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**The University of California
Transportation Center**

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University of California at Davis

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IS METHANOL THE TRANSPORTATION FUEL OF THE FUTURE?

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Abstract—A solution to growing petroleum imports and continuing urban air-pollution problems is the use of clean-burning nonpetroleum fuels in motor vehicles. Methanol is widely viewed as the most attractive candidate for transportation fuel of the future. We examine how methanol gained this preeminent position by analyzing the historical interplay of economic interests, technical judgements, and ideology and then show that the preference for methanol is not the only conclusion to be drawn from the available evidence. An equally good choice may be natural gas.

INTRODUCTION

Because the transportation sector, unlike other energy-consuming sectors, has remained almost completely dependent on petroleum fuels, transportation has gradually required an increased share of the petroleum market. In the U.S., the share used for transportation increased from 53% of petroleum consumption in 1977 to 63% in 1987.¹ 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 be shifted to other energy sources. But to what fuel or fuels will it be switched?

According to the President of the United States, the U.S. Environmental Protection Agency, Ford Motor Co., General Motors, Toyota, the California Energy Commission, and other influential organizations and individuals, the transportation fuel of the future in the U.S. will be methanol.²⁻⁴ This belief that methanol will replace petroleum as the dominant transportation fuel has several explanations: methanol can be made from a large number of materials, many of them available in abundance in the U.S.; it can be made less expensively than almost all other options; it burns more cleanly than petroleum fuels; and, because it is similar to gasoline and diesel fuel, it does not require costly changes in motor vehicles and the fuel-distribution system.

We examine this growing support for methanol in a historical context with the objective of analyzing whether methanol should be the primary transportation fuel of the future. In the analysis, we will compare methanol with compressed natural gas (CNG). We conclude that methanol is not a clearly superior option for replacing petroleum fuels and that until compelling new evidence is provided, public policy should promote a diversity of fuel alternatives.

We address highway applications of alternative fuels and focus on the near- and medium-term future, roughly the next 30 yr. (Barring unforeseen changes, our findings also hold for a longer time frame since methanol and CNG come from the same resources and their production and delivery costs are fairly well known and unlikely to shift relative to each other. Of course, other energy options may become more attractive relative to methanol and CNG.)

ASCENDANCE OF METHANOL POPULARITY

The growing enthusiasm for 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 (NG) was virtually ignored since it was considered to

be even scarcer than petroleum. Curtailments of NG deliveries to customers in accordance with the U.S. government's allocation scheme during the winter of 1976–1977 served to reinforce the notion that NG was a scarce resource that should be reserved for winter heating needs.⁵

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 because it is far too expensive, although this assessment is not endorsed by the agricultural community, who see ethanol as an answer to excess production and low prices of farm goods.

At a Fall 1973 conference on Project Independence sponsored by the U.S. Department of Interior, oil and automotive industry representatives voiced sharp opposition to an initial proposal that national energy policy emphasize methanol over synthetic gasoline fuels.⁶ In a major 1974 energy study, methanol was rated below oil shale and other coal–liquid options because it would have required major changes in motor vehicles and pipeline and fuel distribution systems and would not have supported existing investments in oil refineries.⁷ SRI International prepared a 1976 report for the predecessor agency of DOE that rated synthetic gasoline a far more promising alternative than methanol. They argued that oil companies would be extremely unlikely to adopt methanol because synthetic crude could simply be added to the natural crudes still available to refineries, serving the needs of oil companies wishing to maintain the usefulness of present investments and insulating the consumer from change.⁸

The authors of virtually all of 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.^{7–9} Public and private R&D was heavily weighted toward direct liquefaction of coal.¹⁰ Indeed, as late as 1981, only 5 of the 31 most advanced synthetic fuels projects in the U.S. were intended to produce methanol as a primary product and, of these, several were intended to co-produce high-Btu, pipeline-quality substitute NG.¹¹ Two additional projects were designed to manufacture methanol and to convert the methanol into synthetic gasoline in order to make the fuel compatible with the existing motor-vehicle and fuel-distribution systems, thus essentially downgrading the methanol into a lower-octane, higher-polluting fuel at additional cost.

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 Corp. began to indicate that the cost of producing refined shale oil and petroleum-like liquids from coal would be \$60–\$100 per oil-equivalent barrel in first generation plants.¹² Later-generation plants were projected to have much lower costs.

The air-pollution benefits derived from methanol first gained attention, although as a secondary issue, in the early 1980s. A study prepared for the California Energy Commission (CEC)¹³ 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. The authors of this landmark study concluded that, given the State's high priority for reducing air pollution, the most attractive use of coal, then thought to be the most promising future source of portable fuel, was to convert it to methanol for the transportation and electric utility sectors. This study was important because the CEC has proven to be the most influential advocate of methanol through the 1980s, their major justification being the air-quality argument.^{14,15}

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 NG 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 much more cheaply and cleanly from NG 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 methanol transportation fuels represented the most significant opportunity for improving urban air quality.¹⁶ At that time, ozone air-quality standards were being violated in virtually all major metropolitan areas, affecting over 80 million people.

