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Alcohol-Fueled Vehicles

An Alternative Fuels Vehicle,
Emissions, and Refueling
Infrastructure Technology
Assessment

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Assessment

Prepared for the Washington State
Department of Ecology and the
Department of Transportation

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Executive Summary

Methanol-Fueled Vehicles

- Methanol, produced from natural gas, has traditionally been used as a solvent and as a feedstock for the production of other chemicals. In the fuels market, methanol represents an alternative to gasoline or diesel combustion in light or heavy-duty compression-ignition engines or it may be used as a feedstock to produce methyl tertiary butyl ether (MTBE). MTBE is used as an oxygenated, octane enhancing additive in reformulated gasoline.
- A gallon of M-85 (85 percent methanol and 15 percent unleaded gasoline) has a pump price of \$0.80 to \$0.85 (in California). It takes approximately 1.6 gallons of M-85 to provide the equivalent energy content of one gallon of gasoline. Thus, the cost of M-85 is equivalent to an ex-tax gasoline price of \$1.28 to \$1.36 per gallon.
- The risks associated with fire depend on a fuel's volatility, flammability limits, and ignition temperature. M-100 fires do not produce a highly visible flame, while M-85 produces a flame as visible as that of gasoline for the duration of a burn. As methanol fires burn less intensely, they may cause less damage than a gasoline fire.
- Of the approximately 1,300 methanol-fueled vehicles worldwide (in 1990), most are operating in fleet trial programs in California. No aftermarket kits are commercially available to modify a vehicle to operate on methanol.
- The flexible-fueled vehicle (FFV) concept, in which a continuum of blends from pure gasoline to M-85 can be delivered from a single fuel tank, became possible with the development of optical (refractive index), conductivity based, or capacitive sensors that reflect changes in the fuels dielectric constant. Sensor output is routed to a microprocessor that sends correct compensation and calibration information to the engine computer. Spark advance and fuel injector pulse width are automatically modified to promote high efficiency and low emission combustion. The use of M-85 is thus transparent to the driver in terms of performance, durability, and reliability.
- Factory-built methanol-fueled light duty vehicles are currently available in the mid-sized automobile and van vehicle classes. GM offers a variable fueled 3.1L Lumina; Ford a 3.0L FFV Taurus and a 4.9L Econoline Van or Club Wagon; and Chrysler their 2.5L Dodge Spirit and Plymouth Acclaim. Chrysler's FFVs are being offered at the same price as their gasoline-fueled counterparts. In 1994, Chrysler expects to offer FFV versions of their Dodge Intrepid, Eagle Vision, and Chrysler Concorde.
- Methanol-powered versions of heavy-duty engines are now commercially available. Detroit Diesel Corporation offers a glow-plug methanol version of their 9.2L 6V-92TA 2-stroke diesel engine. This engine has been emissions certified by both the EPA and the California Air Resources Board. Most other heavy-duty engine manufacturers have tested prototype methanol-fueled engines.
- Much of the emissions data reported in the literature has been gathered from the testing of mid to late 1980s technology light-duty methanol vehicles. One must distinguish between emissions from early and current generation FFVs and methanol vehicles dedicated for M-85 or M-100 use. Emissions tests from a 1993 model year Ford FFV Taurus yield identical CO and NO_x emissions

when operating on M-85 and gasoline. NMOG emissions are reduced by approximately 25 percent when operating with M-85. Further ozone-forming benefits occur as the oxygen in the oxygenated hydrocarbon portion of a methanol-fueled vehicle's exhaust does not participate in ozone formation. M-85 hydrocarbon exhaust emissions have about 41 percent of the reactivity or ozone-forming potential of gasoline emissions.

- Hydrocarbon emissions benefits also occur due to a reduction in evaporative diurnal, hot soak and running losses. Evaporative losses are significant—even in mild summer weather, evaporative losses from gasoline-powered vehicles can account for 45 percent of all vehicle hydrocarbon emissions.
- Total fuel cycle analyses indicate that when methanol is produced from the steam reforming of natural gas, a slight greenhouse gas benefit, on the order of 2 percent, is obtained relative to the use of reformulated gasoline. When produced from coal, methanol contributes about 60 to 80 percent more CO₂-equivalent per mile, while methanol production from wood, should it prove to be both technically and economically feasible, offers significant greenhouse gas reductions. In heavy-duty engines, diesel fuel offers a reduced warming impact as contrasted to methanol.
- Performance and driveability of methanol-fueled vehicles is essentially the same as for gasoline-powered vehicles. Except for materials composition, the fuel sensor and the cold-start system; the mechanical parts of a methanol vehicle are the same as those in a gasoline vehicle. Maintenance operations and procedures are essentially the same as for gasoline vehicles.
- For equivalent energy storage, the required methanol volume is about 1.8 times the equivalent gasoline volume or 2.5 times the equivalent diesel volume. Due to methanol's highly corrosive nature, the majority of underground tanks used to store petroleum fuels are not suitable for methanol. New fiberglass tanks, meeting stricter codes, are sufficient for storing either methanol or gasoline.
- A small portable methanol refueling station with an above ground 1,000 gallon tank with double containment and a methanol compatible dispensing pump is estimated to cost about \$40,000. This type of station is appropriate for small "start-up" methanol fueled fleets. A larger refueling station might run from \$50,000 to \$150,000 for above and below ground installation services depending upon whether all or portions of the existing petroleum dispensing station can be adapted and reused.
- The costs associated with establishing a methanol fuel fleet program include incremental vehicle purchase costs, costs associated with the design, permitting and installation of an on-site methanol storage and dispensing system, differential fuel expenses, incremental maintenance costs, and costs associated with differential vehicle resale values. Start-up costs include training and education for managers, administrators, vehicle operators, and mechanics.
- An analysis of the present value of purchasing and operating a methanol fueled vehicle over a five year service life, assuming a fuel use tax equivalent to that of gasoline on an energy content basis, indicates a 70 percent increase relative to the cost of operating the comparable gasoline-fueled vehicle.

Ethanol-Fueled Vehicles

- Ethanol is an excellent motor vehicle fuel. It can be used at concentrations up to 10 volume percent with no changes to the vehicle. Flexible-fuel vehicles can use fuels with an ethanol content anywhere from 0 to 85 percent and provide a market entry point for E-85 (85 percent ethanol and 15 percent unleaded gasoline). Modified compression ignition (diesel) engines can use an E-95 blend.
- Ethanol is produced by fermenting a sugar solution with yeast. Potential feedstocks include corn, wheat, wood, straw, sugar cane, sugar beets, or grapes. Illinois and Iowa provide 75 percent of our nation's 1.1 billion gallons per year of ethanol fuel while one company, Archer Daniels Midland, accounts for 75 percent of the nation's production.
- The Pacific Northwest has four operating ethanol production factories with a combined capacity of 8.2 million gallons annually. Two facilities are under construction with 31 million gallons of additional capacity.
- Currently, 8 percent of all gasoline sold nationwide is an E-10 blend. A General Accounting Office report concludes that the ethanol industry is capable of doubling or tripling production to 2.2 or 3.3 billion gallons per year during the next eight years. Expansion beyond these levels would likely push feedstock prices high enough to make additional expansion uneconomic.
- The current wholesale price of pure ethanol fuel delivered to the Olympia area is about \$1.50 per gallon. Ethanol is subsidized by a variety of incentives including the federal blenders credit (54¢/gallon) and a 10¢/gallon federal income tax credit (for the first 15 million gallons produced at a facility with a capacity less than 30 million gallons per year). At the Washington State level, ethanol is exempted from the state's 23¢/gallon motor fuel tax and is eligible for a tax credit for ethanol used in E-10 equal to 60 percent of the motor fuel tax. The effective state incentive for E-10 fuels is thus 36.8 cents per gallon of ethanol.
- Two factory-built light-duty vehicles, the 3.0L Ford FFV Taurus and the GM 3.1L Chevrolet Lumina are designed to operate on any blend of gasoline, M-85, or E-85. In the heavy-duty engine area, Detroit Diesel Corporation has submitted emissions test results which indicate, when operating on E-95, that their 6V-92TA alcohol-fueled engine meets even the strict 1994 federal standards for transit bus emissions.
- While tailpipe exhaust emissions data is scarce, available information indicates that carbon monoxide and oxides of nitrogen emissions will be the same in ethanol-powered spark-ignited flexible-fueled vehicles as compared with equivalent gasoline-powered vehicles. A reduction of approximately 20 percent in ozone forming potential may be possible, with the major benefit associated with a reduction in evaporative hydrocarbon emissions.
- The global warming impact of ethanol depends on the feedstock, the fuel used at the conversion plants, and conversion efficiency assumptions. Ethanol produced from corn results in a slight increase in greenhouse gas emissions if the fuel is used in light-duty, spark-ignited engines, and a significant increase, exceeding 55 percent if the ethanol is combusted in heavy-duty diesel engines.

- An analysis of the present value of purchasing and operating an ethanol-fueled vehicle indicates an 85 percent cost increase relative to operating a comparable vehicle powered by reformulated gasoline.
- Except for particulate emissions reductions in limited niches in the heavy-duty engine market, neither methanol or ethanol would provide large air quality or greenhouse gas emission benefits. Similar to propane and compressed natural gas, the alcohol fuels are worthy of support due to the limited environmental benefits that are offered, for their ability to reduce petroleum imports, through jobs creation in the production of domestic motor fuels, and for their restraining influence on world oil prices.

Contents

Methanol as a Vehicle Fuel	1
Methanol Fuel Characteristics	1
Methanol Supply	2
Methanol Fuel Markets	2
Methanol Commodity Prices	3
Methanol Storage, Distribution and Refueling Infrastructure	5
Pump Prices	5
Environmental, Health, and Safety Issues	6
Human Health Issues	6
Environmental Considerations	7
Fire Hazards	8
Methanol-Fueled Light-Duty Vehicles	9
History	9
Methanol Vehicle Conversions	10
Flexible-Fueled Vehicles	10
Tailpipe Emissions from FFVs'	12
Tailpipe Emissions from Dedicated Methanol-Fueled Vehicles	15
Advanced Methanol-Fueled Vehicles	17
Factory-Built Light-Duty Methanol-Fueled Vehicles	18
Heavy Duty Methanol Engine Development	20
Historical Overview	20
Methanol Heavy-Duty Engine Availability and Emissions Performance	21
Heavy-Duty Methanol Engine Price and Performance	26
Emissions Characteristics of Vehicles Using Neat Methanol and Methanol Fuel Blends	29
Photochemical Reactivity	29
Fuel Composition	30
Evaporative Emissions	32
Cold Weather and Mileage Effects on Tailpipe Emissions	33
Global Warming Impacts of Methanol-Fuel Use	34
Methanol-Fueled Vehicle Performance Characteristics	35
Refueling Infrastructure Requirements	38
Methanol Vehicle Owning and Operating Costs	39
Incremental Vehicle Costs	40
Fuel Price Differential	40
Refueling Station Expenditures	41

Ethanol Fueled Vehicles	43
Ethanol Fuel Characteristics	43
Ethanol Supply	44
Current and Future Ethanol Fuel Markets	45
Supply Infrastructure	46
Ethanol Production Costs	46
Incentives and Prices	46
Environmental, Health, and Safety Issues	48
Ethanol-Fueled Light-Duty Vehicles	49
Factory-Built, Light-Duty Ethanol-Fueled Vehicles	50
Heavy-Duty Ethanol Engine Development	51
Emissions Characteristics of Vehicles Using Neat Ethanol and Ethanol Fuel Blends	52
General Emission Characteristics	52
Fuel Composition	53
Global Warming Impacts of Ethanol Fuel Use	53
Ethanol-Fueled Vehicle Owning and Operating Costs	54
References	57
List of Acronyms	61

Tables

1. Pump Price Comparison for Gasoline and M-85 Fuel	6
2. Flammability Characteristics of Fuels	9
3. Exhaust Emissions from Current Technology Methanol-Fueled Vehicles	12
4. M-85 Flexible/Variable Fuel Vehicle Emissions Durability Test Results	13
5. Exhaust Emissions from Flexible-Fueled Vehicles When Operating on Gasoline and M-85.....	13
6. Plymouth Voyager FFV and GTMV Emissions Results	14
7. Emissions from Dedicated M-85 Vehicles	16
8. Exhaust Emissions for Prototype Dedicated Neat Methanol-Fueled Vehicles.....	16
9. Exhaust Emissions for M-100 Vehicles Equipped with an Electrically Heated Catalytic Converter.....	17
10. 1993 Ford FFV Taurus Exhaust Emission Test Results	18
11. Tailpipe Emissions for 1992 Model Year VFV Chevrolet Lumina	19
12. U.S. EPA Heavy-Duty Engine Exhaust Emission Standards	21
13. Detroit Diesel Corporation Methanol-Fueled 6V-92TA Emissions Test Results	23
14. Caterpillar Prototype Methanol-Fueled 3406 Engine Exhaust Emission Results	24
15. Exhaust Emissions from Prototype Methanol-Fueled 7.6L Navistar DT-466 Engine.....	25
16. Volvo 9.6L Diesel Pilot-Injected Engine Exhaust Emission Test Results	25
17. M.A.N. 11.4L Spark-Ignited Methanol Engine Emissions Test Results	26
18. Methanol and Diesel Engine Costs.....	26
19. California School Bus Demonstration Vehicle Prices	27
20. Incremental Increase in Transit Fleet Annual Operating Cost over Baseline Diesel Operation	28
21. Ozone Reactivities of Alcohol Fuels versus Gasoline.....	29
22. FFV/VFV Emissions when Fueled with Various Methanol Blends.....	31
23. CARB Proposed Commercial Specifications for M-100 Fuel.....	31
24. CARB Proposed Commercial Specifications for M-85 Fuel.....	32

25. Evaporative Losses for Methanol Blends Used in Pre-1990 FFV/VFV's	32
26. Running Losses and Refueling Emissions versus Ambient Temperature	33
27. Projected In-Use Organic Emissions for Gasoline and Advanced Design Methanol Vehicles	33
28. Mileage Dependence of Emissions for Methanol-Fueled Vehicles	34
29. Grams per Mile CO ₂ -Equivalent Emissions for Reformulated Gasoline and Methanol	34
30. Summary of Global Warming Impacts of Alternative Fuels	35
31. FFV 0-60 Miles per Hour Acceleration Times	35
32. Comparison of M-85 and Conventional Gasoline Prices	40
33. Alternative Fuel Comparative Economics	41
34. Present Value of Operating Costs for Alternative-Fueled Vehicles	42
35. Pump Price Comparisons for Gasoline and E-85	48
36. Emission Standards and Average Emissions for Ethanol-Fueled Brazilian Light-Duty Vehicles	49
37. Ethanol-Fueled DDC 6V-92TA Heavy-Duty Engine Emissions Test Results	52
38. Commercial Specifications for E-85 and E-100 Fuel	53
39. Total Fuel Cycle, CO ₂ -Equivalent Emissions for Reformulated Gasoline and Ethanol.....	54

Figures

1. Wholesale Methanol Price Trends	3
2. Range for Methanol Production Costs	4
3. Ozone Reduction Potential of M-85	15
4. Methanol-Fueled DDC 6V-92TA Bus Engine Hardware Changes.....	22
5. Exhaust Emission Variation versus Fuel Methanol Content	30
6. Comparison of M-85, Gasoline, and Gasoline-Equivalent Fuel Economy	36
7. M-85 Refueling Station Layout.....	39
8. Chevrolet Lumina Ethanol-Fueled VFV Components	51

Introduction

Interest in alternative motor vehicle fuels has grown tremendously over the last few years. The 1990 Clean Air Act Amendments, the National Energy Policy Act of 1992 and the California Clean Air Act are primarily responsible for this resurgence and have spurred both the motor fuels and vehicle manufacturing industries into action. For the first time, all three U.S. auto manufacturers are offering alternative fuel vehicles to the motoring public. At the same time, a small but growing alternative fuels refueling infrastructure is beginning to develop across the country.

Although the recent growth in alternative motor fuels use is impressive, their market niche is still being defined. Environmental regulations, a key driver behind alternative fuel use, is forcing both car makers and the petroleum industry to clean up their products. As a result, alternative fuels no longer have a lock on the clean air market and will have to compete with conventional vehicles in meeting stringent future vehicle emission standards.

The development of cleaner burning gasoline powered vehicles has signaled a shift in the marketing of alternative fuels. While they will continue to play a major part in the clean vehicle market, alternative fuels are increasingly recognized as a means to reduce oil imports. This new role is clearly defined in the National Energy Policy Act of 1992. The Act identifies alternative fuels as a key strategy for reducing imports of foreign oil and mandates their use for federal and state fleets, while reserving the right to require private and municipal fleet use as well.

Alternative fuels are adopting a regional look as well, as states begin to recognize the economic potential of promoting fuels and or industries indigenous to their area. In the agricultural Midwest, ethanol has developed a strong following, while states rich in natural gas reserves such as Texas, Oklahoma and Colorado are pushing natural gas and to a lesser extent propane as the fuel of choice. California, which has the largest vehicle population of any state in the nation, is promoting a variety of fuel choices including methanol and electric vehicles. California's requirement for "zero-emission" or electric vehicles is of particular interest, as a number of states have adopted California's Low Emission Vehicle program. This program mandates the sale of electric vehicles in the later part of the decade.

In Washington State, a similar debate over the role of alternative transportation fuels is occurring. Currently, there are 5,823 alternative fuel vehicles registered in Washington. Approximately four-fifths of these vehicles are powered by propane, with the remainder operating on compressed natural gas. While only a small fraction of the 5.1 million vehicles registered in the State, interest in these fuels is growing as shown by recent State and local initiatives.

At the state level, the Clean Air Washington Act of 1991 identifies alternative fuels as a strategy for reducing vehicle emissions and singles out the need to develop a statewide compressed natural gas refueling infrastructure for local and state government fleets. The State has also mandated the purchase of low emission vehicles for the state fleet, including the direct purchase or conversion of vehicles to operate on alternative fuels. County and city governments, as well as school districts and private individuals have also begun to incorporate alternative fuels into their fleets plans. Examples include Pierce Transit, which is operating approximately 50 compressed natural gas (CNG) powered buses; Washington Natural Gas whose corporate fleet includes more than 480 CNG-fueled vehicles; and King County, which has committed to operating nearly all of its vehicle fleet on either CNG or propane fuel within the next two to three years.

As interest in alternative fuels grows, questions regarding fuel availability, vehicle costs, refueling requirements, economic viability and environmental performance arise. The Washington State Energy Office, in cooperation with the Departments of Ecology and Transportation has been investigating these topics, and have prepared the following alternative fuel and refueling infrastructure technology assessment reports. The first report covers the gaseous fuels-natural gas and propane. Additional reports will address alcohol fuels and electric vehicles, followed by a summary report on all of the fuels evaluated. The final report will compare the various alternative transportation fuels and will include a discussion of federal and state regulations affecting alternative fuel use.

Methanol as a Vehicle Fuel

Methanol is produced from natural gas and is frequently used in both light and heavy duty alternative fueled vehicle demonstration fleets. Methanol (CH_3OH) is the simplest alcohol fuel composed of one carbon atom, one oxygen atom and four hydrogen atoms. The advantages of methanol include its being a high octane liquid fuel, less chemically reactive towards ozone formation than gasoline, cooler burning and it is not derived from petroleum. High performance racing cars have used methanol fuel for decades. Disadvantages include a lower energy density than gasoline, a higher cost, and a limited supply infrastructure.

Methanol Fuel Characteristics

Methanol and gasoline are quite different fuels. The main similarity is that they are both liquids. Alcohols have been recognized as excellent fuels for spark ignited engines virtually since the advent of such engines. The high octane rating (a measure of their resistance to explosive auto-ignition) and their high latent heats of vaporization (an aid to fuel-air mixture cooling and hence density) have made them preferred fuels for use in high-compression ratio, high-output engines.

A high octane rating in itself has no direct fuel economy benefit. A higher compression ratio engine, which demands a higher-octane fuel for spark ignited engines, is simply more efficient than one with a lower compression ratio and hence provides greater fuel economy. Lean operation (an approach to the theoretical air-standard cycle efficiency) can permit further improvement of efficiency and fuel economy.

