Chapter 3

Substituting Methanol for Gasoline in the Automobile Fleet

Much recent attention has been focused on the potential for using methanol as a primary vehicle fuel, either neat (100 percent methanol, or M1OO) or mixed with up to 15 percent gasoline (M85). Among its advantages as an automotive fuel are its familiar liquid form, its ease of manufacture from natural gas, and the availability of processes allowing its manufacture from coal and biomass,[1] its high octane level allowing higher engine power (at constant displacement), and its potential as a cleaner burning fuel than gasoline. The technology to use M85 as an automotive fuel has been demonstrated and could be commercially available within a few years, and development programs in the United States, Japan, Germany, and elsewhere are working to improve the efficiency, driveability, and emission characteristics of methanol-burning engines and to allow operation with M1OO (cold-starting is a problem with this fuel). Cities and States with vehicular air quality problems have expressed particular interest in methanol use, and California has had an active program to stimulate the development of a fleet of methanol-

Photo credit: General Motors Corp.

Chevrolet Lumina Flexfuel auto can use straight gasoline, M85, or any combination in between.

[1]Gasoline can also be produced from these feedstocks as well.

capable vehicles since 1978.[2] Also, Congress has passed measures to stimulate development and sales of methanol-capable vehicles, and is actively considering legislation to develop alternative-fuel fleets in cities suffering from ozone problems. The Alternative Motor Fuels Act of 1988, Public Law 100-494, allows manufacturers to use dedicated and flexible fuel vehicles to help meet Corporate Average Fuel Economy (CAFE) standards. The law allows the manufacturers to calculate fuel mileage by including only the petroleum portion of fuel usage with the vehicles operating with petroleum use at its minimum level.[3]

If Federal, State, or local governments restrict gasoline use in urban areas, methanol is in a good position to compete for a significant share of the highway vehicle fuel market. Without restrictions on gasoline sales, however, methanol must overcome a number of obstacles to compete successfully. These include a potentially high price in relation to current gasoline prices (particularly in the early years of a methanol program), lack of incentives to establish a supply and distribution infrastructure, and possible strategic problems associated with potential supply sources. Also, because methanol's potential air quality benefits have become a critical factor in its support, questions about the magnitude and nature of these benefits must be satisfactorily resolved.

EFFECTS ON AIR QUALITY

Support for measures to promote methanol has focused primarily on its potential to reduce urban ozone in areas with significant smog problems, e.g., Los Angeles and the Northeast corridor. Methanol's potential energy security benefits as well as its potential for improvements in automotive emissions of toxic pollutants and in fuel efficiency and performance are also important. Methanol has been presented as superior to gasoline as a vehicle fuel because of several favorable physical and chemical characteristics: the low photochemical reactivity of methanol vapors emitted in vehicle exhaust or fuel evaporation; high octane level; wide flammability limits; high flame speed; low volatility; and low combustion temperature. Methanol's low reactivity means that emissions of unburned methanol, the primary constituent of methanol vehicle exhaust and fuel evaporative emissions,[4] have less smog-forming potential than an equal weight of organic emissions from gasoline-fueled vehicles and infrastructure[5] (however, other, more reactive constituents of methanol vehicle emissions complicate the analysis of the overall smog benefit). The octane and flammability characteristics allow a methanol engine to be operated at higher (leaner) air-fuel ratios than similar gasoline vehicles, promoting higher fuel efficiency and lower carbon monoxide and exhaust organic emissions than with gasoline, though causing a potential problem with NO_x control. The low volatility should reduce evaporative emissions if the effectiveness of evaporative emissions controls is not compromised. The high octane level allows higher engine compression ratios to be used, promoting efficiency and power.[6] And methanol's relatively low combustion temperature should reduce "engine out" NO_x emissions (that is, emissions prior to the exhaust stream entering the catalytic converter) compared to emissions from gasoline engines, other things equal.

In general, then, the substitution of methanol vehicles for gasoline vehicles will affect emissions of smog-forming organic compounds and nitrogen oxides, toxics, and carbon monoxide. This section discusses each of these emissions, with the primary focus on organic compounds because their reduction

California is now also evaluating the use of propane, compressed natural gas, and electricity as alternative fuels.

[3] If a dedicated methanol vehicle uses M85, which is 85 percent methanol and 15 percent gasoline, the law allows the vehicle fuel economy to be calculated as if the 15 percent gasoline usage were its total fuel consumption. A flexible fuel vehicle would receive half the CAFE credit available to dedicated vehicles, based on the assumption that such vehicles will use methanol fuels 50 percent of the time. Each manufacturer is limited in the total alternative fuel credit it can claim to 1.2 mpg.

[4] J. Milford, "Relative Reactivities of M85 Versus Gasoline-Fueled Vehicle Emissions," contractor report prepared for Office of Technology Assessment, Jan. 18, 1990. In tests of M85 cars, methanol accounted for approximately 70 percent of total vehicle emissions by weight.

[5] J.A. Alson, J.M. Adler, and T.M. Baines, "Motor Vehicle Emission Characteristics and Air Quality Impacts of Methanol and Compressed Natural Gas," D. Sperling (cd.), *Alternative Transportation Fuels: An Energy and Environmental Solution* (Westport, CT: Quorum Books, Greenwood Press, 1989), pp. 109-144.

[6] Specifically, methanol's research octane number of 112, compared to 91 for regular gasoline, should allow the engine compression ratio to be raised from 8.5/9.0 in today's gasoline engines to over 10. There is dispute about how high a compression ratio can be reached. Energy and Environmental Analysis estimates the capability to reach 12.0 for an M1OO vehicle, with a potential 12 percent fuel benefit (Energy and Environmental Analysis, Inc., *Methanol' sPotential as a Fuel for Highway Vehicles*, contractor report prepared for the Office of Technology Assessment, October 1988). Ford Motors, however, projects an increase to only 10.5 to 11.1 (D.L. Kulp, Ford Motor Co., personal communication, Feb. 1, 1990).

is both the centerpiece of efforts to promote methanol use and one of the most controversial technical aspects of the debate over methanol use.

Organic Compounds and Ozone Reduction

Conclusions

There has been substantial controversy about how effective methanol fuels will be in reducing ozone levels. In OTA's view, although considerable effort has been expended to estimate the ozone impacts of introducing methanol vehicles, especially for the Los Angeles Basin, a number of factors confound the estimates and lead us to conclude that methanol has significant *but poorly quantified and highly variable* potential to reduce urban ozone. In particular, there are few examples of emissions tests of methanol vehicles that have measured the individual compounds in their emissions, even though such ''speciation' of emissions is important inaccurately determining their photochemical reactivity. Other confounding factors include the essentially prototype nature of available methanol vehicles, potential future changes in the reactivity of *gasoline* exhausts (altering the trade-off between methanol and gasoline), and uncertainty about future progress in controlling formaldehyde emissions. And whatever net emissions changes are caused by using methanol vehicles, the effect of these changes on levels of urban ozone will vary with location and meteorological conditions. Ozone benefits from reducing organic emissions will occur only in urban areas where ambient concentrations of volatile organic compounds are low enough, relative to NO_x concentrations, that reducing organic emissions is an effective ozone strategy. In some urban areas-Atlanta, for example-and in most rural areas, controlling NO_x is a more promising ozone control strategy, and methanol use will provide little or no ozone benefits.

Some of the more favorable data imply that use of M85 vehicles could yield an "effective" reduction in organic emissions (that is, taking into account both changes in the mass of organic emissions and changes in the reactivity of these emissions) in the range of 20 to 40 percent, assuming that formaldehyde is reasonably well controlled (e.g., in the vicinity of 30 mg/mile or so). On the other hand, some of the less favorable data imply a much lower benefit: no higher than about a 20 to 25 percent reduction even in the most favorable areas (e.g., the Northeast corridor) with good formaldehyde control, much less of a reduction and possibly even an *increase in* some areas such as the Los Angeles basin. And if formaldehyde control efforts are not successful, some of the benefits would be lost, particularly when vehicles age and catalyst effectiveness diminishes.

The prognosis for M1OO dedicated vehicles is more uncertain in some ways, given the scarcity of data and, for M1OO vehicles, the uncertainty associated with cold starting problems. However, the physical characteristics of a 100 percent methanol fuel, if not altered too radically by additives to aid cold starting and to provide taste and flame luminescence, do appear very promising for substantial ozone benefits. In particular, the absence of reactive hydrocarbon species in the fuel guarantees their absence from evaporative emissions and, further, should lead to low levels (compared to gasoline) of such species in the exhaust-reducing the reactivity of these emissions; and methanol's low vapor pressure, low molecular weight, and high boiling point should keep evaporative emissions, including running losses and refueling emissions, at much lower levels than for gasoline. The available emissions tests of M1OO vehicles, though few in number, appear to bolster these expectations.

Discussion

The range of claims about methanol's effectiveness as a means of reducing urban ozone is extremely wide. For example, the Environmental Protection Agency (EPA) claims that methanol vehicles operating with M85 and current engine technology can achieve reductions in "ozone-forming potential"—the net effect of changes in either or both mass emission rates and reactivity of the emissions of volatile organic compounds that are ozone precursors-of about 30 percent from future gasoline-fueled vehicles meeting the Administration's proposed emission standards and fueled with low volatility (9 psi) gasoline.[7] With optimized M85 vehicles—achieving reduced levels of hydrocarbons, methanol, and formaldehyde in their exhausts—the net emission benefit claimed is about 40

[7] U.S. Environmental Protection Agency, *Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel,* Special Report, Office of Mobile Sources, September 1989.

Box 3-A—How Does EPA Arrive at Its Estimates for the Ozone-Reduction Impact of Methanol Vehicles?[1]

EPA has concluded that an "interim" M85 flexible fuel vehicle can obtain a 30 percent reduction in "gasoline VOC-equivalent"' emissions (or about a 40 percent reduction for a fully optimized vehicle), and that an optimized M1OO vehicle can obtain an 80 percent reduction compared to a gasoline vehicle satisfying the Administration's Clean Air Act proposal for hydrocarbons and operating on low volatility, 9 psi gasoline. EPA arrived at these values by the following method:

For M85 interim vehicle:

1. Evaporative emissions were assumed to equal gasoline emissions on a mass basis; emissions composition was calculated by basing the ratio of hydrocarbons to methanol on EPA test data.
2. Exhaust emissions were assumed to equal gasoline emissions on a *carbon* basis (the current standard for methanol vehicles demands that their exhaust emissions be no higher on an equivalent carbon basis than the standard for gasoline). Emissions were assumed to consist only of methanol, formaldehyde, and HC emissions, the latter identical in composition to gasoline emissions. The emissions breakdown was based on ' 'manufacturer's views. Formaldehyde emissions were assumed to be 60 mg/mile.[2]
3. Assigning the HC component of the emissions a relative reactivity of 1.00, reactivity factors were derived for methanol and formaldehyde using an air quality model. EPA calculated methanol's relative reactivity to be *0.19,* and formaldehyde's to be 2.2, on a mass basis.
4. The gasoline VOC-equivalent emissions were calculating by multiplying the mass of each component of the emissions by its reactivity factor, and totaling the results. The calculated VOC-equivalent emissions were 0.95 for gasoline vehicles complying with the Administration's proposed standards, and 0.66 for the M85 vehicles, or a 30 percent reduction.

For M85 optimized vehicles:

1. EPA assumed that evaporative emissions would be unchanged from the interim vehicle, but that exhaust NMHC emissions would drop by 20 percent, methanol emissions by nearly 30 percent, and formaldehyde emissions by 40 percent (to 35 mg/mi) in an optimized vehicle. Multiplying each new component by the same reactivity factors, EPA found that equivalent organic emissions fell by 43 percent from the baseline gasoline vehicle.

For M1OO optimized vehicles:

1. EPA assumed that M1OO vehicles would emit extremely low levels of non-methane hydrocarbons (.05 grams/mile versus 0.31 grams/mile for the optimized M85 vehicle) and formaldehyde (15 mg/mile, the California standard), with a moderate reduction in methanol emissions from the M85 vehicles. These emissions levels are in line with the small number of M1OO emissions tests available. Multiplying the emissions components by their respective reactivity factors gives a gasoline VOC-equivalent emissions rate of 0.19, or an 80 percent reduction from the baseline gasoline vehicle.

[1]The description of EPA's methodology is based on U.S. Environmental Protection Agency, Office of Mobile Sources Special Report, *Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel,* September 1989.

[2]1bid., p. 50.

percent.[8] And with advanced vehicles using M1OO, EPA claims reductions of 80 percent.[9] EPA's estimates are explained in more detail in box 3-A. Critics have questioned the accuracy of the EPA claims; some have estimated that M85 will yield *no* net ozone advantage.[10]

In examining and attempting to understand and evaluate the alternative claims, we examined the literature and data on the emissions and air quality effects of methanol-fueled vehicles, and analyzed some existing emissions data for their ozone-producing implications.

[8]Ibid.

[9]Ibid.

[10]Sierra Research, Inc., *Potential Emissions and Air Quality Effects of Alternative Fuels—Final Report,* SR89-03-04, Mar. 28, 1989. Also, C.S. Weaver, T.C. Austin, and G.S. Rubenstein, Sierra Research, Inc., *Ozone Benefits of Alternative Fuels: A Reevaluation Based on Actual Emissions Data and Updated Reactivity Factors,* Apr. 13, 1990, Sacramento, CA.

The available literature shows a bewildering array of conclusions about methanol's potential as an ozone control measure. A wide range of numerical results and conclusions arises due to differences in:

- assumptions about the penetration of methanol-fueled vehicles into the fleet;
- assumptions about the rate and composition of vehicle emissions (including assumptions about the success of formaldehyde controls);
- choices about what to compare methanol to (e.g., current gasoline vehicles, future gasoline vehicles with advanced controls and low volatility gasoline, and so forth);
- assumptions about how effective future controls on gasoline emissions might be; and
- choices of geographical areas and types of meteorological episodes to examine.

These factors, and their implications for the potential effects of a methanol fuels program, are examined below.

In our separate analyses of available emissions data, we applied calculations of the incremental contributions of various organic compounds to ozone formation[11] to data on emissions of each compound from gasoline and M85-fueled vehicles. Estimates of the relative contributions of various organic compounds were available for seven sets of meteorologic conditions and initial pollution levels, which simulated different geographic areas and types of pollution episodes.

Across a range of pollution episode conditions, and differing estimates of the composition and magnitude of organic emissions from both M85 and gasoline vehicles, our analysis suggests that M85 use could yield as much as a 40 percent advantage over gasoline or, at the negative extreme, as much as a 20 percent increase in ozone potential over gasoline. We conclude that EPA's claim for M85 vehicles—a 30 percent reduction in per-vehicle "ozone-forming potential' '—is plausible for many situations but, even for these, is but a point in a range of possible outcomes.

The 30 percent claim fits well with some of the available vehicle emissions data (EPA's own test data, in particular), though even for these data the claim is applicable only to certain meteorological conditions and geographical areas for which controlling hydrocarbon emissions is an effective means of ozone control (in some areas, it is not). For other emissions test data (tests conducted by the California Air Resources Board, in particular), the 30 percent value appears too high even in the areas where methanol use is expected to be most beneficial. The results are sensitive to the level of formaldehyde in the exhaust, a factor that has been quite variable in tests and which could be affected significantly by ongoing development of catalytic controls. In other words, the existing data seem to support a wide range of possible outcomes.

The ozone benefits of optimized M85 and M1OO vehicles—according to EPA, about 40 and 80 percent reductions in ozone-forming potential, respectively— are even more uncertain than the benefits of current M85 vehicles because the former vehicles exist only in early prototypes. In all likelihood, these vehicles will achieve improvements in ozone reduction capability over current M85 vehicles, though cold starting problems with M1OO vehicles must be solved before such vehicles can be marketed.

The following discussion reviews the factors that affect methanol's ozone benefit relative to gasoline use, focusing in turn on methanol vehicle emissions, gasoline vehicle emissions, geographical area and type of episode, and other concerns. The discussion focuses primarily on M85, with a brief discussion of M1OO.

Methanol Vehicle Emissions—The air quality effects of using methanol vehicles depend on both the magnitude and the composition of the vehicle emissions compared to the gasoline vehicles they replace. Each of these factors has shown wide divergences among the various studies of air quality effects.

Emissions Magnitude-Analysts have used a range of assumptions about the relative magnitude of M85 emissions. Current EPA emissions standards for methanol-fueled vehicles demand that the total mass of carbon in their exhaust emissions be no higher than the total mass of carbon allowed from gasoline vehicles' exhaust.[12] Because M85 emissions consist in large part of methanol, which has a

[11] W.P.L. Carter and R. Atkinson, ' 'Computer Modeling Study of Incremental Hydrocarbon Reactivity, " *Environmental Science and Technology,* vol. *23, pp. 864-880, 1989.*

[12] "Standards for Emissions From Methanol-Fueled Motor Vehicle Engines, " Final Rulemaking, *Federal Register 54,* FR14426, Apr. 11, 1989.

Table 3-l—Organic Emissions Levels for Gasoline and Methanol-Fueled Vehicles

	Exhaust			Evaporative		Total
Emission Test	Methanol (mg/mi)	TNMHC (mg/mi)	HCHO (mg/mi)	Methanol (mg/mi)	TNMHC (mg/mi)	TNMOC (mg/mi)
CARB: gasoline	0.0	330	7.7	0	45	380
M85	160	65	22	55	36	340
Gabele:						
gasoline	0	320	4.8	0	47	370
M85	290	80	27	19	20	440
Williams et al.:						
gasoline	1	230	7.2	0	120	360
M85	220	51	37	85	25	420

KEY:
HCHO=formaldehyde
TNMHC=total non-methane hydrocarbons
NOTE: does not include running losses.