From this historical review of informed opinion, an important question emerges: if NG is the preferred feedstock for making methanol, then shouldn't we consider the option of using NG directly in compressed or liquefied form? Analysts and decisionmakers remark that gaseous fuels are too different from liquid fuels, requiring too many costly changes in motor vehicles and the fuel-distribution system to be widely used;¹⁷⁻²⁰ these are exactly the same argument that were used against methanol 10 yr earlier. Experience indicates that these arguments should be carefully scrutinized. Indeed, other countries, especially Canada and New Zealand, have deliberately chosen CNG over methanol.²

Policy inertia may be a major factor favoring methanol. This suggests the need for a careful reconsideration of methanol's perceived superiority. The salient criteria to consider in an evaluation of new transportation fuels, which will be used in the following comparative analysis of methanol and CNG, are market costs, air-quality impacts, national security impacts, start-up barriers, and vehicle performance attributes.

NATURAL GAS RESERVES

First, as background, we note that worldwide proven NG reserves are increasing. These reserves will surpass the proven petroleum reserves in energy content by 1990 and the gap is expected to widen further in the foreseeable future. A significant proportion of these NG reserves are in the U.S. and its two neighboring countries (see Table 1).

Proven gas reserves in the U.S. were over 30% greater (in energy content) than proven oil reserves in the 1980s. At present rates of consumption, the U.S. has enough economically recoverable conventional reserves of NG to last almost 60 yr and, possibly, as much as 120 yr if economically-recoverable unconventional reserves are included. If the transportation sector

Table 1. Natural gas reserves in 1985 in TCF†, adapted from Refs. 23-27.

Country	Proven Conventional Reserves‡	Undiscovered Recoverable Conventional Reserves‡	Potentially Recoverable Unconventional Reserves§	Total Recoverable Reserves	Total Recoverable Reserves/Annual Production¶
USA	200	775	130-1145	1100-2126	62-121
Canada	100	300	NA [#]	---	36
Mexico	77	200	NA [#]	---	56
World	3400	7600	NA [#]	---	120

†One TCF = 10^{12} SCF = 1 quadrillion Btu; one TCF per year = 0.5 million oil-equivalent barrels per day.

‡Conventional gas comes from onshore and offshore proven and inferred reserves. Recoverable reserves are those estimated to be recoverable at current or near-term prices and with current technology.

§Unconventional reserves include low-flow or tight gas-bearing sands, coal seams, shales, geopressurized brines, and methane hydrates. Gas recovery depends on the state of technology and gas prices; lower values reflect current exploration and development technology and low gas prices (below about \$4.50 per million Btu); higher values reflect advanced technology and higher gas prices.

¶Based on mid-1980s production.

#NA = not available; treated as zero in calculations of the R/P ratios in the last column.

were to switch 100% to NG, then the gas would be used up about twice as fast; somewhat faster if the gas is used for methanol, somewhat slower if used directly as CNG or LNG. The reason it would be exhausted faster as methanol is because methanol production is more resource-intensive than CNG: only about 57% of the original NG energy is available to the motorist, compared to 84% for CNG (taking into account losses in extraction, transport, and compression).²² Thus it is clear the U.S. could sustain an aggressive CNG initiative for a prolonged period; for how long is still uncertain.

The worldwide gas supply situation is even more promising. As a result, there will be little economic incentive for the U.S. to use coal or oil shale as a transportation energy feedstock for many years, perhaps 70 or more. If at that time coal were to become an important source of transportation fuel, the coal could be used to manufacture a substitute NG just as easily and for the same or lower cost as methanol from coal.

COSTS

According to most scenarios, the full cost of owning and operating a CNG automobile or truck will be slightly less than for a comparable methanol vehicle. A comparative cost analysis is summarized below. The analysis is conducted from the perspective of the owner of the motor vehicle. The following assumptions are made: the automobiles are optimized for neat (100%) methanol and CNG, respectively; the fuels are produced and used on a large scale; refueling station costs are fully incorporated; and costs are calculated on a per-km 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 Ref. 22.

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 (Table 2) for

Table 2. Cost parameters and vehicle attributes used in cost analysis.

