THE EMISSION CHARACTERISTICS OF METHANOL AND COMPRESSED NATURAL GAS IN LIGHT VEHICLES

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APCA
FOUNDED IN 1907

The Association
Dedicated to
Air Pollution Control and
Hazardous Waste Management

For Presentation at the
81st Annual Meeting of APCA
Dallas, Texas
June 19-24, 1988

INTRODUCTION

Research into non-petroleum fuels in the late 1960s was motivated by the realization that combustion of gasoline and diesel fuels was responsible for a large portion of urban air pollution. Alternative fuels became an energy policy issue in the 1970s for two reasons: the oil price fluctuations of that decade emphasized the need for the nation to reduce its dependence on imported petroleum, and emissions from new gasoline-fueled vehicles were substantially reduced through the application of progressively more sophisticated control systems. Today, air quality concerns have renewed interest in alternative fuels, with the Environmental Protection Agency (EPA) and State regulatory agencies alike examining every opportunity to reduce emissions.

EPA, under the auspices of the Alternative Fuels Working Group that includes representatives from agencies and departments throughout the executive branch, recently released two documents that evaluate the potential of alternative fuels to improve urban air quality.[1,2] The Department of Energy (DOE) is currently undertaking a comprehensive 18-month study of alternative transportation fuels.[3] The States of California, Colorado, Arizona, and New York either have or are considering alternative fuels programs in selective urban areas. Pending before Congress are several pieces of legislation relating to alternative fuels, with provisions ranging from corporate average fuel economy incentives to automotive manufacturers for selling vehicles capable of operation on non-petroleum fuels to Clean Air Act mandates that centralized vehicle fleets in certain nonattainment areas begin to purchase new vehicles that operate on alternative fuels.

Alternative fuels can be divided into two distinct groups: those that could completely replace gasoline and those that can be low-level additives to gasoline. Much of the current near-term interest, particularly in urban areas with very high levels of carbon monoxide pollution, is in gasoline additives such as ethanol, methanol, and methyl tertiary butyl ether (MTBE), which can be added to the current gasoline pool and provide immediate carbon monoxide reductions. This paper will address two alternative fuels—methanol and compressed natural gas (CNG)—that EPA believes have the potential to be able to completely replace gasoline and/or diesel fuel, at least in certain new vehicle applications, in the near term. Liquefied petroleum gas (LPG) and ethanol are not addressed in this paper because of long-term supply constraints. There are, of course, other fuels that could provide very significant urban emission reductions, such as electricity and hydrogen, but there appears to be little likelihood that these fuels will be feasible in the near term (except for extremely limited applications).

The primary purpose of this paper is to identify the emissions reductions available through the use of methanol and CNG in light-duty vehicles (i.e., passenger cars and light trucks), by projecting realistic emission factors for these fuels and comparing these to emission factors for gasoline vehicles. Since publication of the most recent EPA report on this subject (see reference 1), we have performed additional testing, particularly with CNG vehicles. A secondary purpose of this paper is to outline for the reader some of the non-emissions issues that are relevant in any overall evaluation of the potential of methanol and/or CNG to become primary motor vehicle fuels.

MOTOR VEHICLES AND AIR QUALITY

Ozone is our most serious long-term urban air quality problem. The ozone National Ambient Air Quality Standard (NAAQS) is a maximum one-hour level of 0.12 ppm, not to be exceeded more than three times in a three-year period. Ozone is not emitted directly, but is a product of a series of complex atmospheric processes involving hydrocarbons (HC), nitrogen oxides (NOx), and sunlight. EPA believes that for most urban areas HC control is generally the most promising strategy for reducing ozone levels. Motor vehicles are typically responsible for 30 to 50 percent of urban HC emissions. Based on data through 1986, there are 62 ozone nonattainment areas. As new, cleaner vehicles continue to displace older, more polluting vehicles and as EPA and States implement other controls, we expect many of these areas to move into compliance. Still, 20 to 30 of our largest cities will require major HC emission reductions (on the order of 40 percent or more) to reach attainment, and such reductions will be very difficult to achieve, especially since HC sources are a very diverse group. It must also be noted that recent studies have suggested that ozone levels near the NAAQS level of 0.12 ppm can affect otherwise healthy adults, and the Agency is currently reviewing these new studies to see if the standard ought to be lowered.

The NAAQS for nitrogen dioxide (NO_2) is an annual mean of 0.053 ppm. Motor vehicles generally emit about 40 to 60 percent of urban NOx (NO_2 and NO) emissions. While Los Angeles is currently the only city in nonattainment for NO_2, NOx control is still very much a priority. First, because NOx emissions have not been as tightly controlled as other emissions, continued economic growth will likely mean that overall NO_2 levels will begin to grow at some point in the future and some areas currently in attainment could be threatened with nonattainment. Second, for certain ozone nonattainment areas, EPA encourages NOx reductions as an additional ozone control strategy.