Because methanol has a lower energy content than gasoline on both a mass and volume basis, more fuel is required for equal engine output. For example, gasoline has about two times the energy content of methanol per unit volume, which predicts that the fuel economy with methanol would be about one-half that with gasoline in miles-per-gallon terms. On the other hand, equal volumes of stoichiometric alcohol-air mixtures and stoichiometric gasoline-air mixture have similar energy contents. Since piston engines induct fuel-air mixture on a volume basis, engine power output would not be expected to change significantly if nothing were changed but the fuel.

Methanol's higher heat of vaporization permits a greater fuel density in the engine. It also makes it more difficult to vaporize at normal temperatures. This causes driveability problems especially under cold-start conditions. One hundred percent pure or "neat" methanol (M-100) cannot vaporize sufficiently to form a flammable air-vapor mixture below about 45° F. The straightforward means of overcoming the cold start limitations is the addition of 15 percent by volume unleaded gasoline (designated as M-85).

Flexi-fuel vehicles can use fuels with an methanol content anywhere from 0 to 85 percent. They do not have higher compression ratio engines or utilize lean burn that would be possible if operated only on M-85. Because they must be also capable of burning only gasoline, the vehicles offer few performance advantages. They may offer some air quality benefits and they do provide a market entry point for M-85. M-85 fuels also require the addition of a small amount of speciality lubricant to the fuel.

Modified compression ignition engines can use M-100 fuels. These fuels also need the lubricant additive. The engines are designed and optimized to operate on M-100 and thus can take advantage of the fuel properties by operating at high compression ratios and lean burn conditions. Being compression ignition engines the low vapor pressure of M-100 fuels does not present a cold start problem.

Methanol Supply

Methanol is currently produced from natural gas.¹ The process involves reaction of natural gas with steam and/or oxygen to make synthesis gas, a mixture of carbon monoxide and hydrogen. The synthesis gas reacts under pressure, in the presence of a catalyst, to produce crude methanol. Several commercially available technologies are used for both synthesis gas production and its conversion to methanol. The crude methanol is distilled to produce chemically pure methanol. Methanol used as a fuel would not have to be as pure as chemical grade methanol, simplifying the process. However, until the demand is great enough for fuel grade methanol, chemical grade methanol will be the only grade produced. Coal and biomass can also be used to generate synthesis gas. These conversion technologies are not as advanced as technologies based on natural gas.

It takes about 0.1 million British thermal units (MBtu) of natural gas to produce one gallon of methanol.² This is equivalent to a 60 percent thermal efficiency and represents the energy cost paid for converting from a gaseous fuel to a liquid fuel. Technologies are commercially available which are capable of converting methanol to gasoline, thus eliminating the need for changes in vehicles or the distribution systems. However, we will not consider these technologies in this report.

Methanol is a commodity chemical produced around the world. The production centers have changed over the past decade from those located close to the consumers to areas with substantial reserves of natural gas with little demand for the gas. World production capacity has increased by 92 percent between 1979 and 1989, from 3.8 to 7.33 billion gallons per year. Latin America, Canada, and the Middle East have shown the most dramatic increases. World methanol capacity is projected to increase from its current capacity of 7.8 billion gallons to 11.8 billion gallons by the year 2000.³

The 1992 United States methanol production capacity was 1.6 billion gallons per year and is projected to reach 2.4 billion gallons by 2000. Canadian capacity is 0.7 billion gallons per year with 0.3 billion of new capacity planned by the year 2000. However, even today United States demand for methanol is greater than its production capacity. Net annual methanol imports were 0.4 billion gallons in 1991

Methanol Fuel Markets

Methanol has traditionally been used as a solvent and as a raw material to produce other chemicals. Currently, the chemical industry consumes more than 80 percent of the total methanol produced in the world. Formaldehyde, acetic acid, and solvents are the dominant products. The demand for methanol in the chemical industry is forecasted to grow at an annual rate of 2 to 3 percent.

Methanol is used in fuel markets as an alternative fuel to gasoline and as a feed stock to produce methyl tertiary butyl ether (MTBE), and other ethers. MTBE use is projected to increase dramatically in the next decade and represents the major use of methanol in the fuel market. Historically, phase out of lead additives to gasoline created the MTBE market as an octane additive. Today the requirement for oxygenates in gasoline is providing the market incentive.

Beginning in November 1992, all gasoline sold during the four winter months in 39 U.S. cities that are non-attainment for carbon monoxide must contain 2.7 weight percent oxygen. This equates to an annual MTBE demand of 0.9 billion gallons. In 1995, reformulated gasoline will be required year-round in nine metropolitan areas classified as having severe or extreme designations for ozone. One requirement for reformulated gasoline is that it contain 2.0 weight percent oxygen. Areas designated as marginal, moderate, or serious ozone nonattainment can choose to opt-in to the reformulated gasoline requirement from 1995 to 1997. In 1998, all ozone nonattainment areas must use reformulated gasoline year-round. By 1998, the reformulated gasoline market will require 9 billion gallons of MTBE or its equivalent.

It takes 0.34 gallons of methanol to produce one gallon of MTBE. The demand for oxygenates in carbon monoxide non attainment areas will require 300 million gallons of methanol to produce MTBE or other ethers. In 1998, when reformulated gasoline is required, four billion gallons of methanol will be needed. Fuel methanol demand is on top of the continued chemical uses, estimated at 1.3 billion gallons. These projections are responsible for the construction of new MTBE and methanol facilities around the world.

The use of methanol directly as a motor vehicle fuel is currently very small. California has the largest methanol fleets and uses less than 4 million gallons of methanol per year. The California Energy Commission estimates, assuming methanol is the only alternative fuel used, that California may use up to 1 billion gallons per year in alternative fueled vehicles under the California Pilot Program required by the Federal Clean Air Act. The actual amount required will depend on what alternative fuels are eventually chosen.

During the next decade, methanol will be produced from natural gas to meet the MTBE and chemical market demands. The use of M85 and M100 will be small compared to other uses. There are adequate world wide natural gas supplies to meet the demands, but projecting the price is difficult.

Methanol Commodity Prices

Wholesale methanol prices since 1981 are shown in Figure 1.⁴ The price fluctuations are attributed to the supply and demand balances. The increase in late 1988 was due to production problems at several large production facilities combined with the reduced production capacity brought about when several older less efficient plants shut down in 1986. The combination produced a supply problem and a subsequent rapid escalation in prices. The same phenomena occurs in the petroleum industry when less efficient refineries shut down and there is a major outage at one of the operating refineries.

Figure 1
Wholesale Methanol Price Trends

Source: TECNON

The major components of methanol production costs are plant construction costs and manufacturing costs (especially the cost of natural gas). Sites with well-developed infrastructure, such as roads and electric power, in an established industrial environment have the lowest construction costs. The U.S. Gulf Coast, southern Canada and Trinidad are representative of these areas. At the other extreme are sites without much infrastructure and in remote areas such as Prudhoe Bay Alaska or the Beaufort Sea. The price paid for natural gas depends on the price of competing energy products, especially crude oil, demand for natural gas within the producer countries, and demand for natural gas exports by pipeline or as liquefied natural gas. Generally, locations with low cost natural gas are those with high construction costs.

The Department of Energy (DOE) methanol production cost algorithms are based on natural gas costs, where the plant is located, the size of the plant, the use of current or advanced technology, and the product being either fuel grade or chemical grade methanol. The natural gas component of production cost equals 0.1 times the cost of gas in \$/MBtu. For example, natural gas costing \$1.00/MBtu would contribute \$0.10 to the production cost of a gallon of methanol. Capital and operating costs are the other cost components. For a site in a developed area the capital and operating costs would be \$0.27/gallon of methanol. For a remote site the costs would be \$0.53/gallon. There is a trade-off between the cost of natural gas and the construction costs. The DOE study indicated that methanol could be produced at the lowest cost at those sites with the lowest construction costs. Figure 2 shows the comparison of methanol costs depending on the site, the technology, the capacity, and the natural gas cost. Methanol production costs range from \$0.17 to \$0.76/gallon for a range of natural gas costs from \$0-2.50/MBtu. Obviously, the lower cost facilities will be built first.

The current price of methanol in the Gulf Coast states is \$0.40/gallon. The price delivered to bulk storage facilities in California is \$0.48/gallon and would be about \$0.50 to Seattle. However, the cost of bulk storage facilities must be recovered. To get a bulk rate requires receiving deliveries of 3 million gallons per shipment which is enough to fuel 1,500 vehicles. A 3 million gallon tank would cost about \$1 million.

The price of a truck load of methanol delivered to a refueling station in Seattle would be \$0.70/gallon. The price differences are due to transport costs, intermediate storage costs, and local distribution costs.

Figure 2
Range for Methanol Production Costs

Methanol Storage, Distribution, and Refueling Infrastructure

Methanol production facilities are generally located close to waterways that permit transport by ship or barge. The ships deliver methanol to bulk storage terminals. Trucks then deliver the fuel to the vehicle dispensing pumps. Pipelines are not used because of unresolved cross-contamination problems.

There is one methanol marine terminal in the Northwest consisting of a four million gallon tank in Portland, Oregon. Methanol can also be shipped by truck directly from manufacturing facilities in Alberta, Canada. Seattle's METRO methanol-powered transit bus demonstration from 1987-1990, had one dispensing tank and pump. They arranged for shipments of methanol by tanker truck from Canada whenever they required fuel. This arrangement worked well for their application. California has 35 methanol refueling stations providing M-85 for fleets in both northern and southern California. The methanol is splash blended with the gasoline.

California receives bulk shipments of methanol from the Gulf Coast and Canada into two marine terminals, one in northern and one in southern California. Trucks pick up the methanol, add gasoline and additives to make M-85, and deliver to the refueling outlets. Standard gasoline delivery trucks are used for local distribution.

The equipment costs for a methanol refueling station are \$35,000. This includes a 10-12,000 gallon double wall tank, monitors, pumps and card readers. The installation costs range from \$35-50,000 and depend on the specific location.

Pump Prices

The California Energy Commission paid \$0.59/gallon for methanol delivered to California in 1989. Today's price is \$0.48/gallon. The difference is due to the changing world supply and demand for methanol. The retail pump price of methanol fuel is determined by the wholesale price, transportation costs, state and federal taxes and dealer margins. The pump price in California is \$0.80-85/gallon of M-85. The additional costs include the cost of the 15 percent gasoline added to the methanol, the cost of fuel additives for lubrication and oxidation protection, the cost of delivery to the station, taxes, and dealer margin. A gallon of M-85 has a lower energy content than a gallon of gasoline. It currently takes 1.6 gallons of M-85 to drive the same distance as from one gallon of gasoline. Thus the \$0.80-85 per gallon cost of M-85 is equivalent to a gasoline price of \$1.28-1.36 per gallon. The future cost of methanol and hence M-85 depends on the future cost of methanol.

The cost of chemical grade methanol delivered to Olympia in a tanker truck was quoted as \$0.70/gallon.⁵ Another Seattle company quoted a price of \$0.77/gallon. The actual wholesale cost to a user would probably lie somewhere between \$0.60-0.70/gallon depending on the volume of fuel purchased and whether or not they owned their own bulk storage tank.

The pump price depends on the user's tax status and the relationship between the pump owner and user. A privately owned vehicle purchasing from a private retail pump pays federal and state taxes, dealer profit, and local transportation costs. Public and private fleets would save the dealer margin and public fleets do not pay federal motor fuel taxes.

The price for different users of gasoline and M-85 are compared in Table 1. The gas equivalent price is the price paid for a volume of M-85 equivalent to provide the same driving range as a gallon of gasoline. The gasoline equivalent price is substantially higher than gasoline.

The methanol price needed to make the M-85 equivalent price equal to gasoline prices can be readily calculated. Under current tax rates and a wholesale gasoline price of \$0.60/gallon, the wholesale methanol price would have to be 18.8, 23.2, or 21.2 cents/gallon for the individual, private fleet, and public fleet users respectively. It is unlikely that M-85 will be used until the equivalent cost is equal to

gasoline. This requires both an equalization of tax rates based on energy content and either higher gasoline prices or lower methanol prices. However, if federal or state legislation requires fleets to use non-petroleum fuels, then M-85 may be the lowest cost option available.

Table 1
**Pump Price Comparison for
Gasoline and M-85 Fuel, ¢/gal**

Cost Component	Individual		Private Fleet		Public Fleet	
	Gasoline	M-85	Gasoline	M-85	Gasoline	M-85
Methanol @ 65¢/gal	0.0	55.3	0.0	55.3	0.0	55.3
Gasoline @ 60¢/gal	60.0	9.0	60.0	9.0	60.0	9.0
Local Distribution	5.0	5.0	5.0	5.0	5.0	5.0
Dealer Margin	10.0	10.0	0.0	0.0	0.0	0.0
State Taxes	23.0	23.0	23.0	23.0	23.0	23.0
Federal Taxes	14.1	7.1	14.1	7.1	0.0	0.0
Total	112.1	109.4	102.1	99.4	88.0	92.3
Gas Equivalent Price	112.1	175.0	102.1	159.0	88.0	147.8

Environmental, Health, and Safety Issues

Health and safety issues associated with alcohol fuel use can be classified into three categories: 1) human health issues, 2) environmental issues, and 3) fire hazards.⁶ The health and safety issues with methanol fuel should be considered in the context of gasoline and diesel issues. Many petroleum fuel health and safety risks are accepted since these fuels are, in effect, grandfathered into the transportation system. Methanol fuel has different risks. For example, methanol forms a combustible mixture in a closed space but is more difficult to ignite than gasoline in an open area. M-85 eliminates some of these tradeoffs and makes methanol appear like gasoline to the consumer.

Human Health Issues

Potential human health problems from methanol depend on the exposure to fuel, vapors, or exhaust emissions and any associated acute and chronic toxic effects. Exposure to methanol can occur through ingestion, inhalation, or skin contact.

Acute toxicity is the effect of a single exposure on humans or other organisms. The details of acute toxicity are well documented. There are three stages of methanol poisoning. First a narcotic or drunken state similar to ethanol poisoning occurs. This is followed by a latent period ranging from 10 to 15 hours. Finally, acute effects occur including nausea, failing eyesight and blindness, liver and kidney damage, and death due to respiratory failure. During the latent stage, methanol poisoning can be treated effectively, if identified properly.

Sufficiently large doses of methanol all have the same effect. The minimum lethal dose in the absence of medical treatment ranges between 300 and 1,000 mg/kg (methanol per body weight). The usual mechanism for accumulating a lethal dose of methanol is by drinking it. Drinking only 2 to 4 ounces can be fatal.

Unlike the acute effects of methanol poisoning, the effects of chronic or long term exposure are less well known. The effects of long-term, high-level exposure appear to be similar to acute exposure. The atmospheric exposure cases are above the threshold limit value (TLV) of 260 mg/m^3 .

Exposure situations for methanol will be similar to current transportation fuels. Methanol will be produced, stored, and distributed. Workers involved in these activities will be exposed to low levels of methanol by inhalation and skin absorption. Accidental acute exposures may also occur as a result of siphoning accidents, accidental ingestion by infants, or from storage in "improper" containers. Vehicle users will be exposed to low levels of methanol vapors and occasional skin contact. However, methanol as a constituent in vehicle exhaust replaces most unburned gasoline hydrocarbons and reduces levels of toxic aromatic hydrocarbons like benzene.

Because of methanol's acute effects, the chief worry concerning methanol exposure involves ingestion. Neat methanol is odorless and can be swallowed and kept down; therefore, purposeful drinking can occur more easily than with gasoline. Additives such as gasoline or small concentrations of malodorous chemicals can mitigate this problem. There have been no reported cases of M-85 or M-100 ingestion associated with the demonstration fleets.

As with gasoline, the issue with inhalation of methanol is chronic exposure to vapors. Acute toxicity does not appear to be a problem. Personal and parking garages represent the highest exposure. Measured levels in garages, however, have been found to be below the TLV value of 260 mg/m^3 for methanol exposure over an 8-hour workday.

The inhalation of low levels of methanol does not contribute to a very high dose in the body. Subjection to the worst-case methanol exposure for 15 minutes results in a maximum dose of 0.6 mg/m^3 . This is 500 times lower than the minimum lethal dose. Methanol also occurs naturally in the body from the intake of fresh fruits, vegetables, and alcoholic beverages. Aspartame, an artificial sweetener, breaks down into methanol in the digestive system.

Ambient atmospheric concentrations of methanol will increase as methanol is used, while gasoline hydrocarbons concentrations will decrease. In light of the ubiquitous presence of methanol in human metabolism, low levels of methanol in the atmosphere do not appear to be a problem.

Environmental Considerations

As with petroleum fuels, the use of methanol as a fuel causes concern over the environmental effects of spills and leaks. The effects on aquatic life and soil biota need to be considered for acute exposure and low-level exposures. Remediation procedures for spills need to be established.

Methanol in pure form has a very low adsorption tendency in most kinds of soil. Petroleum-derived fuels, on the other hand, are strongly adsorbed by most soils. Petroleum liquids only partially pass through the volume of soil they contact, leaving significant components behind in the soil. In a spill or even a slow-leak situation, soil concentrations of gasoline constituents like benzene can easily reach contamination levels, requiring that measures be taken to clean up the contaminated area.

With a high-level methanol blend like M-85, the situation becomes more complicated. Methanol and gasoline are completely miscible with each other, but when a sufficient quantity of water (around 5 percent) is added to the mixture, the methanol and gasoline tend to separate. This implies that, when an M-85 mixture is spilled, the tendency of the components to separate in the nearby soil will vary with the soil's moisture content and with the volume of the spill or leak. The adsorption behavior of such a mixture is difficult to predict, and depends almost totally on the geologic and hydrogeologic conditions at the site.

High concentrations of methanol are toxic to most plants and animals. In the case of an exposure such as a large spill from a tanker ship, the acute effects of methanol would result in damage to the biota in the immediate spill area. Since methanol is soluble in water, it disperses very rapidly compared to petroleum spills. A methanol spill quickly dilutes to low levels. Studies of organisms in a river ecosystem indicate that fish, mollusks, and crustaceans can tolerate 1 percent methanol or higher and the effects of exposure are reversible.

Fire Hazards

The properties of methanol result in different fire safety risks than with gasoline and diesel fuels. M-100 fires do not produce a highly visible flame. Methanol vapors ignite under different conditions than gasoline and diesel vapors and burn less intensely than petroleum fuel fires. These areas of concern may require different fuel handling procedures and fuel additives.

The lack of a visible flame probably poses a greater hazard in situations where the public is involved. In passenger cars, many people would be exposed to a new fuel and the lack of a visible flame would be a problem. Invisible flames should be less of a problem in the distribution system, where workers can be trained to deal with this characteristic. The primary approach to providing a visible flame is with fuel additives. Many petroleum-like hydrocarbons and oxygenated hydrocarbons have been evaluated as luminosity additives. Gasoline is a good additive. M-85 produces a flame as visible as gasoline for the duration of the burn.

In the methanol production system, neat methanol (M-100) must be stored. Infrared flame detectors could be used to sense a fire although this precaution is not used in the chemical methanol industry today.

The risk of fires depends on the volatility, flammability limits, and ignition temperature of the fuel as well as the availability of air. Fuel/air mixtures are ignitable within a range between the so-called lean flammable limit and the rich flammability limit. These physical properties lead to two distinct situations for ignition to occur. Vapors can be ignited in an open space while mixing with fresh air. Also, fuel vapors can form a combustible mixture in a closed space, like a fuel tank, with the available air. Although fuel spills in the open pose a greater fire hazard than vapors in a fuel tank since there is usually no ignition source in the fuel tank, fuel spills do not occur frequently. Ignition occurs only when there are sufficient fuel vapors to form a mixture that lies within the flammability limits of the fuel. The low flammability limit and high vapor pressure of gasoline result in combustible mixtures occurring over a wide range of temperatures and distances from a fuel spill. Table 2 summarizes the flammability limits for diesel, gasoline, M-100, and M-85. Methanol will only ignite when the vapor concentration is greater than 6 percent. Thus, in open spaces, methanol vapors are diluted by air and will not ignite as readily as gasoline. Diesel has an even lower vapor pressure and is very difficult to ignite. Adding gasoline affects both the vapor pressure and flammability limits. M-85 is expected to behave more like gasoline because of its high vapor pressure.