Gasoline	Methanol	CNG	Costs and Other Parameters
0.95	—	—	Retail price of gasoline, \$/gallon, excluding taxes
—	0.50-0.80	—	Methanol price, \$/gallon, plantgate or at the port if imported
—	0.14-0.23	—	Domestic transportation cost and retail mark-up, \$/gallon
—	—	5-8	Cost of gas to station, \$/mmBtu
—	—	2.3-4.5	Station mark-up, \$/mmBtu [†]
0.20	0.10	1.60	Fuel taxes, \$/gallon for liquids, \$/mmBtu for natural gas
35	—	—	Lifetime vehicle fuel efficiency, mpg
—	+10-20	+10-25	Thermal efficiency relative to a gasoline-powered car, %
9.5	9.5	10.2-10.3	Vehicle price, \$10 ³ (1985)
213	213	213-262	Life of vehicle, 10 ³ km
1150	1150	1197	Weight of vehicle, kg
9	9	9	Real interest rate for a car loan, %
400	400	300-400	Maintenance costs, \$/year

[†]Station costs for CNG were calculated independently, taking into account 15 different cost and operations factors. For details, see Refs. 21 & 22.

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 single-fuel CNG and methanol vehicles are compared, has the following attributes: 35 mpg, 1150 kg, 420 km range, and a vehicle life of 213,000 km at 16,000 km per year. It is assumed that a methanol car costs the same as a gasoline car and that a dedicated single-fuel CNG car costs \$700–\$800 more (for fuel-storage cylinders). The retail price of gasoline, including taxes, is assumed to be \$1.15 per gal, compared to an estimated \$0.74–\$1.13 per gal for methanol and \$8.90–\$14.10 per thousand Btu for CNG. The cost parameters and vehicle attributes are listed in Table 2 and fully documented in Refs. 21 and 22.

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, because we are assuming optimized single-fuel vehicles, similar power. They are assumed to be 10–20% and 10–25%, respectively, more fuel efficient than the baseline gasoline car.

The cost of owning and operating these methanol and CNG cars, relative to those of a gasoline-powered vehicle, based on the foregoing assumptions, are as follows: methanol car, +0.06 to +1.42 cents per km; CNG car, –1.86 to +2.60 cents per km. The analysis showed that the lifecycle cost of a CNG auto tends to be less than for a methanol vehicle, although not for all assumed values of the cost parameters. The ranges of the results correspond to uncertainties in cost parameters and vehicle attributes, as presented in Table 2. The lower lifecycle costs for CNG are attributable to the lower fuel and maintenance costs and potentially longer engine life, which more than offset the extra cost of CNG containers (in all but the higher-cost case).

The next criteria are non-market costs such as national security and air quality. These costs are not included in the private or consumer costs calculated previously. These non-market costs are important because they are the primary justification for government intervention to support new fuels.

NATIONAL ENERGY SECURITY

The security risk associated with dependence on foreign gas for methanol or CNG is that once the very low-cost foreign gas is used up, which could occur fairly quickly (depending on the rents sought by foreign governments), the gas remaining is mostly controlled by OPEC countries and the U.S.S.R.²⁸ This OPEC-controlled gas may be subject to the same price and supply disruptions as petroleum.

Neither methanol nor CNG will provide significant energy security benefits. However, because methanol and CNG are made from the same feedstocks, with CNG requiring similar or less feedstock to provide the same amount of usable energy, CNG would use similar or less feedstock from any particular geographical source. It follows that CNG is preferred to methanol from an energy-security perspective.

AIR QUALITY

Perhaps the most important externality of vehicular fuel use is air pollution. Motor vehicles are the principal cause of urban air pollution, accounting for 57% of nitrogen oxide (NO_x) emissions, 44% of reactive hydrocarbons, and 75% of carbon monoxide (CO) in California.²⁹ As indicated earlier, the continuing failure of most metropolitan areas in the U.S. to meet ambient ozone standards (ozone is formed from reactions involving NO_x and hydrocarbons) has been offered as a justification for introducing methanol. While it seems certain that some

air-quality benefits would occur with either methanol or CNG, data and modelling results are not in agreement on how large those benefits would be, especially for ozone.³⁰⁻³²

For a host of reasons it is difficult to specify accurately the differences in emissions and air-quality impacts between different fuels, especially concerning ozone. First, emission rates are not simply predetermined by combustion technology, but vary for a given technology (and fuel) according to tradeoffs between emissions, costs, performance, and driveability. A particular fuel may be potentially less polluting than gasoline, but the constraints of automotive design may result in these potential benefits not being realized. Under typical circumstances, engines are configured to emit the maximum allowed by statute in order to enhance other attributes, such as cost (by reducing the cost of pollution control equipment) or engine power. 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 (because reduction catalysts do not work well with excess air) and CO and HC emissions and engine power would be lower than for an engine operating near stoichiometric ratios, which is used for most of today's gasoline engines. Third, a distinction must be made between optimized single-fuel engines and retrofitted or bi-fuel engines; we focus on optimized single-fuel engines as the desirable ultimate technology because they are superior in emissions, costs, and performance.