SOURCE: J. Milford, "Relative Reactivities of M85 Versus Gasoline-Fueled Vehicle Emissions," contractor report prepared for the Office of Technology Assessment, Jan. 18, 1990.

high oxygen content and thus a lower carbon/mass ratio than most hydrocarbons, this standard allows M85 emissions of carbon-based compounds (methanol, hydrocarbons, and formaldehyde) to be significantly higher than gasoline emissions on a *total mass* basis. With the likelihood that manufacturers of both M85 and gasoline vehicles will tailor their control systems to Federal standards, some analysts have assumed that M85 and gasoline vehicles will have equivalent emissions on a carbon basis.[13] However, in emission tests of current vehicles, M85 vehicles tend to have lower organic emissions on a carbon basis than the gasoline vehicles. As shown in table 3-1, emissions tests of flexfuel vehicles operating on M85 and gasoline conducted by the California Air Resources Board (CARB), Environmental Protection Agency, and General Motors reported exhaust plus evaporative nonmethane organic emissions rates (excluding running losses, which were not measured) for M85 equal to 89, 119, and 117 percent by total mass of the gasoline emissions,[14] well below gasoline carbon equivalent rates.[15] These and other measured emission rates suggest that it might be reasonable to assume that M85 emissions may range as low as a *total mass* equivalence with gasoline emissions. EPA has chosen a midpoint between these assumptions-exhaust emissions equivalent on a carbon basis (reflecting the standard), evaporative emissions equivalent on a mass basis—which seems reasonably consistent with at least some of the available emissions data. Given the substantial difference in actual emission rates between mass equivalence and carbon equivalence (for the balance of individual emissions components measured in the EPA emissions tests, "carbon equivalent" total M85 emissions would be about 80 percent higher than "mass equivalent" emissions), the range between the two represents a wide range of consequences with respect to ozone reduction.

Emissions Reactivity-The primary basis for most claims of M85's and M 100's ozone reduction capability is the low photochemical reactivity of methanol, itself-that is, its low propensity to form ozone in the atmosphere--compared to gasoline emissions. However, emissions from M85 (and M1OO, as well) consist of more than just methanol; formaldehyde and a range of hydrocarbons similar to those produced by gasoline-fueled vehicles are also present. In particular, methanol vehicles produce highly reactive formaldehyde in larger quantities

[13] For example, this is the assumption used in T.Y. Chang et al., "Impact of Methanol Vehicles on Ozone Air Quality," *Atmospheric Environment*, vol. *23, No, 8, pp. 1629-1644, 1989.*

[14] California Air Resources Board, Mobile Sources Division, "Definition of a Low-Emission Motor Vehicle in Compliance with the Mandates Of Health and Safety Code Section *39037.05,' May 1989;* P.A. Gabele, "Characterization of Emissions from a Variable Gasoline/Methanol Fueled Car," personal communication, October 1989; and R.L. Williams, F. Lipari, and R.A. Potter, "Formaldehyde, Methanol, and Hydrocarbon Emissions from Methanol-Fueled Cars," General Motors Advanced Engineering Staff, Warren MI, 1989; J. Milford, op. cit., footnote 4.

[15] If the M85 and gasoline vehicles had carbon equivalent emission rates, the M85 vehicles would typically have mass emission rates well OVer 150 percent of the gasoline rates. J. Milford, op. cit., footnote 4.

than gasoline vehicles do.[16] The balance of the various reactive emissions compounds determines the overall reactivity of the emissions, and thus determines the effectiveness of methanol in reducing ozone levels.

Accurate estimates of M85 emissions reactivity require emissions measurements that are speciated, i.e., measure the amounts of each reactive compound in the emissions. Unfortunately, most emissions tests of methanol vehicles provide, at best, only limited breakdowns of organic compounds, e.g., unburned methanol, formaldehyde, and nonmethane hydrocarbons. Although such breakdowns are useful in gauging rough reactivity differences, they are of limited use in establishing reliable measures of ozone reduction potential. OTA identi.tied only three tests of methanol vehicle emissions, involving four vehicles, in which the data had been speciated in detail.[17] Using the data from these tests, we estimated the incremental contribution to ozone formation that each compound found in the emissions would make (i.e., the compound's "incremental reactivity' using results from a computer modeling study .18 We then combined these estimates with assumptions about the total mass of each type of emissions to estimate the relative reactivities of the M85 emissions compared to gasoline emissions.

The most significant finding of our analysis is that the test-to-test variability of the composition of exhaust nonmethane hydrocarbons from both M85 and gasoline *and thus their reactivity* is quite high. Particularly striking is the difference in composition and reactivity between the EPA and CARB tests, because both use the same fuel—indolene--yet the reactivity of the exhaust NMHC generated in the EPA tests is over 50 percent higher than the exhaust NMHC in the CARB tests. *This difference in NMHC reactivity drastically affects the estimated ozone benefits achievable by M85; using EPA's estimates of total mass emissions, we arrive at much more favorable (M85) results using the EPA test data than we do using the CARB data.* Figure ***3-1*** displays the relative reactivities of emissions from M85 versus gasoline-fueled vehicles using the EPA and CARB data. As shown, the EPA-based M85 ozone benefits range from 6 to 34 percent (that is, the M85 relative reactivities range from 0.94 to 0.66) for the 7 episode cases simulated, whereas the CARB-based benefits range from –20 (that is, an estimated *increase in* ozone formation)to+21 percent (reactivities range from 1.20 to 0.79).

An important source of controversy about the overall reactivity of both M85 and M1OO emissions is the likelihood of achieving long-term, effective control of formaldehyde. If formaldehyde emissions of the methanol vehicles increase from assumed levels, e.g., with catalyst aging, the reactivity benefits of shifting to methanol will decrease as well. For example, formaldehyde emissions for the emissions tests included in OTA's reactivity analysis ranged from 22 to 37 mg/mile, compared to about 5 to 8 mg/mile with straight gasoline.[19] These levels are low compared to other studies, which have reported formaldehyde emissions ranging to in excess of 100 mg/mi,[20] but higher than the proposed California standard of 15 mg/mile. It is possible that the low levels of formaldehyde were due to the relatively low miles accumulated by the vehicles: the CARB vehicles, for example, had 11,000 and 22,000 miles,[21] for example. As shown in figure 3-2, at formaldehyde emissions rates of 100 mg/mile, the reactivity benefits of M85 are largely lost when compared to advanced technology gasoline vehicles, and are reduced substantially compared to current technology vehicles.[22] Because catalyst aging does reduce formaldehyde control effectiveness with currently available catalyst technology, the potential loss of benefits is a real concern, and will remain so until improved catalysts are developed.

A final point here is that existing M85 (and the few M1OO) vehicles are prototypes, not production vehicles, and policymakers should be wary of

16Environmental Protection Agency, Office of Mobile Sources, op. cit., footnote 7. EPA's formaldehyde reactivity factor is 2.2 (compared to gasoline hydrocarbons) on an equal mass basis; its methanol reactivity factor is 0.19.

17These are the CARB, EPA, and GM tests discussed above, J. Milford, op. cit., footnote 4.

18W.P.L. Carter and R. Atkinson, op. cit., footnote 11.

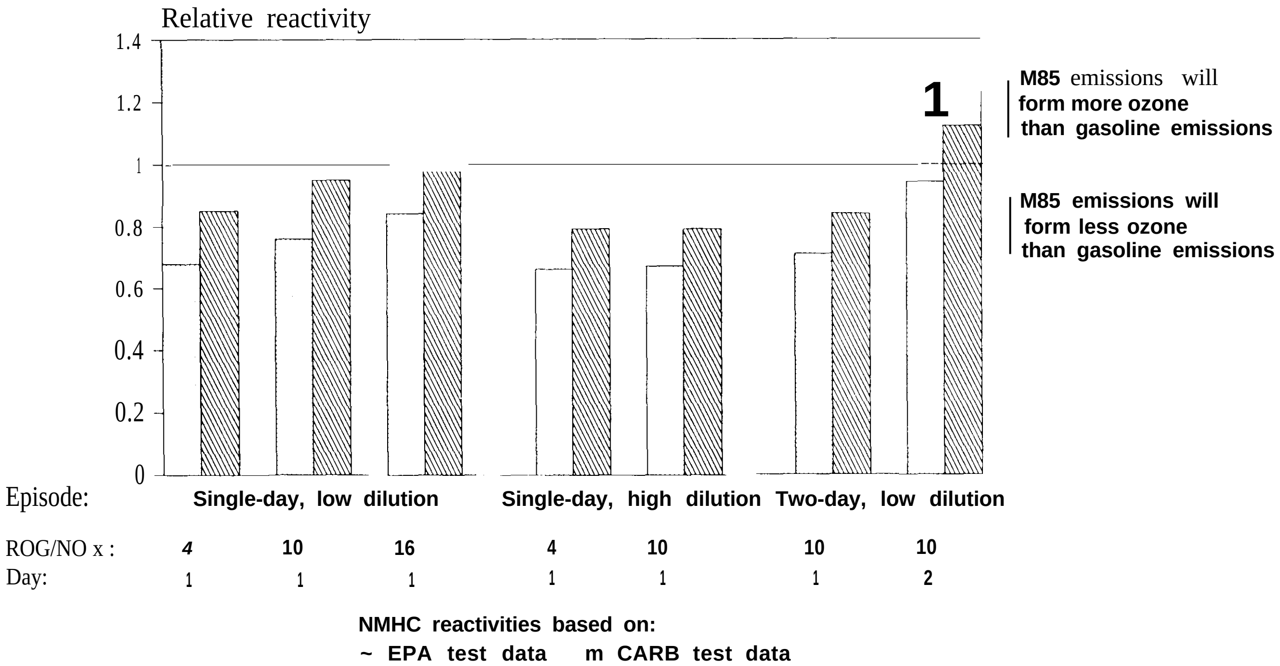
19J. Milford, op. cit., footnote 4.

20R. Snow et al., "Characterization of Emissions from a Methanol Fueled Motor *Vehicle," Journal of the Air Pollution Control Association (JAPCA),* vol. *39, pp. 48-54, 1989.*

21California Air Resources Board, May 1989, op. cit., footnote 14.

22Ibid.

Figure 3-l—"Relative Reactivity" (Ozone-Forming Capability) of Emissions From M85-Fueled Vehicles v. Gasoline-Fueled Vehicles



Assumptions: 1. gasoline NMHC emissions rate based on proposed standards.

2. M85 mass emissions rate and breakdown into NMHC, formaldehyde, and methanol based on EPA analysis. Assumes M85 and gasoline exhaust emissions equal on a carbon basis, evaporative emissions equal on a mass basis.

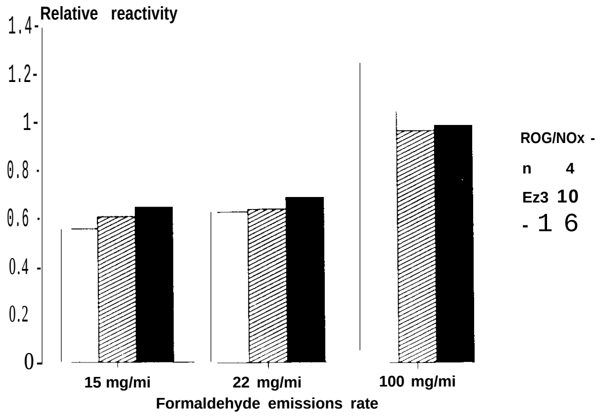
SOURCE: J. Milford, "Relative Reactivities of M85 Versus Gasoline-Fueled Vehicle Emissions," contractor report prepared for the Office of Technology Assessment, 1990.

extrapolations from their tested performance to the expected performance of a commercial fleet. Most of the vehicles have relatively low mileage and thus low degradation of catalysts and other equipment[23]. Further, in the process of moving from prototypes to mass-produced vehicles designed to satisfy consumers for at least 10 years, vehicle manufacturers will make important trade-offs among emissions, efficiency, durability, and performance; some methanol advantages could diminish in the process unless prevented by regulation. For example, though vehicle designers may be capable of holding total organic emissions well below those of gasoline vehicles on a carbon basis, they may choose not do so in order to reduce cost or enhance performance. On the other hand, most of the existing vehicles have engines and pollution control systems that are relatively minor adaptations of gasoline-fueled systems and not representative of systems optimized for methanol. Also, most vehicles were not designed or set up to attain minimum emissions levels, and most are multifueled rather than dedicated vehicles. Thus, existing vehicles cannot take full advantage of methanol's physical properties and do not perform as well as methanol proponents expect an optimized methanol vehicle would.

Gasoline Vehicle Emissions-Gauging the relative benefits of introducing methanol fuels involves comparing the emissions and air quality impacts of adding a number of methanol vehicles to the impacts of adding the same number of gasoline vehicles. Since the methanol vehicles would be added at some time in the future, analysts should compare them to future, not current, gasoline vehicles and fuel quality. The problem here is that we cannot predict with accuracy how well *either* a future methanol or a future gasoline vehicle is going to perform, or how

[23]According to Sierra Research (1989, op. cit., footnote 10), first generation M85-fueled methanol vehicles have experienced severe deterioration of emissions control equipment with increasing mileage. Acurex Corp., contractor to the State of California Advisory Board on Air Quality and Fuels, did not find this type of deterioration in their evaluation for the Board. Personal communication Michael Jackson, Acurex Corp.

Figure 3-2—Sensitivity of Relative Reactivities of M85 Emissions to Formaldehyde Emissions Levels



NOTES: M85 reactivity is compared to future gasoline vehicles; M85 vehicle as tested by California Air Resources Board.

SOURCE: J. Milford, "Relative Reactivities of M85 Versus Gasoline-Fueled Vehicle Emissions," contractor report prepared for the Office of Technology Assessment, 1990.

changes in gasoline composition may affect emission levels or reactivity.

Future gasoline vehicles will likely have lower mass emissions of hydrocarbons (and NO_x, another ozone precursor) than today's vehicles, in response to more stringent emissions standards. The magnitude of the standards for the next few years are not certain at this time, and it is not known whether a second, more stringent round of standards will be required in the future. And the effect of uncertainty about the magnitude of future gasoline emissions is compounded by uncertainty about the reactivity of these emissions. Because catalytic converters will tend to work best on the most reactive substances, future increases in catalyst effectiveness might tend to reduce exhaust reactivity by selectively removing the most reactive substances left in the exhaust. In support of this hypothesis, available tests of the reactivity of the emissions from gasoline-fueled vehicles, conducted by General Motors, have shown reductions in reactivity in moving from current models to models with advanced catalytic converters.[24] If future gasoline-fueled vehicles have exhaust emissions that are lower in reactivity than today's vehicles, then the level of ozone produced by future vehicles will be lower than projected by existing modeling studies,[25] and this will reduce the relative benefits of methanol substitution.

Unfortunately, the cause of the reactivity changes observed in the GM tests is obscured by differences in vehicle mileages and in the gasolines used in the "current" and "advanced" vehicles tested. For example, the current vehicles were fueled with regular gasoline that may have had a higher fraction of extremely reactive alkenes and lower fraction of less reactive alkanes than the indolene used in the advanced vehicles; conceivably, this may explain part of the differential reactivities.[26] If the fuel differences, rather than differences in catalyst efficiency, were the primary cause of the differences in reactivity, then the results of these tests suggest a strong future role for gasoline reformulation as a strategy for reducing urban ozone. With such a strategy, however, the relative benefits of methanol substitution would be reduced. Further tests of gasoline and methanol-fueled vehicles, with better controls on fuel quality and vehicle mileage, are needed to clarify the effects on exhaust emission reactivity of improved emission controls and altered fuel composition.[27]

Geographical Area and Type of Episode—The effectiveness of methanol fuels as an ozone control measure will vary considerably from area to area, with some areas benefiting significantly and some not benefiting at all. In particular, methanol's effectiveness will tend to be high in areas that characteristically have low ratios of reactive organic gas (ROG) levels to NO_x levels, such as Baltimore or Philadelphia, and will tend to be low in areas with high ratios, such as Houston.[28] Other area variables affecting methanol effectiveness include average temperatures and mixing heights of the atmosphere. Low mixing heights (low dilution) are most characteristic of ozone episodes in California cities; high

[24] A.M. Dunker, "The Relative Reactivity of Emissions from Methanol Fueled and Gasoline-Fueled Vehicles in Forming ozone," General Motors Research Laboratories, Warren MI, 1989.

[25] These studies typically account for lower per-vehicle mass emissions in future years but assume that the hydrocarbon component of vehicle exhausts is identical in composition to that of current vehicles.

[26] Ibid.

[27] Presumably, the research program on alternative fuels begun by the auto and oil industries—see ch. 8 discussion on reformulated gasoline—will add significantly to the database.

[28] J. Milford, op. cit., footnote 4.