In closed spaces such as fuel tanks, M-100 vapors form a combustible mixture over most of the range of ambient temperatures. The vapors in a gasoline tank are generally too rich to ignite and are combustible only when it is very cold outside (about -45°F to a few degrees below 0°F), or when an empty fuel tank has just been filled. The higher vapor pressure of M-85 makes it too rich to burn above 10°F. The vapor space in fuel delivery trucks also forms a combustible mixture when a gasoline load has been dropped and the fuel is displaced with fresh air. For this reason, the petroleum industry uses special procedures when refilling an empty tank. The velocity of the fuel stream is limited while the drop tube is above the fuel level to prevent explosions from static discharges from the fuel stream.

With M-100, the vapors in a fuel tank are combustible under ambient temperatures which are usually between the flammability limits in Table 2. At the proper temperature and mixture, a spark or other ignition source could cause the vapors in a fuel tank to explode. A flame arrestor on the tank vent will prevent ignition sources outside the tank from igniting the vapors in the tanks. Fuel pumps inside the fuel tank are another potential source. The gasoline content of M-85 raises the vapor pressure enough so that the mixture in the tank is too rich to ignite.

The energy content of methanol and the heat required to vaporize methanol result in a less intense flame than gasoline. Methanol fires will burn less intensely and may cause less damage. Due to the physical properties of M-85, the hazard from fires is similar to gasoline although it is safer because of a less intense flame.

Table 2
Flammability Characteristics of Fuels

<u>Fuel Property</u>	<u>Diesel</u>	<u>Gasoline</u>	<u>M-100</u>	<u>M-85</u>
Vapor pressure @ 100° F, psi	0.4	9-15	4.6	7-9
Flammability limits				
vapor concentration(percent)				
lower limit	0.6	1.5	6.0	4
upper limit	7.5	7.6	36.5	23
Temperature range for combustible mixture				
in an enclosed space, °F				
lower	128	-45	45	-40
upper	150	-6	109	10

Methanol-Fueled Light-Duty Vehicles

History

Methanol has been used as an automotive fuel since the 1930's. From time to time, major automakers have considered methanol and other alcohols for light-duty vehicle use. In 1951, General Motors displayed two concept cars which were partially fueled by methanol. Methanol has also long been favored as a racing fuel, due to its safety attributes and ability to generate additional horsepower.⁷

Methanol can be used in vehicles in several different ways -- as a gasoline additive; in its "neat" or nearly pure form; or as a blend of concentrations from a single fuel tank in a "flexible fueled" vehicle configuration.^{7,8} In fuels with less than 15 percent methanol, methanol is considered to be an additive, rather than the base fuel.⁹ Generally, conventional original equipment manufacturer's vehicles can operate on a mixture of up to 15 percent methanol and petroleum fuel with few adjustments or material changes required.⁸

The most common methanol based fuel blend is M-85. Blending gasoline with methanol improves cold weather starting and driveability, while reducing engine wear.⁹

Of the approximately 1,300 methanol-fueled vehicles worldwide in 1990, most are operated in fleet trial programs conducted in California.^{7,9} Most of the vehicles entering fleet service in California during the 1980's were mechanically carbureted "dedicated" vehicles equipped for the use of neat or nearly neat methanol.¹⁰

Starting in 1986, factory prepared flexible fuel vehicles became available. These vehicles are capable of running on any mix of methanol and gasoline supplied from a single fuel tank. These vehicles make use of a sensor which determines the fuel blend by measuring such composition dependent properties as the index of refraction, the dielectric constant, or the inductance of the fuel.⁷ Feedback to the vehicles's electronic fuel injection system automatically supplies the correct air to fuel mixture to minimize emissions while optimizing combustion efficiency and engine performance. A closed loop exhaust gas oxygen sensor is used to fine tune the fuel to air ratio.

Methanol Vehicle Conversions

Methanol is not considered to be a good fuel for vehicle conversion programs due to its corrosive effect on many materials used in older vehicles.¹¹ In addition, no aftermarket kits are available to modify a vehicle to operate on methanol.¹²

From 1981 to 1991, the state of California offered an alcohol vehicle conversion tax credit of up to 55 percent of the conversion cost with a maximum of \$1,000 per vehicle. While a number of conversions have been completed by corporate fleets and private vehicle owners, and conversions appear to offer a short lead time approach towards increased methanol fuel use, no commercial methanol vehicle conversion industry has materialized.¹⁰

Converted vehicles are also limited to operations on neat or near neat methanol as flexible fuel vehicle fuel sensing technologies are not commercially available.¹⁰ Additional costs are incurred when vehicle models selected for conversions require developmental work including emissions calibration and testing. The prospects for the development of an effective alcohol fuels conversion industry thus hinge upon cooperative efforts between original equipment manufacturers (OEMs) and conversion companies.

The Bank of America operated a fleet of about 290 converted methanol vehicles. They report a "simple" conversion cost of approximately \$300 for parts and four to six hours of in-house labor per vehicle. A simple conversion consists of fuel tank replacement, carburetor or fuel injection modifications, and ignition retiming. Advanced methanol conversions done for the bank by Future Fuels of America included rebuilding engines with higher compression ratio pistons and reportedly cost an average of \$1,850 per vehicle.¹⁰

Flexible-Fueled Vehicles

The Flexible-Fueled vehicle concept, in which a continuum of blends from pure gasoline to pure methanol can be delivered from a single fuel tank, became possible with the development of an optical fuel sensor by the Netherlands Research Institute for Road Vehicles. This device measures the refractive index of the fuel which allows the vehicle's on-board computer to determine appropriate flow and ignition system adjustments.¹³ In 1982, the Ford Motor Company began the development of an FFV 1.6L 1983 model year Escort. Six Ford Escorts were produced in 1985 with three placed in field operation.

General Motors entered the alcohol fuels arena with a variable-fuel version of a 2.8L port-fuel injected Corsica. This vehicle was equipped with an electrical conductivity based fuel sensor. General Motors also tested the concept on a 2.5L engine equipped with a throttle body injection system.¹³ Chrysler introduced their Methanol Concentration "Smart Sensor" in May of 1991. This fuel sensing device is totally transparent to the driver and allows for operations on any mixture of gasoline and M-85, including 100 percent unleaded gasoline. The "Smart Sensor" determines the fuel composition by measuring changes in the dielectric constant of the fuel, and uses this information to optimize engine control, spark advance, and fuel injection to yield peak efficiency, high fuel economy, and low emissions.¹⁴

Flexible-fueled vehicles are seen as a transitional step towards an alcohol-based fuel economy. With the availability of vehicles capable of operating on gasoline, alcohol, or any combinations of the two fuels, a customer can purchase an FFV in anticipation of the fuel becoming available. The advantages of flexible-fueled vehicles include: ¹⁵

- Allowing for customer ability to choose the best available or least cost fuel.
- Permitting an orderly transition to methanol while a fuel supply infrastructure is under development.
- Minimizing barriers of fuel availability and reduced driving range.

Methanol-fueled vehicles are virtually identical to gasoline powered vehicles except for the fuel sensor and the composition of materials in the fuel-related systems. ⁹ A 1986 Ford FFV Crown Victoria equipped with a 302 CID V-8 engine differs from a production gasoline powered version in the following areas: ¹³

Fuel System

- Fuel tank and filler tube -- nickel plated for compatibility with methanol.
- Fuel sending unit -- materials changed for methanol compatibility.
- Fuel pump -- materials changes and fuel pump redesign.
- Fuel filter -- a special adhesive is used within the filter.
- Fuel pressure regulator -- the diaphragm is constructed of a methanol compatible elastomer.
- Fuel injectors -- higher flow capacity injectors are specified to meet the wider range of fuel flow requirements.

Electronic Engine Control System

- Fuel sensor -- monitors the percentage of alcohol in the fuel blend, thus enabling the microprocessor to determine the optimum air to fuel ratio. A digital unit on the dashboard displays the percentage of methanol in the fuel mixture.
- Microprocessor -- programming changes are incorporated to permit operation over the entire range of permissible methanol/gasoline blends. The microprocessor receives input from one additional sensor (the fuel sensor) and controls one additional device (the cold start system).
- Cold start system -- a solenoid valve meters additional fuel into the intake manifold for improved cold weather starting and driveability.

Engine - Related Components

- Spark plugs -- spark plugs are required with greater side wire heat transfer than the stock version.
- Engine oil -- engine oil which is specially formulated for a wide variety of methanol/gasoline blends. The recommended oil change interval may also be reduced.

Prototype light-duty flexible-fueled vehicles have generally been priced at about \$2000 more than their conventional counterparts when produced in demonstration quantities. ⁷ As production volumes increase, costs are expected to fall. The Environmental Protection Agency (EPA) has held discussions with vehicle manufacturers and has concluded that there are areas where cost savings over gasoline vehicles will be likely, as well as areas where cost increases will occur. Overall, the EPA's analysis suggests that there will be no net cost differences between dedicated methanol vehicles and future gasoline vehicles. ¹⁶

For FFVs, the fuel sensor plus requirements for materials compatibility with both fuels result in a slight cost increase. After consultation with automotive company engineers, the EPA predicts that an FFV will have up to a \$300 cost increment over a comparable gasoline vehicle. ¹⁶ Others have projected that the costs of light-duty methanol vehicles will be about \$300 to \$500 above those for conventional vehicles given large scale production in 1993 or 1994. ⁷

It is possible that marketing requirements and Corporate Average Fuel Economy (CAFE) advantages to vehicle manufacturers may reduce price differences to negligible values. The Alternative Motor Fuels Act of 1988 provides impetus for FFV development by providing an incentive of up to 1.2 miles per gallon (mpg) in CAFE credits beginning in 1993. ¹⁴ As the fuel economy for an FFV is computed only on the gasoline portion of the fuel, an M-85 FFV achieving 25 mpg on gasoline would be equivalent to a conventional vehicle obtaining 167 mpg. ⁷ Chrysler has announced that there will be no cost premium for its 1993 model year 2.5L FFV Dodge Spirits and Plymouth Acclaims.

Tailpipe Emissions from FFV's

A large amount of emissions data has been gathered from the testing of mid to late 1980's technology methanol fueled vehicles. EPA has summarized this data in a computerized data base containing emissions test results assembled from 13 studies covering 10 different vehicle models and 64 different engine and vehicle combinations. Exhaust emissions from current technology methanol-fueled vehicles are summarized in Table 3. ¹¹

Table 3
Exhaust Emissions from Current Technology
Methanol-Fueled Vehicles¹, grams/mile

<u>Pollutant</u>	<u>Average Emissions</u>	<u>Range</u>
CO	1.7	0.43-3.2
NOx	0.61	0.04-0.88

1 FTP data are summarized for 40 vehicles meeting federal CO and NOx emission standards.

The methanol-fuel vehicle CO and NOx emissions appear to be about the same as for current gasoline-powered vehicles. This behavior is expected for carbon monoxide emissions as CO levels are strongly correlated with air to fuel ratio, and both current methanol and gasoline vehicles are designed for stoichiometric operation. ¹¹

The Colorado Alternative Fuels Task Force also found that CO emissions from spark-ignited methanol vehicles are similar to those for gasoline-powered vehicles. Reactive hydrocarbon tailpipe emissions are decreased, while the lower Reid Vapor Pressure of the methanol fuel results in reduced evaporative hydrocarbon emissions relative to gasoline. ¹⁷ Alcohol evaporative emissions are also lower in ozone forming potential. Formaldehyde emissions are a concern with methanol powered vehicles and the state of California has imposed a tailpipe emissions standard of 15 milligrams per mile. ¹⁸

The composition of the gasoline used to make M-85 fuel can significantly affect the quantity and composition of both exhaust and evaporative emissions. ¹⁹ The California Air Resources Board is conducting in-use durability testing of a number of flexible or variable-fueled methanol vehicles. Low mileage emissions summaries are given in Table 4. ²⁰

Table 4
M-85 Flexible/Variable Fuel Vehicle Emissions Durability Test Results
Federal Test Procedure, grams/mile

<u>Year</u>	<u>Model</u>	<u>Mileage</u>	<u>NMOG</u>	<u>NMHC</u>	<u>CO</u>	<u>NOx</u>
1989	Toyota	5,000	0.762	0.320	6.340	0.274
	Corolla	11,000	---	---	3.832	0.182
1987	Ford Crown	5,000	0.141	0.07	1.54	0.60
	Victoria(4)	50,000	0.694	0.125	2.41	0.636
1988	Chev.	2,000	---	0.09	2.069	0.157
	Corsica(3)	18,000	0.580	0.081	4.484	0.229
1988	Nissan	6,000	---	---	3.091	0.124
	Stanza	15,000	1.164	0.052	4.341	0.17
1990	Plymouth	1,500	---	---	1.058	0.317
	Voyager(2)	12,000	0.244	0.029	1.706	0.356
1990	Plymouth	2,000	---	---	1.642	0.298
	Voyager	12,000	0.334	0.057	8.044	0.256
	Turbo(2)					

Source: California Air Resources Board

The Auto/Oil Air Quality Improvement Research Program has evaluated emissions from a fleet of 19 pre-1990 Flexible Fueled Vehicles (FFVs). The FFVs were tested on industry average gasoline as well as two methanol/gasoline blends (M-10 and M-85). Exhaust, evaporative, and running loss emissions were measured and contrasted with the Auto/Oil 1989 model year gasoline-powered reference fleet.²¹

While tailpipe NMOG emissions for the M-85 FFV fleet are 55 percent higher than for the gasoline-powered fleet, the ozone forming potential of the emissions actually decrease by 18.2 percent when reactivity adjustments are taken into consideration. CO and NOx emissions are reduced by 30.8 and 18.3 percent, respectively. Emissions from gasoline powered vehicles and prototype flexible or variable fueled vehicles are given in Table 5.²¹

Table 5
Exhaust Emissions from Flexible Fueled Vehicles When
Operating on Gasoline and M-85 grams/mile

<u>Emission</u> <u>Constituent</u>	<u>Gasoline-Powered</u> <u>Fleet Average</u>	<u>Methanol FFV</u> <u>Fleet Average</u>	
		<u>Gasoline</u>	<u>M-85</u>
NMOG	0.18	0.24	0.28
CO	2.79	2.81	1.93
NOx	0.60	0.40	0.49

Source: Auto/Oil Air Quality Improvement Research Program

The lower CO emissions from the M-85 vehicles "may be attributable to the oxygenates in the fuel, slightly better catalyst performance, and/or the need for less enrichment during transient operation due to methanol's inherent performance qualities..."²¹ The lower sulfur content of the M-85 fuel may also contribute to decreases in CO emissions.

The flame temperature of methanol is 2245°C (4433°F). This compares to a flame temperature for gasoline of 2743°F (4970°F).⁹ Due to methanol's relatively low flame temperature, it has been hypothesized that methanol-fueled vehicles should yield lower NOx levels. In part, the lower engine-out NOx production benefits are offset by a delay in three-way catalytic converter "light-off" under cold-start conditions.²²

Standard ceramic-based catalysts do not function until they are heated by a vehicle's hot exhaust gases to a light-off temperature of approximately 630°F to 700°F. Thus, emissions from the first few minutes after a cold start pass through the catalytic converter without being treated.²² These cold start emissions can contribute up to 70 percent of the total tailpipe exhaust emissions as measured under EPA's FTP testing procedure.^{23, 24} Light-off problems are compounded with methanol-fueled vehicles as the alcohol burns at a lower temperature than gasoline. It is also possible that low-NOx characteristics could be traded off by vehicle manufacturers to gain other benefits such as fuel economy performance, or providing a less expensive catalytic converter.¹¹

The South Coast Air Quality Management District has been operating ten flexible-fueled 1990 Plymouth Voyager ride share vans. Five are equipped with a sequential port injected 2.5L engine delivering 142 hp (on M-85) while five "gasoline tolerant methanol" Voyagers are equipped with a turbocharged 2.2L engine delivering a maximum output of 175 hp. Emissions tests conducted by the CARB indicate a reduced ozone forming potential of 53 and 40 percent for the gasoline tolerant and flexible fueled power trains when operating on M-85.¹⁹ Low-mileage vehicle emissions test results are summarized in Table 6 and Figure 3.²⁵ For comparative purposes, "zero-mile" FTP emissions results for a 1992 model year gasoline powered Voyager are included.

Table 6
Plymouth Voyager FFV and GTMV Emissions Results,
grams/miles

<u>Vehicle</u>	<u>Odometer Reading</u>	<u>Fuel</u>	<u>NMOG</u>	<u>CO</u>	<u>NOx</u>
1990 2.2L Plymouth	1,976	M-85/In	0.279	2.14	0.199
Voyager-GTMV	2,418	Indolene	0.269	5.291	0.168
1990 2.5L Plymouth	2,411	M-85/In	0.387	1.758	0.190
Voyager-FFV	2,589	Indolene	0.183	2.168	0.128
1992 Plymouth	"zero	Indolene	0.21	0.80	0.28
Voyager-Gasoline ¹	mile"				

1 From EPA's Manufacturer's Test Car List database.

Figure 3
Ozone Reduction Potential of M-85

Significant ozone reduction benefits are attainable given methanol use in areas where hydrocarbon control is appropriate. Because methanol vehicle emissions are less photochemically reactive, the EPA will consider crediting state Implementation Plans for ozone reduction of 34 to 83 percent (depending on vehicle technology) given the use of methanol-fueled vehicles in place of gasoline ones. Emission credits decline as the percentage of gasoline in the fuel blend increases. EPA has set the same CO and NOx emissions standards for methanol light-duty vehicles as for gasoline vehicles and has stated that no credits for CO or NOx emissions reductions can be claimed in State Implementation Plans where methanol use is mandated.⁹

Tailpipe Emissions from Dedicated Methanol-Fueled Vehicles

The clean alternative fuel advantage of dedicated methanol over gasoline use in terms of urban ozone formation is due both to lower levels of vehicle hydrocarbon emissions and to the lower photochemical reactivity of these emissions. The EPA has stated that, "On a reactivity equivalent basis, methanol flexible fuel vehicles (FFVs) are projected to emit at least 30 percent less volatile organic compounds (VOC) than typical future in-use gasoline vehicles, while optimized, dedicated methanol (M-100) vehicles are projected to emit 80 percent less VOC than future gasoline vehicles."¹⁶

Emissions tests conducted on 1981-1985 versus 1986-1988 model year dedicated methanol vehicles shows an improvement in emissions performance for the second generation vehicles.¹⁸ The California Air Resources Board has conducted tests on two dedicated M-85 Ford Crown Victorias equipped with 5.0L engines modified to an 11 to 1 compression ratio and using sequential electronic fuel injection with the original gasoline vehicle catalyst. Also tested was a 1989 Toyota Corolla equipped with a 1.6L engine with an 11 to 1 compression ratio and lean burn combustion. The Corolla is equipped with a close coupled catalyst and an underfloor oxidation catalyst to control formaldehyde emissions. Exhaust gas recirculation was also added to reduce NOx emissions. CARB test results are given in Table 7.²⁰

Table 7
Emissions from Dedicated M-85 Vehicles, grams/mile

<u>Vehicle</u>	<u>Mileage</u>	<u>NMOG</u>	<u>CO</u>	<u>NOx</u>
1986 5.0L	2,500	--	0.80	0.36
Ford Crown	30,000	--	1.21	0.311
Victoria (2 vehicles)	50,000	0.364	0.721	0.335
1989 1.6L	4,000	0.481	2.028	0.437
Toyota Corolla	14,000	0.486	4.60	0.466

Source: California Air Resources Board

More recently, three dedicated methanol vehicles were tested under the Auto/Oil Air Quality Improvement Research Program (AQIRP). A GM Lumina dedicated M-85 vehicle with a 3.1L engine was equipped with the following engine and exhaust system changes: ²⁶

- Compression ratio increase to 11 to 1.
- Combustion chamber redesign for increased turbulence.
- Reduced spark plug heat range.
- Engine spark and air-fuel calibrations optimized for best emissions, fuel economy, and driveability.
- Close coupled catalytic converter built into the exhaust manifold.
- A catalytic converter designed for methanol was installed under the floor.