Carbon monoxide (CO) is the one urban pollutant that is almost exclusively a motor vehicle problem. It is a direct product of incomplete fuel combustion, which is much more prevalent with automotive engines than with stationary fuel combustion. Vehicles are generally responsible for 80 to 90 percent of CO emissions in urban areas. The NAAQS for CO is a 9 ppm eight-hour average and a 35 ppm one-hour average not to be exceeded more than once per year. There are currently 65 areas in nonattainment for CO, but the future situation is much more promising than for ozone. Because new gasoline vehicles emit much less CO than old vehicles, our projections show that all but about 5 to 15 areas will move into attainment by the late 1990s simply with the improvements brought about by our existing motor vehicle standards.

The final NAAQS pollutant of concern is particulate matter. Prior to 1987 the standard was expressed on a total suspended particulate basis, and the majority of EPA's data is still on this basis. Now the standard is expressed on an inhalable particulate basis, and considers only those particles less than 10 micrometers in diameter. The new standards of 50 micrograms per cubic meter as an annual mean and 150 micrograms per cubic meter for a 24-hour average are projected to be approximately equivalent in stringency to the older total suspended particulate standards.[4] Thus, while the exact number of nonattainment areas for the new standards is not known at this time, it is expected to be significant. While vehicles that use unleaded gasoline emit very low levels of particulate, diesel trucks and buses are important sources of inhalable particulate, particularly in central city areas. Diesel particulate is a special concern because of both its small size and hazardous composition. While this paper will only address light-duty applications for alternative fuels, it should be noted that EPA, bus engine manufacturers, and the transit industry are considering both methanol and CNG as possible fuels to meet much more stringent particulate emission standards that take effect for new transit bus engines in 1991.

ALTERNATIVE FUELS IN LIGHT-DUTY APPLICATIONS

Gasoline Vehicle Emissions

Over 95 percent of all fuel consumed in passenger cars and light trucks in the U.S. is gasoline.[5] Accordingly, gasoline-fueled applications are the appropriate context in which to consider alternative fuels with passenger vehicles.

Any projection of the future potential of alternative fuels to reduce gasoline passenger car emissions must recognize the very large reductions that have occurred over the last two decades. Congress and EPA established progressively more stringent passenger car emission regulations that culminated with the following standards that have been in effect since 1981 and which apply to EPA's Federal Test Procedure: 0.41 grams per mile (gpm) exhaust HC, 3.4 gpm exhaust CO, 1.0 gpm

exhaust NOx, and 2.0 grams per test evaporative HC (these standards must be met by all new gasoline and diesel passenger cars sold in the U.S., except for those sold in California, which has somewhat more stringent standards). These standards have provided the impetus for the development of sophisticated emission control technologies which have greatly reduced passenger car emissions, as shown in Tables I and II (all emissions data in this paper are over the Federal Test Procedure).[6] Table I shows that zero-mile emissions from new gasoline passenger cars have been reduced by between 84 and 98 percent between the years 1966 and 1986. It is well known that emissions tend to increase with vehicle age, and of course in-use emissions are the relevant issue. Table II shows that while in-use emissions reductions have not been quite as great as zero-mile emissions reductions, they have ranged from 62 to 88 percent, which is quite an achievement. These very large per mile emission reductions have resulted in lower overall motor vehicle pollutant burdens in the late 1970s and 1980s even with growth in the economy, number of vehicles, vehicle miles traveled per vehicle, etc.

It is essential to recognize that the regulatory program currently in place, with very stringent emission standards for gasoline passenger cars, provides a much more challenging context in which to project emission reductions for alternative fuels. When gasoline engines were basically uncontrolled in the 1960s, emissions were nearly exclusively a function of fuel type, and the substitution of fuels with inherently more benign properties such as methanol and CNG would clearly reduce vehicle emissions. Today, however, emissions are a primary design concern and are a function not only of the fuel being utilized, but of many other variables such as the level of the applicable emissions standards, the type of engine design, the specific calibration of various design parameters, etc. And, of course, emissions are just one of many items of interest to automotive engineers, and must always be viewed in combination with other important characteristics such as power, driveability, reliability, fuel economy, and cost. The relevant issue is not just whether emissions reductions are possible with a given fuel. The answer to that question is almost always yes, and in fact emissions from gasoline passenger cars could probably be reduced further at greater cost or with sacrifices in other aspects of vehicle performance. The more relevant issue is whether alternative fuels have properties that will inherently reduce emissions of certain pollutants, while at the same time obviating the need for more complex emission controls or sacrifices in other performance characteristics.

Relative Reactivity of Hydrocarbon Compounds

One concept that is critical to the understanding of the potential for methanol and CNG vehicles to reduce urban ozone levels is that of photochemical reactivity of organic compounds (organics is used here to refer to all unburned and partially

combusted fuel compounds, i.e., HC and oxygenated HC). Gasoline itself is a mixture of HC compounds, and the combustion of gasoline results in a large number of individual organic products. Although many of these organic compounds in gasoline exhaust are considered to be toxic, the primary justification for their regulation is their role in the formation of ozone. Because there are far too many organic compounds in gasoline exhaust to regulate individually, and because almost all organic compounds participate in ozone photochemistry, EPA regulates gasoline vehicle organics under HC standards for exhaust and evaporative emissions.