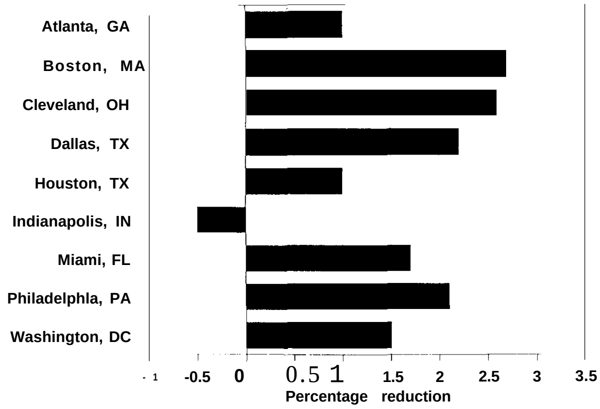
mixing heights (high dilution) are characteristic of summertime conditions in the Eastern United States.[29] In our analyses, methanol was more effective in the high dilution cases.[30] Figure 3-3, based on a Ford Motor Co. analysis, shows the strong differences among various cities in changes to peak l-hour ozone concentrations caused by the introduction of large numbers of M85 vehicles. City -specific changes in ozone range from an 0.5 percent *increase in* peak l-hour concentrations to a 2.7 percent decrease.[31] The changes in ozone concentration shown in figure 3-3 are small because, by the year 2000, automobiles will produce less than a quarter of total urban organic emissions (see ch. 2), so even a total elimination of vehicles would not cause a massive reduction in ozone concentrations in most cities. Also, the Ford analysis assumes that total gasoline and methanol emissions will be the same on a carbon basis, an assumption that will tend to minimize the estimated ozone benefit of methanol.

Methanol effectiveness will also tend to diminish in the later days of multiday episodes, which are common in the Los Angeles area and Northeast. The cause of this effect is a shift towards higher ROG/NO_x ratios, and lower methanol effectiveness, over the course of the episode, because NO_x is shorter lived in the atmosphere than most ROG species and thus tends to become depleted overtime.

Finally, methanol's effect on organic emissions will likely yield little or no benefit in many rural areas, because ozone production in these areas tends to be NOX-limited, i.e., there is an excess of organic gases in the atmosphere and reducing them somewhat does little good.[32]

Other Ozone Concerns—Although flexible fuel M85 vehicles allay some worries about fuel supply and vehicle resale value,[33] they raise concerns about the effect of methanol/gasoline mixtures other than M85. Unless government regulations *require* methanol use in ozone nonattainment areas, flexible fuel vehicles allow vehicle owners to shift back and forth from M85 to gasoline depending on fuel price and

Figure 3-3—Year 2000 Reductions in Peak l-Hour Ozone Concentrations From M85 Use



SOURCE: T.Y. Chang, S.J. Rudy, G. Kuutasal, and R.A. Gorse, Jr., "Impact of Methanol Vehicles on Ozone Air Quality," *Atmospheric Environment, vol. 23, No. 8,* pp. 1629-1644, 1989.

availability, mixing the two fuels in their tanks and diluting or negating potential air quality benefits associated with methanol use. In fact, significant use of gasoline in flexible fuel vehicles could potentially yield an *increase in* ozone-causing emissions because gasoline/methanol mixes that are preponderantly gasoline, aside from offering little benefit in exhaust emissions, have higher volatility than straight gasoline, and thus higher evaporative emissions.

M1OO Vehicles and Organic Emissions— Quantitative predictions of the ozone reduction benefit obtainable from M1OO seem somewhat premature, given the limited data and remaining uncertainty about the nature of additives and cold starting characteristics. There are few M1OO vehicles in existence and sparse emissions data. However, these data are less variable than existing M85 data,[34] perhaps implying that the absence of a gasoline component in the fuel makes the emissions benefits more robust than with M85. EPA believes that M1OO will produce very low evaporative emissions based on their experience with an M1OO Toyota Carina and

[29] Ibid.

[30] Ibid.

[31] T.Y. Chang et al., op. cit., footnote 13.

[32] S. Sillman and P.J. Samson, "Impact of Methanol Fueled Vehicles on Rural and Urban Ozone Concentration During a Region-wide Ozone Episode in the Midwest," conference on Methanol as an Alternative Fuel Choice: An Assessment, Johns Hopkins University, Dec. 4-5, 1989, Washington DC.

[33] That is, they can be used, and thus sold, in areas where an extensive fuel supply network has not Yet been built.

[34] P.A. Lorang, "Emissions From Gasoline-Fueled and Methanol Vehicles,' Conference on Methanol as an Alternative Fuel Choice: An Assessment Johns Hopkins Foreign Policy Institute, Washington DC, Dec. 4-5, 1989, Draft.

their evaluation of the effects of M1OO's physical characteristics, and about two-thirds lower exhaust NMHCs than even optimized M85 vehicles.[35] The expectations for lower evaporative emissions—including running losses and refueling emissions—appear reasonable given M1OO's low volatility and molecular weight and high boiling point. Similarly, because unburned fuel provides much of the organic emissions in vehicle exhausts, M1OO's chemical makeup is consistent with low exhaust NMHCs. However, mass emissions rates can increase substantially if the vehicles experience cold start problems. Also, assumptions of low mass emissions rates presume that the use of additives, to assist cold starting and add flame luminescence and taste to the fuel, will not affect evaporation rates and engine-out emissions, and that M1OO use will not affect control system effectiveness. These assumptions cannot be tested with available data. Reliable emissions estimates must await considerable testing for confirmation.

EPA also believes that the *reactivity* of M1OO emissions will be much lower than M85 reactivity because, as noted above, they expect M1OO's emissions of reactive NMHC emissions to be substantially lower than M85 levels, and formaldehyde levels to be better controlled.[36] Although it is certain that formaldehyde control levels will improve from today's capabilities, it is not possible to predict how successful current efforts will be. However, given the certainty that the evaporative emissions will have substantially lower reactivity than gasoline evaporative emissions (since the M1OO emissions consist only of methanol vapors), and the high probability that the M1OO vehicles will have fewer reactive NMHCs than M85 vehicles, the expectation of lower overall ozone-forming potential seems quite reasonable.

OTA concludes from the available evidence that there is good reason to consider methanol as offering likely long-term improvements to urban air quality, but less justification for confident predictions of up to 90 percent reductions in (effective) ozone precursor emissions. The quantitative effect on air quality, and specifically on levels of urban ozone, of shifting to methanol vehicles is uncertain, because of remaining questions about the magnitude, composition, and reactivity of organic emissions from optimized vehicles. Also, the effect will depend on the fuel chosen (pure methanol or a methanol/gasoline mix) and on whether the vehicles are flexible fuel or dedicated to a single fuel, as noted above. Finally, the effect will be dependent on the atmospheric conditions in the area. For example, in areas where the atmosphere contains a high ratio of reactive hydrocarbons to nitrogen oxides (for example, Atlanta), ozone formation will be limited by NO_x rather than by hydrocarbon concentrations; under these conditions, hydrocarbon reductions obtained from methanol may yield little reduction in ozone.

If current assumptions about methanol vehicles' organic emission characteristics-that is, a 30 percent reduction (compared to low volatility gasoline in current vehicles) in *effective* emissions[37] with M85 and current technology, an upper bound of 90 percent reduction with M1OO and advanced technology—prove correct, moderate but important reductions in total area-wide emissions of volatile organic compounds can be achieved if significant numbers of vehicles are converted. OTA estimates that if 25 percent of the light-duty vehicles in the 38 worst ozone nonattainment areas (areas with design values[38] of 0.15 ppm or higher) are switched to methanol by 2004, the areas will achieve average reductions in effective emissions of volatile organic compounds of 1.3 percent for M85/current technology vehicles and up to 4.1 percent for M1OO/advanced technology vehicles.[39] The reason these reductions are small is that, by the year 2004, light-duty vehicles will produce less than one-fifth of the organic emissions in most urban areas; in other words, complete elimination of the light-duty fleet could not eliminate more than one-fifth of the organic emissions.

35U.S. Environmental Protection Agency, op. Cit., footnote 7.

36Ibid.

37That is, measured in terms of the emissions' actual ozone-forming potential.

38The design value is the fourth highest of all of the daily peak 1-hour ozone concentrations observed within the area over the most recent 3-year period.

39Office of Technology Assessment, *Catching Our Breath: Next Steps for Reducing Urban Ozone*, OTA-O-412 (Washington DC: U.S. Government Printing Office, July 1989), table 7-10.

Nitrogen Oxides (NO_x)

Another concern about the potential ozone benefits of methanol use is methanol's effect on NO_x, emissions. NO_x is a crucial ozone precursor, so that any changes in its emissions can have consequences on ozone levels. Methanol's physical characteristics work in both directions with respect to NO_x emissions: for example, the higher compression ratio (compared to that possible in gasoline engines) made possible with methanol use tends to increase NO_x, emissions, the lower flame temperature and latent heat of vaporization tend to decrease emissions. Available tests of M85 vehicles have found NO_x emissions levels to be uniformly lower with M85 than with gasoline for dual-fuel vehicles,[40] probably because these vehicles do not have increased compression ratios; on the other hand, tests with dedicated vehicles show a mixed performance (some had higher NO_x emissions, some lower) with regard to comparable gasoline vehicles,[41] presumably because of the higher compression ratios in methanol vehicles. It appears reasonable to assume that methanol vehicles using three-way catalysts will be able to achieve the same levels of $NO_=$ emissions, on average, as comparable gasoline-fueled vehicles. However, some economic analyses favorable to methanol have assumed that methanol engines will achieve high efficiency by operating lean, i.e, by increasing the air/fuel ratio.[42] In this, designers may face a conflict between maximizing fuel efficiency and minimizing NO_x. Increasing the air/fuel ratio-operating lean—would likely reduce *engine-out $NO_=$* levels (because the excess air keeps engine temperatures down) but would interfere with use of NO_x reduction catalysts, potentially increasing *controlled* levels of NO_x.[43] In some areas, an increase in NO_x emissions could have a significant deleterious impact on ozone concentrations.

Carbon Monoxide

Aside from organic emissions and NO_x, methanol use will affect emissions of carbon monoxide (CO). If the engines are run with high air/fuel ratios to maximize efficiency, they should produce lower CO than comparable gasoline vehicles if they can start well; because much of gasoline CO emissions are produced during cold start, starting problems could increase methanol CO emissions. If the vehicles are run with air/fuel ratios at stochiometric levels, as with gasoline, CO emissions should be similar to levels achieved by comparable gasoline vehicles, and perhaps a bit higher.[44]

Toxic Emissions

Methanol use will also reduce significantly (or nearly eliminate, for M1OO) emissions of some toxic substances, primarily benzene, 1,3-butadiene, polycyclic organic material, and gasoline fumes. This reduction has been cited by supporters of methanol as a critical benefit of methanol use.[45] Methanol use will, however, increase direct emissions of formaldehyde, a highly toxic substance, and this has raised concerns. Whereas gasoline engines generally emit formaldehyde at rates considerably less than 10 mg/mile,[46] methanol vehicles typically emit formaldehyde at rates several times this much.[47] As noted above, the M85 vehicles considered in our analysis[48] emitted 22 to 37 mg/mi of formaldehyde, and these rates were comparatively low compared to other tests. On the other hand, EPA has measured much lower formaldehyde rates, but for relatively new vehicles.[49] Automakers have expressed concern that long-term catalytic control of formaldehyde, over a

[40] M.A. DeLuchi et. al., 'Methanol vs. Natural Gas Vehicles: A Comparison of Resource Supply, Performance, Emissions, Fuel Storage, Safety, Costs, and Transition,'' Society of Automotive Engineers Technical Paper 881656, October 1988.

[41] Ibid.

[42] U.S. Environmental Protection Agency, op. cit., footnote 7.

[43] Reduction catalysts require stoichiometric (or richer) mixtures of air and fuel (a stochiometric mixture has just enough air to fully burn the fuel) to operate properly. They cannot operate with significant levels of excess oxygen, which would occur with "lean' '-excess air-air/fuel mixtures.

[44] DeLuchi, op. cit., footnote 37.

[45] U.S. Environmental Protection Agency, op. Cit., footnote 7.

%1 the three sets of tests reported in J. Milford, op. cit., footnote 4, the *highest rate* was 7.7 mg/mile.

[47] M. DeLuchi, op. cit., footnote 37, reports that EPA estimates that in-use methanol vehicles emit about 106 mg/mile over their life.

[48] J. Milford, op. cit., footnote 4.

[49] U.S. Environmental Protection Agency, op. cit., footnote 7, and M. DeLuchi, op. cit., footnote 37.

vehicle lifetime, represents a serious challenge to the industry .50

Formaldehyde emissions are a concern in enclosed places such as parking garages and tunnels (or areas where diffusion is restricted, e.g., urban "canyons"), where levels of any pollutant can rise to much higher levels than in ambient air, as well as in ambient air, where the primary concern is longer term exposure of large populations. The former situation is definitely an important concern, especially with occasional malfunctioning vehicles, but similar concerns about gasoline emissions may be equally important. Concerns about ambient exposures to formaldehyde are made ambiguous by the substantial quantities of ambient formaldehyde caused by emissions of hydrocarbon precursors—more than half of atmospheric formaldehyde appears to be due to this "indirect" source.[51] Because methanol use will cause a decrease in emissions of some formaldehyde precursors, the net effect of methanol on ambient formaldehyde may actually be a reduction in concentrations.[52] Studies by Carnegie Mellon University estimated an increase in *peak* formaldehyde but little change in average levels with methanol substitution.[53] However, this and other estimates are extremely sensitive to assumptions about formaldehyde emission rates, and these remain uncertain.

Greenhouse Emissions

Methanol use is expected to provide, at best, only a small greenhouse gas benefit over gasoline, and then only if the vehicles are significantly more efficient than gasoline vehicles. According to Sperling and DeLuchi,[54] use of flexible fuel vehicles with M85 will yield essentially no benefit, assuming a 5 percent efficiency increase and current methanol production technology. At the optimistic extreme, use of M 100 with a 25 percent efficiency gain (in our view, an unrealistically high value) and advanced methanol conversion technology will yield a 12 percent gain.[55] The primary uncertain factors in the ''net greenhouse gas emission' calculation are vehicle efficiency, methanol production efficiency, the effect of increased methanol production on natural gas leakage and on venting and flaring, and the potential for use of coal as a methanol feedstock.

Production efficiency is somewhat uncertain primarily because some of the natural gas that might be available for methanol production is cheap enough to create interesting trade-offs between high efficiency/high capital cost and lower efficiency/lower capital cost facility designs.

As for venting and flaring, some proponents of methanol as a transportation fuel have noted that considerable amounts of natural gas are today either vented to the atmosphere or flared, producing greenhouse gases (both carbon dioxide and methane itself are greenhouse gases, with methane by far the more potent of the two) with no corresponding energy benefit. To the extent that development of a methanol economy would capture and convert this gas, net greenhouse emissions would be reduced. However, the extent of venting and flaring is likely to be reduced with or without methanol demand because of gas' growing use as a chemical feedstock and as a clean-burning combustion fuel. It seems unrealistic to award methanol with this potential environmental benefit. (There is further discussion of this issue in app. 3A.)

Because coal may eventually become the raw material source for a U.S. methanol-fueled highway fleet, many in the environmental community have concerns about the long term impact of methanol use on emissions of greenhouse gases. Methanol from coal will produce substantially higher emissions of greenhouse gases than the current gasoline-based system, primarily because coal has a high carbon-to-hydrogen ratio and because the current processes of producing methanol from coal are inefficient.

Although these concerns appear realistic, world natural gas supplies appear capable of fueling even

[50] David Kulp, Manager of Fuel Economy and Compliance, Ford Motor Co., personal communication.

[51] T. Russell, Carnegie Mellon University, presentation on Methanol Impacts on Urban Ozone and Other Air Toxics, conference on Methanol as an Alternative Fuel Choice, Johns Hopkins University, Washington, DC, Dec. 4-5, 1989.

[52] Ibid.

[53] J.N. Harris, A.R. Russell, and J.B. Milford, "Air Quality Implications of Methanol Fuel Utilization,'' Society of Automotive Engineers Technical Paper 881198, 1988.

[54] D. Sperling and M.A. DeLuchi, *Alternative Fuels and Air Pollution*, draft report prepared for Environment Directorate, Organization for Economic Cooperation and Development, March 1990.

[55] Ibid.

a large methanol program for several decades at least, and future process changes to improve coal-based production efficiency and to sequester the CO_2 produced during methanol conversion could allay these concerns. On the other hand, if energy security concerns become paramount-certainly a possibility given recent history-producing methanol from domestic coal might suddenly appear much more attractive. However, because *gasoline* can be made from natural gas and coal, avoiding methanol or other alternative fuels that can be manufactured from coal in no way guarantees that coal will not eventually become the feedstock source for our transportation fuels.

OTHER ENVIRONMENTAL/ SAFETY EFFECTS[56]

Aside from air quality changes, a broad shift to methanol vehicles will create environmental changes because methanol's characteristics are substantially different from those of gasoline. From an overall safety and human health perspective, methanol represents some new dangers but probably not a net increase in risk.

Both methanol and gasoline are harmful if inhaled, absorbed through the skin, or ingested. Because minute quantities of methanol occur naturally in the body, ingestion or absorption of small quantities—i.e., a few drops-would be relatively harmless. However, methanol is more likely than gasoline to be fatal if swallowed, and an amount equal to only about 10 teaspoonful can be a fatal dose to an adult (In contrast, a full mouthful of gasoline will generally be less than a fatal dose). A 3-year-old child could be killed by a dose little more than a tablespoon full.[57] For this reason, and because methanol is tasteless, some analysts are very concerned about the potential for accidental ingestion. In all likelihood, a bad-tasting additive would be used to guard against this danger. Further protection could be offered by required antisiphoning screens in methanol fuel tanks, and a ban on methanol use in small engines.[58] And, unlike gasoline, methanol is not an effective solvent for oils and grease and will not be stored in and around the house for such purposes. This should decrease exposure considerably. Finally, remedies for methanol ingestion are more effective in preventing damage than those for gasoline.