The other two vehicles, designed to operate on M-100, consisted of a 1988 Nissan M-100 Sentra research vehicle equipped with a 12:1 lean burn 1.8L port fuel injected engine and a 1989 Toyota Corolla equipped with a 11:1 compression ratio lean burn 1.6L port fuel injected engine. The Nissan Sentra was equipped with a swirl control valve to increase turbulence. A single under body three-way catalytic converter was used for emissions control.

The Toyota emissions control package consisted of dual catalytic converts, one close-coupled to the exhaust manifold and the second in an underbody location. Tailpipe emissions for the three dedicated methanol vehicles are summarized in Table 8. ²⁶ While the GM Lumina has equal or lower exhaust emissions than the best FFV/VFV vehicles tested under the AQIRP program, the dedicated M-100 Nissan and Toyota vehicles fall within the range of FFV/VFV vehicle emissions performance.

Table 8
Exhaust Emissions for Prototype Dedicated Neat Methanol-Fueled Vehicles, grams/mile

	<u>GM Lumina</u>	<u>Nissan Sentra</u>	<u>Toyota Corolla</u>
Tailpipe Emissions (6-test average)	<u>M-85</u>	<u>M-100</u>	<u>M-100</u>
NMOG	0.10	0.36	0.20
CO	0.80	0.82	1.67
NOx	0.22	0.51	0.39

Source: Auto/Oil Air Quality Improvement Research Program

Advanced Methanol-Fueled Vehicles

Currently available FFVs are basically gasoline vehicles with only rudimentary modifications to permit methanol use. They must be capable of operating on straight gasoline and are thus unable to be optimized to take full advantage of methanol's wide flammability limits, high octane number, and higher flame speeds. Compared to gasoline, methanol can maintain stable combustion with leaner air to fuel ratios, thus, an optimized lean burn combustion engine could be possible that could comply with NO_x emissions regulations without the need for a reducing catalyst. It is postulated that future advanced-technology methanol vehicles could provide as much as an 80 to 90 percent reduction in ozone forming potential and significantly lower CO emissions while simultaneously maintaining NO_x emissions at levels comparable to current gasoline-powered vehicles.¹¹

Future developments in light-duty methanol vehicles will likely include: 7, 16

- Higher compression ratios or variable-boost turbochargers to improve fuel efficiency and allow smaller, lighter engines to be utilized;
- Improved cold-starting approaches to allow for reduction or elimination of the gasoline content;
- Leaner fuel/air ratios for greater fuel economy and reduced emissions of carbon monoxide, aldehydes, and unburned methanol;
- Low concentration fuel additives for flame luminosity, protection against ingestion, and enhanced cold starting to replace the 15 percent gasoline blends;
- Electrically heated catalysts to reduce cold-start emissions;
- Dual catalysts to reduce unburned methanol and aldehyde emissions;
- Catalytic dissociation of methanol powered by exhaust heat; and
- Cooling system, catalyst volume, and evaporative emission control system optimization.

Tests conducted by the California Air Resources Board on prototype M-100 vehicles equipped with electrically heated catalytic converters have produced exceptionally low hydrocarbon, CO, and NO_x emissions. Emissions test results for a 1988 model year Chevrolet Corsica and a 1989 Volkswagen Jetta are given in Table 9.²⁷

Table 9
Exhaust Emissions for M-100 Vehicles Equipped with an
Electrically Heated Catalytic Converter, grams/mile

	<u>Mileage</u>	<u>NMOG</u>	<u>CO</u>	<u>NO_x</u>
1988 Chevrolet Corsica with EHC	Low	0.01 0.01	0.52 0.37	0.10 0.12
1989 VW Jetta with EHC	Low	0.03 0.02	0.85 0.68	0.05 0.04

Indications are that it should be relatively straightforward for FFV's to qualify under California's Transitional Low Emission Vehicles (TLEV) standard. Meeting the Low Emission Vehicle (LEV) standard also seems achievable with the Ultra Low Emission Vehicle (ULEV) standard within range. Future dedicated and optimized M-100 fueled vehicles offer reduced evaporative emissions and lower reactivity than combustion products from M-85 blends and should also be able to qualify under the ULEV category.²⁷

Factory-Built Light Duty Methanol Fueled Vehicles

Ford Motor Company

Ford has delivered over 1,120 methanol fueled cars since 1981 which have achieved over 30 million miles of service. ^{15, 27} Over 600 carbureted dedicated fuel Escorts were placed in service between 1981-1983 with eight electronically fuel injected Escorts tested in 1983-1984. Two hundred and forty FFV Crown Victorias were put into fleet use between 1986 and 1989 with 250 FFV Taurus' delivered in 1991.

The current Ford Taurus FFV's operate without driver interaction on any blend of M-85, E-85, and gasoline. A modified electronic fuel injected engine is employed with an alcohol/gasoline combustion strategy. The FFV features an alcohol resistant fuel system; cold start capability to (-) 20°F; and higher performance and better fuel efficiency when operating on alcohol.

Ford has agreed to produce 2,500 1993 model year 3.0L Taurus FFVs, certified to California's 1994 TLEV standard, for delivery primarily in California starting in November, 1992. ^{27, 28} Ford also built 200 1992 model year Econoline Van and Club Wagon flexible-fuel vehicles. ²² The FFV Taurus is equipped with a 20 gallon fuel tank versus the 16 gallon tank available on a gasoline powered Taurus. The Taurus FFV achieves low exhaust emissions through use of a sequential multiport fuel injection system; dual heated oxygen sensors; exhaust gas recirculation; and dual three way catalytic converters. Emissions results for the FFV Taurus using both gasoline and M-85 are given in Table 10.

The Ford FFV Econoline Van is available in E-150 or E-250 cargo van or in 7 or 8-passenger Club Wagon models. The vehicles are equipped with a 4.9L in-line 6-cylinder engine and an automatic transmission. The FFV vans and wagons are provided with an oversized 34 gallon fuel tank versus the 22-gallon tank which is standard on gasoline-powered Econoline vans. The FFV vans and wagons can operate on straight gasoline or any combination of gasoline and methanol up to 85% methanol.

Table 10
1993 Ford FFV Taurus Exhaust Emissions
Test Results, grams/mile

	<u>NMOG</u>	<u>CO</u>	<u>NOx</u>	<u>Formaldehyde</u>
TLEV Certification				
Standard				
50,000 miles	0.125	3.4	0.4	0.015
100,000 miles	0.156	4.2	0.6	0.018
1993 3.0L FFV				
Taurus, M-85				
50,000 miles	0.091	1.4	0.1	0.012
100,000 miles	0.110	1.8	0.1	0.015
1993 3.0L FFV				
Taurus, Indolene				
50,000 miles	0.12	1.4	0.1	0.001
100,000 miles	0.14	1.7	0.1	0.002

Source: CARB Executive Order A-10-541, December 14, 1992.

General Motors Corporation

General Motors (GM) produced 20 VFV Chevrolet Corsicas in early 1989. These vehicles were followed by 200 1991 model year Chevrolet Lumina delivered in late 1990. Chevrolet's 1991 Lumina was a fully validated production car. GM has agreed to deliver up to 4,200 3.1L VFV Chevrolet Lumina sedans to California in 1992 and 1993 with additional units delivered to the federal Department of General Administration and other fleet operators. It appears that GM will receive orders for only about 1,200 units in 1992. 27, 29

Like the Ford FFV, GM's VFV Lumina is capable of burning any blend of gasoline, M-85 or E-85. The 1992 GM Lumina carried a price premium of \$2,000. Emission results for a 1992 model year Lumina operating on M-85 and gasoline are given in Table 11. 30

Table 11
Tailpipe Emissions for 1992 Model Year
VFV Chevrolet Lumina, grams/mile

	<u>NMOG</u>	<u>CO</u>	<u>NOx</u>	<u>Formaldehyde</u>
1992 3.1L VFV Lumina, M-85	0.11	1.70	0.07	0.02
1992 3.1L VFV Lumina, Gasoline	0.15	1.0	0.12	0.00

Source: National Renewable Energy Laboratory, Alternative Fuels Data Center

Chrysler Corporation

Chrysler delivered approximately 100 FFV Dodge Spirits and Plymouth Acclaims to the California and Federal Governments during 1992. 27 Chrysler expects to produce 2,100 1993 model year FFVs which will be available for purchase by fleet or retail customers. Production beyond the initial 2,100 FFVs will be strictly market-driven with Chrysler tooling up to manufacture as many as 100,000 FFV's in both the 1994 and 1995 model years. 22, 29 Beginning in 1994, Chrysler expects to offer FFV version of their Dodge Intrepid, Eagle Vision and Chrysler Concorde. 31

Chryslers 1993 model year FFVs are being offered at the same price as their conventionally fueled counterparts. The Dodge Spirit and Plymouth Acclaim are equipped with a 2.5L, four-cylinder multipoint fuel-injected engine, and a three speed automatic transmission. Range with an 18-gallon fuel tank is approximately 275 miles. 29 The 1993 model year midsize four-door FFV Plymouth Acclaim is available under the Washington Department of General Administration's state procurement contract for a price of \$9,833. The conventional midsize automobile available under the 1993 model year state of Washington contract, the 3.0L Dodge Dynasty, carries a price of \$10,587.

The Japanese and European car companies have not announced equivalent methanol fueled vehicle production plans and thus far have provided only prototype vehicles to both CARB and the EPA. Volvo, however is introducing in-line five and six cylinder engines for its 1992 model year 960 series, which requires only minor modifications to function as a dedicated methanol-burning vehicle. 22 Volkswagen has also begun limited distribution of a flexible-fuel Jetta. 7

Heavy Duty Methanol Engine Development

Historical Overview

The petroleum shortages of the 1970's led to research that indicated that alcohol fuels can partially or completely displace diesel fuel in heavy-duty engine applications. Methods of using alcohol fuels, in order of increased diesel fuel displacement, include solutions, emulsions, fumigation, dual fuel injection, spark ignition, and the use of ignition improvers. Power output, thermal efficiency and exhaust emissions vary significantly depending upon the combustion technique employed.³²

Methanol was not an obvious choice for use in heavy-duty diesel powered engines. Conventional diesels operate with a compression-ignition cycle in which the fuel spontaneously ignites when it is injected into hot compressed air. Methanol features both a high ignition temperature, which resists compressions ignition, and a high heat of vaporization, which produces a fuel/air charge cooling effect.⁷

If the ignition problems can be overcome, methanol offers several environmental advantages over conventional diesel fuel. First, methanol burns without producing particulates. Due to its lower flame temperature, methanol-fueled heavy-duty engines feature reduced engine-out NOx emissions.⁷ Finally, methanol-fueled heavy-duty engines can be equipped with oxidation catalysts to reduce hydrocarbon and carbon monoxide emissions below those of conventional diesel-powered units.

Due to its clean burning potential, a variety of efforts have been made to overcome methanol's compression ignition limitations. These may be categorized as:⁷

- Dual fuel, in which a small quantity of "pilot" diesel fuel is injected to initiate combustion;
- Spark ignition, used by Maschinenfabriken Augsburg-Nürnberg (M.A.N.) of Germany;
- Glow plugs, used by Detroit Diesel Corporation (DDC) and Caterpillar; and
- Ignition-promoting fuel additives, such as Avocet, used by Cummins Engine Company, DDC, and Daimler-Benz.

The dual fuel approach to methanol use is no longer under active investigation due to unacceptably high particulate emissions. After-market retrofit kits that aspirate alcohol-water mixtures into engines to displace diesel fuel also suffer from unacceptably high particulate emissions, as well as peak combustion pressures that may exceed manufacturers' specifications, resulting in shorter engine life and the voiding of manufacturers' warranties.⁷

M.A.N. equipped its in-line 6-cylinder, 11.4L 4-stroke spark-ignited methanol-fueled heavy-duty engines with an oxidation catalyst and achieved excellent emissions results for all pollutants except NOx.³³ M.A.N.'s first methanol engine in the U.S. entered transit bus service in San Rafael, California in 1983. Ten M.A.N. methanol-fueled diesel transit buses were delivered to Seattle in 1987. Maintenance and spark plug replacement requirements imposed significantly greater costs than a conventional diesel and all of the M.A.N. spark-plug methanol engines have now been removed from service.^{7, 15}

Detroit Diesel Corporation has developed a glow-plug methanol-fueled version of its 9.2L 6V-92TA 2-stroke diesel engine. Between 1984 and 1991 nearly 100 DDC methanol-fired engines were provided to transit operators in North America with an additional 50 methanol engines placed in heavy-duty school bus service in California.^{7, 15} Over 3.6 million miles were accumulated on these engines. DDC is now actively marketing an EPA and CARB emissions certified, fully warranted electronically controlled methanol version of their 6V-92 diesel engine.⁷ DDC also applied their alcohol-fuel technology in demonstration versions of their 7.1L 6L-71TA heavy-duty engine. Other engine manufacturers, including Cummins, Caterpillar, Navistar, Volvo, Daimler-Benz, and K-H-D (Deutz) have tested prototype methanol-fueled diesel engines.

In 1985, the EPA proposed stringent technology-forcing heavy-duty engine particulate emissions standards for introduction in the 1991 to 1994 time frame. As they operate in urban locations which often feature poor air quality, the transit bus was required to meet the same standards in 1991 that heavy-duty trucks have to face in 1994. The Clean Air Act Amendments of 1990, however, postponed the introduction of the 1991 bus standard to 1993.³³ Current and future heavy-duty engine emission standards are summarized in Table 12.³⁴

Table 12
U.S. EPA Heavy Duty Engine Exhaust Emission Standards,
Grams/Bhp-hr Measured During the EPA Transient Test

<u>Model Year</u>	<u>HC</u>	<u>CO</u>	<u>NOx</u>	<u>Particulates</u>
1991	1.3	15.5	5.0	0.25
1993 (Urban Bus)	1.3	15.5	5.0	0.10
1994	1.3	15.5	5.0	0.10
1994 (Urban Bus)	1.3	15.5	5.0	0.05*
1998	1.3	15.5	4.0	0.10
1998 (Urban Bus)	1.3	15.5	4.0	0.05*

- For urban buses, EPA can relax the particulate standard to 0.07 grams/Bhp-hr if 0.05 is not achievable.

Interest in alternative fueled heavy-duty engines intensified with passage of the Alternative Motor Fuels Act (AMFA) of 1988 (P.L. 100-494). The AMFA establishes a number of programs that are to be carried out by the federal Department of Energy in conjunction with other federal agencies, state and local governments, and industry. Key programs include:³⁵

- The Alternative-Fuel Federal Light-Duty Vehicle Programs;
- The Truck Commercial Application Program; and
- The Alternative-Fuels Bus Testing Program.

Under the Commercial Truck Program, three methanol-powered packer trucks equipped with DDC engines are being compared with a similar number of diesel units powered by the same engine family. The federal Department of Transportation's Urban Mass Transportation Administration (UMTA) has, under their Clean Air Program, placed approximately 60 methanol-fueled transit buses into service at seven locations.³⁴

Methanol Heavy-Duty Engine Availability and Emissions Performance

Detroit Diesel Corporation

DDC manufactures a family of two-stroke diesel engines, which are widely used in North American transit buses. The 300 to 350 hp rated 9.2 L 6V-92TA engine is equipped with a turbocharger and aftercooler ahead of the blower. The turbocharger is an advantage in that it boosts inlet temperatures and promotes methanol self-ignition. Additional changes required to permit the 6V-92 to effectively compression ignite methanol include: 25, 33

- An increased compression ratio (23 to 1);
- A modified blower and electronic control system;
- Higher fuel flow injectors;
- The inclusion of glow plugs which are used for starting and to assist combustion during warmup;
- A solid state glow plug controller;
- Blower bypass control during transient operation; and
- Materials changes for compatibility with methanol.

Hardware changes for the methanol-fueled bus engine are depicted in Figure 4. 15

Figure 4
Methanol-Fueled DDC 6V-92TA Bus Engine Hardware Changes

The DDC methanol-fired engine appears almost the same as its diesel counterpart, fits into the same bus chassis, and should be familiar to mechanics and maintenance personnel. A catalytic converter is issued as standard equipment with the methanol engine. The heart of DDC methanol engine technology is the Detroit Diesel Electronic Control System. Functioning much like the electronic fuel injection system in automobiles, the units controls the quantity and timing of fuel injected into the engine to maximize performance and minimize emissions. The controller also tells the glow plug controller when to turn the glow plugs on and off, depending on engine speed, load, and coolant temperature.²⁵ The performance life of the plugs is thus extended.²² The unit also sets the position of the blower bypass damper.

The 6V-92TA methanol transit bus engine produces lower values for all regulated emissions than its diesel counterparts, meets all future emissions standards today, and performs as well as a diesel engine of equal power.²⁵ The engine is in full-scale production and is certified to both EPA and CARB exhaust emission standards. Exhaust emission results for 1992 and 1993 model year 6V-92TA engines operating with M-100, M-85, and 99 percent methanol blended with 1 percent Avocet are given in Table 13.^{15, 29, 34} For comparative purposes, emissions from a 1991 model year 6V-92TA diesel fueled engine are also given.¹⁵

Table 13
**Detroit Diesel Corporation Methanol-Fueled 6V-92TA
Emissions Test Results, grams/Bhp-hr**

<u>Model Year, Fuel</u>	<u>HC</u>	<u>CO</u>	<u>NOx</u>	<u>Particulates</u>
1993 Urban Bus Standard	1.3	15.5	5.0	0.10
1993, M-85 ¹	0.2	1.6	4.1	0.03
1993, M-100 ²	0.1	2.1	1.7	0.03
1993, M-99+1% Avocet	0.22	0.61	3.96	0.039
1991, Diesel ³	0.4	2.1	4.8	0.25

1 CARB Executive Order A-290-28, dated December 14, 1992.

2 CARB Executive Order A-290-26, dated August 12, 1992.

3 EPA Federal Certification Test Results for 1991 Model Year.

DDC initially developed its methanol fueled engine technology on their 300 to 350 hp 6V-92 and 240 hp 6L-71 mid-range engines in their 2-cycle product lineup. The company expects to expand this technology to engines of higher and lower horsepower. A methanol version of DDC's 4L-71 engine would produce from 160 to 200 hp and could be used in such applications as medium duty trucks, refuse trucks, school buses, airport shuttles, and street sweepers. The largest on-highway trucks could be served by a methanol version of DDC's 350-400 hp 8V-92 engine.^{15, 36}

Caterpillar

Caterpillar has modified an in-line 6-cylinder, 10.5L, 4-stroke, direct injected 3306 engine with turbocharger and aftercooler to run on M-100. Ignition is accomplished by surface catalization promoted by a glow plug.³³ The prototype engine will start at 0°F when the glow plug is switched on for 30-seconds before cranking. Principle modifications to the 3306 include:

- Use of a glow plug with a special ceramic encasing a metal filament;
- Increased fuel flow oil lubricated injectors;
- Injector modifications consisting of an extra axial hole to facilitate the spread of flame between individual spray jets.
- Advanced and longer duration injection timing to accommodate the increased fuel flow.