Fourth, exact fuel composition must be specified since some methanol emission and modelling data are based on a fuel consisting of 100% methanol, while others are based on a mix of 10 or 15% gasoline with methanol (which results in much more pollution). Evaluation becomes even more complicated for multifuel methanol/gasoline engines since they will be operated on varying blends of methanol and gasoline. Fifth, the ozone-formation process is highly complex and is sensitive to meteorological and topographic conditions; even the most sophisticated photochemical air quality models have error margins of 30% or more.³³

Sixth, no reliable estimates have been made of lifecycle formaldehyde emissions, a critical consideration because formaldehyde is a product of methanol combustion and a highly reactive hydrocarbon. Seventh, only in the Los Angeles area have 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. Eighth, emission data for dedicated single-fuel CNG engines are much sparser and less accurate than for methanol engines; moreover, no dispersion or photochemical modelling of CNG emissions has ever been conducted.

This list could continue. The point is that emission and air-quality data for CNG and methanol are highly uncertain and should be interpreted with care. Nevertheless, current knowledge suggests that the use of both CNG and methanol would probably lead to lower ozone levels than gasoline use (the authors of one study argue that methanol may increase ozone³⁴). CNG may be slightly better than methanol because methane, the principal organic pollutant from CNG vehicles, is 100 times less reactive than unburned methanol, the principal organic pollutant from methanol vehicles. In addition, the secondary organic emissions may be less reactive than formaldehyde, the secondary organic emissions of methanol vehicles.

Compared to gasoline, CNG will emit much less carbon monoxide, which is a major winter-time problem in most cities, and similar or possibly higher levels of NO_x , while methanol will emit less carbon monoxide (but more than would CNG) and, depending on the air/fuel ratio, possibly less NO_x .³⁵

Again, because of the lack of credible ozone modelling, the effects of methanol and CNG vis-a-vis gasoline and vis-a-vis each other are uncertain. Some of the pitfalls of this type of air-quality analysis are apparent from recent efforts to study the effects of methanol use. In the mid-1980s, the authors of several studies concluded that the use of methanol would reduce peak ozone concentrations in urban areas by 10-30%.³⁶⁻³⁸ These conclusions depended strongly, however, on several assumptions. For example, the authors of each study assumed a different volume of gasoline blended with the methanol (from 0 to 15%), and all assumed that NO_x emission levels would remain unchanged relative to gasoline and that the reactivity of methanol pollutants would be the same in multi-day smog episodes as in single-day episodes.

A careful assessment based on more recent evidence^{22,32,34} suggests that the substitution of

methanol (M85) for gasoline in all motor vehicles may result in a *maximum* reduction in peak ozone levels of 0–15%. The most recent and sophisticated modeling effort, conducted at Carnegie-Mellon University, found that in the Los Angeles area, the use of M85 methanol in all mobile sources except motorcycles and planes would result in only a 6% reduction in peak ozone levels.³¹ If M100 were used, the reduction would be 13%; if M100 were used, but assuming higher formaldehyde levels in the exhaust emissions (55 mg/mile instead of 15 mg/mile), the reduction would be 7%; and if M100 was used in advanced technology engines, a 15% reduction results (9% if 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, Harris et al³² found that ozone would be reduced 21%. In practice, even these reductions would not occur for several decades because of the slow turnover rate of vehicles, the initial use of multifuel cars, and the presumably low initial market penetration rate.

In summary, while methanol provides the potential for achieving a part of the maximum ozone reduction achievable through changes in the transport sector, the magnitude of these potential improvements is modest; moreover, these potential reductions with methanol require the use of M100 and very low formaldehyde emissions, two conditions that may not be attainable.

In contrast to methanol, very little research has been conducted on natural gas vehicles and none on the ozone impacts of CNG emissions.³⁵ Published assessments of emissions from CNG vehicles³⁹ have often been overstated because they were based on retrofitted dual-fuel cars and not on optimized single-fuel vehicles. Such assessments offer little help in evaluating the relative attractiveness of different energy paths. What little data do exist, as summarized above, suggest that there is no scientific basis for claiming that either fuel is superior to the other from an air quality perspective.

A related concern is emission of greenhouse gases. CNG is slightly superior to methanol. A full systems analysis of carbon dioxide and trace greenhouse gases emitted during production, transport, and combustion of both fuels indicates the following.⁴⁰ If the feedstock is natural gas, methanol generates about the same quantity of CO₂-equivalent greenhouse gases as gasoline, while CNG generates about 15% less. If the feedstock is coal, both fuels produce about 60% more greenhouse gases; if the feedstock is biomass, the net production is close to zero for both fuels.