Methanol is absorbed through the skin more quickly than gasoline.[59] Such absorption could be a problem if methanol is handled as badly as gasoline currently is handled, especially in self-service stations. Gasoline spills from overfilling of tanks, from expansion when fuel is introduced into warm tanks during the summer, and from improperly set fuel cutoff valves are common,[60] and would presumably remain common with methanol if additional precautions are not taken. However, prolonged or frequent contact are necessary for acute symptoms, and methanol's inadequacy as a solvent should help reduce such contact.[61] Also, straightforward technical solutions to this problem are available, including tank redesign to reduce potential for spillage, cutoff valves set to prevent continued filling after initial cutoff, and so forth. Although technical solutions can be overridden, they could still provide a substantial reduction in methanol exposure risk.

Methanol should present less of an open-air fire and explosion hazard than gasoline because it ignites much less readily and, once ignited, burns with considerably lower intensity. A methanol fire is easier to fight because the methanol is soluble in water and thus can be diluted, whereas gasoline will float on top of water and continue to burn. M1OO's invisible flame (M85's flame is visible) is an important drawback, however; chemists are looking for a trace additive that would make the flames

[56] Material from P.A. Machiele, "Flyability and Toxicity Tradeoffs With Methanol Fuels,' Society of Automotive Engineering Technical Series 872064, 1987, unless otherwise referenced.

[57] T. Lotovitz, "Acute Exposure to Methanol in Fuels: A Prediction of Ingestion Incidence and Toxicity, " National Capital Poison Center, Oct. 31, 1988.

[58] Fuel used for lawnmowers and other small engines often is stored in households, in small containers, with significant incidence of accidental ingestion.

[59] B. Bayeart et al., "An Overview of Methanol Fuel Environmental, Health and Safety Issues," American Institute of Chemical Engineers 1989 Summer Meeting, Symposium on Alternative Transportation Fuels for the 1990's and Beyond, Aug. 22, 1989, Philadelphia PA.

[60] Gasoline spillage will likely be reduced significantly when Stage II vapor recovery controls (with automatic fuel cutoffs) are adopted fOr gasoline station pumps.

[61] P.A. Machiele, ' 'Perspective on the Flammability, Toxicity, and Environmental Safety Distinctions Between Methanol and Conventional Fuels," AIChE 1989 Summer National Meeting, Philadelphia, PA, Aug. 22, 1989.

visible. Nevertheless, the potential reduction in both incidence and intensity of fires will be an important safety issue, because gasoline fires associated with vehicle accidents are a major cause of injury and death in the United States.

A potential disadvantage of neat methanol, M1OO--but not of M85—is that methanol vapors in an enclosed space, such as a half-full gas tank, form a combustible mixture and thus can present a fire or explosion hazard. Bladder-type fuel tanks, which avoid creating an air space as the tank empties, may be necessary for M1OO vehicles.[62] An alternative or additional safety precaution would be flame arrestors at the mouth of the fuel tank. These could serve double duty as anti-siphoning devices, to prevent accidental ingestion. Flame arrestors are now used in all flexible and variable fueled vehicles.[63]

Methanol's volubility also will greatly affect its impacts in the event of a spill. In open waters, methanol would disperse rapidly and decompose rapidly as well. The major problem would be severe toxicity in the immediate vicinity of a spill, with large spills in enclosed harbors or similar areas being a particular problem. If methanol were spilled on land, its volubility and low viscosity would allow it to penetrate porous ground and enter aquifers more readily than gasoline. Methanol would be likely to disperse rapidly throughout an aquifer, limited only by the slow movement of the water. For shallow aquifers with high oxygen contents, the methanol would be decomposed by natural processes fairly quickly; where oxygen contents were low, however, decomposition would be slow. Toxicity problems in drinking water aquifers would occur where the spill was in close proximity to wells, where the water flow in the aquifer moved 'plumes" of methanol to the wellbores, or simply where the volume of the spill was large in comparison to the volume of the aquifer. In contrast, a gasoline spill of similar magnitude would disperse less quickly into and through an aquifer, but its failure to degrade could cause the aquifer water to become unpalatable and remain so for years. If bad-tasting additives were added to methanol (for consumer safety), however, the potential for palatability problems from spills would exist for methanol as well.

Methanol's advantages over gasoline in a spill situation might be partially nullified if chemicals are added to methanol to provide taste (as a safety precaution to reduce incidence of accidental ingestion), flame color, or improved cold starting capability. Selection of such chemicals should account for the desirability of compounds that can be neutralized easily or that are biodegradable to less harmful components.

COST COMPETITIVENESS

The economic competitiveness of methanol used as a gasoline substitute is a source of intense and ongoing controversy, with alternative positions ranging from claims that methanol will eventually be less expensive than gasoline, on a $/vehicle mile basis, at *current gasoline and world oil prices*[64] to claims that methanol will remain noncompetitive until gasoline prices reach $1.50/gallon (in 1989 dollars) or even higher.[65] Price estimates for neat methanol delivered to the United States have ranged from as low as $0.25/gallon to as high as $0.75/gallon for methanol produced from natural gas, and higher for methanol produced from coal (distribution costs, service station markup, and taxes would be added to these prices). This wide range stems from different assumptions about natural gas prices, technological selections, required rates of return, infrastructure requirements, required chemical purity,[66] and other factors, and the substantial variability of plant costs in remote locations. And estimates for the appropriate conversion factor between methanol and gasoline prices (that is, the multiplier of methanol price to make it comparable to gasoline price), to account for differences in energy content and efficiency between the two fuels, range from 1.5 or 1.6 (assuming that methanol vehicles will be 25 to 30

[62] M.A. DeLuchi et al., op. cit., footnote 37.

[63] Alan Lloyd, South Coast Air Quatity Management District, personal communication.

[64] Office of Mobile Sources, U.S. Environmental Protection Agency, "Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel," September 1989.

[65] W.J. Schumacher, "The Economics of Alternative Fuels and Conventional Fuels," SRI International presentation to the Economics Workshop, California Advisory Board on Air Quality and Fuels, Feb. 2, 1989, San Francisco, CA.

[66] Methanol sold in today's market generally is "chemical grade" methanol, which is quite pure. It has been suggested that a lower purity methanol, producible with some cost savings, might be satisfactory as a motor fuel.

percent more efficient than equivalent gasoline vehicles) to 2.0 (assuming that methanol and gasoline vehicles will be equally efficient). Because the extremes of the ranges imply such different prospects for methanol, it is important for policymakers to understand the bases for the various positions and to be able to judge their reliability.

One thing is quite certain about future methanol prices—if methanol is to emerge as a major transportation fuel, expected prices must be high enough to stimulate major new capacity additions. Although some countries might be willing to build new capacity to operate at a loss, to obtain foreign exchange or to pursue social policy, only expectations of profit are likely to bring forth enough new capacity to allow a significant shift to methanol for transportation use. And although substantial shut-in capacity exists today, perhaps as much as a billion gallons/yr, it is a small fraction of the methanol volume that would be necessary to fuel even a small percentage of the U.S. auto fleet. For example: Were 10 percent of U.S. commercial fleet vehicles amenable to fueling from dedicated stations converted to methanol, an additional methanol demand of 2.7 billion gallons per year would be created;[67] and, were California somehow to convert its automobile fleet entirely to methanol, that State alone would demand 25 billion gallons of methanol per year—four times current world capacity .68

Assuming that natural gas-currently the most economic feedstock for methanol-remains the primary feedstock, we discuss in appendix 3A (See end of chapter) the factors that are critical in determining methanol's cost and competitiveness with gasoline. As noted in the appendix, various analysts have selected a wide range of assumptions about most of the factors. Aside from differences that may arise from vested interests (oil industry analysts may tend to prefer pessimistic assumptions, analysts working for chemical plant manufacturers—potential methanol producers—may tend to choose optimistic assumptions), differences stem from technical uncertainties as well as uncertainties about market reactions and government policies.

Given the large number of 'optimistic/pessimistic' selections possible, it is difficult to define a reasonable maximum/minimum range for methanol costs. Nor can we readily define a' 'most likely' cost. We can, however, attempt to put possible methanol costs into perspective by examining a few scenarios and defining cost ranges for them. In the scenarios that follow, production and shipping costs are based on the Department of Energy (DOE) analysis prepared by Chem Systems, Inc.[69] Rates of return (RORs) are real (corrected for inflation), after tax rates.

1. Transition period. In the early years of a methanol program, new plants will likely be of moderate scale (2,500 metric tons per day, or MTPD) and use standard technology (steam reforming). Required rates of return will tend to be high because of high market risk, though somewhat restrained by low technical risk. Likely RORs will be perhaps 15 to 20 percent unless there are strong nonmarket guarantees that methanol demand will keep growing; even with such guarantees, plant developers must be wary of overbuilding unless they can sign long-term contracts with distributors. With strong assurances, possibly including take-or-pay contracts,[70] required ROR might be as low as 10 percent. Shipping will likely be in tankers of about 40,000 dead weight tons (DWT) scale, but larger tankers might be feasible a few years into the program if producers are given strong market guarantees[71] and the lack of suitable ports can be overcome[72] (presumably, this cannot occur for several years). If the vehicles are fuel flexible and if methanol supply is constrained at first to port cities, distribution costs will be low;[73]

67 D.A. Dreyfus and A.B. Ashby, "The Prospects for Gas Fuels In International and Interfuel Competition%" International Energy Workshop, IIASA, Luxemburg, Austria, June 16-18, 1987. These fleet vehicles and equipment account for about 15 percent of U.S. gasoline demand.

68 Energy and Environmental Analysis, op. Cit., footnote 6.

69 U.S. Department of Energy, Office of policy, Planning, and Analysis, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Three: Methanol Production and Transportation Costs,* DOE/PE-0093, November 1989.

70 A take-or-pay contract is one where fuel buyers agree to pay for a fixed volume of fuel each period whether they accept the fuel or not. Previous experience with such contracts in the natural gas industry does not, however, offer much assurance to developers-these contracts were routinely broken.

71 If large tankers can be readily converted to carry gasoline or other products and if there is a demand for such vessels, the risk associated with building larger tankers may be reduced.

72 It may also be possible to simply transfer the methanol to smaller ships offshore, though this option maybe limited by weather conditions.

73 Although distribution costs for gasoline should be low as well, lowering the retail price with which methanol price must be compared.

Table 3-2—Component and Total Methanol Supply Costs During a Transition Phase

Part of fuel cycle	Strong market guarantees	Free market, few guarantees
Production[a]	0.42	0.55-0.65[d]
Shipping	0.02-0.03 or 0.04-0.08[b]	0.03-0.08
Distribution	0.03	0.03
Markup	0.06-0.09	0.09-0.12
Taxes	0.12	0.12-0.13
Retail Price	0.65-0.69 or 0.67-0.74	0.82-1.01
Midrange Price[c]	0.68-0.72	0.85-0.95
Efficiency Factor	1.9	1.9
Gasoline Equivalent Price, $/Gallon	1.29-1.37	1.61-1.81
Low gas cost case (gas at $.50/MMBtu for many sites) $/Gallon	1.19-1.27	1.51-1.71

Higher cost gas cases: each increase of $O.50/MMBtu yields a methanol price increase of about $O.05/gallon of methanol, or about $0.10/gallon increase in the gasoline equivalent price.
a Natural gas cost is $l.O0/MMBtu.
b Two to three Cents represents very large tankers shipping over moderate to long distances; 4 t0 8 cents represents smaller tankers. Import duty for chemical-grade methanol assumed to be dropped.
c Range reduced to avoid extremes with little probability.
d Range represents 15 to 20 percent required Rate of Return (ROR).

SOURCE: Office of Technology Assessment, 1990.

however, fuel flexibility and guaranteed markets may be incompatible unless methanol prices are artificially maintained lower than equivalent gasoline prices or flexible fuel vehicles are required to refuel with methanol within market areas around ozone nonattainment cities. Similarly, retail markups will be high unless there are market guarantees or government regulations requiring minimum levels of methanol sales from each station. Taxes would likely be based on methanol's energy content in a "market guarantees scenario," to promote methanol use; in a free market scenario, taxes might instead be set to reflect miles driven, to avoid a tax loss (because of methanol's potentially higher efficiency in use) and to require methanol vehicles to pay their share of road services.[74] Finally, vehicles are most likely to be fuel flexible, and would likely have a modest (e.g., 4 to 7 percent) efficiency gain over gasoline.

Table 3-2 presents the component and total costs of methanol supplies during the transition period, for both "market guarantees" and "free market" scenarios.

2. Established methanol supply and demand, low shipping costs, dedicated vehicles. Assuming that methanol demand becomes strongly established in the United States, eventually producers should be willing to build larger, advanced technology plants,[75] and vehicle manufacturers may move to dedicated vehicles to achieve improved air quality benefits and higher efficiencies. With a larger program, the potential for equivalent programs in other countries, and other worldwide increases in gas use, there is an increased potential for higher gas feedstock costs—unless continued exploration turns up large new reserves, which is quite possible. Average distribution costs should increase because of greater distances associated with wider distribution of methanol, including availability in many inland areas. Whether the fleet moves from flexible fuel to dedicated vehicles depends on government air quality regulations and security interests (flexible fuel vehicles have certain energy security advantages over dedicated vehicles). In this scenario, there should be a stronger possibility that large, dedicated tankers (250,000 DWT) will become the primary methanol

[74] It may not be likely that governments would tax methanol this way, but taxing methanol strictly on a Btu basis could be construed as a subsidy of methanol vehicle use.

[75] Assumes use of catalytic or noncatalytic partial oxidation for the synthesis gas generation section, at considerable savings in Capital costs. Improvements are also assumed for the methanol synthesis section, e.g., Davy McKee mixed flow reactor, or Mitsubishi fluidized bed rector. U.S. Department of Energy, op. cit., footnote 69.

Table 3-3—Component and Total Methanol Supply Costs in an Established Market Environment

Part of fuel cycle	Some continued guarantees	Free market, few guarantees
Production[a]	0.28-0.30	o.34-o.39[b]
Shipping	0.02-0.03	0.02-0.03
Distribution	0.05-0.06	0.05-0.06
Markup	0.06-0.09	0.06-0.09
Taxes	0.12	0.13-0.14
Retail price	0.53-0.60	0.60-0.71
Efficiency factor	1.67-1.82	1.67-1.82
Gasoline equivalent price, $/Gallon	0.89-1.09	1.02-1.27’
Low gas cost case (gas at $0.50/MMBtu for many sites)		
$/Gallon	0.81-1.06	0.91-1.24
Higher gas cost cases: Each increase of $0.50/MMBtu yields increased methanol costs of $0.04-$0.05/gallon, or about $0.07-$0.1 O/gallon of gasoline equivalent.		
Flex-fue/ *case* (all vehicles are flexibly fueled)		
$/Gallon	1.01-1.14	1.14-1.35
Higher capita/ cost case (required rate of return (ROR) without government guarantees assumed to be 20 percent)		
$/Gallon	NA	1.08-1.42

a Natural gas cost is $1 .00/MMBtu

b Free market ROR is assumed to be 15 percent; market guarantee case assumes 10 percent.

c The factor of 1.67 is applied to 61 cents, not 60 cents, and the factor of 1.82 is applied to 70, not 71 cents, because the 13 cent taxis appropriate only if the efficiency factor is 1.82, and the 14 cent tax applies only to the factor of 1.67.

SOURCE: Office of Technology Assessment, 1990.

transporters, significantly reducing shipment costs. With lower risks, required rates of return should be lower (in this scenario, we assume a free market required rate of return of 15 percent; this may be considered low for many sites, but capital should be available at such rates in several Middle Eastern sites with large gas reserves, assuming a stable political climate), and retail markups may come down even without government sales requirements. For the “market guarantees” case, the measures needed to keep RORs at 10 percent presumably will not need to be as strong as those required in the short term. If retailers move to dedicated vehicles, methanol vehicles could be significantly more efficient than gasoline vehicles; a likely value for the efficiency increase is about 15 percent, but there is a wide range of uncertainty. Note that a move to dedicated vehicles is most likely if distribution is wide; in that case, distribution costs must go up.

Table 3-3 presents the component and total methanol supply costs for this case.

These scenarios imply that on a cost basis methanol will be difficult at the outset to introduce as a gasoline substitute, but that its prospects for economic competitiveness should improve substantially once a market is established and economies of scale can be achieved. In the short term, high risks, inability to achieve scale economies, and the need to start out with proven, and nonoptimal technology is likely to make methanol a rather expensive fuel compared to gasoline. In the longer term, fuel and other costs can come down and fuel use efficiencies rise to lessen the economic gap between methanol and gasoline. However, there remain significant uncertainties and disagreements about just how expensive methanol will be in the long term, with key uncertainties associated with feedstock costs, vehicle efficiency, shipping and distribution system costs, financial risks and required rates of return, and other factors. At the same time, there is some uncertainty associated with the future price of gasoline even *at stable oil prices.* Changing crude oil quality, new government requirements to reduce volatility and otherwise improve gasoline’s environmental performance, and refiner pressure for price increases to correct historically low rates of return all may work to raise prices.

How long will a “transition period” last? Neglecting development of natural gas feedstocks, which will likely become more expensive with time, we would guess that the methanol fuel cycle might reach the lower cost, ''stable market' phase within 8 to 12 years from the beginning of commercial production of fuel and vehicles.