Two Caterpillar 3306 methanol fueled diesel engines were evaluated in long distance transport operation as part of Canada's Methanol in Large Engines (MILE) program. While wear was equivalent to a diesel and volumetric fuel consumption was 2.4 times that of an equivalent diesel, glow plug durability was not more than 200 hours, which represents a major limitation. ³³

Caterpillar also tested two glow plug-assisted, in-line, 6-cylinder 14L, 350 hp M-100 fueled 3406B engines in heavy-duty trucks from October 1987 to August, 1989. This was a demonstration project only with no specific alternative fuel engine production plans. Exhaust emissions from the two trucks, which were not equipped with oxidation catalysts, are given in Table 14. ³⁰

Table 14
Caterpillar Prototype Methanol-Fueled 3406 Engine
Exhaust Emission Results, grams/Bhp-hr

<u>Engine Model</u>	<u>Fuel</u>	<u>HC</u>	<u>CO</u>	<u>NOx</u>	<u>Particulates</u>
3406B DITA	M-100	4.45	12.35	3.05	0.15
3406B DITA	M-100	3.67	13.02	3.27	0.10

Cummins Engine Company

The Cummins L-10 is a 10L in-line, 6-cylinder turbocharged engine commonly used in heavy duty trucks. Cummins is attempting to use the ignition-promoting fuel-additive combustion approach, which consists of blending small amounts of an ignition promoter, such as Avocet, plus lubricants and corrosion inhibitors, with the methanol fuel. ³³

This combustion approach allows for methanol-diesel operations without extensive engine alterations and without added engine components such as spark plugs and distributors, or glow plugs and controllers. Although the additive approach offers lower capital and maintenance costs, fuel costs increase. Avocet additions add from 20¢ to 70¢ per gallon of fuel, depending on the concentration used. ⁷ The manufacturer projects that prices will substantially decrease as production volumes increase.

Cummins has also found that extensive engine changes are also necessary, including: ³³

- Higher compression ratio;
- Fuel flow rate increases;
- New injectors for improved spray pattern;
- New pistons with improved combustion chamber design; and
- Cam follower changes to optimize injection timing.

Navistar International

Navistar has tested a prototype methanol fueled version of their medium/heavy-duty 250 hp, 7.6L 4-stroke DT-466 engine. Exhaust emissions from this engine and from a DTA-466 diesel engine using a low-sulfur, low aromatics 1994 California diesel fuel are given in Table 15. Both engines are equipped with oxidation catalysts. ¹⁷

Table 15
Exhaust Emissions from Prototype Methanol-Fueled
7.6L Navistar DT-466 Engine, grams/Bhp-hr

<u>Engine, Fuel</u>	<u>HC</u>	<u>CO</u>	<u>NOx</u>	<u>Particulates</u>	<u>Fuel Economy, MPG</u>
DT-466, M-100	0.06	0.06	3.52	0.05	4.0
DT-466, Low-Sulfur Diesel	0.19	0.61	4.20	0.08	9.0

FEV of America, in cooperation with Navistar International, has been awarded a contract by the California Air Resources Board to evaluate the application of exhaust gas recirculation (EGR) as a means of further reducing the NOx emissions from their DTM-466 methanol engine.³⁷

Volvo

The Volvo diesel is a 9.6L, 6-cylinder, turbocharged direct injected engine. Volvo has tested a diesel fuel pilot ignited version of this engine both with and without the use of an oxidation catalyst. Without the catalyst, HC and CO emissions are greater for the methanol engine than for the diesel while particulates and NOx are reduced. All emissions are reduced when the catalytic converter is added. Exhaust emission test results are indicated in Table 16.

Modifications required to adopt the base Volvo diesel to a pilot-injected version include:³³

- A small distribution pump and single-holed injector for the pilot diesel. The original injector and supply system is used for methanol fuel.
- Cold start is accomplished with diesel fuel alone and employs an air pre-heating system.

Table 16
Volvo 9.6L Diesel Pilot-Injected Engine Exhaust
Emission Test Results, grams/Bhp-hr

<u>Engine, Fuel</u>	<u>HC</u>	<u>CO</u>	<u>NOx</u>	<u>Particulates</u>
Volvo TD 100 Methanol + Diesel ¹ (Without Catalyst)	1.45	7.67	5.45	0.30
Volvo TD 100 Methanol + Diesel (With Catalyst)	0.12	2.69	5.51	0.27
Volvo TD 100C Diesel	0.85	3.01	8.34	0.52

¹ Over the EPA Transient Cycle Test, approximately 80 percent of the fuel volume used was methanol.

While it is doubtful that the dual-fuel operation could meet strict future emission standards, particularly for smoke, it is possible that air quality benefits could be achieved through converting in-use engines to dual fueled operation. ³³

M.A.N.

The M.A.N. methanol-diesel is an in-line, 6-cylinder, spark-ignited 11.4L 4-stroke engine. Due to the use of an oxidation catalyst, emissions for this engine, indicated in Table 17, are extremely low for all pollutants except NO_x (tests have confirmed that an oxidation catalyst can actually increase NO_x to levels above engine-out conditions). ³³

Table 17
M.A.N. 11.4L Spark-Ignited Methanol Engine
Emissions Test Results, grams/Bhp-hr

<u>Engine, Fuel</u>	<u>HC</u>	<u>CO</u>	<u>NO_x</u>	<u>Particulates</u>
M.A.N. D2566, M-100 (With Oxidation Catalyst)	0.05	0.31	6.61	0.043

Heavy-Duty Methanol Engine Price and Performance

Costs of new heavy-duty methanol-diesel engines are high due to production in small quantities. Currently, the cost of an original equipment manufacturer heavy-duty compression ignition engine is two to two and a half times the cost of an equivalent diesel engine. ¹⁷ As production volumes increase, incremental engine costs are expected to decline to perhaps \$2,000 to \$3,000 above present diesel costs levels, depending upon the ignition approach used and the quantity of engines produced. ⁷ Estimated costs of methanol engines for present day and mature configurations are compared with baseline diesel engine costs in Table 18. ³³ Costs for future diesel engines are also expected to increase due to the need for regenerative particulate traps.

Table 18
Methanol and Diesel Engine Costs

<u>Description</u>	<u>Diesel</u>	<u>1989 Methanol</u>	<u>2000 Methanol</u>
Base Diesel Engine	\$12,500	\$12,500	\$12,500
Injection/Governor System	2,000	---	---
Methanol Fuel System		500	500
Governor (Electronic)		3,000	1,500
Ignition System		1,000	1,000
Catalytic Converter		3,000	2,500
Per Engine Development Cost		10,000	---
Total Engine Cost	\$15,000	\$30,000	\$18,000

Costs for demonstration methanol vehicles carry a substantial price premium. A demonstration of six buses at Windsor Transit in Canada carries a cost premium of \$45,000 per bus. This premium includes not only the methanol fueled engine, but modifications to the bus itself including stainless steel fuel tanks and lines, special fuel pumps, filters, and coolers; and a flammable vapor detection system.³³ A similarly large price premium exists for the 78-passenger alternative fuel school buses purchased under California's Safe School Bus Clean Fuel Efficiency Demonstration Program. Demonstration vehicle prices are indicated in Table 19.³⁸

Table 19
California School Bus Demonstration Vehicle Prices

<u>Bus Type</u> <u>(Number Purchased)</u>	<u>Engine</u> <u>Type</u>	<u>Fuel</u>	<u>Horsepower</u>	<u>Cost Per</u> <u>Bus</u>
Carpenter Bus Company (100)	DDC 6V-92	M-85	253	\$140,193
Blue Bird Bus Company (100)	Tecogen Tecodrive 7000 Turbo-Charged	CNG	222	\$117,530
Thomas-Built Bus Company (200)	Caterpillar 3116 TA Advanced Diesel	Low- Sulfur Diesel	229	\$82,808

A recent study by Booz-Allen & Hamilton assesses the use of propane, compressed natural gas, liquefied natural gas, methanol and advanced diesel fuel by small transit operators. For comparative purposes, the study determined "total alternative fuel costs" for each of three different fleet sizes: a 10-bus, a 50-bus, and a 200-bus fleet. The total fuel costs over baseline diesel operation are summarized in Table 20 for methanol and advanced diesel buses equipped with particulate traps. The total estimated costs include direct fleet fuel, maintenance and bus replacement costs; refueling facility operating and amortized capital costs; and required maintenance facility modifications.²⁹ In all cases, methanol was found to be the most expensive fuel alternative.

Table 20
Incremental Increase in Transit Fleet Annual Operating Cost over Baseline Diesel Operation

	<u>10-Bus Fleet</u>		<u>50-Bus Fleet</u>		<u>200-Bus Fleet</u>	
	<u>Methanol</u>	<u>Diesel w/Trap</u>	<u>Methanol</u>	<u>Diesel w/Trap</u>	<u>Methanol</u>	<u>Diesel w/Trap</u>
Increased Fuel Costs	\$43,371	0.	\$289,143	0.	\$1,156,571	0.
Fuel Facility Operating Costs	\$1,650	0.	\$1,900	0.	\$2,400	0.
Increased Fleet Maintenance Costs	\$30,000	\$15,000	\$200,000	\$100,000	\$800,000	\$400,000
Increased Fleet Replacement Costs	\$16,667	\$16,667	\$83,333	\$83,333	\$333,333	\$333,333
Annualized Fuel Facility Capital Costs	\$7,687	0.	\$14,907	0.	\$44,676	0.
Annualized Maintenance Facility Capital Costs	\$8,762	0.	\$17,524	0.	\$35,049	0.
Total:	\$91,688	\$31,667	\$574,376	\$183,333	\$2,372,029	\$733,333

A major reason that methanol-fueled heavy-duty vehicle operating costs are higher than equivalent diesels is that demonstration engines in the field have not exhibited equal energy consumption to their diesel counterparts. The miles per gallon ratio for methanol to diesel energy equivalence is 2.3 to 1. The field average for DDC 6V-92 methanol-fueled engines is approximately 2.7 to 1.²⁵

Heavy-duty methanol compression ignition engines also require significantly more maintenance than a diesel engine. Fuel injectors and cylinder linings in particular have demonstrated poorer durability than for diesels.¹⁷ Significant improvements in DDC methanol-fueled engine reliability, expressed as mean miles between failure, occurred after 1990 due to the use of the Lubrizol fuel additive and optimized calibration to reduce glow plug on-time.²⁵

The methanol fuel additive is basically a detergent, similar to that found in gasoline, which prevents plugging of injector spray tip holes. The additive also includes a lubricity improver and a corrosion inhibitor. The selection of proper lubricants, use of high quality fuel and lube oil filters is essential to ensure optimum service life, performance, and reliability of methanol-fueled engines.²⁵

Cold weather starting ability of methanol engines equipped with a glow plug assist is comparable to or better than diesels. For the DDC 6V-92, acceleration is similar to the diesel version as both engines display the same torque curve.

Emissions Characteristics of Vehicles Using Neat Methanol and Methanol Fuel Blends

Photochemical Reactivity

The clean fuel advantage of methanol over gasoline in terms of urban ozone formation is due to both lower levels of vehicle evaporative and tailpipe exhaust non-methane organic (NMOG) emissions coupled with a lower photochemical reactivity for the emissions that are present.¹⁰

The State of California has moved to regulate organic emission products on the basis of reactivity, or ozone-forming potential, rather than mass.²⁷ The ozone-forming potential (grams ozone/grams NMOG) is defined as the increase in ozone level expected to occur when the incremental NMOG emissions from a vehicle are added to an urban air parcel and exposed to sunlight. Data required to determine the ozone-forming potential include mass and composition of NMOG emissions, ozone reactivities by chemical species, an airshed specific emissions inventory, meteorological assumptions, and appropriate atmospheric chemistry assumptions.³⁹

The California Air Resources Board has determined reactivity factors for individual chemical species and used them to compute exhaust reactivity adjustment factors for transitional low-emission vehicles. Methanol (M-85) emissions have been assigned an initial reactivity adjustment factor of 0.41. This means that NMOG emissions from an M-85 fueled TLEV vehicle could be as high as $0.125/0.41 = 0.30$ grams per mile and still have the same ozone impact on the environment as a vehicle designed to conventional standards. Exhaust reactivity adjustment factors for gasoline and alcohol fuels are given in Table 21.²⁷

Researchers at the Radian Corporation used Carter reactivity factors for individual chemical species to determine relative ozone-forming potentials for emissions from various alternative fuels. Values of 0.88 and 0.61 grams ozone per gram NMOG exhaust were determined for M-85 and M-100, respectively.

Table 21
Ozone Reactivities of Alcohol Fuels versus Gasoline,
grams of ozone per gram of NMOG

<u>Fuel</u>	<u>MIR</u> ¹	<u>MOR</u> ²
Gasoline	3.44	1.30
Methanol	0.56	0.28
Ethanol	1.33	0.72

1 MIR is the ozone forming potential (grams of ozone/gram NMOG) when the reaction is limited by organic content.

2 MOR is the ozone-forming potential when the reaction is limited by atmospheric NO_x concentration.

EPA and the CARB have also developed new definitions for methanol-derived hydrocarbon emissions. "Organic Material Hydrocarbon Equivalent" (OMHCE) is a mass based emissions measurement that takes into account the fact that oxygen in the oxygenated hydrocarbon portion of a methanol-fueled vehicle's exhaust does not participate in ozone formation.²⁷ Another standard, which is designed to equalize methanol emissions on a mass basis with those from gasoline fueled cars, is the "Organic Material Non-Methane Hydrocarbon Equivalent (OMNMHCE).

The U.S. EPA published emission standards for light-duty methanol vehicles in the April 11, 1989 Federal Register. The standards applicable for CO and NOx emissions are identical with those for gasoline powered vehicles. The objective of EPA's organic emission standard is to limit the ozone producing potential of methanol vehicles to no more than that of conventional vehicles. Thus, higher total HC mass emissions are allowable for methanol vehicles because, in the aggregate, each gram of methanol exhaust contributes less to ozone formation than that for conventional vehicles.⁹

The regulations are attempting to establish a "level playing field" and provide parity between the treatment of gasoline- and methanol-fueled vehicles. Unfortunately, when tailpipe emission standards for alternative fueled vehicles are established for equivalent control on the basis of ozone-forming potential, the alternative fuels no longer offer any air quality benefits, assuming that both conventional- and alternative-fueled vehicles are designed to "just meet" the standards.²⁷

Fuel Composition

Because methanol vehicle emissions are less photochemically reactive, EPA will consider crediting state implementation plans for ozone reductions when they include the mandated use of methanol-fueled vehicles in place of gasoline vehicles. EPA credits for evaporative emissions are 100 percent given the use of neat methanol. The emissions credit for dedicated fuel vehicles is dependent upon the vehicle technology and declines as the percentage of gasoline in the fuel mix increases.⁹ Flexible fueled vehicles present difficulties due to their variable fuel mix capability. As EPA has established the same CO and NOx emissions standards for methanol and gasoline vehicles, no CO or NOx emissions credits may be claimed.

Measurements taken on FFVs equipped with stock catalysts and operated for 50,000 miles indicate that increasing the methanol content of the fuel decreases the exhaust emissions for all priority pollutants. This relationship is indicated for the FTP driving cycle in Figure 5.¹³

Figure 5
Exhaust Emission Variation versus Fuel Methanol Content

The effects of methanol/gasoline mixtures on vehicle emissions were determined for a fleet of 19 pre-1990 prototype flexible/variable-fueled vehicles under the Auto/Oil Air Quality Improvement Research Program. The methanol-fueled vehicles were tested on three fuels: an industry average gasoline and M-10 and M-85 methanol blends. Exhaust organic emissions, expressed as OMHCE, were 37 percent lower with M-85 than with M-10, while CO was 31 percent lower, and NOX was 23 percent higher. AQIRP findings are summarized in Table 22.²¹

Table 22
FFV/VFV Emissions When Fueled with Various Methanol Blends
grams/mile

	Industry Average Gasoline (M-0)	M-10	M-85
OMHCE	0.29	0.27	0.18
CO	2.81	2.59	1.93
NOx	0.40	0.40	0.49

The California Air Resources Board has proposed regulations that establish specifications for commercial alternative fuels. The purpose of the specifications is to ensure that the fuels are of consistent quality so that they produce the expected emissions benefits.³⁷ CARB's methanol specifications are summarized in Tables 23 and 24.^{7, 37}

Table 23
CARB Proposed Commercial Specifications for M-100 Fuel

<u>Specification</u>	<u>Value</u>	<u>Test Method</u>
Methanol	96 Vol. % (min.)	
Distillation	4.0°C (range)	ASTM D 1078-86
Other Alcohols and Ethers	2.0 Mass % (Max.)	ASTM D 4815-89
Hydrocarbons, Gasoline or Diesel Fuel	2.0 Mass % (max.)	ASTM D 4815-89
Luminosity	---	Visible Flame Required
Specific Gravity	0.792 +/- 0.002 @ 20/20° C	ASTM D 891-89

Table 24
CARB Proposed Commercial Specification for M-85 Fuel

<u>Specification</u>	<u>Value</u>	<u>Test Method</u>
Methanol	84 Vol. % (min.)	Annex A1 to ASTM D-2
Gasoline, Unleaded	14.5+/- 0.5 Vol. %	
Higher Alcohols (C ₂ - C ₈)	2.0 Vol. % (max.)	ASTM D 1415-89
Hydrocarbons plus Aliphatic Ethers	13-16 Vol. %	ASTM D 1415-89
Luminosity	---	Visible Flame Required

In addition to the specifications listed in Tables 23 and 24, limitations are established for acidity, lead, phosphorus, sulfur, gum, water, total particulates, and fuel appearance. The methanol fuels are required to produce a luminous flame that is visible under maximum daylight conditions throughout an entire burn duration. For M-100, the fuel must have a distinctive and noxious taste for the purposes of preventing human ingestion, and upon vaporization, must have a distinctive odor so that its presence can be detected in air at a concentration not over one-fifth of its lower limit of flammability.⁷

Evaporative Emissions

Fuel evaporation is a major source of vehicular NMOG emissions during the summer. Even in mild summer weather (60 to 84°F), evaporative losses from gasoline-powered vehicles can account for 45 percent of all vehicular NMOG emissions.⁴⁰

Evaporative emissions reported in the literature vary considerably and are sensitive to effectiveness of control technology, fuel composition, and vapor pressure. Evaporative emissions substantially increase given the 90°F weather typically associated with ozone episodes.

Evaporative losses for the methanol blends used with the AQIRP FFV/VFV test fleet are summarized in Table 25. Averaged in-use diurnal, hot soak, and running loss emissions are also given for a twenty-vehicle 1989 model year gasoline-powered reference fleet. While the diurnal and hot soak emissions for the FFV/VFV fleet are comparable to the gasoline fleet, the running losses are considerably reduced.²¹

Table 25
Evaporative Losses for Methanol Blends Used in
Pre-1990 FFV/VFVs, OMHCE, grams/test

	<u>Gasoline Powered Fleet</u>	<u>M-0</u>	<u>Methanol Fleet M-10</u>	<u>M-85</u>
Diurnal	0.44	0.82	1.13	0.37
Hot Soak	0.50	0.59	1.22	0.69
Running Losses	8.24	0.32	--	0.54

Running and refueling loss estimates for post-1981 light-duty gasoline- and methanol-fueled vehicles are summarized for two temperature ranges in Table 26.⁴¹ The evaporative emissions for M-100 are expected to be very low due to methanol's extremely low volatility as indicated by its 5.0 psi Reid vapor pressure.¹⁶

Table 26
Running Losses and Refueling Emissions versus
Ambient Temperature, NMHC, grams/mile

<u>Light-Duty Vehicles</u>	<u>Running Loss</u>		<u>Refueling Loss</u>
	<u>60-84°F</u>	<u>80-95°F</u>	<u>80-95°F</u>
Gasoline-Powered	0.28	0.59	0.25
M-85	0.19	0.38	0.17
M-100	0	0	0

The EPA has projected in-use organic emission losses for advanced (1995-1999 era) FFVs, FFVs optimized for M-85, and dedicated optimized M-100 vehicles. As indicated in Table 27, the advanced M-85 vehicles are predicted to emit over 60 percent less organics than their gasoline-powered counterparts while the optimized M-100 vehicles completely eliminate evaporative losses.¹⁶

Table 27
Projected In-Use Organic Emissions for Gasoline and
Advanced Design Methanol Vehicles, NMHC, grams/mile

	<u>Gasoline-</u> <u>Vehicles</u> <u>(9.0 psi RVP)</u>	<u>Interim-</u> <u>Technology</u> <u>FFVs</u>	<u>FFV</u> <u>Optimized</u> <u>for M-85</u>	<u>Vehicles</u> <u>Optimized</u> <u>for M-100</u>
Hot Soak/Diurnal	0.18	0.058	0.058	0.0
Running Loss	0.16	0.049	0.049	0.0
Refueling Loss	0.07	0.053	0.053	0.0
Total Evaporative Losses	0.41	0.16	0.16	0.0

Cold Weather and Mileage Effects on Tailpipe Emissions

An examination of a Ford Escort, operating with M-85 fuel, indicates that CO, THC, and formaldehyde exhaust emissions increase substantially when the vehicle is operated at reduced temperatures. FTP CO emissions increase 400 percent over baseline levels at 40°F and further increase to over 700 percent when the test temperature is reduced to 20°F. Total hydrocarbon emissions increase by 217 percent and 513 percent at 40°F and 20°F, respectively.⁴² Increases of this magnitude are also found with gasoline-powered vehicles and are consistent with increased carburetion fuel enrichment at lower temperatures.