It has long been recognized that different organic compounds have different photochemical reactivities, i.e., each compound has a unique rate at which it reacts in the complex photochemical reactions that lead to ozone formation. Our present exhaust and evaporative HC emission standards implicitly assume that the mix of individual HC constituents remains fairly similar from one gasoline vehicle to the next, which is probably a reasonable assumption. But in the context of fuels that are considerably different than gasoline, it is no longer valid to simply assume that unburned fuel-related emissions will have the same overall photochemical reactivities as gasoline vehicle HC emissions.

One important characteristic of ozone formation is the reaction of organics with the hydroxyl radical (OH). Table III lists the OH rate constants for a number of organics, all of which are present in gasoline vehicle emissions except for methanol, normalized so that the reaction rate of butane, one common gasoline constituent, is unity.[7] This table can be used as one indicator of relative reactivity, while acknowledging that other parameters such as maximum ozone yield, NO_2 oxidation rate, and HC/NOx ratio are also important.

Methane, the primary constituent of natural gas and the dominant HC constituent in CNG vehicle exhaust (and which also exists in gasoline and methanol exhaust as well), is the simplest compound to address in this regard. As reflected by the relative reaction rate shown in Table III, it is considered to have such a negligible photochemical reactivity that EPA recommends that methane be excluded from State Implementation Plan emission inventories and regulatory controls.[8] EPA's current motor vehicle HC standards do in fact include methane, but EPA proposed a non-methane HC standard in the early 1980s and would likely reconsider this issue if certification of CNG vehicles appeared imminent. Past practice has been to assume that the methane component of CNG emissions has zero reactivity while the remaining HC have an overall reactivity similar to gasoline vehicle HC. This paper will follow that practice, and thus will focus on non-methane HC from CNG vehicles.

Methanol vehicle organics are a somewhat more difficult issue to address. The fairly limited data base suggests that when pure methanol is used as a fuel, the organic emissions are largely unburned methanol, with a much lower percentage of formaldehyde, and only trace amounts of a small number of HC compounds. When gasoline is added to methanol fuel to aid cold starting, then there is a higher percentage of HC emissions. As with CNG vehicles, it has been commonplace to assume that methanol vehicle HC have reactivity profiles similar to those of gasoline vehicle HC. But what about the relative reactivity of the unburned methanol and formaldehyde emissions?

Table III shows that methanol itself tends to have a relatively low reaction rate with the hydroxyl radical, while formaldehyde has a relatively high reaction rate. In order to assess the overall ozone impact of substituting methanol vehicle organics for gasoline vehicle organics, a number of computer simulation studies have been performed. These studies simulated air chemistry and transport within certain urban areas, and accounted for entrainment and dilution of local pollutant inventories into the urban airsheds. Based on these studies, EPA has developed a model that provides reactivity factors for methanol and formaldehyde relative to typical non-oxygenated HC from gasoline vehicles. This model is the subject of a separate paper being presented at this APCA session.[9] Based on this model, the average reactivity factors are projected to be 0.43 for methanol and 4.8 for formaldehyde. That is, on an equivalent carbon basis, the methanol molecule has only 43 percent of the potential to form ozone as the typical gasoline HC molecule, while the formaldehyde molecule has a 4.8 times higher potential. It must be emphasized that this model simplifies a very complex process that is best simulated by detailed computer programs. There are a number of caveats pertaining to the studies upon which the model was based as well as the model itself, which limit the scope of its applicability. While EPA believes it is useful as an analytical tool, EPA does not consider it to be appropriate for use in formulating standards or other binding regulatory decisions.

Methanol Vehicle Emissions

Methanol has long been considered to be an excellent motor vehicle fuel. Its simple molecular structure, high octane, wide flammability limits, high flame speed, and low flame temperature result in a fuel that can potentially be burned in a very clean and efficient way relative to petroleum fuels. Because methanol is such a different fuel than gasoline, it is helpful to distinguish between two types of methanol vehicles--current technology and advanced technology methanol vehicles. These two types of methanol vehicles would be expected to differ with respect to both engine design and vehicle emissions. Methanol is not considered to be a good fuel for retrofit programs because of its corrosive effect on many materials used in older vehicles.

Current Technology Methanol Vehicles. Current technology methanol vehicles utilize engines that are very similar to engines used in today's gasoline vehicles, with modifications to allow the engine to operate well, but not optimally, on a blend of 85 percent methanol and 15 percent gasoline (M85). These are the types of methanol vehicles currently involved in demonstration programs, and would have emissions and efficiency characteristics very similar to flexible fuel vehicles (FFVs) or variable fuel vehicles (VFVs) operating on M85.