We do not envision a well-defined period that ends at a single point, with lower cost, larger scale systems then taking over essentially all at once. Instead, there will be a transition period associated with high cost factors of production, followed by a gradual shift of the various factors of production towards lower cost, larger scale units, and eventually a period of established, lower cost methanol supply. For example, some higher "transition" costs, e.g., high service station markups, could be reduced quickly, essentially as soon as it became clear that a stable market for methanol fuel was developing and capital improvements would be paid off with little risk. On the other hand, planning, financing, and building a fleet of large methanol-dedicated tankers would not be likely to even begin for a few years, and then would require a few more years before the first tankers began to haul methanol. And building larger scale production plants would also take a number of years. Presumably, the first of these lower-unit-cost factors of production would not affect market costs until they controlled enough of the market to begin competing among themselves (unless they were overbuilt, with excess supply of that factor requiring the new factors to bid low for market share). Until then, their owners would obtain higher profits because of the price structure established by the predominant, smaller scale, higher cost tankers, production plants, or other factors. In contrast to the other factors of production, feedstock costs would likely start at low costs because of the current availability of sites with abundant gas reserves, low development costs, and lack of alternative markets, and eventually move to higher costs as methanol demand outgrows the availability of the lower cost reserves.

The scenarios apply to methanol manufactured in locations that combine low natural gas prices with moderate construction costs. Generally, locations that offer low construction costs because of a well-developed infrastructure also have prohibitively high natural gas costs; and locations with virtually free gas (because they are so isolated that the gas has no other possible markets) also have very high construction costs because they lack infrastructure and have poor availability of both trained workers and critical supplies. This implies that essentially all methanol used for transportation in the United States would be imported, probably from areas that are at least partially developed at this time.

Despite the apparent economic advantages of imported methanol, some support for a shift to methanol has come from policymakers who desire to see the United States supply more of its own transportation fuel. One option for U.S.-produced methanol is to manufacture it on the North Slope and ship it to the lower 48, primarily because the North Slope has gas reserves of at least 37 trillion cubic feet (TCF) and no ready markets.[76] North Slope methanol may have difficulty competing with other sources because of higher cost, however. The California Energy Commission has estimated that the delivered (wholesale) cost of North Slope methanol to Los Angeles would be roughly $1.00/gallon of methanol,[77] as much as triple the cost of competing sources. Similarly, a recent study by SRI International estimated North Slope methanol production costs at about $0.40/gallon of methanol assuming a $0.51/mmBtu gas price. Even with the high transportation costs associated with transporting the fuel by pipeline to Valdez and shipping it to the lower 48 States, the delivered cost would still be under $1.00/gallon of methanol.[78] The level of uncertainty associated with these estimates is high, however, with delivered methanol cost dependent on the "value" of the gas resource as reflected in its price, the availability and practicality of the Trans Alaskan Pipeline as part of the delivery system, and capital costs of modular methanol plants delivered and installed on the North Slope. Some analysts believe the cost of methanol can be less than these estimates.[79] In particular, shipping costs may not be

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[76] Currently, gas that is produced with North Slope oil is either reinfected to maintain reservoir pressure or is used as part of enhanced oil recovery operations in the Prudhoe Bay Field.

[77] California Energy Commission *AB234 Report: Cost and Availability of Low-Emission Motor Vehicles and Fuels. Volume II: Appendix*, August *1989.* The price ranges from $0.90 to $1.1 I/gallon with natural gas costs ranging from $0.33 to $2.00/mmBtu.

[78] W.J. Schumacher, op. cit., footnote 65.

[79] David L. Ku@, Manager, Fuel Economy Planning and Compliance, Ford Motor Co., personal communication. It is worth noting that the charge for using the Alaskan pipeline is due to be reduced substantially; further, because oil throughput in the pipeline is expected to decline during the coming decade, there is substantial incentive to give methanol an attractive rate if this will keep the pipeline operating at full capacity.

high if, as expected, North Slope oil production declines and substantial excess capacity is available on the Trans Alaskan Pipeline System. Even with low pipeline tariffs, however, it appears that North Slope methanol would be priced, at retail, at least $0.15 to $0.20 more per gasoline gallon equivalent than low cost imported methanol. Of course, a "premium" of this magnitude might seem a reasonable price to pay for a secure, domestic source of transportation fuel if energy security concerns were to escalate.

Methanol can also be made from coal, which the United States has in abundance, but the total production costs are likely to be considerably higher than costs for gas-based methanol. Amoco reports probable manufacturing costs for methanol from coal as approximately $ 1.00/gallon.80 A recent report by the National Research Council estimates methanol-from-coal's crude oil equivalent price to be over $50/barrel.[81] As with North Slope methanol, the level of uncertainty associated with the cost estimates is high and the potential exists to reduce costs substantially with advanced technology. For example, advocates of coal-based systems that produce methanol in conjunction with electricity in a gasification/combined cycle unit claim methanol costs comparable to those of natural gas-based systems.[82] DOE's evaluation of this type of system implies that it could achieve significant cost reductions from other coal-to-methanol processes, producing methanol at costs of about $0.58/gallon using $35/ton midwestern coal and assuming a 10 percent (real) rate of return.[83] This is still significantly higher than methanol produced from natural gas, unless the latter proves to be a higher risk source and requires a higher rate of return. Also, because gasification/combined cycle plants of this type are primarily power producers,[84] the potential methanol supply from this source would be limited by the growth of electricity demand and by U.S. willingness to satisfy increased demand primarily with coal plants.

Similarly, methanol can be made from wood and other biomass materials, at highly uncertain costs because of the extreme variability of the cost of the biomass materials. The National Research Council's estimate for the crude oil equivalent price of methanol produced from wood using demonstrated (but not commercial) technology is over $70/barrel.[85] Because biomass gasifiers suitable for producing synthesis gas (these are either pyrolysis or oxygen blown gasifiers) have not gotten the development attention that coal-fed gasifiers have, some researchers believe that methanol produced from biomass could eventually be competitive with coal-based methanol.[86] Such an outcome would require improvements in both conversion technology and in all aspects of the growing and harvesting cycle for biomass-to-methanol production.

If oil prices-and thus gasoline prices-rise, the relationship between gasoline and methanol prices may change, and methanol may become more competitive. Under some circumstances, methanol prices need not rise in lockstep with gasoline prices. For example, if methanol producers were using natural gas feedstocks that had few or no other markets, gas prices in these areas might not be tied closely to oil prices. For such a scenario, rising oil prices probably would lead to improved methanol competitiveness.[87] Other causes of likely different rates of gasoline/methanol price escalation include the different proportion of feedstock conversion costs embodied in each fuel, the differences in current market conditions for natural gas and oil (gas is in oversupply), and the differing role that shipping costs play in oil and natural gas prices.

80J. Levine, Amoco Corp., personal communication.

81Committee on Production Technologies for Liquid Transportation Fuels, National Research Council, *Fuels to Drive Our Future* (Washington, DC: National Academy Press), 1990.

82G.W. Roberts, "Methanol as an Alternative Fuel," testimony before the Subcommittee on Energy Research and Development, Committee On Energy and Natural Resources, United States Senate, June 8, 1989.

83U.S. Department of Energy, Office of Policy, Planning, and Analysis, op. cit., foomote 69, assuming 20 percent capital recovery rate. In this analysis, the derived methanol price is particularly sensitive to the assumed value of the electricity produced.

84Ibid.

85Committee on production Technologies for Liquid Transportation Fuels, op. cit., footnote 81.

86T.E. Bull, "Liquid and Gaseous Fuels from Biomass," D. Hafemeister et al. (eds.), *Energy Sources: Conservation and Renewables*, American Institute of Physics, New York, NY, 1985. Suitable gasifiers would probably be small units that could be prefabricated in a factory and simply assembled in the field.

87Similarly, the prices of coal and biomass should not rise as fast as oil prices, and methanol from these sources may eventually become competitive.

On the other hand, there are counterarguments to the proposition that methanol and gasoline prices need not be closely linked. In particular, if the fuels are readily interchanged by the driver (that is, if flexible fuel vehicles are used), gasoline and methanol prices would tend to be locked into an "equivalent price/mile" relationship. Also, feedstock costs may be linked to world oil prices through liquefied natural gas trade and competition between natural gas and middle distillates for utility and other markets.

Just as methanol competitiveness might improve with rising oil prices, it might suffer if oil prices fall. This leaves methanol-and *any* alternative to gasoline-vulnerable to Organization of Petroleum Exporting Countries (OPEC) production increases designed to depress world oil prices and win back lost market shares. Such a price drop would have beneficial side effects, however, in particular the economic stimulation provided by lower energy prices, but the longevity of such effects would depend on the willingness and ability of alternative fuel suppliers to maintain a market presence. Of course, the U.S. Government, if it wished, could protect methanol market share with tariffs and other mechanisms.

INFRASTRUCTURE

Transforming a significant portion of the vehicle fleet to methanol use would be a major undertaking. Aside from the obvious "chicken and egg" problem--neither methanol suppliers nor vehicle manufacturers wish to take the first step without the other segment of the market in place—methanol distribution is likely to require a substantial investment in new equipment. Methanol is hydroscopic (it attracts and absorbs water) and corrosive to some materials now used in gasoline vehicles and distribution systems. It may prove to be incompatible with materials in much of the existing infrastructure-gas station pumps and storage tanks, pipelines, tanker trucks, ocean going tankers, etc.,[88] and thus may require significant quantities of equipment to be duplicated or modified.8g It will require new vehicles, because conversion of existing vehicles will be too expensive because of the materials compatibility problems and the need for changes in onboard computers and other components. And, because of methanol's low volumetric energy density, more trucks, ships, and pipeline capacity will be needed to move an amount of fuel equivalent to the gasoline replaced.

In gauging infrastructure costs for a shift to methanol or other alternative fuels, it is important to factor in potential *gasoline* infrastructure investments that might be avoided if methanol or other fuels absorb some of gasoline's market share. This potential exists because many analysts expect U.S. gasoline consumption to grow significantly over the next two decades; the Energy Information Administration, for example, projects a 0.6 percent/year increase, from 7.34 mmbd in 1989 to 8.38 mmbd by 2010.[90] This growth, and interregional shifts in gasoline consumption, are likely to require building significant amounts of new pipeline capacity, truck transport capacity, and other infrastructure elements unless use of alternative fuels offsets the requirements.

The *pace* of introduction of the alternative fuels will be a critical factor in determining the extent to which infrastructure costs for the new fuels will be offset by reductions in gasoline infrastructure requirements. Similarly, government actions to slow the growth in fuel consumption, in response to air pollution, global warming, and energy security issues, can alter the potential for infrastructure offsets. Congress currently is discussing the imposition of new fuel economy regulations for automobiles and light trucks, in response to global warming and energy security concerns. And some of the nonattainment areas where much new alternative fuel infrastructure would be built have been experimenting with transportation control plans to hold driving down below forecasted levels. Success for either or both strategies could hold down the growth in vehicle miles traveled and improve the efficiency of travel, reducing gasoline demand and thus reducing the potential for infrastructure offsets. On the

[88]Chem Systems, Inc., "A Briefing Paper on Methanol Supply/Demand for the United States and the Impact of the Use of Methanol as a Transportation Fuel," prepared for the American Gas Association September 1987.

[89]Several companies in the United States are now offering EPA-approved in situ lining technology so that existing *gasoline* storage tanks can be made methanol-compatible for about .$4,000/tank. G.D. Short, ICI Products, personal communication, January 1990.

[90]Energy Information Administration, *Annual Energy Outlook 1990, DOE/EIA-0383(90),* January 1990, table A.3.

other hand, if gasoline demand stabilizes, there may be some potential for modifying gasoline equipment, such as storage tanks, to accommodate methanol at lower cost than building new facilities. Generally, the *incremental* costs of alternative fuels infrastructure, over and above what would have been spent anyway for gasoline infrastructure, will be lower if alternative fuels reduce the *growth in* gasoline demand rather than actually reducing gasoline demand from current levels.

The Department of Energy has estimated the U.S. infrastructure requirements (that is, excluding overseas production facilities and shipping infrastructure) for methanol displacement of 1 mmbd of gasoline. The analysis assumes that a fleet of flexible fuel vehicles (FFVs) using M85 will accomplish the displacement.[91] DOE estimates that total costs for storage tanks, loading and other equipment at existing marine-based petroleum product terminals, tank trucks, and approximately 91,000 service station conversions will be $4.8 billion, $4.1 billion of which is used for the service stations.[92] At a $275/vehicle incremental cost for mass-producing FFVs, the total additional cost for the vehicle fleet is $16.6 billion. As discussed above, distribution costs would change somewhat if all new tankage and other equipment were required (because of increasing total fuels demand) rather than being able to convert existing facilities from gasoline use to satisfy part of the infrastructure demand. In its study, DOE implicitly assumed that gasoline demand would have been stable without the introduction of alternative fuels, in contrast to the Energy Information Administration projection. Also, the estimate for infrastructure costs is extremely sensitive to the assumptions made about vehicle costs. Unforeseen problems with excess wear, formaldehyde control, and so forth could easily push costs higher; cost savings obtained from engine downsizing and associated vehicle weight savings, if efficiency and power gains are at the high end of the potential range, might just as easily push costs downwards.

ENERGY SECURITY IMPLICATIONS

With relatively generous worldwide reserves of crude oil available, current interest in gasoline substitutes is based not on the threat of actual physical scarcity of oil but on the potential for supply disruptions and large and sudden increases in price. This concern is heightened by the concentration of oil reserves in the volatile Middle East and the expectations of many analysts that OPEC will regain its former large market power in the 1990s. Development of alternative fueled systems—vehicles, supply sources, and distribution networks—is viewed as both a means to reduce dependence on oil, lowering the economic impact of a disruption and/or price rise, and as leverage against oil suppliers—''raise the price too high, or disrupt supply, and we will rapidly expand our use of competing fuels. ''

Analysts have argued both for and against the proposition that a U.S. turn to methanol would provide an important strategic advantage. OTA concludes that, under some circumstances, the addition of methanol to the U.S. transportation fuel inventory could improve U.S. energy security for at least a few decades, even though most or all of the methanol would be imported. (The major security benefit would be to reduce U.S. exposure to economic damages from a future oil supply disruption and/or price shock.) Longer term prospects depend on the scale of worldwide natural gas demand and the course of future gas discoveries. The degree of security benefit will depend primarily on the scale of the program and the nature of the vehicles, with flexibly fueled vehicles coupled with an extensive methanol distribution network offering maximum benefits. The benefit may also depend on the extent that the United States acts to promote the entry of more secure suppliers into emerging methanol markets. Because the transition to methanol fuels will be expensive, and because methanol could remain more expensive than gasoline for many years, its energy security and other potential benefits, in relation to its costs, should be weighed carefully against alternative means to achieve the same benefits.

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[91] U.S. Department of Energy, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Five. Vehicle and Fuel Distribution Requirements (Draft), Office* of Policy, Planning, and Analysis, January 1990.

[92] Ibid. The analysis assumes that all delivery is by tanker truck, which can service 75 percent of the U.S. population from the terminals. Achieving 100 percent access to methanol would require pipeline transport and additional cost. Part of the infrastructure is converted from gasoline, part new—for example, half of the tankage needed is assumed to be converted.

Table 3-4—Market Shares of Oil and Gas Production and Reserves by Region in 1985
(percent)

	Total natural gas production	Total natural gas reserves	Total oil production	Total oil reserves
Canada	5.2	2.9	3.1	1.0
United States	26.1	5.7	18.9	3.8
OPEC	14.6	31.6	29.2	67.9
Central/South America	4.1	3.7	8.8	9.1
Western Europe	10.1	6.5	7.4	3.1
Eastern Europe & U.S.S.R.	34.1	43.5	20.8	8.7
Africa	0.6	0.6	3.0	1.3
Far East & Oceania	4.4	4.8	7.8	4.7
Other	0.8	0.6	0.9	0.9
Total	100.0	100.0	100.0	100.0

SOURCE: U.S. Energy Information Administration, International Energy Annual 1986, DOE/EIA-0219(86), Oct. 13, 1987.

As discussed in chapter 2, the scale of a methanol program is critical to its national security benefits because the benefits of a small-scale program may be correspondingly small-unless, of course, such a program **was** merely a first phase in a larger effort.

At a larger scale, a methanol fuels program could reduce the United States' overall demand for oil and its level of oil import dependence. Under certain restricted circumstances,[93] this could reduce the primary economic impact of an oil disruption if the prices of methanol did not rise in lockstep with oil prices. Also, **a** large-scale methanol fuels program—perhaps coupled with similar programs in other countries--could reduce pressures on world oil supplies, reduce OPEC market dominance, and lessen the potential for future market disruptions. Further, the threat of rapid expansion of the program would be far more credible after the basic distribution infrastructure was widely emplaced and economies of scale achieved.