An analysis of emissions data, coupled with odometer readings, was conducted for 54 methanol-fueled cars. The general mileage dependence for exhaust emissions is indicated in Table 28.¹⁸

Table 28
Mileage Dependence of Emissions for Methanol-Fueled Vehicles,
grams/mile

	Odometer Reading (in Miles)			
	0-5,000	10,000-15,000	20,000-25,000	>30,000
OMHCE	0.35	0.36	0.43	1.0 ¹
CO	3.05	3.17	3.41	5.92
NOx	0.63	0.68	0.74	0.77

1 Strongly influenced by two outliers.

The New York State Energy Research and Development Authority is sponsoring a demonstration program in which four 5.0L FFV Ford Crown Victorias are tested as part of the New York State Thruway Authority's vehicle fleet. Two of the FFVs were operated on gasoline for the first 50,000 miles, then switched to M-85. New York found that the increase in FTP emissions with mileage was greater for gasoline than for M-85. In fact, the fuel specific deterioration rates for gasoline exceeded those for M-85 by factors of two to four.¹³

Global Warming Impacts of Methanol-Fuel Use

M.A. DeLuchi of the Center for Transportation Research at Argonne National Laboratory (ANL) has completed an assessment of alternative transportation fuels in terms of their ability to reduce greenhouse gas emissions. Table 29 shows the grams per mile CO₂-equivalent emissions for individual greenhouse gases emitted over the entire fuel cycle for reformulated gasoline, methanol from natural gas, and methanol from wood. Total fuel cycle emissions include tailpipe and evaporative emissions from vehicles, as well as emissions from all upstream extraction, refining and transportation processes.^{28, 43}

Table 29
Grams per Mile CO₂-Equivalent Emissions for Reformulated Gasoline and Methanol

Fuel Cycle Stage and Emissions	Reformulated Gasoline	Methanol from Natural Gas	Methanol from Wood
Vehicular Use			
CH ₄	1.0	0.5	0.5
N ₂ O	17.4	17.4	17.4
NMOG	8.4	3.2	3.4
CO	18.4	21.6	21.6
NOx	18.0	18.0	18.0
CO ₂	270.5	216.6	(-)9.5
Total Vehicular	333.7	277.4	51.4
Upstream Processes			
CH ₄	5.3	8.7	4.6
N ₂ O	3.0	2.0	7.1
NMOG	1.2	0.8	1.3
CO	0.6	0.4	2.1
NOx	13.8	29.2	26.3
CO ₂	133.6	166.4	112.0
Total Upstream	157.5	207.4	153.3
Totals	491.2	484.8	204.7

The California Energy Commission (CEC) also conducted an examination of greenhouse gas emissions for various fuel choices. Vented and flared gas associated with oil production, processing, transport and distribution, and vehicular use were considered. In addition to methanol derived from natural gas, methanol produced from coal and diesel fuel from crude oil were examined. The CEC findings are given in Table 30.⁴⁴

Table 30
Summary of Global Warming Impacts of Alternate Fuels
CO₂-Equivalents, grams/mile

<u>Fuel</u>	<u>CO₂-Equivalent Emissions</u>
Gasoline from crude oil	455 to 507
Diesel from crude oil	360 to 378
Methanol from natural gas	414 to 471
Methanol from coal	764 to 891

The ANL and CEC results indicate that the use of methanol derived from steam reforming of natural gas offers only a slight greenhouse gas benefit when used to displace gasoline. When produced from coal, for the production technologies considered, methanol contributes about 60 to 80 percent more CO₂ per mile than gasoline from crude oil.⁴⁴ These relationships are, of course, dependent upon assumptions regarding methanol production technologies, conversion and vehicle efficiencies, and fuel quality. Greenhouse gas reductions could be obtained should methanol production from wood prove to be both technically and economically feasible.

In heavy-duty compression-ignition engines, diesel fuel offers a reduced warming impact as contrasted to methanol due to the high conversion efficiency and superior fuel economy of the diesel engine.⁴⁴ Approximately 2.3 to 2.7 gallons of methanol are required to displace one gallon of diesel fuel. Both fuel consumption and engine out CO₂ emissions are minimized with diesel-fueled heavy-duty engines.

Methanol-Fueled Vehicle Performance Characteristics

Performance and driveability of methanol-fueled vehicles is essentially the same as for gasoline powered vehicles.⁹ In fact, performance testing indicates that after their initial break-in period, FFVs are able to accelerate quicker when operating an M-85 than with gasoline.¹³ Acceleration data for a flexible-fuel Ford Escort and Ford Crown Victoria are given in Table 31.¹⁵

Table 31
FFV 0-60 Miles per Hour Acceleration Times

<u>Vehicle</u>	<u>Fuel</u>	<u>2-Test Average</u>
Ford Escort	M-85	15.8 seconds
	Gasoline	16.7 seconds
Ford Crown Victoria	M-85	12.2 seconds
	Gasoline	12.6 seconds

Range: Methanol-fueled vehicles have less range than gasoline vehicles because of methanol's lower energy content. Approximately 1.8 gallons of methanol is required to provide the equivalent energy content of one gallon of gasoline. While larger fuel tanks are typically provided on FFVs, their volume is limited by vehicle design and thus does not totally compensate for the energy content difference. Both the Ford Taurus, Chevrolet Lumina, and the Dodge Spirit FFVs are equipped with oversized 18 or 20-gallon fuel tanks. When operating on M-85, these vehicles have approximately 65 to 70 percent of the range of their gasoline-powered counterparts.

Fuel Economy: M-85 has roughly 60 percent of the energy content of gasoline (assuming 65,800 Btu/gallon for M-85 and 115,400 Btu/gallon [low heating value] for gasoline). Thus, it is desirable to compare gasoline fuel economy to M-85 fuel economy on an energy-equivalent basis. This is often referred to as the "gasoline-equivalent" fuel economy. The relationship between M-85, gasoline, and gasoline equivalent fuel economy is depicted in Figure 6.¹³ A fuel economy of 10.3 miles per gallon (MPG) when operating on M-85 is approximately 18.1 MPG when expressed in terms of gasoline-equivalent fuel economy.

Figure 6
Comparison of M-85, Gasoline, and Gasoline-Equivalent Fuel Economy

Methanol has chemical and combustion properties which make it an inherently more energy-efficient fuel than gasoline. The most important properties are its high-octane rating, which allows for a higher compression ratio; its wide flammability limit, which permits good combustion under lean or high air-to-fuel ratio conditions; and its higher power output.¹⁶

Even FFVs that are not optimized for methanol's fuel properties provide approximately a five percent efficiency and performance improvement when operating on methanol. This increase is derived from the fact that methanol's high latent heat of vaporization results in evaporative cooling, which provides a denser intake charge. The subsequent increase in exhaust products results in greater effective work and a higher engine power output.¹⁰

FFV technology under development within the 1993-1995 time frame is expected to employ limited optimization to capture benefits from methanol's combustion properties and provide up to a seven percent energy efficiency improvement relative to gasoline. Modifications may include:¹⁰

- A reduced spark retard due to methanol's higher octane rating and faster flame speed,
- Optimized EGR scheduling with reduced engine-out NOx emissions due to methanol's lower combustion temperature, and
- Reduced enrichment during cold starts, due to methanol's wider flammability limits.

Increased optimization of flexible fuel engine technology could provide up to a 10 percent energy-efficiency increase by the year 2000, while dedicated methanol engine technology for the year 2000 and beyond could provide a 10 to 20, or perhaps even 30 percent increase in efficiency over equivalent gasoline engine technologies. ^{10, 16} Efficiency increases are available through high-compression ratio design, supercharging, adoption of lean burn technology, optimized gearing, and the opportunity to downsize engine displacement and cooling requirements. ¹⁰

Cold-Starts: The most significant performance difference between methanol and gasoline-powered vehicles is in the area of cold starting. ⁹ As methanol is more difficult to vaporize than gasoline, it is more difficult to ignite in a cold engine. Cold starts present a greater problem in mechanically carbureted rather than fuel-injected vehicles, with the problem compounded in cold climates.

Cold start problems are significantly decreased when M-85 is used instead of neat methanol. Manufacturers of dedicated methanol vehicles have employed several techniques, including block heaters, fuel heaters, and volatility enhancing fuel additives to alleviate cold starting concerns. ⁹

Maintenance Requirements: Methanol vehicles operated during the 1980-era California fleet demonstration program required more maintenance than their gasoline-fueled counterparts. ¹⁰ Similarly, ten M-85 test vehicles operated by the Argonne National Laboratory required more frequent service than a gasoline-powered control fleet. ⁹ It is believed that, with the selection and use of improved materials, by the 1993 time frame, methanol vehicle designs will progress to the point where maintenance costs are comparable with gasoline. ^{9, 10}

Other than material composition, the mechanical parts of a methanol vehicle are the same as those in a gasoline vehicle. Two additional components in the methanol flexible-fueled vehicle are the fuel sensor and the cold-start system. The computer control device is also configured differently. ⁹

Flexible-fueled vehicles have been designed by the original equipment manufacturers with the specific intention that operations and maintenance features be essentially the same as for gasoline vehicles. Due to its toxicity and absorption through the skin, care must be taken and gloves should be worn when handling methanol. ^{9, 17} Maintenance procedures should also be conducted in well-ventilated areas to prevent excessive inhalation of fumes.

Oil Change Intervals: Methanol can remove the lubricating film from rubbing surfaces, such as cylinder walls, and prevent it from reforming. ³³ Methanol vehicle manufacturers currently recommend a different type of engine oil than is used in gasoline vehicles, but with the same frequency of change. Oil chemical analysis can be used to monitor lead and iron concentrations in engine oil and to establish oil change frequencies for vehicles operated under particular duty cycles. ⁹

Engine and Fuel Systems Wear: One of the methanol combustion products (formic acid) is quite corrosive to iron and can cause premature engine and exhaust system wear. ³³ In early conversions of vehicles to methanol operation, the corrosive nature of the fuel caused difficulties with wear, particularly with heavy-duty engines. ⁹ It is expected that wear and corrosion concerns will be eliminated in original equipment manufacturer vehicles that contain materials that are resistant to methanol corrosion.

Spark Plugs: In early methanol-fueled vehicles corrosion of engine parts led to increased spark plug fouling. With methanol-compatible materials, fouling should be equivalent to, or less than that for conventional vehicles. ⁹ Operating experience with factory-built vehicles should indicate whether spark plug life is comparable to that for gasoline-fueled vehicles.

Refueling Infrastructure Requirements

The capital costs required to service and fuel methanol-fueled vehicles can be substantial. Infrastructure development includes: ⁸

- A fuel distribution system (to transport the fuel to the station or refueling area);
- A fuel station or special service area (including land, buildings, and equipment);
- A fuel dispensing system (to transfer the fuel from the storage tank to the vehicle); and
- Initial education and training (for management, mechanics, and operators).

Most methanol is currently transported by truck. Transportation costs for methanol should be roughly equivalent to gasoline per unit of volume. As methanol has about half the energy density of conventional fuel, close to twice as much methanol must be transported to operate a fleet a comparable distance. ⁸

For equivalent energy storage, the methanol volume is about 1.8 times the equivalent gasoline volume or 2.5 times the equivalent diesel volume. Storing and dispensing methanol or methanol-blended fuel may involve such considerations as: ³³

- Vapor recovery during bulk filling from supply tanker and during vehicle refueling;
- Use of methanol resistant components and materials, such as stainless steel or nickel plated nozzles, and special hoses and pumps;
- Fine filters at the dispenser to remove contaminants;
- Dikes to contain fuel spills; and
- Storage tank level detectors and/or seepage indicators.

For methanol to achieve even a 5 percent share of the national motor fuel market, the fuel must be available for general-use private automobiles. Studies with focus groups have indicated that to be in "reasonable" supply, the fuel must be available at approximately 20 percent of all retail gasoline stations. ⁴⁵

It should not be assumed that an existing gasoline station can be easily, or inexpensively converted for methanol use. Due to its highly corrosive and toxic nature, the majority of underground tanks used to store petroleum fuel are not suitable for the storage of methanol. New fiberglass tanks, meeting stricter codes, are sufficient for storing either methanol or gasoline. ⁸

For fleet operators desiring on-site refueling capability, using methanol in place of gasoline involves varying amounts of additional expense, depending upon: ¹⁰

- Whether adequate gasoline storage and dispensing factories are in place or if investments in such equipment are necessary (due to site expansion/relocation, environmental requirements, or normal equipment replacement);
- Whether a completely new methanol refueling facility is required, or whether all or portions of an existing petroleum dispensing system can be adapted and reused; and
- Any differential costs for methanol-compatible equipment.

California Energy Commission experience with state-sponsored methanol fueling facilities indicates that about \$50,000 is required for all above and below ground equipment and installation services. ¹⁰ The New York State Energy Research and Development Authority (NYSERDA) estimates that a new methanol refueling station would cost about \$150,000 if it is equipped with one dispensing pump and a 10,000 gallon underground tank, and designed to meet current double containment regulations. ⁷ Existing diesel refueling stations with steel tanks could be converted to methanol by replacement of elastomers (gaskets, hoses) and susceptible metals at a cost of roughly \$40,000. A small, portable methanol refueling station with an above-ground 1,000 gallon tank with double containment and a methanol compatible dispensing pump is estimated to cost approximately \$40,000. This type of station, which can be installed relatively quickly, is appropriate for a small, "start-up" methanol-fueled fleet. ⁷

Methanol fuel may be "splash-blended" with gasoline prior to being transported to the refueling station or it may be blended on-site. A methanol compatible refueling station used in the NYSERDA FFV demonstration program consists of two double-wall steel tanks, which are cathodically protected from corrosion. As indicated in Figure 7, double-walled steel pipe supplies fuel from the 10,000 gallon methanol tank and 2,000 gallon gasoline tank to a blending dispenser. ¹³ Electronic level indicators meter the quantity of fuel remaining in each tank.

Figure 7
M-85 Refueling Station Layout

The NYSERDA methanol-compatible blending dispenser allows various gasoline/methanol mixtures, including M-85, to be dispensed. The original gasoline-compatible hose was replaced with a cross-linked polyethylene inner tube with a wire-reinforced protective sheathing. Electronic underground leak detectors are connected to both audible and visual alarms and monitor both refueling tank and underground piping areas. The refueling facility is also equipped with a methanol-compatible pressure/vacuum vent valve and a card-key fuel monitoring system. ¹³

It is likely that the insurance rates for underground storage tanks containing methanol will be significantly higher than those for petroleum fuels. Methanol storage tanks leaks are considered more serious than gasoline or diesel leaks, as the alternative fuel is regarded as more toxic, plus it is miscible in water. ⁸

Methanol Vehicle Owning and Operating Costs

The costs associated with initiating a methanol fuel fleet program include incremental vehicle purchase or conversion costs, costs associated with the design, permitting and installation of an on-site fuel storage and dispensing system; differential fuel expenses (including possible preferential tax treatment), incremental maintenance expenses, and differences in vehicle resale value. Start up costs include training and education for managers, administrators, vehicle operators, and mechanics. Training and education may include time and costs for: ⁸

- Orientation lectures and seminars;
- Training courses in repair and installation of alternative-fueled vehicle components;
- Visits to other sites which operate methanol-fueled vehicles; and
- Attendance at alternative fuels conferences and workshops.

Key variables associated with performing an alternative fuels program life cycle cost analysis include: ⁸

- Increased vehicle lifetime expectancy;

- Reduced or increased maintenance expenses (parts and labor);
- Vehicle fuel efficiency;
- Near term, transitional, and long term fuel costs;
- Preferential or discriminatory future fuel tax treatment;
- Economies of scale available with OEM manufacturing.

Incremental Vehicle Costs

Various studies have been conducted which attempt to identify the incremental cost associated with manufacturing a flexible-fueled vehicle. A recent study completed for the AQIRP estimates an incremental FFV/VFV cost of \$400 per car.⁴⁶ Another study conducted through the Institute of Gas Technology assumes a premium of \$250 for methanol or ethanol tolerant FFVs.⁴⁷ Chrysler Corporation is currently offering 1993 model year FFV Dodge Spirits and Plymouth Acclaims at the same price as their gasoline-powered counterparts.

Fuel Price Differential

AQIRP's Economics Bulletin No. 1 "The Economics of Methanol" explores the cost of M-85 fuel in the near, transitional, and long terms.⁴⁶ The report points out that most studies of methanol pricing focus on the economics of the fuel in a mature methanol market. Large 10,000 ton per day (TPD) plants which capture significant economies of scale would be feasible given a mature market but would likely be too risky given an emerging market. As a result, M-85 is likely to be expensive relative to conventional gasoline in the near and short terms. It is projected that a price differential of 50 to 60 cents per equivalent gallon is likely in the near and short term (1995), declining to 30 to 40 cents in the medium term (1996-2004), and 10 to 20 cents over the long term (2005-2010). A conversion factor of 1.68 gallons of M-85 per gallon of gasoline is used to reflect an assumed 4 percent vehicle efficiency increase when using methanol-blended fuel. Ex-tax gasoline equivalent M-85 retail prices are given in Table 32.⁴⁶

Table 32
Comparison of M-85 and Conventional Gasoline Prices¹

	<u>Near Term</u>	<u>Short Term</u>	<u>Medium Term</u>	<u>Long Term</u>
Gasoline Equivalent M-85 Retail Price, \$/Equivalent Gallon, (No Taxes)				
Los Angeles	1.36	1.43	1.40	1.19
New York	1.47	1.54	1.50	1.30
Conventional Gasoline Price Estimates \$/Gallon, (No Taxes)				
Los Angeles	0.78	0.92	1.07	1.07
New York	0.84	0.98	1.11	1.11

¹ All prices are in cents per equivalent gallon expressed in 1988 dollars.

The Colorado Governor's Alternative Fuels Task Force estimated ex-tax methanol costs, in dollars per equivalent gallon, of \$1.36 in 1991; \$1.62 in 1995, and \$1.86 in the year 2000.¹⁷

Refueling Station Expenditures

Refueling station costs are dependent upon both station size and throughput. Four categories of station size have been defined, based upon the number of vehicles using the facility.¹⁷ They are:

- Public Stations - Stations accessible by vehicles in all sizes of fleets and by the general public.
- Small Fleet Stations - Stations which are located on the fuel user's site and which refuel from one to ten vehicles.
- Medium Fleet Stations - Stations which are located on the fuel user's site and which refuel medium scale fleets of 30 to 50 vehicles.
- Large Fleet Stations - Stations which are located on the fleet users site and which refuel large fleets of 60 to 100 vehicles.

Costs for refueling stations, as described in the Refueling Infrastructure section of this report, are approximately \$40,000 for a portable refueling station applicable for a small fleet; \$50,000 for a medium scale fleet refueling system; and \$60,000 to \$150,000 for a large fleet or retail gasoline outlet containing a 10,000 underground methanol storage tank and a blending dispenser. On a per vehicle served basis, the refueling infrastructure costs are approximately \$8,000 to \$4,000, \$1,666 to \$1000, and \$2,500 to \$600 for the small, medium, and large stations, respectively. Bulk or discount fuel purchase rates are typically available for the large and public-scale stations where fuel is purchased in tank truck lots (typically 10,000 gallons).