START-UP BARRIERS

Until now, this paper assessed the relative attractiveness of vehicles optimized for a particular fuel because such an evaluation is important for selecting which fuel will ultimately be superior. But the ultimately superior option may never be reached because of start-up barriers; start-up barriers are therefore considered here as one more factor to consider in the evaluation. The principal start-up barriers, listed in Table 3, are the cost of establishing new fuel stations and the higher cost and inferior attributes of vehicles that are required to operate on both gasoline and the new fuel.

Table 3. Start-up barriers for methanol and CNG multifuel vehicles relative to gasoline; based on Refs. 17, 21, 22, and 41.

Parameter	Methanol	CNG
Refueling station	\$40,000	\$300,000 or more
Multifuel vehicle		
Initial cost	+\$0 to 200	+\$1600 (retrofit) + \$750 (factory)
Operating cost [†]	the same or more	less
Lifecycle cost [†]	the same or more	less or more
Performance [†]	the same or better	worse
Luggage space	the same	less
Cold start [†]	worse	the same

[†]For operation on the non-gasoline fuel.

Multifuel vehicles are addressed in Table 3 because they are the vehicles generally considered in analyzing the initial period of a fuel transition. The qualitative and quantitative judgements in the table are based on the assumption that large numbers of vehicles are produced and large volumes of fuel are sold. In general, the introduction of methanol faces smaller start-up barriers than CNG. For limited vehicle and fuel sales, methanol would tend to have an even larger advantage.

One major barrier is the absence of retail outlets for each fuel. With minor modifications, a retail gasoline outlet can accommodate methanol; the cost is somewhere between \$5000 and \$60,000 per station, depending upon whether a new underground tank is needed. A new tank is needed if the existing tank is corroded (in which case it should be replaced anyway), if new government rules require the tank to have double walls, or if the tank is made of fiberglass that is incompatible with methanol (as are about 10% of the tanks in the U.S.). The cost for a CNG station is much greater—up to \$250,000 just for a compressor and over \$300,000 per station.²² In some cases the CNG refueling facilities could be established on the site of gasoline stations, as long as they are located near a high-pressure natural gas pipeline.

The start-up constraints related to the vehicle are also substantial for CNG. The problems are that (i) CNG, a gas, is much more different from gasoline than is methanol, a liquid; and (ii) during the initial stages of a transition, it will be of critical importance that multifuel vehicles be used to reduce the disadvantage of limited availability of fuel at retail outlets.

Multifuel methanol/gasoline vehicles have the advantage of involving the use of a single fuel system and, if manufactured in large quantities, of costing just a little more than a gasoline vehicle. Also, from the vehicle operator's perspective, a methanol multifuel vehicle would be indistinguishable from a gasoline vehicle. The fuel, whether methanol or gasoline, would be put in the same tank, and the driver would not need to do anything different. The only difference to the driver would be slightly greater power (maximum of +10%) and a shorter driving range per tankful if mostly methanol was being burned. This multifuel vehicle would be only somewhat compromised from an optimized for-methanol vehicle.

A bi-fuel CNG/gasoline vehicle, on the other hand, would be far inferior to a dedicated CNG, gasoline, or methanol vehicle. The bi-fuel vehicle would have less power, redundant fuel tanks and fuel delivery systems, one for natural gas and one for gasoline, and would therefore cost considerably more than a gasoline vehicle; the cost would be \$1600 or more extra for an aftermarket retrofit or about \$750 extra if made in the factory, according to industry estimates. It would also have much less trunk space because of the extra fuel tank. A transition CNG vehicle would therefore be acceptable only to those consumers who accumulated very high mileage (allowing them to pay off the higher initial capital cost with the lower fuel cost), did not require much trunk space, and did not demand high performance.

This analysis of start-up costs clearly indicates methanol's superiority. Several caveats are in order, however. If transition vehicles operate on both gasoline and the new fuel, which indeed would be the case unless government were to mandate that all fuel stations, or a percentage of them supply the new fuel, as was the case with unleaded gasoline in 1975,⁴² then two drawbacks appear, both of which work against methanol. First, methanol's air quality benefits will be negligible, even less than for optimized single-fuel vehicles, because chemical reactions take place when methanol and gasoline are mixed, resulting in higher levels of evaporative hydrocarbon emissions, and because catalyst performance, even with redesigned catalysts, would probably be compromised when obligated to handle both fuels. There is no evaporative emission problem with a bi-fuel CNG/gasoline vehicle because NG is mostly methane (CH_4), which is essentially non-reactive.

