 1970s and has dominated pollution control efforts since. While industry, government regulators, and even environmental groups have become accustomed to the certainty that that system provides, it is unsuited to the needs of the 1990s and beyond. It would be ironic indeed if, as the Soviet Union and Eastern Europe turn away from command-and-control techniques, we were to strengthen our embrace. Although the move away from uniform emission standards will be unnerving to those involved, it should be done -- gently, but decisively.

<u>R&D Recommendations</u>

To expand the body of knowledge about alternative fuels, their impacts, and strategies for introducing them, and to inform the decisionmaking process, we recommend that priority be given to the following research areas.

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

2. The automotive industry should be directing much more basic R&D toward the design of engines and fuel storage systems optimized for methanol and natural gas.To our knowledge, no vehicular engine optimized in all respects for these fuels exists. It appears that most automotive industry research is now devoted to multifuel alcohol-gasoline engines, not optimized methanol and natural gas vehicles (nor other environmentally supperior options). Engines optimized with respect to performance and emission parameters, for given engine costs, should be built and evaluated for each fuel type. The State of California should investigate options to accelerate these activities.

3. California should encourage auto manufacturers to increase R&D of electric and hydrogen vehicles and batteries, and increase government participation in these activities. Key areas to target for technological improvement of vehicles are the recharging time of advanced batteries, the further development of reliable and cost-effective control of gases boiled off from cryogenic fuels, and improvements in the mass energy density and desorption temperatures of metal hydrides. [FUEL CELLS] The first major use of electric and hydrogen vehicles will undoubtedly be in the Los Angeles area. Yet R&D on electric and hydrogen vehicles at the major automakers has languished. West German and Japanese companies have invested more heavily in these environmentally-attractive vehicle technologies than U.S. automakers. The CEC, South Coast AQMD, and CARB have directed minimal resources at these technologies; they should dramatically increase their R&D support for these promising options. The proposals by Los Angeles to purchase 10,000 electric vehicles and by CARB to require that 10% of vehicles in 2003 be zero emitting send the correct signal. Expanded initiatives would be desirable.

4. Given that clean electricity should figure prominently in our transportation future, powering electric vehicles or splitting water to make

hydrogen, research and development of sustainable, pollution-free electricity-generating technologies, especially photovoltaics, should be a high priority of state and national energy policy. Solar energy should prove to be the most cost-effective source of renewable, clean, non-CO_2 producing energy available. The California Energy Commission has provided initial support for photovoltaic technology. This level of support should be dramatically increased.

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

6. Investigations of alternative designs of incentive-based regulation of fuels and vehicles need to be greatly expanded. Scarcely any effort has been made to answer questions regarding the use of incentive-based regulatory programs in the transportation sector. Much more progress has been made in understanding and implementing incentive-based programs in other energy-consuming sectors of the economy. In this report, we have applied our insights and knowledge about the transportation and energy sectors in recommending a shift toward incentive-based regulation -- using marketable credits for both fuel and vehicle regulation, and adjusting price signals to incorporate air pollution, global warming and energy security externalities. We are convinced this is the correct path to be following and that immediate efforts should be made to incorporate these general principles and strategies. Further research is needed to provide more specific guidance.

APPENDIX

Table A-1: Cost Parameters and Vehicle Attributes Used in Cost Analysis

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

Note: Station costs for CNG were calculated independently, taking into account 15 different cost and operations factors. For details, see Deluchi et al., 1988.

LITERATURE CITED

Acurex. 1981. Alternative Fuel Strategies for Stationary and Mobile Engines, Vol. 3. Mount

Acurex. 1982. Clean Coal Fuels: Alternate Fuel Strategies for Stationary and Mobil Engines, Executive Summary. CEC, P500-82-020, Sacramento:

Calif.

Aerospace Corporation. 1980 "Alcohol Fuels from Biomass, Appendix A," in US NAFC, Fuel Alcohol, Appendix. Washington DC, pp. 1-253.

Aerospace Corporation. 1982. Assessment of Methane-Related Fuels for Automotive Fleet Vehicles. Springfield, Va., NTIS, DOE/CE/50179-1.

