MOBILE SOURCE ALTERNATIVE FUEL TECHNOLOGIES

A SUMMARY OF METHANOL, ETHANOL, CNG, LNG, LPG, HYDROGEN, DIMETHYL ETHER, BIODIESEL, FISCHER TROPSCH, ELECTRIC, HYBRID-ELECTRIC, AND FUEL CELL TECHNOLOGIES

Prepared for

Environmental Protection Agency
Office of Mobile Sources - Fuels and Energy Division
401 M Street, SW
Washington, DC 20460

Contract 68-C5-0010
Work Assignment 2-10

By

ICF Incorporated
9300 Lee Highway
Fairfax, VA 22031-1207

and

Arcadis Geraghty & Miller
555 Clyde Avenue
P.O. Box 7044
Mountain View, CA 94039

September 1998

TABLE OF CONTENTS

SECTION 1

INTRODUCTION AND SUMMARY

1.1 OBJECTIVE

The objective of this document is to present unbiased summary discussions of eleven alternative transportation fuels, i.e., fuels that are alternatives to currently used gasoline and diesel fuels:

- Methanol
- Ethanol
- Compressed Natural Gas (CNG)
- Liquefied Natural Gas (LNG)
- Propane (Liquefied Petroleum Gas, LPG)
- Hydrogen
- Electric Vehicles
- Fuel Cells
- Dimethyl Ether
- Biodiesel
- Fischer Tropsch

---

[1] Although electric vehicle technology is not literally an alternative fuel, electric vehicles are alternatives to current gasoline and diesel fueled vehicles, and they are included here in that context.

Attention is confined to highway vehicle application of these fuels, i.e., for light-duty passenger cars through heavy-duty tractor-trailer trucks. The discussion focuses on the fuels themselves and on the vehicle technologies appropriate to each fuel. The current status and future potential of each fuel and vehicle technology is considered.

1.2 FORMAT

The eleven alternative fuels are discussed in Sections 2 through 12. Each alternative fuel discussion is organized with a general review of the fuel first (considering basic fuel facts, infrastructure, health and safety issues, costs, suppliers/backers, and availability) followed by discussion of light-duty vehicles and heavy-duty vehicles (considering vehicle technology and equipment, performance, emissions, availability and cost, and summary remarks). Section 13 includes the Fleet Experiences with brief discussions about the aftermarket conversion of vehicles as applied to each fleet experience. Appendix A is a discussion of light- and heavy-duty emissions. Appendix B is a list of available vehicles and a Status Summary & Outlook. Appendix C is an Annotated Bibliography. Appendix D is the References that were used to prepare this report.

SECTION 2

METHANOL

2.1 GENERAL DISCUSSION

2.1.1 Methanol as a Motor Vehicle Fuel

Methanol, also called methyl alcohol or wood alcohol, is the simplest alcohol and may be visualized as methane with one hydrogen atom replaced by an OH group: CH_3OH. It is a commercially produced chemical commonly used as a feedstock, extractant, and solvent for a wide variety of applications. Methanol has been used as an automotive racing fuel for approximately 50 years. Since the 1970s, methanol has received increased attention as an alternative to gasoline and diesel fuel to reduce motor vehicle cxhaust emissions and curtail the need for imported petroleum.

Methanol has the potential to be a "renewable resource fuel" because it can be produced from biomass. It can also be produced from fossil fuels, and in fact nearly all methanol is currently produced from natural gas. Methanol production options are discussed in more detail in Section 2.1.2, Infrastructure.

Environmental impacts from methanol production include those caused by increasing agriculture, which are land requirements, pesticides, fertilizers, farm machinery (using fossil fuels), and water. If coal were to be used, the environmental impacts of mining would need to be taken into account. Processing coal into methane can generate large quantities of solid and liquid wastes including acid mind drainage, ash, and process wastewaters high in organic compounds including aromatics. Methanol spills will not cause major environmental consequences to water sources, even though methanol is soluble in water. However, methanol spills can have a short term consequence in still water (i.e., lakes) ecosystems. Because methanol can be rapidly biodegraded by indigenous soil and water microorganisms, a significant depletion in water oxygen concentrations can occur and harm aquatic organisms. Chances of accidental spills could be increased over the occurrence with traditional fuels since higher volumes of methanol must be transported to have equivalent energy outputs.

Methanol has various advantages and disadvantages relative to gasoline, diesel fuel, and other alternative fuels. Some of these are briefly mentioned in this subsection, and they are discussed in more detail in Sections 2.2 and 2.3 which describe light-duty and heavy-duty methanol vehicle technologies.

The volumetric heating value or energy density (e.g., Btus per gallon) of pure methanol is approximately one-half that of gasoline and slightly less than one-half that of diesel fuel. Therefore, assuming equal fuel energy efficiencies, methanol vehicles would have approximately one-half the driving range as gasoline or diesel vehicles with the same size fuel tanks, or they would require fuel tanks roughly twice as large to achieve the same range. However, a reduction in this ratio is realized for light-duty vehicles when gasoline is blended with methanol and the fact that methanol vehicles generally have better thermal efficiencies than gasoline vehicles.