There has been a very large amount of emissions data generated from current technology methanol vehicles over the last few years. EPA recently published a paper that summarized the current data base, which has been computerized and is available to interested parties.[10] The data base currently includes results culled from 13 different studies by EPA, the California Air Resources Board, and other organizations involving 10 different vehicle models and 64 different engine and vehicle configurations. Since many of these first generation methanol vehicle prototypes were not designed to meet any specific emission requirements, some vehicles failed either the CO or NOx federal emissions standards (both of which have been proposed to apply for methanol vehicles as well). The data base includes exhaust emission test data for 40 vehicle configurations that met the proposed methanol vehicle standards and Table IV gives the average and range for exhaust emissions over the Federal Test Procedure for these vehicles. The average mileage of these vehicles was on the order of 10,000 miles, although individual vehicle mileage ranged from zero to over 100,000 miles.

With respect to CO and NOx emissions, the data in Tables I, II, and IV are very instructive. It is clear that average current technology methanol vehicle emissions for CO and NOx are somewhat higher than the zero-mile emissions for current gasoline vehicles shown in Table I, but considerably lower than the 50,000-mile emissions for these gasoline vehicles given in Table II. Since the methanol vehicles had, on average, accumulated around 10,000 miles, CO and NOx emissions appear to be about the same for today's gasoline and methanol vehicles. This is to be expected for CO emissions, as CO levels are a strong function of air-to-fuel ratio and current gasoline and methanol vehicles have all generally been designed to operate at stoichiometric air-to-fuel ratios. Because methanol has a relatively low flame temperature, it has been speculated by some that methanol vehicles should yield lower NOx levels. With current NOx standards, however, we believe that manufacturers will likely trade off methanol's low-NOx characteristic to gain other benefits such as fuel economy, performance, or a less expensive catalytic converter.

The analysis of the ozone impact of organic emissions from current technology methanol vehicles is more complex. Instead of using organic emission factors from the data base (the data are much more limited for organics than for CO and NOx because of differences in measuring and reporting these emissions among various organizations), EPA has assumed that the organic emission levels of current technology methanol vehicles at zero miles would be the maximum levels permitted under the proposed methanol vehicle standards (which essentially require that methanol vehicles emit no more than the amount of carbon allowed from gasoline vehicles). The data base was utilized, however, to project the proper methanol to hydrocarbon to formaldehyde ratios. The projected total (exhaust plus evaporative) organic emissions, at zero miles, are 0.71 gpm methanol, 0.048 gpm formaldehyde, and 0.21 gpm HC.[10] Further assuming estimated in-use deterioration factors for organic emissions from methanol vehicles based on HC deterioration from current gasoline vehicles, Table V gives projected 50,000-mile organic emissions from current technology methanol vehicles and compares those levels to those given earlier for current gasoline vehicles. It can be seen that methanol vehicles emit greater amounts of methanol and formaldehyde, but less HC. Utilizing the reactivity factors given earlier in the paper of 0.43 for methanol and 4.8 for formaldehyde, and assuming that HC from methanol vehicles are similar to the HC from gasoline vehicles, the projected in-use methanol vehicle emissions would provide a 35 percent reduction in ozone producing potential relative to current gasoline vehicles.

The EPA model used to generate the relative reactivities is a simple generalization of the complex modeling that must be performed to project ambient ozone impacts. Nevertheless, the many studies that have been performed to date support the contention that methanol is less reactive than typical gasoline HC, and that therefore, as long as formaldehyde emissions are not excessive, current technology methanol vehicles will provide some ozone benefits. Our best estimates at this time are 30 to 40 percent reduction in peak ozone levels for a one-day episode. Research continues in many of these areas, in particular with respect to whether the lower reactivity of methanol will continue to provide ozone benefits in a multi-day ozone episode.

Advanced Technology Methanol Vehicles. There are reasons to believe that future engine and vehicle designs optimized to take full advantage of the combustion properties of methanol fuel could provide much larger emission benefits than those discussed above for current methanol vehicles. Current methanol vehicle prototypes are basically gasoline vehicles with only the most rudimentary modifications to permit methanol combustion. Gasoline cannot be combusted at a very high air-to-fuel ratio because of engine misfire and the fact that stoichiometric air-to-fuel ratios are necessary in order to allow the NOx reduction function of the catalytic converter to operate properly. But methanol's wide flammability limits,

high octane and higher flame speed allow it to maintain stable combustion at much leaner air-to-fuel ratios than gasoline. And methanol's low combustion temperature inherently produces low engine NOx levels. These properties suggest the possibility of an optimized lean burn, high compression methanol engine with good driveability which would be able to comply with NOx emission standards without the need for a reduction catalyst. Such an engine would likely provide very significant benefits in terms of low CO emissions and improved energy efficiency. Once again, we would not expect NOx emission reductions from such an engine design, although methanol's low-NOx characteristic facilitates the application of the lean burn concept.