Alson, Jeff, J. Adler and T. Baines. 1989. Motor Vehicle Emission Characteristics and Air Quality Impacts of Methanol and Compressed Natural Gas. In Sperling, ed., Alternative Transportation Fuels, An Environmental and Energy Solution. Westport, Conn.: Quorum Books.

American Gas Association. 1985. The Gas Energy Supply Outlook Through 2010 Arlington, Va.

Argonne National Laboratory. 1979. Environmental and Economic Evaluation of Energy Recovery from Agricultural and Forestry Residues. Argonne, Ill.: ANL/EES-TM-58.

Barnes, C. S. and E. J. Hobert. 1979. Alcohol manufacture -- wastewater treatment. Water 6:4, 22-23.

Bechtold, R. L. 1987. Compendium of Significant Events in the Recent Development of Alcohol Fuels in the United States. ORNL/Sub/85-22007/1. Springfield, Va.: National Technical Information Service.

Berg, Larry (member of executive committee of South Coast Air Quality Management District). 1984. Testimony to U.S. Congress, H. of Rep., Comm. on Energy and Commerce, Subcomm. on Fossil and Synthetic Fuels, Methanol as Transportation Fuel, 98th Cong., 2d sess., 4 and 25 April 1984. Washington, D.C.: GPO, 1984, 98-145, p. 26.

Berg, M. 1985. The potential market for electric vehicles: results from a national survey of commercial fleet operators. Transp. Res. Rec 1049, 70-78.

Bockris, J., B. Dandapani, D. Cocke and J. Ghoroghchian. 1985. On the splitting of water. Int. J. Hydrogen Energy. 10:3, 179-201.

Bohi, D. R. and W. D. Montgomery. 1982. Oil Prices, Energy Security, and Import Policy. Washington, DC: Resources for the Future.

Brinkley, J., W. Tyner and M. Mathews. 1983. Evaluating Alternative Energy Policies: An Example Comparing Transportation Energy Alternatives, The Energy Journal 4:2, 91-104. This is a summary of volume 2 ("Costs and Benefits") of Purdue University (1981-82).

Brunner, J. and D. Wood. 1988. Assessment of U.S. market for electric vans. Procs., 9th Inter. Electric Vehicle Symp. EVS88-072. Nov. 13-16, Toronto, Canada, Mississauga Canada: Kerwill Publications.

Burns, T. 1989. The future of oil: a Chevron view. In D. Sperling, ed., Alternative Transportation Fuels: An Environmental and Energy Solution, pp. 11-20. Westport, Conn.: Quorum Books.

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

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

California Air Resources Board. 1986. Emissions Inventory 1983, Technical Support Division, Sacramento, California.

California Air Resources Board. 1990. Proposed Regualtions for Low-Emission Vehicles and Clean Fuels. Staff Report, Sacramento, California, August 13.

California Council for Environmental & Economic Balance. 1987. Alternative Fuels as an Air Quality Improvement Strategy, Sacramento, California.

California Energy Commission. 1986a. Energy Development Report. Sacramento, California.

California Energy Commission. 1986b. Biennial Fuels Report. Sacramento, California.

California Energy Commission. 1987. Fuels Report, Sacramento, California.

California State Legislature. 1987. Assembly Bill No. 234, October.

Canadian Facts. 1986. Management Summary: Natural Gas for Vehicles -- Conversion Motivation Study. Burnaby, B.C.: British Columbia Hydro Gas Operations.

Cann, J. H. 1988. Presentation by B.C. Hydro of Canada to Gas Symp. April 19, Washington, DC.

Carlson, D. E. 1989. Low cost power from thin-film photovoltaics, Solarex Thin Film Division, Newtown, Pa.

Carter, W. P. L., R. Atkinson, W. D. Long, L. L. N. Parker and M. C. Dodd. 1986. Effects of Methanol Fuel Substitution on Multi-Day Air Pollution Episodes. ARB-86. Riverside: Statewide Air Pollution Res. Cent. Univ. of Calif.