The authors of the Institute of Gas Technology (IGT) study of the comparative economics of alternative fueled vehicles present a comparison of the costs of purchasing and operating methanol, ethanol, reformulated gasoline and conventional gasoline vehicles. Methanol is projected to have a price ranging between \$1.59 to \$2.07 per equivalent gallon while ethanol costs \$2.07 to \$2.35. Both prices include 24 cents per gallon in federal and state taxes. Fuel price assumptions contained within the IGT study are summarized in Table 33.⁴⁷

Table 33
Alternative Fuel Comparative Economics
(Cost per Equivalent Gallon of Gasoline)

<u>Fuel</u>	<u>Production Cost</u>	<u>Distribution Cost</u>	<u>Service Station Markup¹</u>	<u>Capital, O&M, and Profit²</u>	<u>Taxes</u>	<u>Total</u>
Gasoline	\$0.70	\$0.06	\$0.09	--	\$0.24	\$1.09
Reformulated Gasoline	0.80 to 0.90	0.06	0.09	--	0.24	1.19 to 1.29
Methanol	1.15 to 1.58	0.10	--	0.10 to 0.15	0.24	1.59 to 2.07
Ethanol	1.64 to 1.87	0.09	--	0.10 to 0.15	0.24	2.07 to 2.35

1 Current station capital, operating and maintenance costs, including profit.

2 Capital, operating and maintenance expenses, and profit for the alternative fuel station.

The IGT also determined the present value of the operating costs for vehicles using the various alternative fuels as well as gasoline. The authors assume that the base vehicle is driven 15,000 miles per year at a fuel economy of 21 miles per gallon gasoline equivalent. The analysis is based on 5-year ownership at an interest rate of 10 percent.⁴⁷ Maintenance cost differentials are not taken into account while fuel costs are based on the mid-point of the range indicated in Table 33. Vehicle price premiums and the present value of operating costs are given in Table 34.⁴⁷

Table 34
Present Value of Operating Costs for Alternative-Fueled Vehicles

<u>Fuel Type</u>	<u>PV Operating Costs</u>	<u>Vehicle Price Premium</u>	<u>Total PV of Operating Costs</u>
Gasoline	(\$2954)	\$0	(\$2954)
Reformulated Gasoline	(\$3361)	\$0	(\$3361)
Methanol	(\$4960)	\$250	(\$5210)
Ethanol	(\$5990)	\$250	(\$6240)

As shown in Table 34, conventional gasoline produces the lowest operating cost net present value. Methanol and ethanol are projected to be 76 and 111 percent, respectively, more costly to use than conventional gasoline.⁴⁷

Clearly substantial infrastructure costs must be borne before methanol can be made available on a widespread basis. It is also likely that, in the near term, methanol is likely to be priced higher than conventional or oxygenated gasoline. Except for light-duty vehicle hydrocarbon emission reductions and particulate emissions reductions in heavy-duty engine market niches, methanol is not expected to provide Washington residents with significant air quality or greenhouse gas emission benefits. Similar to propane and compressed natural gas, the alcohol fuels are worthy of support due to the limited environmental benefits that are offered, for their ability to reduce petroleum imports, through jobs creation and economic development in the production of domestic motor fuels, and for their restraining influence on world oil prices.⁴⁸

Ethanol Fueled Vehicles

Ethanol is an excellent motor vehicle fuel. It can be used in existing vehicles at concentrations up to 10 volume percent with no changes to the vehicle. Flexi-fuel vehicles are available that can use fuels containing any ethanol concentration from 0 to 85 percent. Detroit Diesel sells a heavy duty engine that is certified to operate on 95 percent ethanol fuels. The price of ethanol fuels is still higher than gasoline and thus offers no economic incentive for their use. The air quality benefits from using ethanol fuels are not well defined, although it is expected they will be equal to or better than gasoline. The current supply of ethanol is limited and will go to its highest and best value, which is as a blending stock to produce oxygenated fuels. Ethanol fuels pose less of a safety and spill concern than petroleum fuels.

Ethanol Fuel Characteristics

Ethanol and gasoline are quite different fuels. The main similarity is that they are both liquids. Alcohols have been recognized as excellent fuels for spark ignited engines virtually since the advent of such engines. The high octane rating (a measure of their resistance to explosive auto-ignition) and their high latent heats of vaporization (an aid to fuel-air mixture cooling which results in an increased charge density) have made them preferred fuels for use in high-compression ratio, high-output engines.

A high octane rating in itself has no direct fuel economy benefit. A higher compression ratio engine, which demands a higher-octane fuel for spark ignited engines, is simply more efficient than one with a lower compression ratio, and hence provides greater fuel economy. Lean operation, or supplying combustion air in excess of stoichiometric requirements, can permit further improvements in efficiency and fuel economy.

Because ethanol has a lower energy content than gasoline on both a mass and volume basis, more fuel is required for equal engine output. For example, gasoline has about 1.5 times the energy content of ethanol per unit volume, which indicates that the fuel economy with ethanol would be about one-third less than that with gasoline in miles-per-gallon terms. On the other hand, equal volumes of stoichiometric alcohol-air mixtures and stoichiometric gasoline-air mixture have similar energy contents. Since piston engines induct fuel-air mixture on a volume basis, engine power output would not be expected to change significantly if nothing were changed but the fuel.

Ethanol's higher heat of vaporization permits a greater fuel density in the engine. It also makes it more difficult to vaporize at normal temperatures. This causes driveability problems, especially under cold-start conditions. E-100 cannot vaporize sufficiently to form a flammable air-vapor mixture below about 59°F. The straightforward means of overcoming the cold start limitations is the addition of 15 percent gasoline.

Pure ethanol has a Reid vapor pressure (RVP) of only 2.5 psi, i.e., it is not very volatile. However, when ethanol is added to gasoline, it increases the RVP of the blended fuel. The RVP increase reaches a maximum of 1 psi at the 4 percent ethanol volume. Higher concentrations do not increase the RVP further. The RVP for ethanol blends normally exceeds the RVP standards for gasoline. In 1979 the EPA granted a waiver from the RVP standards to E-10. The importance of RVP is its effect on evaporative emissions and drivability. In general, the higher the RVP of the fuel, the greater the evaporative emissions. If RVP is too high, the car may vapor lock, or if it is too low, the car may be difficult to start and perform poorly before the engine warms up.

Reformulated gasoline will be required in nine severe ozone non-attainment areas beginning in 1995. RVP limits, a 2.0 weight percent oxygen requirement, lower benzene concentrations and other restrictions will apply. The ethanol industry is concerned that ethanol could not be used to supply the oxygen

because it would exceed the RVP limits. They are currently seeking to extend their current waiver to include reformulated gasolines. Ethanol can be converted to ethyl tertiary butyl ether (ETBE) that does not cause the RVP problem. ETBE may ultimately be the only way that ethanol is used in blended fuels.

E-10 can be used in existing spark ignited engines without any changes. There may be a slight decrease in fuel economy because of the lower fuel energy content, but it is hardly measurable.

Flexi-fuel vehicles can use fuels with an ethanol content anywhere from 0 to 85 percent. They do not have higher compression ratio engines or utilize lean burn that would be possible if operated only on E-85. Because they must be also capable of burning only gasoline, the vehicles offer few performance advantages. They may offer some air quality benefits and they do provide a market entry point for E-85. E-85 fuels also require the addition of a small amount of speciality lubricant to the fuel.

Modified compression ignition engines can use E-95 fuels. These fuels also need the lubricant additive. The engines are designed to operate on E-95 and thus take advantage of the fuel properties and operate at high compression ratios and lean burn conditions. Since there are compression ignition engines, the low vapor pressure of E-95 fuels does not present a cold start problem.

Ethanol Supply

Ethanol ($\text{CH}_3\text{CH}_2\text{OH}$) is an alcohol composed of carbon, hydrogen and oxygen. It is a clear colorless liquid and is the same alcohol found in beer, wine, and whiskey. Ethanol was one of the first fuels considered for motor vehicles during the time of Henry Fords's Model T. Ethanol's price is the major reason for it never taking a dominate role as a transportation fuel. Other fuels have been available at lower prices, especially petroleum derived fuels.

Ethanol is produced by fermenting a sugar solution with yeast. The sugar can come from corn or wheat (starch crops), wood or straw (cellulose crops), or sugar cane, sugar beets, or grapes (sugar crops). Yeast converts the sugar into ethanol and carbon dioxide. The ethanol is separated from the water solution by distillation. A denaturant, often unleaded gasoline, is added to the ethanol to make it unfit for drinking purposes and not subject to beverage taxes. Ethanol fuel leaving a production facility contains up to 5 percent gasoline and is designated E-95, for 95 percent by volume of ethanol.

The feedstock chosen for ethanol production depends on the net cost of the crop and the cost of the conversion process. Research is underway to permit the economic use of woody crops for ethanol production. Brazil, which has 4.2 million cars operating on E-95, uses sugar cane as its principal feedstock. Ninety-five percent of the ethanol fuel produced in the United States is derived from corn.

Corn is composed of more than just starch. The starch is converted to sugar and then fermented to ethanol. The other components are available for by-products. Two basic processes, dry-milling and wet-milling, are used in the U.S. The major difference is the by-products produced from the corn. Dry-milling operations, accounting for 33 percent of ethanol production, produce ethanol and distillers dried grains, a cattle feed. Wet-milling facilities produce ethanol, corn oil, corn gluten feed, and corn gluten meal, and sometimes high fructose corn syrup. The corn oil, gluten feed, and gluten meal have a higher value than the distiller's dried grains, giving an economic advantage to wet-milling operations.

U.S. ethanol fuel production capacity increased from 20 million gallons in 1979 to 1.1 billion gallons in 1991. The increased capacity was stimulated by state and federal incentives beginning in 1978. The subsidies made up the difference between the production cost of ethanol and the wholesale price of gasoline. Production facilities with capacities greater than 40 millions gallons per year represent 86 percent of the total capacity.⁴⁹ One company, Archer Daniels Midland, accounts for 75 percent of the nation's production. Two states, Illinois and Iowa, provide 75 percent of the nation's ethanol fuel capacity. Ethanol fuel production is currently dominated by a single large producer and the capacity is located in the corn belt region of the country.

A General Accounting Office report determined that the ethanol industry is capable of doubling or tripling domestic ethanol production to 2.2 or 3.3 billion gallons per year during the next eight years, with American farmers supplying the corn needed for this production increase.⁵⁰ They determined the overall net farm cash income would increase by an average of about 1.3 percent. They also predicted the overall food component of the consumer food price index would increase by an average of only 0.1 percent--a 10-cent increase on a \$100 food purchase. Expansion of ethanol production beyond these levels would probably push corn prices high enough to make additional ethanol production uneconomic.

The Pacific Northwest has four operating ethanol production facilities with a combined capacity of 8.2 million gallons per year. The oldest plant is operated by Georgia-Pacific in Bellingham, Washington. This facility is unique because it uses sugar from its wood pulping operation for ethanol production. The annual production capacity is three million gallons. A smaller plant, 0.7 million gallons, is operated by Pabst Brewing Company in Olympia, Washington. This plant uses recovered brewery wastes as the source of sugar and was built in part to reduce biochemical oxygen demand loading on the waste water treatment facility. The two other regional ethanol plants are located in Idaho and Montana. J.R. Simplot operates a 3 million gallon plant in Caldwell, Idaho, using potato processing wastes as feedstock. Alcotech, in Ringling, Montana, operates a 1.5 million gallon facility using distressed grains for feedstock.

Two new regional facilities are under construction. Northwest Agri-Products has recently built a 1 million gallon per year facility in Moses Lake, Washington. The feedstocks are potato and grain wastes. Construction is scheduled in the fall of 1993 for a 30 million gallon facility in Great Falls, Montana. The American Ethanol Corporation facility will use a wet-milling process with wheat as the feedstock and produce ethanol and a gluten food by-product. Plans are to come on-line in late 1993.

The supply and demand for ethanol fuels have been in relative balance during the past 14 years. At times, some fuel was imported from Brazil, while at other times, ethanol has been exported to Brazil. The recent oxygenated fuel requirements will greatly increase the demand for ethanol fuel. This demand will be met by both an increase in production capacity and a displacement of fuel from the traditional E-10 markets to the oxygenated fuel markets. The displacement will occur because of ethanol's higher value as an oxygenate.

Current and Future Ethanol Fuel Markets

During the last twelve years, ethanol addition to gasoline provided an E-10 fuel that was marketed as gasohol. Today, 8 percent of all gasoline sold in the U.S. is E-10. Ethanol is added to extend the gasoline fuel supply and sometimes provides an extra profit margin for the retailer due to favorable tax incentives. In 1991, Washington motorists purchased 9 million gallons of ethanol blended with gasoline, or 90 million gallons of gasohol. In 1993, up to 25 million gallons of ethanol could be blended with gasoline to meet Washington's oxygenated fuel requirement.

The 1990 Clean Air Act Amendments created new market opportunities for ethanol fuels. Beginning in 1992, all gasoline sold in thirty-nine carbon monoxide non-attainment areas must contain 2.7 weight percent oxygen during the winter months. The Puget Sound, Vancouver, and Spokane areas must meet this requirement. Ethanol at 7 volume percent would provide the necessary oxygen.

Ethanol can also be converted into ETBE, using the same technology used to make MTBE. The advantages of ETBE, over ethanol, are that ETBE does not absorb water and it does not increase the vapor pressure of the blended fuel. This may be a significant new market if reformulated gasolines are required in more areas of the country. ETBE qualifies for the blender tax credits, which may encourage its use. Arco Chemical recently announced plans to produce ETBE. The price of the oxygenate is the deciding factor.

Ethanol will be used to meet the oxygenate and reformulated gasoline requirements, as long as it is cost effective to the user. Currently, E-10 is the most cost effective oxygenate choice. ETBE is not available in commercial quantities and MTBE costs more. The use of E-85 in flexible fueled vehicles is currently not cost competitive with other alternative fuels. Its use will only be to demonstrate the technology. Until the cost of producing ethanol is comparable to other alternative fuels, it will only be used as a chemical additive to meet oxygenated fuel requirements.

Supply Infrastructure

Ethanol production is concentrated in the mid-Western states. Once the regional suppliers of ethanol have sold all their production capacity, the marginal supply comes from the mid-West. The ethanol is transported by railroad to distribution terminals. The fuel is then shipped by truck to the user. The same rail cars and trucks used to transport gasoline can be used to transport ethanol.

Ethanol is soluble in water, which can cause problems in the supply infrastructure. Residual water in containers or bulk storage tanks used to store or distribute ethanol will be absorbed into the ethanol. The distributors and retailers of E-10 learned early on that they must remove water from their distribution and storage containers before marketing the product. They must also insure that the system remains dry. Other than the requirements to keep water out of the system, ethanol can be distributed and handled like gasoline.

The carbon steel tanks used for gasoline storage can be used for ethanol concentrations from 10 percent up to 100 percent. Fiberglass tanks may not be suitable for ethanol storage. Delivery pumps should be certified for use on fuels containing greater than 10 percent ethanol as some gasket materials are not compatible with ethanol. The estimated equipment cost for a new tank, pump, and key card system is \$35,000 for a 10 to 12,000 gallon capacity system. Installation costs are site specific and cost from \$30 to 50,000 additional.

Ethanol Production Costs

Production costs are categorized as net feedstock costs (grain costs minus value of byproducts), cash operating expenses, including labor, maintenance, electricity, insurance, and capital costs. There is much debate and many conflicting reports on the cost of producing ethanol fuel. In general, net feedstock costs account for about 40 percent of the production cost, with operating costs and capital costs about 30 percent each.⁵¹

Corn is generally the lowest net cost feedstock available in the United States for ethanol production. The income from sale of byproducts lowers the cost attributed to the ethanol. Total production costs are estimated to be between \$0.90 and \$1.80 per gallon of ethanol depending on the size of the production plant, the technology used, and corn prices. Substantial expansion of the corn to ethanol industry could increase corn costs and thus production costs.

The Federal Department of Energy (DOE) is funding research with the goal of producing ethanol fuel from cellulosic crops for \$0.60 per gallon by the year 2010. The concept is one of growing crops dedicated for conversion to ethanol on agricultural land not needed for food production. The 200 million acres that the Department of Agriculture estimates will no longer be required for food production by the year 2000 could provide 200 billion gallons of ethanol fuel. However, many institutional, environmental, and technical barriers must be overcome before an industry of this scale develops.

Incentives and Prices

Since 1978, the federal government has provided tax incentives to encourage the use of ethanol fuels and to help generate markets for corn. The current incentives include lower excise fuel taxes, tax credits for use of blended fuels, and tax credits for fuel producers. The excise taxes are scheduled to expire on September 30, 2000, and the blender credits on December 31, 2000.⁵²

The current federal excise fuel tax for gasoline fuel is 14.1 cents/gallon. The excise tax for fuels containing 10 percent by volume ethanol (E-10) is 8.6 cents/gallon, an incentive of 5.4 cents per gallon of E-10. The effective incentive for ethanol is 54 cents per gallon of ethanol since only 10 percent of the fuel is ethanol. Thus, a user could buy ethanol at a 54 cents per gallon higher price than gasoline, blend it with gasoline at the 10 percent level and have an E-10 fuel that costs the same as gasoline.

The excise tax on fuels with 85 percent or higher ethanol content is also 8.6 cents per gallon. The effective ethanol incentive is 10.1 cents per gallon when used to produce E-85. E-85 also qualifies for a blenders credit.

Blenders credits are available for any combination of ethanol and gasoline. This credit is equal to 54 cents per gallon of ethanol used in the blended fuel. The tax credit must be reduced by the amount of any benefit provided by the reduced excise tax available for the mixture, i.e., 8.6 cents for E-10 and E-85. The tax credit must also be claimed as gross income and is thus subject to the taxpayers marginal income tax rate. This effectively reduces the incentive. For example, if the fuel blenders income tax rate is 25 percent then the ethanol incentive would effectively be equal 40.5 cents. The current tax incentives favor the use of E-10.

The federal government provides one more incentive to small producers of ethanol fuels. Effective in 1991, the first 15 millions gallons of ethanol produced by owners of facilities with a combined capacity less than 30 million gallons can claim a 10 cent per gallon federal income tax credit. This credit is also taxable.

Washington state exempts ethanol fuel from the states 23 cent per gallon motor fuel tax. It furthermore gives a tax credit for the ethanol used in E-10 equal to 60 percent of the motor fuel tax. The effective state incentive for E-10 fuels is thus 36.8 cents per gallon of ethanol. This incentive will sunset December 31, 1999.

The state incentive for concentrations other than 10 percent equals the percentage of ethanol in the fuel times 23 cent per gallon. For example, E-85 would pay a motor fuel tax of 3.45 cents per gallon because only the 15 percent gasoline portion is taxed.

Ethanol has historically been priced at the wholesale cost of gasoline plus available tax credits. Usually there is a 2 to 4 cent reduction in ethanol price to cover handling costs and to serve as an incentive for the retailers to sell the blended fuel. If ethanol can effectively compete with MTBE as both an oxygenate and an octane enhancer, then the price paid for ethanol should increase.

The current wholesale price of pure ethanol fuel delivered to Olympia is about \$1.50 per gallon. The pump price of E-85 depends on the wholesale gasoline price, the users tax status and the relationship between the fuel supplier and user. A privately owned vehicle purchasing from a private fuel supplier would pay federal and state taxes, dealer profit, and local distribution costs. Public and private fleets would save the dealer margin cost. Public fleets are exempt from federal motor vehicle fuel taxes.

Table 35 shows the pump price components for different users of gasoline and E-85 assuming a 5 cent per gallon local distribution cost and 10 cent per gallon dealer profit. The gas equivalent price is the price paid for a volume of E-85 providing the same driving range as a gallon of gasoline, assuming that 1.3 gallons of E-85 provides the same driving range as one gallon of gasoline. Thus, the gas equivalent price of E-85 is 1.3 times the price of one gallon of E-85.