One important issue with optimized methanol vehicles is fuel specification. All of the potential improvements discussed above could be achieved through the use of either M85 or pure methanol (M100) fuel. Almost all prototype and demonstration vehicles to date have utilized M85, both to improve cold startability and to provide a more luminous flame in case of a fire. But there are several tradeoffs associated with choosing between M85 and M100, including several with safety ramifications (for example, the addition of high-volatility gasoline makes M85 more likely to ignite and a more severe burn relative to M100). But most important for purposes of this paper, the use of M85 could significantly reduce the potential ozone benefits available from the use of methanol fuel. The use of M85 would increase total evaporative HC emissions, and would increase the proportion of reactive HC (as opposed to less reactive methanol) in both exhaust and evaporative emissions. Thus, from an environmental perspective, M100 is the preferred fuel. In order to utilize M100 a breakthrough in cold starting will be necessary, which has not been achieved to date, but is the focus of considerable research.

Toyota Motor Corporation is the first automotive manufacturer to make available vehicles utilizing many of the concepts discussed above. Toyota has recently commercialized the lean-burn concept on selected gasoline vehicle models in the Japanese market. They adapted the lean-burn concept to methanol by increasing the engine's compression ratio and making other changes to the intake system, the control system, and the exhaust catalyst. These modifications resulted in a methanol engine which yielded stable combustion at leaner air-to-fuel ratios with better energy efficiency, higher torque, improved driveability, and lower engine-out NOx emissions than the gasoline engine counterpart already available in the Japanese market.[11]

The 1.6-liter, 4-cylinder engine was installed in two Toyota Carina vehicles with inertia weights of 2250 lbs. The vehicles can operate under Federal Test Procedure conditions on both M100 and M85. These two vehicles have been loaned to EPA and the California Air Resources Board (CARB). All of the

emission data available for these two vehicles are given in Table VI.[12,13] The methanol and HC data combine both the evaporative and exhaust components, and so can be compared to the total HC values given in earlier tables. Since all of the Carina testing has been performed at low-mileage, it is appropriate to compare Table VI with Table I. As with the current technology methanol vehicle data, CO and NOx emissions are fairly similar. The trend of somewhat lower CO emissions and somewhat higher NOx emissions (though still below the EPA standard) is to be expected with the lean burn calibration.

Once again, the largest emissions benefits would be with respect to ozone producing potential. The data for methanol, formaldehyde, and HC emissions in Table VI include both exhaust and evaporative emissions expressed on a gram per mile basis. Since we do not have emissions data from the methanol Carina at high mileage, the only calculation that can be done is to compare the ozone producing potential of the low-mileage Carina to zero-mile gasoline vehicles. Using the reactivity factors developed earlier, the emissions from the Carina fueled with M85 would yield an 83 percent reduction in ozone producing potential, while the emissions from the M100 testing suggest a reduction of 86 percent compared to zero-mile gasoline vehicles.

It must be emphasized that even this Toyota Carina must be viewed as only a partial step toward an optimized methanol vehicle. It would be expected that future, more comprehensive research programs will provide vehicles with more favorable emission characteristics than those of the Carina. At this time, EPA projects that future advanced technology methanol vehicles could provide as much as a 80 to 90 percent reduction in ozone producing potential and significantly lower CO emissions, while simultaneously maintaining NOx emissions at levels comparable to current gasoline vehicles.

Related Concerns with Methanol Vehicles. Are the types of potential emission reductions discussed in the previous sections realistic? Will the automotive industry and consumers accept methanol vehicles? These questions are critical in any evaluation of the potential of alternative fuels to reduce motor vehicle emissions absent a legislative fuel use mandate.

Methanol is considered to be an excellent vehicle fuel by most of the automotive industry. It is a very efficient fuel, with current technology vehicles generally exhibiting slightly higher efficiencies and advanced technology vehicles projected to be considerably more efficient. Methanol almost always provides a boost in power output, although this can be traded off with efficiency. And being a liquid fuel that can be produced from natural gas and coal, there are no barriers to widespread supply and distribution of methanol.

Potential drawbacks associated with methanol include formaldehyde emissions, vehicle range, and cold startability. Formaldehyde's role in ozone formation has been included in earlier sections, but it is also of concern as a human toxin and carcinogen. EPA has analyzed the potential formaldehyde exposure scenarios in great detail, and has concluded that formaldehyde levels from current technology vehicles do not appear to present a serious public health concern.[14] Formaldehyde emissions from advanced technology vehicles should be much lower, possibly approaching the levels from gasoline vehicles. Formaldehyde emission levels will clearly continue to be a top priority for research by the industry and analysis by EPA and other regulatory agencies.

Methanol has only half the volumetric energy content of gasoline, so vehicle range is a serious concern. This debit is partially offset by methanol's increased efficiency (a small factor for current vehicles but more significant for advanced vehicles) and also by the addition of gasoline in the case of M85. Carrying approximately 50 percent more fuel on-board in traditional tanks seems unlikely, so the alternatives would be reduced range or the application of bladder tanks. The latter might permit the additional fuel to be carried on-board with acceptable safety characteristics.