Second, it is unclear how often methanol/gasoline vehicles would be fuelled with methanol since methanol is expected to be more costly (per vehicle mile) than gasoline into the foreseeable future. CNG, on the other hand, will be less expensive than gasoline. The price ratio in Canada and New Zealand of CNG to gasoline is roughly 0.5–0.8 and is likely to be similar in the U.S.⁴³ Thus, consumers will have a strong incentive to use CNG on a regular basis, once they make the initial vehicle purchase or retrofit. Surveys in New Zealand and Canada indicate that bi-fuel CNG vehicles operate on CNG about 75–90% of the time, and that the rate would be even higher, especially in Canada, if fuel were more readily

available.^{44,45} Thus, a small number of bi-fuel CNG vehicles would use as much CNG fuel as would a much larger number of bi-fuel methanol vehicles use methanol, and may therefore generate proportionately greater air quality benefits per vehicle.

Third, as will be discussed later, the methanol start-up advantages, while apparently significant, tend to be transitory when scrutinized in the context of actual transition conditions.

WHICH VEHICLE TECHNOLOGY IS MORE DESIRABLE?

A fair comparison of the relative attractiveness of CNG and methanol vehicles is difficult because the evaluation is sensitive to whether the vehicle is optimized for the new fuel, whether it operates on multiple fuels, and a determination of comparability. Unfortunately, as we have documented elsewhere,²² most evaluations have been sloppy in making these distinctions in a way that is systematically biased against CNG.

The bias comes from the fact that CNG technology is less advanced than methanol technology and that multifuel CNG technology, as discussed in the previous section, is more inferior to single-fuel CNG technology than is multifuel methanol technology relative to single-fuel methanol technology. Current CNG vehicles (about 400,000 worldwide in 1988) are retrofitted gasoline vehicles. They were designed and built for gasoline, are burdened by redundant fuel systems, and use carbureted fuel control and heavy steel tanks for fuel storage; they are far inferior to single-fuel vehicles designed for CNG and equipped with modern lightweight composite-material storage cylinders and electronic fuel control. CNG vehicle and storage technology has languished because the auto manufacturing industry has not taken much interest in CNG.

Methanol vehicle technology is also primitive, but it has received more attention from the auto industry and is further advanced than CNG vehicle technology; it benefits from about 15 yr of intermittent research on alcohol vehicles by Ford and Volkswagen, lesser efforts by other manufacturers, and also from the experience of producing over 3 million ethanol-powered cars in Brazil.

But even if both technologies had received equal attention, gaseous fuel technology would still be less advanced than liquid-fuel technology, for the simple fact that virtually all motor vehicles have been designed to operate on liquid fuels for over a century.

While a bi-fuel methanol/gasoline vehicle has important advantages over a bi-fuel gas/gasoline vehicle, an optimized single-fuel CNG vehicle would compete well against an optimized methanol vehicle. An optimized CNG vehicle would have the disadvantage of about 60% shorter driving range for a comparable fuel tank volume and, depending on differences in such parameters as the compression and air/fuel ratio, about 0-10% less power than a comparable methanol vehicle. The range can be extended by using more or larger fuel tanks or by increasing the pressure in the tanks, but more tanks means less interior space and more weight, while higher pressure incurs greater compression and fuel tank costs.

On the other hand, optimized CNG vehicles would have similar or lower emissions, similar or lower lifecycle costs, and there would be no problems with cold starts. The problem of cold starts with methanol (the inherent difficulty in starting in temperatures less than about 5°C) can be mitigated by various techniques, including automatic heating of fuel lines, small gasoline tanks to be used only for starting, and fuel dissociation, but it is uncertain whether methanol vehicles (using either M85 or M100) will ever be fully satisfactory in cold climates, where about half the U.S. and virtually all the Canadian population lives.⁴⁶

In summary, past comparisons of CNG and methanol have often been biased against CNG because they used retrofitted bi-fuel CNG autos as the basis of comparison. These primitive technologies are not representative of what is likely to be commercialized in the future. Future CNG vehicles will be far superior to the retrofitted vehicles now operating in New Zealand, North America and Italy. The major disadvantage of single-fuel CNG vehicles is their limited range, although there are no consumer choice studies that specify the importance of this disadvantage,^{47,48} while the disadvantages of methanol vehicles are cold-start difficulties and, relative to CNG, perhaps slightly higher lifecycle costs.

DIESEL ENGINES

We have addressed only spark-ignition engines up to this point, but CNG and methanol may also be used in compression-ignition (diesel) engines. CNG yields roughly the same advantages and disadvantages relative to methanol in both types of engines: similar improvements in emissions, lower cost, somewhat less power, and redundant fuel systems. The important difference is that both methanol and CNG provide major emissions improvements, dramatically reducing particulate and sulfur oxide emissions. The use of methanol will also significantly reduce nitrogen oxide emissions.³⁵

From an energy transition perspective, diesel vehicles are much less important than spark ignition vehicles. Diesel urban transit buses will probably be the first market penetrated by methanol and/or CNG, because of recently promulgated emission regulations that take effect in 1991, but this market is dispersed and tiny, a total of only about 30,000 barrels per day in the U.S.⁴⁹ Further penetration is likely to lag behind penetration of the gasoline market, because diesel engines do not turn over as quickly, CNG and methanol are more economically attractive relative to gasoline than to diesel fuel, and diesel trucks tend to travel over larger areas and therefore are more sensitive to limited fuel availability. In the U.S. the entire diesel fuel market is only about one-fifth the size of the gasoline market, although it is expected to increase in both absolute and relative size.