Chadwick, M. J., N. H. Highton, N. Lindman, eds. 1987. Environmental Impacts of Coal Mining and Utilization. Oxford: Pergamom.

Chevron. 1985. The Outlook for Use of Methanol as a Transportation Fuel. Richmond, Calif.: Chevron.

Collins, M. M., Hamilton, W. F. and Carriere, W. M. 1982. Impacts of Electric Vehicles on Electric Power Generation, draft final report, CR-1-983, prepared for the Electric Power Research Institute, Palo Alto, California.

Cook, B. 1988. Bureaucratic politics and regulatory reform: the EPA and emissions trading. Westport, CT, Greenwood Press.

Cummins. 1988. Progress report on the Cummins L10 natural gas engine, Soc. of Automotive Eng. Int. Fuels & Lubricants Meeting Exp. Oct. 10-13, Portland, Ore.

Daly, H. 1976. Cited in A. Lovins. 1977. Soft Energy Paths: Toward a Durable Peace p. 68. NY: Harper & Row.

DeLuchi, M. A. 1989. Hydrogen vehicles: an evaluation of fuel storage, performance, safety, environmental impacts, and cost. Int. J. Hydrogen Energy 14: 81-130.

DeLuchi, M. A. 1990. Social costs of petroleum transportation fuels. Research Report, Transportation Research Group, University of California, Davis.

DeLuchi, M. A. 1990. Greenhouse gas emissions and transportation fuels: an update.

DeLuchi, M. A., R. A. Johnston and D. Sperling. 1988. Methanol vs. natural gas vehicles: a comparison of resource supply, performance, emissions, fuel storage, safety, costs, and transitions. SAE 881656.

DeLuchi, M. A., R. A. Johnston and D. Sperling. 1989. Transportation fuels and the greenhouse effect. Transportation Research Record, No. 1175, pp. 33-44. Initial studies performed by the World Resources Inst. and by Acurex for the Cali. Energy Comm. have similar results.

DeLuchi, M. A., D. Sperling and R. A. Johnston. 1987. A Comparative Analysis of Future Transportation Fuels. UCB-ITS-RR-87-13, U.C. Berkeley: Inst. of Trans. Studies, p. 364.

DeLuchi, M. A., Q. Wang and D. Sperling. 1989. Electric vehicles: performance, lifecycle costs, emissions, and recharging requirements. Transportation Research 23A: No. 3, pp. 255-278.

Energy Information Administration (EIA). 1988. Annual Energy Outlook 1987. DOE/EIA-0383(87). Washington, DC.

Energy Information Administration (EIA). 1988. Annual Energy Review 1987. Washington, DC.

Energy Information Administration (EIA). 1989. Annual Energy Outlook 1989. DOE/EIA-0383(89), Washington, DC. January.

Engineering Societies' Commission on Energy. 1981. Synthetic Fuels Summary. Springfield, VA.: Natl. Tech. Inst. Serv. FE-2468-82.

Environmental Protection Agency. 1987. Air Quality Benefits of Alternative Fuels, Report prepared for the Vice President's Task Force on Alternative Fuels. Ann Arbor, Michigan: EPA, Office of Mobile Sources.

Faucett Associates. 1988. Future Natural Gas Supply from Selected World Regions: Projected Quantities and Costs. Bethesda, Maryland.

Fearon, J. G. and M. G. Wolman. 1982. Shale oil: always a bridesmaid? Forty years of estimating costs and prospects. Energy Systems and Policy 6:1, 63-96.

Geller, H. 1985. Ethanol fuel from sugar cane in Brazil. Annu. Rev. Energy 10, 135-164.

Gray, C. and J. Alson. 1985. Moving America to Methanol: A Plan to Replace Oil Imports, Reduce Acid Rain, and Revitalize our Domestic Economy. Ann Arbor Michigan: University of Michigan Press.

Gray, C. and J. Alson. 1989. "The Case for Methanol," Scientific American, November, pp. 108-114.

Gray, D. and G. Tomlinson. 1988. Assessing the Economic Impact of Two-Stage Liquefaction Process Improvements. Springfield, Va.: Natl. Tech. Inf. Serv. SAND88-7147.