Table 35 indicates that the gas equivalent pump price of E-85 is substantially higher than gasoline. Ethanol wholesale prices have to be much lower before the pump price of E-85 is equivalent to gasoline prices. At a wholesale gasoline price of \$0.60/gallon, wholesale ethanol prices would have to be 59.0, 61.7, or 59.1 cents/gallon for the gasoline and E-85 to have equivalent user costs to the individual, private, and public fleet users respectively. These values are substantially lower than the current market price for pure ethanol. It is unlikely that E-85 will be widely used until the equivalent cost is equal to that for gasoline. This requires either higher gasoline prices or lower ethanol prices.

Table 35
Pump Price Comparisons for
Gasoline and E-85, ¢/gal

Cost Component	Individual		Private Fleet		Public Fleet	
	Gas	E-85	Gas	E-85	Gas	E-85
Ethanol @ 150¢/gal	0.0	127.5	0.0	127.5	0.0	127.5
Gasoline @ 60¢/gal	60.0	9.0	60.0	9.0	60.0	9.0
Local Distribution	5.0	5.0	5.0	5.0	5.0	5.0
Dealer Margin	10.0	10.0	0.0	0.0	0.0	0.0
State Taxes	23.0	3.5	23.0	3.5	23.0	3.5
Federal Taxes	14.1	8.7	14.1	8.7	0.0	0.0
Total	112.1	163.7	102.1	153.7	88.0	145.0
Gas Equivalent	112.1	212.8	102.1	199.8	88.0	188.5

Environmental, Health and Safety Issues

Apart from combustion and evaporative emissions, certain other properties of ethanol fuel blends may pose environmental, health, and safety questions. These issues include environmental damage from fuel spills, fire and explosion concerns, and toxicity.

Ethanol distribution and use should be safer than gasoline distribution and use. Water spills should cause minimal harm because ethanol is highly soluble and will disperse rapidly. It is also readily biodegradable and will evaporate quickly if spilled on land. Contamination of drinking water supplies is less troublesome than from gasoline or methanol because ethanol is less toxic to humans in equal concentrations.⁵³

Ethanol has fire safety implications similar to those of methanol; compared to gasoline, it has lower volatility, higher flammability limit, lower vapor density, lower heat of combustion, higher heat of vaporization, and low luminosity. These properties cause it to be much less likely to ignite in an open area following a spill. In addition, once it does ignite ethanol's low heat of combustion and high heat of vaporization cause it to burn much slower.

The low flame luminosity of an ethanol flame is a matter of concern if the fuel is on fire. However, the denaturants added to ethanol increase the flame luminosity greatly reducing the problem. Ethanol's combustion properties that make it less dangerous than gasoline with regards to fire safety, do result in concern about its storage in closed containers. At normally occurring atmospheric temperatures, equilibrium mixtures of gasoline vapor and air are beyond the rich flammability limit. An ignition source, such as a spark of static electricity, usually will not result in an explosion or fire. Ethanol, on the other hand, doesn't behave this way. The combination of ethanol's vapor-air equilibria and flammability limits yields a explosive mixture in closed containers. Fortunately, the addition of denaturants also helps overcome this problem by increasing the vapor concentration beyond the flammability limit.

Ingestion of several ounces of pure ethanol would not be harmful to most adults, but it would be of concern for a child. Ethanol differs from methanol because two ingestion scenarios are of interest. First, ethanol fuel could be accidentally ingested, as gasoline is sometimes now. Most gasoline ingestion episodes are due to adults attempting to siphon gasoline from a vehicle, or children drinking from small containers of gasoline intended for use in small household engines or for degreasing. Second, ethanol fuel could be diluted for beverage purposes to avoid alcoholic beverage taxes or age restrictions on purchasing alcoholic beverages.

The frequency of ingestion of ethanol fuels due to siphoning should be no greater than with gasoline. Also since ethanol is not a good degreasing agent the accidents due to childhood intake should be less. Ethanol fuel contains a denaturant to segregate it from taxed beverage ethanol. The Bureau of Alcohol, Tobacco, and Firearms designs denaturants that are difficult to separate from the ethanol. A determined individual could remove the denaturant and provide a potable alcoholic drink even though it may have a strange taste. However, this would probably be the exception rather than the rule. Since ethanol is not toxic in moderate amounts, it is not a major area of concern.

Ethanol-Fueled Light-Duty Vehicles

Almost all of the neat ethanol vehicles operating in the world today are in Brazil, where upwards of 4.5 million ethanol cars and trucks have been placed in service under a national program which began in 1979. ^{10, 29} The majority of these vehicles have been produced in Brazilian auto manufacturing plants, operated by Autolatina (a joint venture of Volkswagen, Ford, General Motors, and Fiat). In 1987, over 90 percent of light-duty vehicles sold in Brazil were designed to operate on ethanol. ¹⁰

Upon implementation of a National Motor Vehicle Emission Control program in 1986, the Brazilian automotive industry created catalytic converters and electronic fuel injection systems that are especially designed for neat ethanol use. Brazilian vehicle emission standards, however, lag far behind both future and current U.S. standards. Brazil's 1992 Phase II emissions limits and the average performance of Brazilian light-duty vehicles, when operating on neat ethanol and gasohol, are given in Table 36. ²⁹ Gasohol in Brazil is comprised of 78 percent gasoline and 22 percent anhydrous ethanol.

Table 36
Emission Standards and Average Emissions for
Ethanol-Fueled Brazilian Light-Duty Vehicles

	Exhaust Emissions, grams/mile		
	HC	CO	NOx
1992 Phase II Standard	1.93	19.3	2.25
Average Vehicle Performance with Neat Ethanol	0.96	6.28	0.80
Average Vehicle Performance with Gasohol	0.80	9.5	0.96

In the United States, the dominate use of ethanol is as a gasoline blending agent. In the near term, prospects for increasing ethanol use in the U.S. depend on additional blending with gasoline rather than use as a neat fuel as: ¹⁰

1. The federal tax subsidy provides an incentive for gasoline distributors to blend ethanol;

2. The use of oxygenated gasoline blends is mandated during the fall and winter to reduce carbon monoxide levels in U.S. cities that are not in attainment with the National Ambient Air Quality Standards for this pollutant;
3. Ethanol is an attractive octane-improving gasoline additive; and
4. Relatively little attention is being given to the development of a neat ethanol distribution system or to the production of dedicated neat ethanol vehicles.

Both neat and flexible-fuel ethanol-powered vehicles have been successfully demonstrated. In 1981, 20 neat ethanol-fueled Volkswagen Rabbits and pick-ups were operated in state agency fleet service in California.¹⁰ Ford's 1987 model year FFV Crown Victoria was designed to use gasoline, methanol, or ethanol in any combination. At least two were placed into operation with ethanol.⁴ Both the 1993 model year 3.0L Ford FFV Taurus and General Motor's VFV Chevrolet Lumina are designed to operate on any blend of gasoline, M-85, or E-85.

In the past few years, the United States Department of Energy has undertaken a nationwide effort to accelerate the production and use of alternative-fueled vehicles and encourage fuel suppliers to build the refueling and service stations necessary to support these vehicles. USDOE has sponsored demonstration programs involving alternative-fueled trucks, buses, and vans, including:²⁹

54	Ethanol-powered vehicles;
2,756	Methanol-fueled vehicles;
1,421	Compressed natural gas vehicles; and
770	Vehicles using other fuels, such as propane or liquefied natural gas.

Factory-Built, Light-Duty Ethanol-Fueled Vehicles

General Motors recently produced 50 ethanol VFVs for operation by the states of Wisconsin and Illinois, the U.S. Departments of Agriculture and Energy, and the federal General Services Administration.^{7, 34} The vehicles are modified 1992 model year 3.1L Chevrolet Lumina methanol VFVs. The ethanol VFVs are production vehicles that are fully certified to all applicable federal emissions and safety standards. A Lumina ethanol VFV is depicted in Figure 8.²⁹ The vehicle's validation program included hot weather and hot fuel testing, cold weather operation, including cold starting and emissions tests; fuel systems materials evaluations, and emissions and fuel economy calibrations.⁷ General Motors also provided service training for both auto dealers and fleet operators to ensure that the ethanol fuel characteristics are understood and the unique service needs of the vehicles are met.

In Wisconsin, the VFV Luminas are placed in daily fleet service and run on E-85. The University of Wisconsin at Milwaukee's Alternative Fuel Research Laboratory, in conjunction with the Argonne National Laboratory and the state of Illinois, is monitoring user convenience, life cycle costs, and tailpipe emissions. Twelve gasoline-powered Luminas are also being evaluated for comparative purposes.²⁹

Figure 8
Chevrolet Lumina Ethanol-Fueled VFV Components

General Motors is in the early stages of ethanol vehicle development, with a goal of expanding their working knowledge of ethanol fuels when subjected to harsh, midwestern state winter conditions. In-service tailpipe emissions test results are not yet available for the VFV Luminas.

The 1993 3.0L Ford Taurus FFV like the VFV Lumina is capable of using any mixture of gasoline, M-85 or E-85.

Heavy-Duty, Ethanol Engine Development

The Detroit Diesel Corporation has been involved with several demonstrations of ethanol in heavy-duty vehicles. Their first project was the re-powering of a Volvo-White tractor with a 300-HP 6V-92 ethanol engine. This tractor operates on E-95, which contains 5 percent gasoline as a denaturant, and is used to move fully loaded trailers at the Coors Brewery operation in Golden, Colorado.¹⁵ A second demonstration project involves the use of DDC 6V-92TA 200-HP engines in four Volvo-GM tractors, owned and operated by Archer Daniels Midland, the largest ethanol producer in the United States. The four ethanol-powered trucks, plus a similar diesel control unit, will be compared under line-haul operating conditions.³⁴

In 1991, two 6V-92 E-99 powered transit buses went into service in Regina, Saskatchewan.¹⁵ With more than one year of service, these buses are providing an average fuel economy of 3.4 diesel equivalent miles per gallon.³⁴

The first dedicated ethanol transit bus demonstration project in the United States began in July, 1992 and involves a cooperative venture between the Greater Peoria Metropolitan Transit District (GPMTD), Federal Transit Authority, Illinois Department of Natural Resources, U.S. Department of Energy, Detroit Diesel Corporation, and Archer Daniels Midland. Fourteen of GPMTD's 49-bus transit fleet will be equipped with E-95 fueled, electronically-controlled, 253-HP DDC 6V-92TA engines.³⁸

The GPMTD's Transportation Manufacturing Corporation (TCM) 35-foot transit buses feature special modifications to the electronic control system, oversized fuel injectors, and glow plugs. The buses are priced at \$247,000 per vehicle, approximately \$22,000 to \$37,000 above that of a comparable diesel coach.³⁸

The GPMTD buses will undergo complete emissions testing to determine whether the ethanol engines meet the in-service emissions requirements of the Clean Air Act. The USDOE/University of West Virginia Portable Heavy-Duty chassis dynamometer will be used to perform most of the emissions tests for the demonstration program.⁵⁴ Additional 6V-92 ethanol fuel demonstration projects are being planned in Minnesota and Nebraska.²⁹

Detroit Diesel Corporation has submitted emissions test results that indicate, when operating on E-95, that their 6V-92TA alcohol-fueled engine meets even the strict 1994 federal standards for transit bus emissions. Emissions test results are indicated in Table 37.^{29, 34}

Table 37
Ethanol-Fueled DDC 6V-92TA Heavy-Duty Engine
Emissions Test Results, grams/Bhp-hr

	<u>OMHCE</u>	<u>CO</u>	<u>NOx</u>	<u>Particulate Matter</u>
1994 Urban Bus Standard	1.3	15.5	5.0	0.05
DDC 6V-92TA, E-95 ¹	0.73	1.71	4.15	0.039

1 With catalytic converter and including deterioration factors.

Emissions Characteristics of Vehicles using Neat Ethanol and Ethanol Fuel Blends

General Emissions Characteristics

The City of Phoenix used an exhaust gas emissions analyzer to determine idle emissions for 418 public vehicles when operating on gasoline and an E-10 blend. Pre-1980 vehicles experienced an average reduction in CO of 28 percent and an average reduction in hydrocarbons of 8 percent. Post-1980 vehicles showed an average CO reduction of 23 percent and an average hydrocarbon reduction of 16 percent.⁵⁵

Researchers from the Ford Motor Company state, "Emissions data from vehicles fueled with neat ethanol (E-100) or high-percentage ethanol blends, such as E-90, are too limited to reliably estimate ozone-forming potentials. Available emissions data indicate that a reduction of about 20 percent in ozone-forming potential may be possible, with the major benefit associated with a reduction in evaporative emissions."³⁹ The Colorado Governor's Alternative Fuels Task Force reached a consensus that carbon monoxide emissions remain the same in ethanol-powered, spark-ignited, flexible-fueled vehicles as compared with equivalent gasoline-powered vehicles. Oxides of nitrogen emissions also remain the same, while particulate emissions, which are quite low to begin with, are slightly reduced.¹⁷ Cold weather emissions performance is expected to be similar to that of methanol. While aldehyde emissions are a concern, they are readily controllable.

The United States Environmental Protection Agency suggests that ethanol's lower combustion temperature would tend to favor reduced NOx emissions. The water content of hydrous ethanol (if used) also works to quench the flame temperature and limit NOx formation. Vehicles using hydrous ethanol in Brazil are equipped with a small gasoline tank that is used to start the vehicle and warm it enough to tolerate the low volatility ethanol.⁵⁶ Ethanol would not provide cold-start emissions benefits under this operating regimen.

The use of neat or near-neat ethanol in heavy-duty compression ignition engines results in reduced particulate emissions. The use of an oxidation catalyst should also result in low hydrocarbon and carbon monoxide emissions. NOx emission levels are comparable to those for conventional diesel engines. Except for the DDC 6V-92, ethanol-fueled heavy-duty engine emissions data is scarce. Ethanol-fueled OEM heavy-duty engines are expected to cost two to two-and-a-half times the cost of an equivalent diesel engine.¹⁷

Fuel Composition

The California Air Resources Board has proposed regulations that would establish specifications for commercial E-85 and E-100 fuel. The specifications are summarized in Table 38.³⁷

Table 38
Commercial Specifications for E-85 and E-100 Fuel

<u>E-85</u>	
<u>Specification</u>	<u>Value</u>
Ethanol	79 Vol. % (min.)
Denatured fuel ethanol	84 Vol. % (min.)
Other alcohols	2 Vol. % (max.)
Gasoline, unleaded	14.5 +/- 0.5 Vol. %
Hydrocarbons, plus aliphatic ethers	15-20 Vol. %
<u>E-100</u>	
<u>Specification</u>	<u>Value</u>
Ethanol	92 Vol. % (min.)
Denatured fuel ethanol	98 Vol. % (min.)
Other alcohols and ethers	2 Mass % (max.)
Hydrocarbons, gasoline or Diesel fuel derived	5 Mass % (max.)

Global Warming Impacts of Ethanol Fuel Use

The global warming potential of ethanol depends largely on whether the feedstock is wood, corn, or grain. The production of ethanol from wood offers large reductions in emissions of greenhouse gases, primarily because wood waste fuel is assumed to be used in the processing plant and the cultivation of wood requires relatively little energy.⁴⁰ In contrast, ethanol produced from corn produces a slight increase in greenhouse gas emissions if the fuel is used in light-duty, spark-ignited vehicles and a significant increase, exceeding 55 percent, if the ethanol is combusted in heavy-duty diesel engines.^{43, 44}

Greenhouse emissions from ethanol derived from corn are substantial as coal is typically used to fuel the conversion plants and corn farming is relatively energy intensive.⁴⁰ The CO₂ equivalent emissions are also extremely sensitive to conversion efficiency assumptions.

Researchers at the Center for Transportation Research at the Argonne National Laboratory evaluated various alternative fuels with respect to their ability to reduce greenhouse gas emissions. Energy required at each stage of the fuel production, transport, and use cycle was considered. Their results are summarized in Table 39.⁴⁰

Table 39
Total Fuel Cycle, CO₂-Equivalent Emissions for
Reformulated Gasoline and Ethanol, grams/mile

<u>Fuel-Cycle Stage and Emissions</u>	<u>Reformulated Gasoline</u>	<u>Ethanol from Corn</u>	<u>Ethanol from Wood</u>
<u>Vehicular</u>			
CH ₄	1.0	0.5	0.5
N ₂ O	17.4	17.4	17.4
NMOG	8.4	3.0	3.0
CO	18.4	21.6	21.6
NO _x	18.0	18.0	18.0
CO ₂	270.5	(-) 9.5 ¹	(-) 9.5 ¹
Total Vehicular	333.7	51.0	51.0
<u>Upstream</u>			
CH ₄	5.3	18.3	1.0
N ₂ O	3.0	97.2	8.3
NMOG	1.2	2.0	1.7
CO	0.6	(-) 0.8	3.2
NO _x	13.8	58.4	25.8
CO ₂	133.6	362.0	41.5
Total Upstream	157.5	537.1	81.4
Overall Total	491.2	588.1	132.5

¹ Negative due to emissions displaced due to the availability of by-products distiller's dried grains and solubles.

Ethanol-Fueled Vehicle Owning and Operating Costs

In their paper addressing the comparative economics of alternative fuels, the Institute of Gas Technology (IGT) projects a cost of \$2.07 to \$2.35 per gasoline equivalent gallon for ethanol.⁴⁷ The IGT cost estimate neglects fuel tax incentives and blenders credits, and assumes that ethanol is taxed, on a Btu basis, the same as gasoline. Cost components are summarized in Table 33. The Colorado Governor's Alternative Fuels Task Force projects an ethanol cost of \$2.00 per equivalent gallon in 1995, increasing to \$2.21 by the year 2000. In contrast, a research goal is to cut ethanol production costs to 60 cents per gallon from non-food feed stocks. This goal may be optimistic.¹²

The IGT also determined the present value of operating costs for a light-duty vehicle operating on ethanol, assuming a \$250 vehicle price premium and vehicle operation of 15,000 miles annually, at a gasoline fuel economy of 21 miles per gallon. The ethanol-fueled vehicle incurred an operating cost of \$6,240 relative to \$2,954, and \$3,361 for vehicles using gasoline and reformulated gasoline, respectively.⁴⁷

It is expected that refueling infrastructure costs for ethanol-fueled fleets would be similar to those for methanol-powered fleets.

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List of Acronyms

AMFA	Alternative Motor Fuels Act of 1988 (P.L. 100-494)
ANL	Argonne National Laboratory
AQIRP	Auto/Oil Air Quality Improvement Research Program
Btu	British Thermal Unit
CARB	California Air Resources Board
CEC	California Energy Commission
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DDC	Detroit Diesel Corporation
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ETBE	Ethyl Tertiary Butyl Ether
FFV	Flexible-Fueled Vehicle
FTP	EPA Federal Test Procedure
GPMTD	Greater Peoria Metropolitan Transit District
GTMV	Gasoline-Tolerant Methanol Vehicle
HC	Hydrocarbons
IGT	Institute of Gas Technology
L	Liter (1,000 cubic centimeters)
LEV	Low Emission Vehicle
LHV	Lower Heating Value
mg/M ³	Milligrams per Cubic Meter
MILE	Methanol in Large Engines Program
MPG	Miles per Gallon
MTBE	Methyl Tertiary Butyl Ether
NMHC	Non-Methane Hydrocarbons
NMOG	Non-Methane Organic Gases
NO _x	Nitrogen Oxides
NYSERDA	New York State Energy Research and Development Authority
OMHCE	Organic Material Hydrocarbon Equivalent
OMNMHCE	Organic Material Non-Methane Hydrocarbon Equivalent
RVP	Reid Vapor Pressure
THC	Total Hydrocarbons
TLEV	Transitional Low Emission Vehicle
TLV	Threshold Limit Value
TPD	Ton per Day
ULEV	Ultra Low Emission Vehicle
UMTA	Urban Mass Transportation Administration
VFV	Variable-Fueled Vehicle
VOC	Volatile Organic Compounds