Cold starting appears to be generally acceptable with M85, so is primarily an issue with M100. A breakthrough is thus necessary in order to be able to reap the maximum ozone benefits of M100, but is not necessary in order to achieve the significant benefits available from an advanced technology vehicle fueled with M85.

Compressed Natural Gas Vehicle Emissions

CNG consists primarily of methane, but also contains smaller quantities of other compounds such as ethane and propane. Its characteristics as a fuel are dominated by those of methane. Methane shares many of the same beneficial fuel characteristics of methanol: simple molecular structure, high octane, ability to combust under lean conditions, etc. The most obvious difference between methane and methanol (and current automotive fuels) is that methane is a gas, not a liquid. This is an advantage in terms of cold startability and cold start emissions. It is a disadvantage with respect to on-board fuel storage.

Unlike methanol, CNG does not pose problems with corrosion, and can be used in existing gasoline vehicles retrofitted with CNG conversion kits. These kits typically permit the vehicle owner to fuel with either CNG or gasoline, and are referred to as "dual fuel" conversion kits. The following section will discuss emissions from such vehicles. The succeeding section will address the performance of dedicated and optimized CNG vehicles.

CNG Dual-Fuel Retrofit Vehicles.   According to the American Gas Association there are approximately 30,000 dual-fuel vehicles operating in the United States.   It has been problematic for EPA to estimate the emissions impacts of such vehicles for several reasons: 1) there has been little reliable emission testing performed, particularly on conversions of recent computer-controlled vehicles, 2) the performance of conversion kits can vary greatly depending on kit manufacturer, the expertise of the installer, the quality of maintenance, etc., 3) the fact that the vehicle can operate on either CNG or gasoline means that overall emissions depend on the fuel that is actually used, and 4) the conversion process itself sometimes interferes with the gasoline combustion process and can lead to increased emissions on gasoline.   It should also be obvious that an engine that must be able to operate on fuels as different as CNG and gasoline cannot be optimized for either fuel (this is true with methanol flexible or variable fuel vehicles as well).

There has been considerable emissions testing of CNG dual-fuel vehicles over the years by EPA, California Air Resources Board, Colorado Department of Health, various Canadian agencies, and others.   Unfortunately, the great majority of this work has involved gasoline vehicles that were not designed to meet the emission standards that have been in effect since 1981.   It should be noted that the evidence is clear that the bulk of CNG dual-fuel conversions of pre-1981 gasoline vehicles resulted in reduced emissions.   But as noted earlier, the relevant baseline is now a gasoline vehicle with a more sophisticated emission control system meeting much more stringent emission standards.

EPA has performed a comprehensive literature search in order to compile a list of CNG dual-fuel retrofits involving 1981 and later model year vehicles that have been emission tested over the Federal Test Procedure on both gasoline and CNG at recognized test laboratories.   At this time we have only identified four vehicles that fulfill these criteria and they are listed in Table VII.   Two of these vehicles were tested by the California Air Resources Board.[15,16]   EPA is currently carrying out a cooperative test program with the American Gas Association and retrofit conversion kit research and marketing companies.   Two of the vehicles shown in Table VII were tested by EPA earlier this year and additional testing of vehicles from other companies is scheduled for later this year.

The data in Table VII clearly indicate that CNG dual-fuel vehicles offer very significant CO emission benefits, ranging up to 98 percent.   This confirms both theoretical expectations (better mixing of gaseous fuel, lean operation, lack of fuel enrichment for starting) and the data from programs involving pre-1981 vehicles.   The data for nonmethane hydrocarbons (NMHC) and NOx emissions are mixed.   NMHC emissions with CNG operation

were higher in one case, essentially equivalent in two others, and significantly lower in the final case, compared to gasoline operation. While the bulk of emissions data from tests of pre-1981 dual-fuel vehicles suggests that NMHC are generally lower with CNG use, it appears that this trend is not so clear with recent conversions. NOx emissions were increased on CNG operation with two of the four vehicles, and reduced slightly in the other two, relative to the NOx emissions on gasoline. This concern is heightened by the fact that spark timing is sometimes advanced on CNG operation in order to compensate for methane's lower flame speed and improve performance. CNG Fuel Systems provided data to EPA that suggested that NOx emissions would be increased further on its vehicle if timing were advanced.

These data suggest the need for further work in this area. Clearly, CNG dual-fuel vehicles can provide very large CO emission reductions when operated on CNG, but the NMHC and NOx emission impacts are far less clear. Related issues include the impact of the conversion on emissions when the vehicle is operated on gasoline, and the emission impacts of calibration changes that may be attractive to vehicle owners for improved efficiency and/or performance.