Hahn, Robert W. 1989. "Economic Prescriptions for Environmental Problems: How the Patient Followed the Doctor's Orders," Journal of Economic Perspectives 3:2, 95-114.

Hahn, Robert W. and Gordon L. Hester. 1990. "Marketable Permits: Lessons for Theory and Practice," Ecology Law Quarterly 16, 361-406.

Hamilton, W. 1980a. Electric Automobiles. New York: McGraw-Hill.

Hamilton, W. 1988. Electric and Hybrid Vehicles, Technical Background Report for the DOE Flexible and Alternative Fuels Study. Prepared for US Dept. of Energy.

Harris, G., P. Phillips, L. Richards and L. Arnoux. 1984. CNG Market Development Study (Auckland, N.Z.: N.Z. Energy Research and Development Committee, Univ. of Auckland, Pub. P86).

Harris, J. N., A.G. Russell and J.B. Milford. 1988. Air Quality Implications of Methanol Fuel Utilization. SAE 881198.

Harvey, G. 1990. Unpublished analysis for Metropolitan Transportation Commission, Oakland, CA, March 1990.

Hay, N. 1988. Letter to D. Sperling, 6 May 1988.

Hay, N. and P. McArdle. 1989. Regulated utilities in the transportation market: toward a level playing field. In Sperling, ed., Alternative Transportation Fuels: An Environmental and Energy Solution, pp. 231-234. Westport, Conn.: Quorum Books.

Hess, R. 1985. Review of Cost Improvement Literature With Emphasis on Synthetic Fuel Facilities and Chemical Process Industries. Santa Monica, Calif: Rand Corp., N-2273-SFC.

Hira, A. U., J. A. Mulloney and G. J. D'Alessio. 1983. Alcohol fuels from biomass. Environ. Sci. Technol. 17:5.

Horowitz, A. and N. P. Hummon. 1987. Exploring potential electric vehicle utilization: a computer simulation. Transp. Res. 21A:17-26.

Hubbard, H. M. 1989. Photovoltaics today and tomorrow. Science 244:297-304.

ICF, Inc. In National Alcohol Fuel Commission. 1981. Fuel Alcohol, Appendix. Washington, DC: GPO.

Jet Propulsion Lab. 1983. California Methanol Assessment. Pasadena, Calif.: JPL, chap. 4.

Jet Propulsion Lab. 1983. California Methanol Assessment #83-14. Pasadena, Calif.

Kaiser, R. and Graver, C. 1980. Analysis of the infrastructure for recharging electric vehicles. SAE Technical Paper #800112, Society of Automotive Engineers, Warrendale, Pennsylvania).

Kant, F., A. Cohn, A. Cunningham, M. Farmer and W. Herbst. 1974. Feasibility Study of Alternative Fuels for Automotive Transport. Prepared by Exxon Research and Engineering Co. for US EPA, PB-23 5580, 3 vols. Springfield, Va: Natl. Tech. Inf. Serv.

Klass, D. 1987. Energy from biomass and wastes: 1985 update. In Energy from Biomass and Wastes X, ed. D. Klass, pp. 13-113. London: Elsevier Applied Science Publishers.

Kurani, K. 1990. CNG in New Zealand: A Case Study. Manuscript in preparation, based on series of consumer surveys in New Zealand.

Larson, W. 1979. Crop residues: energy production or erosion control. J. Soil and Water Conservation 34:74-76.

Lawrence, M., J. Skolnick and L. Lent. 1986. The Cost of Methanol During Transition. Bethesda, Maryland: J. Faucett & Assoc., 86-322-8/11.

Lumpkin, R. E. 1988. Recent progress in the direct liquefaction of coal. Science 239:873-77.

Lunde, L. G. 1980. Some potential impacts on travel of alternative assumptions on the state of electric vehicle technology. Transport Policy and Decision Making 1:361-377.

Mader, J., J. Brunner and O. M. Bevilacqua. 1988. Electric vehicle commercialization. EVS88-P10.