Even if it is used in large quantities, methanol is strategically attractive as a gasoline substitute only to the extent that the potential supply sources are different from the primary suppliers of crude oil, and/or to the extent that natural gas markets remain more open than oil markets to competitive pressures. Table 3-4 compares the market shares of oil and gas production and reserves by region in 1985. The primary difference between the distribution of oil **reserves** and gas reserves is that Eastern Europe and the Soviet Union hold a dominant position in gas but not in oil, and OPEC holds an important position in gas but not nearly to the same extent as in oil. A recent study of potential methanol supply sources concludes that, assuming widespread methanol-for-gasoline substitution, OPEC and the Eastern Bloc nations would likely capture at least 75 percent of the supply market.[94]

Table 3-5 shows the proven reserves and estimated exportable surplus gas[95] of the nations holding large gas reserves. This distribution of potential methanol suppliers does imply a diversification of market share in liquid fuels away from OPEC and the Middle East. However, policymakers may be wary of the potential shift in market power towards the Eastern Bloc. On the other hand, the addition of new sources of transportation fuels, even if they are not major market powers, would add somewhat to the stability of the world market for transportation fuels. Also, the changing political status of Eastern Europe could radically alter the U.S. strategic view of the effect of the development of economic ties between the Eastern Bloc and western energy markets, from sharply negative to sharply positive. Finally, widespread use of methanol as a transportation fuel in Eastern Europe would remove an important source of supply pressure on world oil markets.

There is some question about how to interpret the estimates in table 3-5. Even if the distribution of methanol suppliers evolved in proportion to exportable surplus reserves, the market power associated

[93] The bulk of methanol vehicles would have t. be dedicated vehicles, creating basically a separate market for methanol, and feedstock gas prices would also have to be separated from oil prices. See the discussion in app. 3A.

[94] Chem Systems, Inc., op. cit., footnote 88.

[95] Estimates of exportable surplus account for commitments to domestic markets, including existing and planned chemical plants.

Table 3-5—Proved Gas Reserves and Exportable Surpluses

	As of Dec. 31, 1987 (Tcf)	
	Proved reserves	Exportable surplus
U.S.S.R.	1,450	809
Iran	489	158
United States	187	0
Abu Dhabi	184	155
Qatar	157	152
Saudi Arabia	140	0
Algeria	106	40
Canada	95	12
Venezuela	95	14
Norway	89	56
Nigeria	84	67
Australia	79	53
Mexico	76	0
Indonesia	73	46
Netherlands	64	10
Malaysia	52	29
Other Middle East	122	0
Other Asia Pacific	113	25
Other Europe	77	3
Other Latin America	61	31
Other Africa	56	6
Total world	3,849	1.666

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

with this distribution maybe considerably different than in the oil market. Because the degree of development of known resources is much lower for gas than for oil,new gas production capacity may be obtained from many more sources than can new oil production capacity, at least for the next several decades. For the foreseeable future, therefore, any concerted effort on the part of a group of nations to manipulate natural gas supplies and prices would likely elicit a quick supply response from new sources. This should weaken the market power of the Middle Eastern and Eastern Bloc nations even though they hold the preponderance of gas reserves. Also, the substantial number of undeveloped gasfields around the world gives the United States the opportunity to promote development of secure methanol sources by targeting investment to selected areas. Such a strategy would be a departure from past trade policy but would respond to existing national security concerns. Finally, because current world natural gas reserves are largely the outcome of oil exploration, it is quite possible that intensive exploration aimed at locating natural gas would both add substantially to total reserves and shift the proportion of reserves away from the current imbalance illustrated in the table.[96]

An important factor in determining the national security implications of a substantial shift to methanol use in transportation is the *magnitude* of worldwide development of gas resources. At moderate levels of development, there will always be available potential sources of incremental supply to block market manipulation; high levels of development might eventually tighten supplies, giving market power to the remaining holders of large reserves. The magnitude of development will in turn depend on the scale of any shift to methanol in the United States, the extent to which the shift becomes a worldwide phenomenon, and the development of other uses of natural gas in the world market. A worldwide surge in natural gas development seems quite possible given concerns about the greenhouse effect and urban air pollution,[97] growing recognition that natural gas is a cleaner fuel than its fossil competitors, and recent improvements in gas combustion technologies (for example, more efficient gas turbines for electricity generation). Even if such a surge accelerated a trend towards market tightening, however, this would not occur for several decades at the earliest, and might not occur for far longer if new gas production technologies open up new, large gas resources to development.

The capital-intensive nature of methanol production will also play a role in the relative energy security of methanol supplies (compared to gasoline). Because the country-of-origin must invest in facilities similar to those required for crude oil export (e.g., drilling pads, pipelines, docks) *plus* a methanol production facility that may approach a billion dollars in capital costs (for a 10,000 million-ton-per-day (MTPD) facility),[98] it will have a greater

[96] The potential for finding large new gas reserves is a controversial issue. The group at the United States Geological Survey working on world oil and gas resources generally does not believe that enough new giant gasfields will be found to greatly affect the current distribution of world gas reserves and projected resources (Charles Masters, USGS, personal communication, Mar. 3, 1990).

[97] As noted elsewhere, combustion of natural gas produces less carbon dioxide than competing fossil fuels *per unit Of energy.* Consequently, substituting natural gas for coal or oil will tend to yield greenhouse benefits unless increased gas development creates significantly higher gas leakage to the atmosphere. Because methane-the key constituent of natural gas—is a far more potent greenhouse gas than is CO_2, increased leakage can null@ the combustion benefit.

[98] U.S. Department of Energy, op. cit., footnote 69.

financial stake in maintaining stable fuel shipments than a crude oil exporter. This possible advantage must be tempered, however, by the growing tendency of oil suppliers to invest in refinery capacity and ship petroleum products, including gasoline, instead of lower value crude. To the extent that this trend continues, there may be little difference in this regard between gasoline and methanol. Also, the security advantage offered by the increased financial stake of the suppliers maybe offset somewhat by the possibility that a methanol production facility or refinery may be more vulnerable to terrorism or internal disorder than a simpler crude oil supply system. The trade-off between physical security disadvantage versus financial security advantage is not particularly obvious.

The potential advantage to supply security stemming from the capital intensity of the methanol supply system can be weakened if methanol purchasers agree to financial arrangements that shift plant ownership--and financial risk-to them. Although U.S. ownership of manufacturing facilities in other countries may be attractive in other circumstance, this is not likely to be the case here. Because a methanol plant will be tied to its local gas supply, a supplier country does not have to control the methanol plant to control methanol supply.

Aside from questions about methanol supply, the nature of methanol fuel development in the United States will decide methanol's energy security benefits. For example, there are substantial security differences between a strategy favoring dedicated vehicles and one favoring flexibly fueled vehicles. A commitment to FFVs would allow the United States to play off the suppliers of oil against methanol suppliers, and would avoid the potential problem—inherent in a strategy favoring dedicated vehicles—of trading, for a portion of the fleet, one security problem (OPEC instability) for another (instability in whichever group of countries becomes our methanol suppliers). However, a fleet of FFV's attains important leverage against energy blackmail only if the supply and delivery infrastructure is available to allow them to be fueled exclusively with methanol, if this becomes necessary. Because FFVs don't *require* widespread availability of an alternative fuel supply network to be practical during normal times, adoption of an FFV-based strategy may not include full infrastructure development unless this is demanded by government edict. In fact, because dedicated vehicles are likely to have performance and emissions advantages over FFVs, most policymakers are likely to view FFVs as only a stopgap measure on the way to a dedicated fleet. Here, energy security considerations appear to conflict with air quality goals.

If methanol is eventually produced from coal, the energy security benefits would clearly be substantial—assuming that production costs at that time were reasonably competitive with methanol from natural gas. The previous discussion on methanol cost competitiveness concludes that coal-based methanol would be substantially more expensive than gas-based methanol at current prices and technology. A future shift to coal will depend on future natural gas availability and prices as well as further development in methanol-from-coal production systems that appear to offer substantial cost reductions. Unless security pressures grow strong enough to compel large government subsidization of methanol-from-coal production, a shift to coal seems unlikely for several decades at least.

METHANOL OUTLOOK AND TIMING

The difficulties of providing an infrastructure and the uncertain economics of methanol as a vehicle fuel-especially in the early stages of its introduction when economies of scale cannot be achieved—imply that its widespread use in the general vehicle population is unlikely to progress without government promotion or substantial and lasting increases in oil prices. There is now considerable interest in methanol at the State and local level, primarily as a means to cut urban air pollution, and methanol use in certain dedicated fleets, especially in urban bus transit systems, seems quite possible. At the Federal level, Public Law 100-494 now allows vehicle manufacturers to use methanol vehicles as a means to reduce their measured fleet CAFE (corporate average fuel economy), making it easier to comply with Federal regulations. This would tend to promote the availability of methanol vehicles if manufacturers expect difficulty in complying with fuel economy requirements. Also, recently announced Administration policy towards urban air quality problems favors use of alternative fuels.

Research programs in the United States and elsewhere are working to improve the attractiveness of methanol-fueled vehicles; progress in these programs will increase the likelihood of methanol introduction. And success in reducing the costs and raising the efficiency of methanol production would have important implications for its eventual commercial success (as well as its value as a component of a strategy to lower the concentration of greenhouse gases). On the other hand, improvements in fuel use efficiency and engine control in today's gasoline-fueled light-vehicle fleet, coupled with indications that refiners can restructure the composition of gasoline to help reduce emissions, imply that policymakers may be able to tighten vehicular pollution standards somewhat. Such an action might remove some of the pressure for an urban switch to methanol-fueled vehicles.[99] Also, as discussed above, the magnitude of pollution benefits from a shift to methanol are somewhat uncertain. For M85, the most likely methanol fuel for the first generation of vehicles, available data on organic emissions is variable enough to support conclusions about the fuel's potential ozone benefits ranging from quite optimistic (a 20 to 40 percent 'per vehicle' benefit) to pessimistic (at best about a 20-percent benefit, to possibly an ozone increase). Although M1OO--straight methanol-would likely give clearer, and larger, ozone benefits, remaining questions about cold starting problems, formaldehyde controls, and the nature of any additives that might be used must be answered before benefits can be assured. Given the uncertainties associated with methanol costs and benefits and the advantage in existing infrastructure held by gasoline, the near-term future of methanol use in the U.S. vehicle fleet seems captive to government policy.

If methanol *were* given a' 'push' by government financial and/or regulatory incentives, it should be able to begin to play a significant role in automobile use within a decade. Methanol is among the most "ready' of the alternative fuels because: methanol for chemical use has been produced in quantity for many decades, and thus the production technology is well known; vehicular technology capable of burning M85 is readily available, and could be produced within a few years; methanol vehicles should perform as well as or better than existing gasoline vehicles, so market acceptance problems should be mild-the sole drawback is range, and larger but not excessive fuel tanks should solve this; infrastructure necessary to operate a methanol system is considerable, but the technology is commercially available; enough of its primary feedstock, natural gas, is readily available to support a major methanol system; and methanol costs, though uncertain and probably considerably higher than gasoline on a "per mile" basis (at least for the short term), still appear to be more favorable *with em-sting technology* than the other alternative fuel candidates aside from natural gas. The major uncertainties concerning methanol technology are the practicality of vehicles optimized for pure methanol, especially regarding their cold starting ability, and the prospects for long-term formaldehyde control. OTA's best guess is that these problems will not be 'show stoppers," but we recognize that the size of the roadblock represented by these remaining problems is an area of vigorous dispute within the alternative fuels community.

Over the long term--certainly beyond the year 2000, quite possibly considerably longer--methanol-from-coal or methanol-from biomass systems may become competitive. Given the interesting potential of coal hybrid systems, producing both methanol and electric power from one gasification unit, and of advanced biomass gasifiers, research into these areas appears well worth pursuing.

APPENDIX 3A: FACTORS AFFECTING METHANOL COSTS

The gasoline-equivalent costs of methanol at the retail pump are affected by a variety of factors at each stage of the fuel cycle, beginning with the gathering and other costs of the natural gas feedstock and ending with the efficiency of methanol-fueled vehicles relative to their gasoline-fueled counterparts. This appendix discusses some of the key factors affecting these costs, by stepping through the methanol fuel cycle, and presents likely cost (or performance) ranges for each factor. Costs at each fuel cycle stage will be affected by government policy, which affects risk and may affect other critical factors such as vehicle design, available subsidies, location of markets, and so forth; technological development and trade-offs made; timing (technology costs should decrease over time; feed-

[99] Although increased costs associated with such standards might improve methanol's economic competitiveness. In particular, gasoline restructuring may cost $0.10/gallon or more, depending on the severity of the changes.

stock costs may increase); magnitude of development; and a variety of other factors.

Feedstock Costs

Natural gas feedstock costs are an important component of methanol cost. For efficiencies typical of steam reforming--one of the primary methods of creating the synthesis gas from which methanol is formed--every 10 cent/MMBtu of gas costs contributes about 1 cent/gallon to methanol cost at the plantgate. Although advanced methanol production technologies are more efficient than current commercial technologies, the efficiency increase is not so strong as to markedly alter this relationship.

Consequently, assuming natural gas costs of $1.00/MMBtu implies that the feedstock represents about $0. 10/gallon in the cost of methanol. For each increase (or decrease) in gas costs of $0.50/MMBtu, methanol cost will rise (or fall) by $0.05/gallon.

Gas prices in the United States average about $1.80/MMBtu at the wellhead and about $2.50/MMBtu delivered to electric utilities,[100] the sector able to command the best prices. However, domestic natural gas has been in surplus for several years, holding down prices;[101] it is widely believed that U.S. gas prices will rise substantially over the next decade. Generally, lower 48 gas supplies are not considered an economically viable feedstock for significant increments of new methanol production.

Instead, most analysts believe that the most likely suppliers of gas for methanol will be either ‘remote gas”—gas that has no pipeline markets because of its location---or the very large reserves of gas located in several Middle Eastern nations, the Eastern Bloc, and a few other sites.

Some supporters of methanol use as a transportation fuel have speculated that natural gas that currently is flared or vented could serve as a feedstock for methanol production. The claimed advantages for using such gas are that it would be extremely inexpensive, having no other use, and that its diversion to methanol production would yield a strong environmental benefit. Gas that is flared adds to the atmosphere's burden of carbon dioxide without providing useful energy services; gas that is vented adds to atmospheric concentrations of methane, a far more potent greenhouse gas than carbon dioxide.

On further examination, it seems unlikely that flared/vented gas can provide a viable feedstock supply for methanol production. First, there is not a great deal of such gas. The worldwide volume of flared/vented gas in 1988 was about 3.3 trillion cubic feet (TCF) spread out among dozens of countries and hundreds of fields.[102] A single 10,000 metric tons per day (MTPD) methanol plant requires a gas supply of 100 billion cubic feet (Bcf)/year, and only a dozen countries exceeded that level in their entire national production of flared/vented gas.[103] Furthermore, there are ongoing efforts to drastically reduce this volume of wasted gas, so that volumes available in future years should be significantly smaller.

Second, a world-class methanol plant is highly capital intensive[104] and will demand reliable, high quality, long-lived gas reserves. Flared/vented gas—which is associated with oil production-generally is not highly reliable, nor is it particularly cheap. Variations over time in oil production levels and in gas/oil ratios can cause significant variations in gas production levels. And gathering and compression costs often are high.[105] Current experience with liquefied natural gas (LNG) facilities, of which only 1 of 11 is based solely on associated gas, confirm that developers prefer more reliable nonassociated gas supply for such projects.[106]

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[100] Energy Information Administration, *Natural Gas Monthly,* DOE/EIA-0130(89/05), May 1989, table 4.

[101] The United States *does* import substantial quantities of Canadian gas—over a TCF in 1989—but this was due largely to this gas' price advantage in certain regional markets, not to the unavailability of domestic supplies.

[102] Cedigaz, *Natural* Gas *in the World in 1988.*

[103] Ibid.

[104] According to DOE (U.S. Department of Energy, Office Of Policy, Planning, and Analysis, ***Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Three: Methanol Production and Transportation Costs,*** DOE/PE-0093, November 1989), an advanced scheme, fuel grade, 10,000 metric ton per day methanol plant will cost from 588 to 1,323 million dollars (1987 dollars), including infrastructure, depending on site location.

[105] Jensen Associates, Inc., "Natural Gas Supply, Demand and Price," Economics Workshop, Advisory Board on Air Quality and Fuels, State of California, February 1989.

[106] Jensen Associates, Inc., "Comment on the California Energy Commission Staff Draft 234 Report," May 3, 1989.

Assuming that either remote nonassociated gas or gas in large, established fields in the Middle East or Eastern Bloc will be the primary methanol feedstocks, what will be the likely price of such gas to the methanol producer? The *minimum* price, over the long term, will generally be the sum of the "cost of service," that is, the actual costs of producing and gathering the gas, and some bonus to compensate for resource depletion (although market vagaries can temporarily force prices below this, eventually they must rise to this price or supply will drop). The actual price, however, will depend on negotiations between the gas purchaser (the methanol producer) and gas owner (generally the government). Some governments will demand prices higher than the minimum, to reflect the lack of competition (there may be no competing supply sources with costs of service this low or with a similar competitive advantage, for example, easy access to markets or availability of skilled labor for methanol plant construction), high methanol or LNG prices that can sustain higher-than-cost-based gas prices (in trade jargon, the netbacks from product prices are higher than gas production costs), higher gas costs elsewhere, or simply an attitude that the gas is a valuable national treasure that should not be sold cheaply.

In this analysis, we seek to learn if methanol prices can be low enough to compete with gasoline or, if not, what the minimum subsidy would have to be to provide the supply desired. We have little interest in the outcome of negotiations about who receives the added profits from methanol prices that are higher than necessary to provide sufficient supply. Also, we do not believe that gas pricing will be based on "national treasure' '-type valuation by governments. In the past, governments as varied as Canada's, Algeria's, and Iran's *have* demanded such higher-than-market prices, but in each case they lost market share as a result. Given this history and what we perceive as a general worldwide movement towards acceptance of market realities, we suspect that gas supplies *will* be available at prices reflecting either supply costs or netbacks from product prices. Consequently, we believe that estimates of gas supply costs, coupled with an examination of potential netback gas prices obtainable from high LNG prices, provide an adequate measure of methanol feedstock costs for our analysis.