Advanced Technology CNG Vehicles. CNG is such a different fuel than gasoline that, as with methanol, there is every reason to expect that the optimum engine for CNG will be much different than today's CNG dual-fuel engine, and that such an engine would likely provide greater emission reductions and better performance and efficiency than are available from dual-fuel engines.

For purposes of efficiency and CO emissions, the optimum CNG engine should be a high compression, lean burn engine. CNG may have a slightly more difficult challenge in this regard, relative to methanol, because of its relatively higher flame temperature which increases NOx emissions. The issue is whether it will be possible to reap the efficiency and CO benefits of a high compression, lean burn design while maintaining NOx emissions within acceptable levels.

The most complete attempt to date to design, build, and evaluate an optimized CNG vehicle was undertaken by the Ford Motor Company in 1983 and 1984. Ford built and leased 27 dedicated CNG Ranger pickup trucks in cooperation with the American Gas Association and member utilities. These vehicles have been in service since that time.

The 2.3-liter gasoline engine normally used in the Ford Ranger was modified in several ways to improve it for CNG utilization including higher compression ratio and advanced timing. The final engine provided efficiency and performance very similar to that of gasoline Rangers. Emissions data from three low-mileage Rangers, two fueled with CNG and one fueled

with gasoline, are given in Table VIII.[17] These data correlate fairly well with those for dual-fuel vehicles discussed above. CO emissions for the two CNG Rangers represented a 99 percent reduction relative to the gasoline Ranger. NMHC emissions were 30 percent lower with CNG for both Rangers. NOx emissions were higher in both cases, still below the 2.3 gpm NOx standard that was in effect for light trucks certified in 1984 but higher than the NOx standard of 1.2 gpm that took effect beginning in 1988.

It is clear that the development of advanced technology CNG vehicles is in its infancy and that the Ford Ranger was simply the first attempt to try to optimize a CNG vehicle. It is very likely that future research will yield improvements in emissions, efficiency, and performance, but the question is whether all can be improved simultaneously. At this time EPA projects that future advanced technology CNG vehicles will likely be able to provide reductions of over 90 percent for CO emissions and should be able to provide large reductions in NMHC emissions as well. The magnitude of the NMHC reductions, and of any possible deleterious effects on NOx emissions are not clear at this time.

Related Concerns with CNG Vehicles. Cold startability and formaldehyde emissions, two of the major concerns with pure methanol as a fuel, should not pose problems for CNG. As a gaseous fuel it is generally considered to have good cold start characteristics, and emission testing has shown that formaldehyde levels from CNG vehicles are generally equivalent to or less than levels from gasoline vehicles.

Efficiency and performance of CNG vehicles are significant concerns, particularly with respect to dual-fuel retrofits. Each of the dual-fuel vehicles shown in Table VII suffered a major penalty either in terms of efficiency or acceleration performance. It can be seen in Table VII that the two vehicles tested by EPA had higher efficiencies on CNG than on gasoline after conversion, but in both cases the CNG efficiency was lower than the EPA certification fuel economy data for the pre-conversion gasoline vehicle. This trend is also confirmed by evaluations of pre-1981 vehicle conversions as well. Decreases in efficiency and/or performance are especially relevant with a dual-fuel vehicle because of the potential for the user to be motivated to use gasoline fuel, or to tamper with the CNG control system, both of which would likely increase emissions. Fortunately, there is theoretical and practical evidence (the Ford Ranger) that dedicated and optimized CNG vehicles could have at least equivalent efficiency and performance levels compared to gasoline vehicles.

Vehicle range is probably the issue that most concerns the automotive industry. Estimates are that current CNG storage tanks only provide one-sixth of the range of an equivalent size gasoline tank. Thus, this is not just a problem with dual-fuel vehicles where the CNG tanks must be added to a vehicle with an

existing gasoline tank, but is also a design problem even for dedicated and optimized vehicles. This is certainly one of the major reasons (along with fuel supply and distribution issues which cannot be addressed here) why many experts believe CNG is better suited for centralized urban fleet applications than for general automobile use.

CONCLUSIONS

Vehicle and engine designs available today that operate on methanol and CNG fuels can provide emission benefits. Current technology methanol vehicles (dedicated to operate only on M85 fuel and meeting proposed EPA emissions standards) are projected to reduce the peak one-day ozone producing potential of a motor vehicle by approximately 30 to 40 percent relative to that of a current gasoline vehicle. CO and NOx emissions would not be expected to be affected by the use of current technology methanol vehicles. CNG dual-fuel retrofit vehicles could provide very large CO reductions on the order of 80 to 95 percent compared to current gasoline vehicles. The NMHC and NOx emission impacts can vary greatly depending on the conversion. EPA believes it should be possible to ensure some NMHC, and thus ozone, benefits with CNG dual-fuel retrofits.