Mader, G. and O. M. Bevilacqua. 1989. Electric vehicle commercialization. In Alternative Transportation Fuels: An Energy and Environmental Solution, ed. D. Sperling. Westport, Conn.: Quorum Books.

Marfisi, E. P. et al. 1978. The Impact of Electric Passenger Automobiles on Utility System Loads 1985-2000. EPRI EA-623, Electric Power Research Institute, Palo Alto, California, July.

Marland, G. 1982. The impact of synthetic fuels on global carbon dioxide emissions. Carbon Dioxide Review 1982, ed. W. C. Clark, pp. 406-10 Clarendon. Oxford, England: Clarendon.

McNutt, B., J. Dowd and J. Holmes. 1987. The cost of making methanol available to a national market. SAE 872063.

McNutt, B. and E. E. Ecklund. 1986. Is there a government role in methanol market development? SAE 861571.

Mellon Institute. 1980. Maintaining Automotive Mobility Using Fuel Economy and Synthetic Fuel to Compete with OPEC Oil, by Richard Shackson and James Leach (Arlington, Va.: Applied Energy Services).

Mernitz, K. A. 1984. Progress at a Price: Research and Development of Liquid Motor Fuels in the US and Germany, 1913-1933. Ann Arbor, Mich.: Universty Microfilms Int. For other references, see Sperling, D. (1988).

Michael Brandman Associates, Inc. and Richard O'Toole. 1987. Methanol: An Overview of an Alternative Vehicle Fuel, Prepared for Western Oil & Gas Association, Los Angeles, Calif., August.

Mitre Corporation. 1979. "Potential Availability of Wood as a Feedstock for Methanol Production," in US DOE, The Report of the Alcohol Fuels Policy Review: Raw Material Availability Reports (Springfield, Va.: Natl. Tech. Inst. Serv. DOE/ET-0114/1).

Mitre Corporation. 1977. Silvicultural Biomass Farms. Springfield, Va.: Natl. Tech. Inst. Serv.

Murrell, J.D. and G.K. Piotrowski. 1987. Fuel Economy and Emissions of a Toyota T-LCS-M Methanol Prototype Vehicle. SAE 871090.

National Research Council. 1990. Liquid fuel production options for the U.S. (tentative title). Washington, D.C., National Academy Press.

Nichols, R.J. and J. M. Norbeck. 1985. Assessment of emissions from methanol-fueled vehicles: implications for ozone air quality. Presented at Ann. Meet. Air Pollution Control Assoc., 78th, Detroit.

Nussbaum, Barry. 1990. " ," EPA, presented at 2nd Biennial UC Davis Conference on Alternative Transportation Fuels, 11-13 July. Davis, California.

Oak Ridge National Laboratories. 1987. Transportation Energy Data Book: Edition 9. Springfield, Va. NTIS, ORNL-6325.

Organisation for Economic Co-operation and Development. 1990. Economic Instruments for Environmental Protection. Paris, France.

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

Pace Co. Consultants and Engineers. 1981. Comparative Analysis of Coal Gasification and Liquefaction, prepared for Acurex Corp. and California Energy Commission, 650 S. Cherry St., Denver, Colorado 80222.

Pefley, R., R. Caldeira, P. Russell and K. Suresh. 1987. Methanol-Fueled Vehicles for the Federal Government, Presented at the 10th Annual Energy Sources Technology Conference, Dallas, Texas.

Perry, H. and H. Landsberg. 1981. Factors in the Development of a Major U.S. Synthetic Fuels Industry, Ann. Rev. Energy 6, 248.

Pimentel, D. 1981. Biomass energy from crop and forest residues. Science 212:1115.

Probstein, R. and H. Gold. 1978. Water in Synthetic Fuel Production. Cambridge, Mass: MIT Press.

Purdue University. 1981-2. Transportation Energy Futures: Paths of Transition. West Lafayette, Ind. Partial results were published in Brinkley, J. K., Tyner, W. and Mathews, M. Evaluating alternative energy policies. The Energy Journal 4:2, 91-104.

Russell, P. 1980. History of Western Oil Shale. E. Brunswick, NJ: Center for Professional Advancement.