Based on available estimates of costs of service for various sites around the world, we conclude that gas prices of $1.00 to $1.50/MMBtu should be sufficient to obtain large volumes of gas for methanol production. Table 3A-1 presents estimated cost of service for a variety of sites. Some of the lower estimates-in particular, the Qatar and Australian NW Shelf estimates-reflect large credits for extracting natural gas liquids from the gas before sale. These credits are limited to portions of fields with particularly "wet" gas, and estimated cost of

Table 3A-I—Estimated 1987 Gas Costs and Prices (1988 dollars)

	cost of investment $/MMBtu/yr	service[a] $/MMBtu	Price $/MMBtu
North America			
Gulf Coast	[b]	b	1.42
Alberta	[b]	b	0.95
Prudhoe Bay	[b]	b	0.33
Asia Pacific			
Australia			
NW Shelf	4.34	0.62	0.94
Indonesia			
Sumatra	3.01	0.69	0.93
Kalimantan	2.00	0.46	0.93
Natuna	[b]	b	0.93
Malaysia			
Sarawak	3.87	0.84	1.17
Peninsula Offshore	4.39	1.01	1.17
Thailand	5.94	1.37	1.67
Bangladesh	[b]	.67	.82
U.S.S.R.			
Sakhalin/Yakutsk	[b]	b	1.69
Middle East			
Qatar	4.45	0.14	0.45
Abu Dhabi	2.85	0.66	0.80
Iran	[b]	b	1.00
Latin America			
Trinidad	4.40	1.01	1.06
Venezuela			
Gulf of Paria	6.52	1.50	1.83
Mexico			
Chiapas/Tabasco	[b]	b	0.74
Argentina			
Neuquen	[b]	b	0.97
Tierra Del Fuego	2.75	0.27	0.49
Chile			
Tierra Del Fuego	3.30	0.40	0.57
Atlantic Basin			
Norway			
North Sea	6.91	1.33	1.67
Troms	7.24	1.30	1.66
Nigeria			
Associated	[b]	0.89'	1.08
Nonassociated	[b]	0.48[c]	0.58
Cameroon	[b]	1.95[c]	2.37
Algeria	[b]		0.50
U.S.S.R.			
W Siberia (in Europe)	[b]	b	2.35

[a]Excluding tax
b No valid basis for estimate
World Bank estimate

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

service for future projects will generally be higher. Additional cost-of-service estimates for 13 similar sites show that 11 of the sites have costs between $0.65 and $1.30/MMBtu (the other two are much higher).[107]

Although the amount of gas theoretically available at these prices is large, we do not know how large a methanol market can be supplied by these less-expensive gas sources. Aside from the sheer lack of data about costs of gas service at more than a few sites, it is not clear how much competition there may be for the gas during the next few decades. If developing nations' economies grow substantially during this period, some of the gas will be used locally. Similarly, if world LNG trade grows rapidly, LNG will compete with methanol for some of this gas. The extent of this competition will depend not only on the size of the LNG trade but also on the value of the delivered gas, the value of the methanol, and the costs of methanol production and shipping.

If the worldwide demand for methanol grows large enough, and substantial quantities of low-cost gas find local or export markets, methanol gas supply sources will need to expand to higher cost gas. This possibility is critical because minimum methanol prices are likely to be set according to production and shipping costs for the highest cost marginal supplier rather than the average-cost supplier-at least when methanol is not in substantial oversupply.[108] Consequently, analyses of methanol costs for ''typical" supply situations are relevant to expected methanol prices only so long as the demand for methanol does not force higher cost methanol onto the market. When demand outstrips low-cost production capacity, prices must rise to allow higher cost suppliers to enter the market.

Production Costs

Aside from natural gas feedstock costs, key factors affecting production costs are the production technology, the size of the production facility, and the nature of the site. Current methanol plants produce chemical grade (highly purified) methanol using technology whose basic design is about 20 years old.[109] Large new fuel grade methanol plants could achieve substantial savings because of the economies of scale available if the size of the market allows plants as large as 10,000 MTPD capacity to be built, and because of the increased feedstock utilization efficiency and lower capital costs of advanced designs. The nature of the site is important because it strongly affects the capital costs—necessary infrastructure may or may not be available, labor and materials may have to be imported at high cost, working conditions will affect schedules, etc.—and affects the risk involved in building and operating the plant, which in turn affects the cost of capital (discussed below).

Although a 2,500 MTPD methanol plant is a large plant indeed, most analyses of future methanol costs focus on fuel grade methanol from plants sized at 10,000 MTPD. Increasing plant size gains modest but important scale economies; for example, doubling plant size from 2,500 to 5,000 MTPD reduces capital costs *per unit of methanol produced* by about 1O percent.[110] However, a single 1O,OOO MTPDplant produces over 3 million gallons of methanol each day, or over a billion gallons per year-enough methanol to fuel well over a million alternative fuel vehicles, and over 10 percent of current world methanol production capacity. Consequently, plants this large can only be built if many millions of methanol vehicles are in service or if there is an assured market based on a prior trade agreement.

Aside from increasing plant size, methanol producers can reduce costs by shifting to advanced technologies that cut capital costs, decrease total energy use, and increase plant efficiency. A variety of technologies are available that can reduce costs both in the production of synthesis gas, the first step of the methanol production process, and the catalytic transformation of the synthesis gas into methanol.

The Department of Energy (DOE) has calculated methanol production and delivered costs for large (10,000 MTPD), "advanced scheme" plants producing fuel-grade methanol. For relatively remote sites (e.g., Australia, Indonesia, Malaysia) with no or only partial current infrastructure, and gas costs of

[107] The estimates are confidential.

[108] If methanol is in oversupply—e.g., if methanol demand declines, or methanol production capacity is overbuilt-prices may drop below total production costs to the marginal costs of production, *i.e.,* operating costs plus gas and shipping costs, with no allowance for capital recovery.

[109] G.D. Short, ICI Americas, personal communication September 1989.

[110] U.S. Department of Energy, Office of policy, Planning, and Analysis, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Three: Methanol Production and Transportation Costs,* DOE/PE-0093, November 1989.

$1.00/MMBtu, methanol production costs range from $0.33 to $0.41/gallon for a 20 percent capital recovery rate (CRR). If some of the more developed nations with large gas supplies, e.g., Saudi Arabia, Algeria, and Iran, chose to price their gas equally low, they could produce methanol at closer to $0.30/gallon or even a bit lower for the same CRR.[111]

The advanced plant design selected for this analysis achieves an estimated 25 percent reduction in plant capital costs over a standard scheme plant of the same capacity (10,000 MTPD),[112] as well as a 10 percent savings in feedstock costs because of its higher efficiency. Translated into costs per gallon of methanol produced, moving from current to advanced technology saves $0.06 to $0.07/gallon at a CRR of 20 percent, and $0.09 to $0.10/gallon at a 30 percent CRR.

The *overall* savings associated with building at a very large scale, producing fuel-grade rather than chemical grade methanol (this allows fewer distillation steps to be used), and using advanced technology are very substantial. According to the DOE analysis, moving from a current technology, chemical-grade, 2,500 MTPD facility to an advanced technology, fuel-grade, 10,000 MTPD facility saves $0.12 to $0.22 for each gallon of methanol produced, depending on the site chosen, assuming 20 percent CRR. This implies that production costs are likely to drop sharply as a methanol fuel program matures—as early plants using standard technology at 2,500 MTPD scale eventually give way to much larger plants using advanced technology. The time frame over which this process will occur depends on the confidence of developers in the new technologies, the rapidity of the movement of methanol vehicles into the fleet, the vehicle technology (fuel flexible or dedicated) chosen, and developer confidence in continued growth of methanol demand.

Production costs could be further reduced over the long term, though uncertainty is very high because some of the most promising new processes have not gone beyond bench-scale application. In particular, current research in the field aims to catalytically convert methane directly to methanol without producing an intermediate synthesis gas.[113] Successful development of such a process would likely reduce production costs substantially, as well as raising the conversion efficiency of the process—adding to methanol's attractiveness because improved efficiency would reduce the net production of CO_2 from the methanol fuel cycle. Lawrence Berkeley Laboratory currently is exploring the use of catalysts that mimic the enzyme produced by bacteria that ingest methane and convert it to methanol. Thus far, the researchers have managed only to produce methanol in very small quantities.[114]

A less radical approach to improved methanol production, under investigation at Brookhaven National Laboratory, uses a new catalyst suspended in a liquid[115] that will convert synthesis gas to methanol at low temperatures and pressures--100 °C and 100 psi compared to 250 °C and 750 psi required by conventional catalysts.[116] This catalyst also converts a high percentage of the synthesis gas on the first pass, reducing the need for recycling, and tolerates normal catalyst poisons, reducing gas cleaning requirements.[117] If perfected, the process should be both cheaper and more energy efficient than current production processes.

Significant uncertainty exists as well about production costs over the shorter term, even if uncertainties in feedstock costs and required capital recovery rates are ignored. Two important sources of uncertainty are, frost, the large variability in building costs at remote sites, and, second, uncertainty about the extent of savings that may be obtained by moving to emerging production technologies such as liquid-phase reactors.

[111] Ibid, table 1.14. In its analysis, DOE chose different values than $1.00/MMBtu for feedstock costs, and we have adjusted their production cost estimates to account for the difference in fuel costs.

[112] Ibid, figure I-4.

[113] J. Haggin, "Alternative Fuels to Petroleum Gain Increased Attention," *Chemical and Engineering News*, Aug. 14, 1989.

[114] Electric Power Research Institute, "Methanol: A Fuel for the Future," *EPRI Journal*, vol. 14, No. 7, October/November 1989.

[115] So-called "liquid-phase catalysts" are not new, and would likely be used in advanced scheme production plants built to satisfy a new transportation market for methanol.

[116] Electric Power Research Institute, Op. cit., footnote 114.

[117] Ibid.

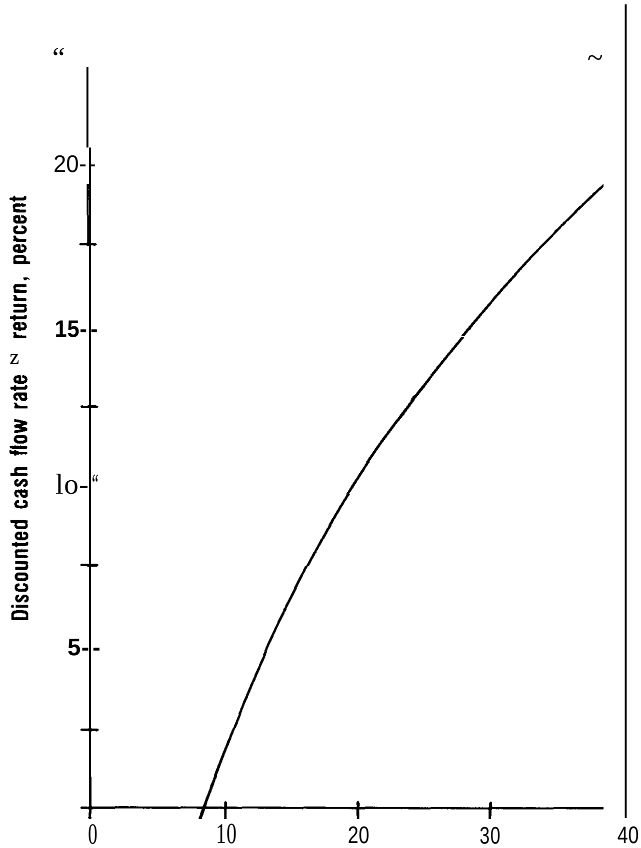
Capital Charges

Even if two competing analyses of methanol costs assume identical capital costs for plants with identical production capacity and output, the role that these costs play in total methanol costs—the capital charge, expressed in $/gallon of methanol produced—can still be quite different if the two analyses assume different returns on investment. In fact, available analyses of methanol costs *have* assumed substantially different rates of return, and these differences play an important role in explaining why the range of methanol costs appearing in the literature is so wide.

The capital costs of a methanol production plant can be translated into a capital charge assigned to each gallon of methanol by breaking down the cost into capital debt and investor equity, estimating the amount of annual earnings needed to both service the debt and provide a return on equity, and dividing these earnings by the number of gallons produced annually. Most analyses of methanol costs have simplified this calculation by assuming a discounted cash flow rate of return (ROR), which in turn defines a capital recovery rate (CRR)--the percentage of total capital costs, net of operating expenses, earned back each year-and applying either parameter to total capital costs. Figure 3A-1 provides a means of translating RORs into CRRs and vice versa.[118] As in the rest of the discussion, the RORs in the figure are real, after tax rates.

A number of studies have examined the sensitivity of methanol costs to assumptions about CRR and ROR, and these studies illustrate clearly that the costs are highly sensitive to these assumptions. For example, Acurex has examined changes in capital charges for methanol produced in 10,000 MTPD plants with differing assumed ROR. For a Texas-based methanol plant, capital charges range from $0.08/gallon for an assumed ROR of 10 percent, to $0.14/gallon for a 17 percent ROR, to $0.25/gallon for a 25 percent ROR.[119] Similarly, the Department of Energy has calculated that capital charges would vary from $0. 17/gallon with a CRR of 20 percent to $0.26/gallon for a CRR of **30** percent, for **a** 10,000 MTPD plant located in a developing nation with only partial infrastructure available.[120] For a lower CRR of 16.2—which is the baseline assumption used by the Environmental Protection Agency in

Figure 3A-l—Comparison of Discounted Cash Flow Rates of Return With Capital Charges Based on a Percentage of Total Fixed Investment Plus Working Capital



Basis: Natural gas reforming, site has well-developed infrastructure in an established industrial environment.

SOURCE: U.S. Department of Energy, Assessment ***of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report thru: Methanol Production and Transportation*** **Costs, DOE/PE-2093, November 1989.**

[118]U.S. Department of Energy, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Three: Methanol Production and Transportation Costs*, DOE/FE-0093, November 1989. The figure applies to a particular set of plant conditions: 3 years for construction 15 years of operation, 37 percent income tax rate.

[119]State of California Advisory Bored on Air Quality and Fuels, *Economics Report: Volume IV*, report to California Advisory Board on Air Quality and Fuels, Aug. 4, 1989 (Acurex Corp., primary contractor).

[120]Department of Energy, Technical Report Three, 1989, op. cit., footnote 110.

recent presentations[121]--capital charges would be $0.14/gallon for this plant.

As noted above, alternative calculations of methanol prices have used an extremely wide range of assumed CRRs and RORs for production plants at the same or similar sites, and this has led to both substantial divergence in estimated prices-as well as confusion among policymakers. At least a portion of this range can be traced to differences in technical judgments about the most likely return to be attained or demanded in specific circumstances. However, more of the range is attributable to differences in the basic assumptions underlying the price calculation. Differences include:

- *Timeframe.* Because the risks associated with methanol production are likely to change with time, the ROR or CRR required will change as well. In a free market scenario, for example, building a large methanol plant in the first decade or two after a fuel methanol market is established may be viewed by investors as quite risky. A single plant would represent a significant percentage of world methanol production capacity-as noted, a 10,000 MTPD plant would represent well over 10 percent of current world capacity—so that alternative markets for the plant's output would not be readily available, and overbuilding would be a significant risk. Later, when millions of vehicles are on-the-road and the overall market is much larger and more mature, the risks associated with a single plant might be greatly reduced. For these reasons, early plants will likely be of smaller capacity, i.e., 2,500 MTPD, and carry a high required ROR unless governments provide strong guarantees. Methanol RORs and capital charges will tend to go down with time, if other factors do not change. Analyses of methanol costs for the long term timeframe must not ignore the problem associated with the potentially expensive transition to a mature market.
- Is *the analysis calculating a probable price after the investment is made, or the price necessary to encourage that investment?* Some price calculations seek the most likely price of methanol assuming that some type of methanol-fueled system has been established; other calculations seek the price of methanol necessary to encourage investment in a methanol system, for example, the wholesale price necessary to encourage investors to build production plants. "What is the most likely price?" may be the appropriate question to ask when examining a scenario where government has required methanol plants to be built; "What is the necessary price?' is more appropriate when the analyst is questioning whether the plants will be built at all.
- *Do the capital cost estimates already incorporate risk?* Many business managers require higher earnings on proposed investments than seem justified by the underlying economics of the investment. This may result from their expectation that their engineers estimated project costs based on so-called "most likely costs,' that is, the costs that would occur most often if many identical plants were built. Managers demand high rates of return based on these cost estimates because there is comparatively little chance of costs being very much below the "most likely' level (savings of 10 or 20 percent might be considered unusual), whereas there are a number of circumstances—in particular, long construction delays—that could force costs to levels double or triple the most likely value. . and investors will demand higher returns to compensate for this risk. On the other hand, some engineers already have incorporated the risks in their estimate by calculating an "expected value" for capital costs, which averages the possible outcomes—including the potential for large cost overruns—and generally produces an estimate higher than the most likely cost.
- *What policy scenario is assumed? The risks* associated with a capital project—and thus the rate of return demanded--obviously depend on the vision of the future assumed by the analyst. An assumption of a free market without government interference might demand a high rate of return to compensate for a high perceived risk; however, there are free market situations that manage risk well, e.g., an explicit contractual agreement to share risks with pricing

[121] C.L. Gray, Director, Emission Control Technology Division, U.S. Environmental Protection Agency, letter of June 8, 1989 to R. Friedman, Office of Technology Assessment. Also, U.S. Environmental Protection Agency, ***Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel,*** Office of Mobile Sources Special Report, September, 1989.

formulas and other mechanisms. Government requirements for methanol vehicles, on the other hand, might lower risks by assuring the existence of market demand—although investors have been burned before by shifts in political support, and may be wary of assigning a low risk to a project dependent on government incentives or regulations. If government support is assumed, the nature of that support is critical to risk—a government requirement for dual-fueled vehicles without a requirement that methanol actually be used might do little to reduce risk; a trade agreement with price guarantees for a plant's output, on the other hand, could reduce the required rate of return to utility levels. Even with a trade guarantee, however, developers may recall the poor experience of natural gas producers in enforcing take-or-pay contracts with pipelines and still demand high rates of return. Also, policymakers should note that if the government provides market guarantees or establishes regulatory requirements for methanol use, the risk has not really been reduced, but instead it has been transferred, from producers to the government itself, to consumers, or to the regulated indus-Q .