SO WHY NO INTEREST IN CNG?

If CNG is as attractive as methanol, why has it received so little attention in the U.S.? The probable explanation is a negative perception of CNG based in part on incomplete knowledge. This has a direct parallel in the professional community's attitude toward methanol during much of the 1970s. In that era, analysts and researchers rejected methanol as being too difficult to implement, requiring new fuel stations, pipelines, and new or modified vehicles. So it is with CNG in the 1980s. In the early 1980s, resistance to methanol by the auto manufacturers and others weakened when it became clear that methanol was the cheapest nonpetroleum liquid fuel option readily available. Key actors began to recognize that under some conditions, the barriers would not be that significant. Indeed, in Brazil, with the full involvement of Ford, General Motors, Volkswagen and others, over 90% of new cars had been operating exclusively on alcohol since 1983.

It is clear that analysts and researchers were deceived by the apparent start-up costs of methanol into making a negative overall assessment, despite methanol's longer-term benefits. CNG is now subjected to the same criticisms. Though the start-up barriers may be more substantial, the long-term potential may be greater. History suggests that we should give CNG a more thorough reexamination.

A second explanation for methanol's prominence is an understandable resistance to CNG by oil marketers. Gasoline and diesel fuel distributors would lose control of fuel marketing if natural gas, currently distributed by a network of pipeline-transmission companies, were to replace methanol, a liquid that eventually could be fully integrated into the petroleum-distribution system. Also, in the short term, methanol (unlike CNG), can be blended in small quantities into gasoline, further enhancing the relative attractiveness of methanol to the oil industry.

Third, despite forecasts that real natural gas prices will rise and therefore stimulate more exploration that will result in discoveries keeping pace with production and demand, there is still some skepticism about the price elasticity of the gas supply. This skepticism is rooted in the long history of restrictive regulation, which began to be phased out in 1978. Some industry and government officials are not convinced that sufficient gas will be domestically available at competitive prices for enough time to warrant developing the transportation fuels market.

Fourth, NG companies have not promoted CNG. This is a root cause of general lack of interest in CNG. If gas utilities, who are the local suppliers of NG in the U.S. and would be the principal or sole marketer of gas to motorists, are not interested, then others understandably will not be willing to invest the time and resources necessary to initiate this new fuel.

The chief economist of the American Gas Association argues that state regulatory bodies have built a web of rules that effectively removed the incentive for gas utilities to market CNG to the transportation market.⁴³ These regulations were created many years ago to protect the captive users from monopolistic pricing and supply cut-offs. In the 1970s these regulations resulted in moratoria on new hook-ups and bans on most types of advertizing and marketing. These rules are being phased out in the 1980s, but significant impediments to gas marketing remain. In a 1982 American Gas Association survey of gas utilities 78% said that their state public utility commissions still imposed restrictions on natural gas advertizing; although the survey has not been repeated, it is believed that similar restrictions are still common.^{43,50} Hay and McArdle⁴³ give the example that in many states only advertizing that includes an energy conservation message can be included in the utility's cost of service. They point out that promotional rates for development of new markets and applications remain a regulated matter for utilities, though not for their competition.

In practice, as a byproduct of continuing natural gas deregulation in the 1980s, impediments to the entry of gas utilities into the transportation fuels market have been reduced. Regulatory impediments may be more perceived than real. Nonetheless, many years of restrictive regulation have left gas utilities with little expertise in marketing and strategic planning and an inertia that is hard to redirect. The fact is, natural gas utilities have not played a leadership role in exploring and developing the CNG option.

Overall, then, CNG has had few proponents, and therefore no constituency, to help it overcome the lack of imagination which thwarts its introduction.† This lack of a constituency may be reason to discard CNG, since any new fuel will need forceful support if it is to move forward—as illustrated by the farm lobby's success in introducing ethanol fuel, an economically inferior option. We argue, however, that because the merits of CNG are potentially large, concerned organizations, including state and federal governments, should (i) support further analysis and development of CNG technology so that decisions about its merit and desirability can be made on a more informed basis, and (ii) impose changes in the regulation of natural gas utilities and encourage those utilities to be more aggressive in promoting CNG.

WHEN IS METHANOL PREFERRED?