Russell, T. 1987. Quantitative Estimates of Air Quality, SAE 872054.

Santini, D. and J. J. Schiavone. 1988. An Overview of problems to be resolved when meeting the 1991 bus particulate emissions standard. Presented at the 67th Ann. Meet. of the Transportation Res. Board, Jan. 11-14, Washington DC.

Sathaye, J., B. Atkinson and S. Myers. 1989. Promoting alternative transportation fuels: the role of government in New Zealand, Brazil, and Canada. In Alternative Transportation Fuels: An Energy and Environmental Solution, ed. D. Sperling. Westport, Conn.: Quorum/Greenwood. In press.

Schurr, S., J. Darmstadter, H. Perry, W. Ramsay and M. Russell. 1979. Energy in America's Future. Baltimore, Md: Johns Hopkins Univ. Press.

Sierra Research, Inc. 1988. The Feasibility and Costs of More Stringent Mobile Source Emissions Controls. Prepared for the US Cong. Off. of Tech. Assess. Sierra Research, Sacramento, Ca. Jan. 20.

Sierra Research, Inc. 1988. Potential Emissions and Air Quality Effects of Alternative Fuels. SR88-11-02, Sacramento, Calif.

Smith, K. D., D. W. Fong, D. S. Kondoleon and L. S. Sullivan. 1984. Procs., Int. Alcohol Fuel Symp on Alcohol Fuel Tech., Ottawa, Canada, pp. 2-373 to 2-383.

Soil Conservation Service. 1978. National Erosion Inventory Estimate. Washington DC: USDA.

Sperling, D. 1984. An analytical framework for siting and sizing biomass fuel plants. Energy 9:11-12, 1033-40.

Sperling, D. 1987. Brazil, ethanol and the process of system change. Energy 12:11-23.

Sperling, D. 1988. New Transportation Fuels: A Strategic Approach to Technological Change. Berkeley/London: Univ. of Calif. Press. 532 pp.

Sperling, D., ed. 1989. Alternative Transportation Fuels: An Environmental and Energy Solution. Westport, Conn.: Quorum Books/Greenwood Press.

Sperling, D. and M. A. DeLuchi. 1989. Is methanol the transportation fuel of the future? Energy, pp. 469-489.

Sperling, D. and J. Dill. 1988. Unleaded Gasoline in the U.S.: A Successful Model of System Innovation, Transportation Research Record 1175.

Sprowl, J. P. 1985. "Gas Utility Advertising: An Overview of Recent Commission Decisions," The Natural Gas Lawyer's Journal 1, 1:137-144.

Stanford Research Inst. Intl. 1976. Synthetic Liquid Fuels Development: Assessment of Critical Factors. Washington, D.C.: GPO, ERDA 76-129/1.

Stanford Research Inst. Intl. 1978. Alcohol Fuels Production Technologies and Economics. Menlo Park, Calif: SRI Int., EJ-78-C-01-6665.

Stanford Research Inst. Intl. 1978. Mission Analysis for the Federal Fuels from Biomass Program. Springfield, Va.: Natl. Tech. Serv.

Steifel, B. and D. Sperling. 1990. Lead Banking and Trading: A Case Study, Univ. of Calif., Davis, Institute of Transportation Studies.

Synthetic Fuel Corporation. 1985. Comprehensive Strategy Report, Appendices (Washington, D.C.).

Systems Application, Inc. 1983. "Impact of Methanol on Smog: A Preliminary Estimate," SAI Publication No. 83044. Also see SAI, 1984, The Impact of Alcohol Fuels on Urban Air Pollution: Methanol Photochemistry Study (Springfield, Va.: NTIS, DOE/CE/50036-1).

Tanner, R., A. H. Miguel, J. B. de Andrade, J. S. Gaffney and G. E. Streit. 1988. Atmospheric chemistry of aldehydes: enhanced peroxyacetyl nitrate formation from ethanol-fueled vehicular emissions. Environ. Sci. and Tech. 22:1026-34.

Taylor, J. J. 1989. Improved and safer nuclear power. Science 244:318-325.