. *Where is the methanol assumed to be coming from?* As discussed earlier, a number of countries, with differing physical, political, and social conditions, are available to provide methanol to U.S. markets. Factors such as the potential for political instability or natural disasters greatly affect capital risk.

Capital charges for methanol production can thus legitimately vary over a wide range depending on assumptions about the timing of the investment, government policies, and other factors. For example, in estimating the likely price of methanol after the system is in place, analysts may examine historical capital recovery rates of similar investments and apply these to methanol CRRs. On the other hand, for estimating the methanol price necessary to encourage investment, analysts may instead examine the industry decisionmaking process to establish the minimum "hurdle rate' for ROR, that is, the minimum estimated value of ROR necessary for eliciting a positive investment decision. Surveys of oil and chemical firms conducted by Bechtel Financing Services indicate that capital recovery rates and rates of return required by investors for new methanol plants will be much higher than historical rates of return for the industry. In particular, building such plants in developing countries would add substantially to required returns: risk premiums added to required aftertax rates of return for building in developing countries would be in the range of about 5 percent. Bechtel concluded that minimum rates of return for the sites they surveyed (Texas, Canada, Trinidad, Alaska, Saudi Arabia, and Australia) ranged from 14 to 19 percent.[122] Also, the firms indicated that assumptions of long project investment life, e.g., 20 years of full operations, are unrealistic, with perhaps 10 years of full operations being an acceptable assumption. Shortening assumed project lifetime has a major impact on estimates of the product costs needed to support the investment.[123] These rates and shortened plant lifetimes imply capital recovery rates ranging from ***30*** percent for even low-risk sites (Texas, Canada, Western Australia) to 40 percent or higher for the highest risk sites (Trinidad and Saudi Arabia). These rates seem astonishingly high compared to the 16.2 percent CRR assumed by EPA.

Changes in the perception of risk, and thus changes in required CRR, may change the order of preference for alternative sites. As capital risk increases, sites with high feedstock costs and high operating costs but low capital costs—in particular, sites in developed areas with considerable available infrastructure--become more attractive, and more remote sites, with low gas costs but high capital costs, become less attractive. Of course, estimates of breakeven methanol costs are not the only factor influencing site decisions. Plants with high capital costs and low operating costs may be judged more favorably than their breakeven costs seem to dictate, because these plants can at least maintain a positive cash flow if methanol prices plunge, whereas a less capital intensive plant with high operating costs may be forced to shut down in similar circumstances. And to make things even more complicated, it is

[122] Assumptions of analysis: aftertax return on investment, current dollars assuming 5 percent inflation. William E. Stevenson Bechtel Financial Services, Inc., letter of May 17, 1989 to Mr. Charles R. Imbrecht, Chairman, California Energy Commission. ROR values in the text are real, adjusted for the assumed inflation. Nominal RORs were 20 to 25 percent.

[123] For example, Bechtel computed methanol costs for a plant in Saudi Arabia to be 24 percent higher (36 cents v. 29 cents/gallon) when assumed years of operations were shortened from 20 years to 3 years of partial and 10 years of full operations.

highly unlikely that a site-by-site comparison of the same technology will represent a true decision, because plant designers will add capital cost to maximize efficiency at sites with high gas costs, but choose less efficient, but cheaper, designs at sites with low gas costs.

A further, crucial point is that some of the areas that may produce methanol are the same, or quite similar to, the areas where new petroleum refineries will be built to satisfy growing world demand for gasoline and other petroleum products. Some of the arguments for projecting high rates of return on new methanol facilities may apply quite well to projections of the rates of return that may be required for the new refineries.[124] If so, methanol priced high to reflect high investment hurdle rates may be competing with gasoline whose price has also risen, reflecting the same forces that drove up the methanol prices. On the other hand, if volatility in oil prices is considered a key source of uncertainty in future energy markets, it is worth noting that refineries have a built-in buffer from the effects of this uncertainty, because a reduction in product prices—e.g., gasoline prices--caused by a drop in oil prices will be accompanied by a corresponding drop in refinery feedstock costs; the methanol price drop that would likely accompany an oil price drop (assuming methanol were competing with gasoline for market share) might *not* be accompanied by a corresponding drop in natural gas feedstock costs. The resulting volatility in methanol profit margins may make anew methanol plant a riskier investment than a new refinery.

Long-Distance Shipping

Long-distance shipping costs are dependent on the type of carriers used. Although methanol currently is shipped at high cost in multicompartment chemical tankers, a large-scale expansion of methanol production and shipping would require the use of large, dedicated carriers. DOE calculates the costs of long-range transport by large, 40,000 deadweight ton (DWT) carriers to be about $0.06/gallon for a *6,000 mile* (one-way) distance and about $0.09/gal for a 9,000 mile distance.

Much larger tankers would be considerably more economical-about a third as much per gallon for 250,000 DWT, according to DOE.[125] There are questions about when such tankers could be deployed, however. Only one U.S. port (Louisiana) can handle tankers this large, and only a few ports (none currently on the East or Gulf coasts) can handle even 120,000 DWT tankers, Thus, either new port facilities would have to be built; or methanol could be transported to smaller carriers at a nearby port, perhaps in the Carribean (at additional cost), or at an offshore terminal; or offshore docking facilities with pipelines leading to onshore terminals would be necessary. Also, 40,000 DWT tankers can use the Suez and Panama Canals, and the larger tankers cannot. Furthermore, the amount of methanol embodied by one tanker load of 200,000 DWT--about 68 million gallons, or about enough methanol to fuel a fleet of 5 million vehicles for a week—implies that tankers of this size will become practical only when methanol demand has grown both large and stable--perhaps implying dedicated rather than flexible fuel vehicles (unless market stability is obtained by government regulations requiring methanol purchase within nonattainment areas or, less likely, by methanol prices consistently lower than gasoline equivalent prices. Thus, assumptions of very low long-distance shipping costs based on extremely large carriers are problematic, at least for a considerable time after any transition to methanol transportation fuels has begun.

Distribution Costs

Both gasoline and methanol will have differential distribution costs depending on location, and both fuels will be more expensive when their distribution costs are higher. Methanol has lower energy density than gasoline, however, so that methanol should be less competitive in areas with high "per gallon" distribution costs.

124 That is, the risks associated with the plants are largely associated with their location rather than with the nature of their technology or the markets for their products. Location-specific risks include risks of gas supply contract abrogation; force majeure events; exchange rate changes; currency inconvertibility; unfavorable tax law changes; forced sale without full compensation and expropriation (W.E. Stevenson, Bechtel Financing Services, Inc., "Capital Servicing Costs of Fuel Methanol Plants," presentation to California Energy Commission, May 3, 1989).

125 On the other hand, Energy and Environmental Analysis estimates shipping costs for 200,000 to 300,000 DWT carriers at $0.04 to $0.06/gallon, about twice DOE's estimate. Energy and Environmental Analysis, Inc., *Methanol's Potential as a Fuel for Highway Vehicles,* contractor report prepared for the Office of Technology Assessment October 1988.

126 U.S. Environmental Protection Agency, op. cit., footnote 121.

In its analysis of methanol costs, EPA has assumed that distribution costs will be $0.03/ gallon,[126] assuming that methanol will be delivered primarily to cities with ozone control problems, and these are primarily coastal port cities. EPA's distribution costs appear reasonable for large port cities. For inland cities with waterway access (e.g., St. Louis, Detroit), costs might be somewhat higher. For inland cities with no waterway access, distribution costs could be considerably higher than EPA's estimates, conceivably $0.05/gallon or more higher.

With one exception (Chicago), the worst (top 10 in highest l-hour concentrations) ozone nonattainment cities are coastal, port cities.[127] If methanol were used only in these cities, distribution costs would be low. However, many cities currently in nonattainment are inland, and some have no waterway access. Also, if methanol is introduced more generally as part of a strategy to lower oil imports, it will need to be available in areas with high fuel distribution costs. Because of its low energy density, methanol will be less competitive with gasoline in such areas.

Retail Markup

Markups of $0.09 to $0.12/gallon are common for gasoline.[128] If the financial risk in retailing methanol is similar to that of retailing gasoline, methanol's ''per gallon" markups should be no higher than this, and indeed may be lower, given the potential to pump methanol more quickly than gasoline (because of its low volatility), the possibility that methanol vehicles will carry larger storage capacity than gasoline vehicles (to compensate for methanol's lower energy density) and thus purchase more fuel per fillup, and the significant portion of station costs that are dependent on the number of fillups rather than the actual pumping volume per fillup.[129] Some analyses (e.g., EPA's) have assumed retail markups for methanol as low as $0.05/gallon, which implies that service stations' operating costs, and thus their markup, will depend more on energy content than on actual fuel volume sold.

Under certain circumstances, however, methanol's markup could be as high or higher than gasolines. For example, if methanol vehicles do not have additional storage, they will have shorter range than gasoline vehicles and will buy fewer Btu's of fuel at each fillup. In that case, retail markups for methanol would be expected to be similar to gasoline markups even if the market risk in retailing methanol is low. And if market risk is high, e.g., during the transition period when demand is growing, retailers are likely to demand a higher markup for methanol to compensate for the higher risks involved in installing methanol-compatible equipment and maintaining retail space during a time of uncertain demand for methanol. If flexible fuel vehicles are the primary users of methanol, unless these vehicles are *required* to use methanol within the service areas, both conditions—high market risk, and methanol and gasoline vehicles buying about the same volume of fuel per fillup--are likely, and retail markups for methanol should be higher than gasoline's $0.09 to $0.12/gallon. The original Administration plan for alternative fuels *did* contemplate a methanol refueling requirement.

Another part of markup is the taxes charged to methanol. Gasoline taxes average about $0.24/ gallon. If methanol is taxed strictly on a Btu basis, taxes should be about $0.12/gallon. With higher efficiency vehicles, this will reduce total tax revenues somewhat. If fuel tax revenues are viewed by government as a user fee for highways and traffic services, methanol taxes conceivably could be raised to equalize taxes between methanol and gasoline on a' 'per mile' basis. Given the likelihood that Federal and State Governments will be actively promoting methanol use, however, it seems likely that these governments will adopt a "per million Btu" rather than a "per mile" basis for taxation.

Methanol/Gasoline Conversion Factor

Gasoline and methanol are not compared directly on a ''gallon v. gallon' basis, because a gallon of methanol has only about half the energy content of

127U.S. Congress, Mice of Technology Assessment, *Catching Our Breath: Next Steps for Reducing Urban Ozone*, OTA-O-412 (Washington, DC: U.S. Government Printing Office, July 1989), table 3-2.

128M.A. DeLuchi, R.A. Johnston, and D. Sperling, "Methanol vs. Natural Gas Vehicles: A Comparison of Resource Supply, Performance, Emissions, Fuel Storage, Safety, Costs, and Transitions,' SAE TechnicalPaper # 881656, 1988.

129For example, the size requirement of the station is dependent on the total time needed per fillup. Even if pumping takes longer, the time needed to park, remove and replace the filler cap, and pay for the fillup is independent of fuel volume.

a gallon of gasoline.[130] To compare the prices of the two fuels, the methanol price must be multiplied by a factor that reflects both the difference in energy contents and any differences in the fuel efficiency of equivalent gasoline and methanol vehicles.

Factors for converting an M1OO cost into a ''gasoline equivalent' cost range from about 1.5 to 2.0, the latter reflecting methanol's actual volumetric energy content compared to gasoline's, the former reflecting a most optimistic view of the efficiency potential of a mass-produced dedicated M100 vehicle.[131] The lower conversion factors are based on the ability of methanol engines to run at a higher compression ratio (because of methanol's high octane level) and higher ("leaner") air/fuel ratio (allowed by methanol's higher combustion flame speed and other attributes) than equivalent gasoline engines, as well as on the cooling of the air/fuel mixture caused by methanol's high latent heat of vaporization.[132] The higher conversion factors are based on an assumed methanol vehicle weight penalty of up to 100 pounds for added fuel and a larger fuel tank (causing a 2 to 4 percent fuel economy penalty[133]), and the need for manufacturers to trade off fuel efficiency against other factors such as emissions and performance.[134] The emissions trade-off is especially important because methanol is being promoted largely as a means to reduce urban air pollution.

Assuming that the focus on emissions reduction will continue and that manufacturers will make numerous design trade-offs in the process of moving from laboratory and vehicle prototypes to mass production, OTA believes that a reasonable range for the methanol/gasoline conversion factor is about 1.67 to 1.82 (10 to 20 percent efficiency improvement) for the long term assuming optimized vehicles dedicated to M100, with both extremes of the 1.5 to 2.0 range appearing to be much less likely. Vehicles dedicated to M85 may have a range of conversion factors shifted slightly higher, e.g., towards lower efficiency, though the shift should be small. Flexible fuel vehicles are likely to achieve still smaller efficiency gains; a methanol/gasoline conversion factor of about 1.9[135] (equivalent to an M85/gasoline conversion factor of 1.7) appears reasonable. There is, however, some possibility that FFVs may attain higher efficiency running on methanol, but this would likely come at the expense of the vehicle's general performance running on gasoline; that is, the vehicles could be designed to run optimally on M85 or M100, with the ability to run on gasoline (although not as well as with a gasoline vehicle) retained for an emergency.

The fairly wide ranges of 'reasonable' costs for different segments of the fuel cycle, discussed above, lead to a wider range of potential methanol costs in comparison to gasoline costs, in equivalent terms. However, the cost ranges derived in the body of this report are actually narrower than the true range of costs presented in the ongoing debate about the wisdom of supporting methanol's entry into the transportation sector. It seems to us that some of the differences in the cost estimates presented in this debate—in particular, the tendency of some price estimates to range up to very high values-stem from a basic analytical misunderstanding exhibited by some analysts. In surveying a variety of potential plant sites, production technologies, and plant builders and operators, analysts have gathered a wide range of expected plant capital and construction costs, required investment hurdle rates, and other factors affecting methanol costs. This range will, in turn, lead to a very wide range of potential methanol costs and prices. *It is rarely appropriate to display this full range as "the range of likely methanol costs and prices." In* reality, those sites that lead to high infrastructure or raw material costs, those companies demanding very high hurdle rates, and those tech-

[130] Methanol contains about 56,600 Btu per gallon (lower heating value) versus 115,400 to 117,000 Btu per gallon (lower heating value) for gasoline. Source: S.C. Davis et al, *Transportation Energy Data Book: Edition 10*, Oak Ridge National Laboratory report ORNL-6565, September 1989; and David Kulp, Ford Motor Co., personal communication.

[131] A 1.5 conversion factor reflects a greater than 30 percent improvement in efficiency compared to the efficiency achieved by a comparable gasoline-powered vehicle. EPA has based its economic analysis of methanol on a 30 percent efficiency advantage (EPA, Office of Mobile Sources, *Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel,* September 1988).

[132] Energy and Environmental Analysis, Inc., op. cit., footnote 125.

[133] Ibid.

[134] For example, hi@ compression engines tend to produce more NO_x, and very lean air/fuel mixtures, while reducing engine-out NO_x levels, will interfere with the performance of reduction catalysts designed to reduce tailpipe NO_x emissions.

[135] Industry analysts believe that FFVs will have a 4 to 7 percent efficiency advantage at equal performance, implying methanol/gasoline conversion factors of 1.87 to 1.92.

nologies with high expected capital costs or operating costs will not play a role in a realistic methanol supply scenario *unless the* sites, companies, and technologies that will produce lower cost methanol cannot produce enough supply to satisfy methanol requirements. For example, the construction industry may require anywhere from 20 to 30 percent hurdle rates for methanol investments. It is not appropriate, however, to use 20 to 30 percent as the appropriate hurdle rates in cost analysis (or 25 percent, the arithmetic average, or whatever the weighted average is) unless the companies requiring the lower end of the hurdle rates represent only a small fraction of industry construction capacity. The group of companies actually willing to bid on methanol construction is likely to be restricted to those that will accept perhaps 20 to 25 percent rates; the "30-percenters" probably won't bid.

This suggestion to ignore the high end of the cost range applies *only* when the range reflects differences in known quantities-that is, different companies' actual hurdle rates, or known differences in construction costs between alternative technologies—rather than differences due to uncertainty, e.g., a cost range that reflects the lack of experience in building a particular technology under untried circumstances.