The emission benefits available from both methanol and CNG would be greater in dedicated vehicles optimized for the individual alternative fuels. From an environmental perspective, both fuels would be best utilized in high compression, lean burn designs that should yield very large NMHC/ozone and CO benefits. But with only very preliminary designs and data at this time, it is impossible to project specific emission reductions with any certainty. EPA believes reductions of up to 90 percent for both pollutants with both fuels may be achievable, although the validity of this conclusion is dependent on the resolution of specific engine design issues for both fuels.

Table I.   Average zero-mile emissions from gasoline cars
           (grams per mile over the EPA federal test procedure)

Model Year	Exhaust HC	Evap HC	Total HC	CO	NOx
1966	7.2	4.5	11.7	78	3.4
1986	0.23	0.55	0.78	1.2	0.54
Reduction	97%	88%	93%	98%	84%

Table II.   Average 50,000-mile emissions from gasoline
            cars (grams per mile)

Model Year	Exhaust HC	Evap HC	Total HC	CO	NOx
1966	8.1	4.5	12.6	89	3.4
1986	1.0	0.6	1.6	13	1.3
Reduction	88%	87%	87%	85%	62%

Table III.   Reaction rates with hydroxyl radicals relative to
             butane

Compound	Relative Reaction Rate
Methane	0.003
Methanol	0.40
Benzene	0.51
n-Butane	1.0
Toluene	2.4
Ethylene	3.4
Formaldehyde	3.6
Acetaldehyde	6.4
m-Xylene	9.7
Propylene	10.4

Table IV.   Summary of exhaust emissions from current technology
             methanol vehicle data base[a] (grams per mile)

Pollutant	Average Emissions	Emissions Range
Methanol	0.47	0.12-1.00
Formaldehyde	0.035	0.00-0.17
CO	1.7	0.43-3.2
NOx	0.61	0.04-0.88

[a] Data are from the 40 vehicle configurations that met current federal CO and NOx emission standards.

Table V.   Projected 50,000-mile organic emissions and ozone
            producing potential from current technology gasoline
            and methanol vehicles (grams per mile)

Fuel	Methanol	Formaldehyde	Total HC	Ozone Potential
Gasoline	0	0.007	1.60	100%
Methanol	1.57	0.106	0.48	65%

Table VI.   Emissions from low-mileage methanol Toyota Carinas
             (grams per mile)

Test Site	Fuel	Methanol[a]	Formaldehyde	HC[a]	CO	NOx
Toyota	M85	–	–	–	0.93	0.69
CARB	M85	–	0.014	–	0.70	1.00
EPA	M85	0.23	0.007	0.07	1.07	0.75
EPA	M100[b]	0.33	0.011	0.02	0.74	0.76

[a] Methanol and HC emissions are total (exhaust plus evaporative) emissions. Methanol and HC were not measured separately, but were projected from FID readings based on ratios determined from the EPA methanol vehicle emission data base for both M85 and M100.

[b] This vehicle cannot be started on M100 at low ambient temperatures.

Table VII.   Exhaust emissions from CNG/gasoline dual-fuel cars
(grams per mile)

Test Site	Vehicle	Fuel	NMHC	CO	NOx	Eff 1[b]	Eff 2[c]	Accel[c]
EPA	CNG Fuel Sys.	Gasoline	0.30[a]	9.8	0.40	-20%	Base	Base
	1984 Delta 88	CNG	0.25[a]	1.7	1.18	-10%	+10%	-30%
EPA	Total Fuels	Gasoline	0.27[a]	1.4	1.07	-10%	Base	Base
	1987 Crown Vic.	CNG	0.36[a]	0.45	0.93	-5%	+10%	-35%
CARB	Dual Fuel Sys.	Gasoline	0.36	3.3	0.56	NA	Base	NA
	1983 Ford LTD	CNG	0.35	0.07	0.47	NA	-20%	NA
CARB	Pacific Light.	Gasoline	0.26	7.0	0.70	NA	Base	NA
	1985 GMC Pickup	CNG	0.05	0.20	1.06	NA	-20%	NA

[a]   Non-Methane HC was not measured, but was calculated assuming that methane was equal to 25% of gasoline HC emissions and 90% of CNG HC emissions.

[b]   Post-Conversion energy efficiency over the FTP relative to EPA certification fuel economy data for the specific gasoline vehicle model.

[c]   These final two columns use the post-conversion gasoline fuel mode as a baseline for comparison with the CNG fuel mode (negative numbers mean lower efficiency or less acceleration with CNG).

Table VIII. Exhaust emissions from low-mileage CNG and
            gasoline Ford Rangers[a] (grams per mile)

Test Site	Fuel	NMHC	CO	NOx
Ford-1984	Gasoline	0.20	3.2	1.1
Ford-1984	CNG	0.14	0.03	1.9
EPA-1988	CNG	0.14[b]	0.04	2.0

[a] The CNG Ranger was designed to have approximately the same efficiency and acceleration characteristics as the gasoline Ranger.

[b] Non-Methane HC was not measured, but was calculated assuming that methane was 90% of CNG HC emissions.

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NOTE TO EDITORS