Tesche, T.W. 1984. Photochemical Dispersion Modeling: Review of Model Concepts and Applications Studies, Environment International 9:465-489.

Three-Agency Methanol Task Force. 1986. Report, prepared jointly by California Air Resources Board, California Energy Commission, and South Coast Air Quality Management District, Sacramento, California.

Townsend, Dan. 1990. "   ," ARCO, presented at 2nd Biennial UC Davis Conference on Alternative Transportation Fuels, 11-13 July. Davis, California.

Trindade, S. and A. Vieira de Carvalho. 1989. Transportation fuels policy issues and options: the case of ethanol fuels in Brazil. In D. Sperling, ed., Alternative Transportation Fuels: An Environmental and Energy Solution, pp. 163-186. Westport, Conn.: Quorum Books.

Turrentine, T. 1990. Memorandum, August 23. Study being conducted by UC Institute of Transportation Studies for California Energy Commission.

Ullman, T. L. and C. T. Hare. 1982. Emission Characterization of Spark-Ignited, Heavy-Duty, Direct-Injected Methanol Engine. EPA 460/3-82-003. Ann Arbor, Mich: US Environ. Protect. Agency.

U.S. Department of Energy. 1980. Synthetic Fuels and the Environment. Washington, DC: DOE, DOE/EV-0087.

U.S. Department of Energy. 1987. Energy Security (Washington, D.C.: DOE,

DOE/S-0057).

U.S. Department of Energy. 1988. Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Washington, DC.

U.S. Energy Information Administration. 1987. Annual Energy Outlook 1986, NTIS, Springfield, Virginia.

U.S. Office of Technology Assessment. 1980. Energy from Biological Processes. Washington, DC: GPO, Vol. II, p.173.

U.S. Office of Technology Assessment. 1980. An Assessment of Oil Shale Technology. Washington DC: GPO.

U.S. Office of Technology Assessment. 1982. Alternative Energy Futures, Part I: The Future of Liqunified Natural Gas Imports Washington, D.C.: GPO. U.S. Congress.

U.S. Office of Technology Assessment, Catch Our Breath: Next Steps for Reducing Urban Ozone. OTA-O-412 (Washington, DC: Government Printing Office, July 1989).

U.S. Bureau of Census. 1907. Census of Manufactures: 1905, Automobiles and Bicycles and Tricycles. Bull. 66, p. 19. Washington DC: GPO.

U.S. Bureau of Mines, cited in Krammer, A. 1981. An attempt at transition: the Bureau of Mines synthetic fuel project at Louisiana, Missouri. In Energy Transitions: Long Term Perspectives, ed. L. J. Perlman, A. W. Giebelhaus, M. D. Yokell, p. 65. Boulder, Colo: Westview.

U.S. Environmental Protection Agency, Off. Air Quality Planning and Standards. 1985. Compilation of Air Pollutant Emission Factors, Vol. 1, Stationary Sources. AP-42, 4th ed. Research Triangle Park, N.C.

US Synthetic Fuels Corp. 1985. Comprehensive Strategy Report, p. H-10. Washington, DC.

Wang, Q., M. A. DeLuchi and D. Sperling. 1989. Emissions from electric vehicles. Transportation Research Group, University of California, Davis.

Webb, R. F., C. B. Moyer and M. D. Jackson. 1989. "Methanol and Compressed Natural Gas Distribution and Costs," in D. Sperling, ed., 1989, Transportation, Energy, and the Environemnt (tentative title) (Greenwood Press).

Wolk, R. and N. Holt. 1988. The Environmental Performance of Integrated Gasification Combined Cycle (IGCC) Systems. Palo Alto, Calif: Electr. Power Res. Inst.

Wright, J. D. 1988. Ethanol from biomass by enzymatic hydrolysis. Chemical Engineering Progress, Aug. 62-74.

APPENDIX

Table A-1: Cost Parameters and Vehicle Attributes Used in Cost Analysis

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

Note: Station costs for CNG were calculated independently, taking into account 15 different cost and operations factors. For details, see Deluchi et al., 1988.