Relative to CNG, methanol is not superior economically or environmentally, does not offer more energy security and, in an optimized vehicle, will not necessarily be more attractive to consumers. The only clear advantage of methanol relative to CNG is in terms of initial start-up barriers.

This advantage will not be an important factor in most situations, however. Consider the scenario of a rapid transition away from petroleum, presumably under crisis conditions. In this case, the network of fuel outlets for the new fuel would be expanded rapidly enough that most buyers would be able to opt for the single-fuel vehicle fairly soon after the transition was initiated. As a result, multifuel vehicles would be a short-lived phenomenon, and the advantage of methanol in a multifuel configuration would be fairly minimal. The advantage of lower capital costs for establishing methanol fuel outlets would also be minor in this scenario. The reason is that initiating a CNG energy system would cost the same or less as a methanol system in the sense that the higher fuel station costs of CNG are incorporated in the retail fuel price, which is lower for CNG than methanol.

Thus higher station capital costs are only an important issue if fuel consumption is low, resulting in fuel station owners not earning a return on their capital investment. If fuel demand is high, as it would be in a rapid transition, then investments in new CNG stations would be readily forthcoming. The high initial station cost would not slow the rate at which fuel stations were established because even though CNG stations are more costly than methanol stations, it is difficult to imagine that capital availability (about \$300,000 per station) would be a problem if a reasonable return on investment was expected. The important issue is return on investment, not capital cost.

†An indication that the natural gas industry may be taking a more aggressive role in penetrating the transportation fuels market is indicated by the establishment in August 1988 of the Natural Gas Vehicle Coalition, with the intent of soliciting participation not only from the gas industry but from the vehicle manufacturing industry, state and local governments, the environmental community, and the oil industry.

If a slow transition is being pursued, the start-up advantages of methanol again are not important. In this scenario, there would be time to exploit those market niches where particular alternative fuels are attractive; indeed, barring major governmental intervention, the market would dictate this incremental approach. In this scenario, (i) optimized CNG vehicles would be attractive as high-usage fleet vehicles because the low cost of fuel would offset the high vehicle cost, (ii) electric vehicles would be attractive in areas with severe air pollution problems because of their very low emissions, even including emissions from the powerplant,⁵¹ and (iii) CNG and methanol would be attractive in urban diesel trucks and buses in polluted areas because of their pollution-reduction effectiveness in diesel engines.⁴¹ Note that methanol is attractive in only one niche in this slow transition scenario (urban-based diesel vehicles in polluted areas).

The lower start-up costs of methanol therefore do not appear to be instrumental either in a rapid transition to alternative fuels or during the initial stages of a slow transition. Methanol may prove to be superior in the latter stages of a slow transition when the limited availability of fuel makes multi-fuel vehicles preferable to most consumers, or in some fuzzy intermediate scenario—but the inability to forecast accurately the future and cognitively to work through sets of uncertain conditions suggests that any such determination is speculative at best. In the face of this uncertainty, it seems clear that lower start-up costs of methanol are not substantial enough to render it an obviously superior choice under any set of conditions.

RECOMMENDATIONS

On the basis of the preceding discussion, we make the following recommendations. First, new fuels should be introduced in a gradual fashion by targeting them to market niches and regions where they have comparative advantages. For instance, CNG should first be introduced in cold weather areas, where methanol would have cold-start problems, and in diesel engines in areas with air quality problems. Electric vehicles, which we address elsewhere,⁵¹ should be introduced in urban areas with air quality problems in situations where range and power are not major concerns, because in most locations, even using a full system perspective, electric vehicles will be greatly superior to methanol and CNG vehicles in terms of air-quality impact.

Second, government support of R&D for other cleaner fuels (e.g., hydrogen or clean electricity) should be increased. Neither natural gas or methanol will provide large air quality (or greenhouse effect) benefits, except perhaps for limited niches in the diesel market.

In concluding, we wish to emphasize that our purpose is not to conduct a vendetta against methanol or its proponents or to suggest that only one alternative fuel be selected. We strongly believe that a concerted effort should be made to remove barriers and to provide incentives for methanol use. But the same should be done for CNG, liquefied natural gas (LNG), electric vehicles and, perhaps further in the future, hydrogen vehicles, because all new fuels different from petroleum face considerable start-up barriers.

While it appears that the methanol and natural gas options are not going to yield huge environmental benefits, we still believe that both should receive support from government—for the environmental benefits they do offer, for their reduction of petroleum imports, for their restraining influence on world oil prices, and because there is a possibility that the overall economic and environmental benefits of these natural gas-based fuels may be greater than we realize. At this point, in the face of a global greenhouse threat, the potential for political instability in key resource supply areas, the U.S. trade deficit, and health-threatening air pollution, it would be irresponsible to proceed with “business as usual” in transportation fuels. But let us proceed in an informed fashion.

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