Methanol is a clear, nearly odorless, and toxic chemical. Because it is a single substance rather than a mixture like gasoline and diesel fuel, its vapor pressure is a distinct function of temperature. This creates two problems: methanol spark-ignition engines are difficult to cold-start because such a small fraction of fuel is in the vapor phase, and the fuel-air ratio of the gases in the ullage space of a methanol fuel tank can be ignited by a spark or flame when the ambient temperature is approximately 40°F to 85°F. Another chemical characteristic of methanol is that it burns with a nearly invisible flame.

While the first methanol vehicles used pure methanol (referred to as M100), more recent original equipment manufacturer (OEM) light-duty vehicles use a blend of 85 percent methanol and 15 percent unleaded gasoline (referred to as M85). The 15 percent gasoline solves the problems referred to in the prior paragraph because:

- It raises the vapor pressure of the mixture to enable cold-starting at temperatures as low as -5°F
- It makes the fuel tank ullage vapors too fuel-rich to ignite (like gasoline) for all ambient temperatures above approximately 20°F
- It enhances flame luminosity
- It adds an odor and taste to the fuel which discourages intentional or accidental ingestion

The history of light-duty methanol vehicles, most all of which now use M85, is summarized in Section 2.2. Heavy-duty methanol vehicles, most of which use M100, are discussed in more detail in Section 2.3.

2.1.2 Infrastructure

Current methanol production and distribution resources are based almost entirely on methanol application as an intermediate chemical and not as an end product. A relevant application is as a feedstock for producing methyl tertiary butyl ether (MTBE), an oxygenate added to gasoline to increase octane rating and/or reduce emissions (ozone-forming compounds, air toxics, and carbon monoxide). Oxygenates are required by the Clean Air Act in reformulated gasoline (RFG). In addition to states that currently use RFG in certain areas with ozone problems, some other states are considering adopting the RFG program voluntarily. Because MTBE accounts for a significant fraction of North American methanol use, methanol demand and price fluctuates accordingly (see Section 2.1.4, Costs).

If methanol was widely used as a vehicle fuel, the increased demand would require a greatly expanded production and distribution infrastructure. Currently methanol is made from natural gas, but if there were a much larger demand, it might also be produced from biomass or coal (particularly if there were financial incentives to encourage production from renewable resources and/or fossil fuels with large U.S. resources). In fact, much of California's interest in methanol was originally motivated by the desire to use clean fuels derived from coal, and the realization that methanol made more technical and economic sense than "synthetic gasoline" in this regard.

Methanol fuel transportation from production facilities to distribution facilities would probably be by railroad, marine vessel, highway, and possibly pipeline analogous to refined gasoline and diesel fuel. Note, however, that more methanol than gasoline and diesel fuel must be transported to support the same number of vehicles (between 1.5 and 2 times as much) because of methanol's energy density.

Currently, there are two methanol fuels produced, M100 and M85, as previously discussed in 2.1.1. Gasoline blending to make M85 is generally carried out at the distribution terminal. It should be noted that the U.S. Department of Energy National Renewable Energy Laboratory (NREL) is sponsoring research to develop a common methanol fuel formulation for all vehicles, and such a development could simplify the methanol fuel distribution infrastructure. Also, if this work is successful, a methanol fueling station would have one methanol suitable for all light-duty and heavy-duty vehicles, as compared to the four different fuels (three gasoline grades and one diesel) dispensed by most current stations. Methanol refueling facilities are similar to gasoline and diesel refueling facilities, except that different materials must be used for some components in order to be compatible with methanol's chemical characteristics, e.g., aluminum components must be replaced or nickel plated to prevent corrosion.

Because methanol's energy density is lower than gasoline's and diesel fuel's energy density, refueling station tanks need to be larger to store the same energy density as conventional fuels and the refueling flow rates must be faster. Relative to compressed and liquefied natural gas refueling facilities, methanol facilities do not require many complicated technical changes, and those which are required are much lower cost. Current availability of methanol refueling facilities is discussed in Section 2.1.6, Availability.

2.1.3 Health and Safety Issues

There has been considerable controversy regarding the health effects and safety of using methanol as a motor vehicle fuel. For example, methanol is more toxic than gasoline; swallowing a few ounces can lead to blindness or death, if untreated. On the other hand, gasoline is carcinogenic, and it is more straightforward to treat someone who has swallowed methanol than one who has swallowed gasoline. It is dangerous to inhale both methanol and gasoline fumes. Dermal absorption is also a hazard for both fuels.

The safety hazards of methanol fires are different than gasoline or diesel fuel fires. Methanol flames have very low luminosity (i.e., they are nearly invisible in daylight), but they also have relatively low radiation heat transfer rates. In the early 1980s, some automobile manufacturers insisted on additives to enhance methanol flame visibility, and this is one of the reasons that M85 is used in today's light-duty vehicles, as previously discussed. However, at automobile races such as the Indianapolis 500, gasoline is banned and methanol is the mandated fuel, partially because it is safer and easier to extinguish in case of a fuel fire. In most vehicle fires, other components of the vehicle also burn making a visible flame. Methanol does not evaporate or form vapor as readily as gasoline, thus pool fires are much less explosive. Under the same conditions, exposed gasoline will emit two to four times more vapor than will exposed methanol. Gasoline vapor is two to five times denser than air, so it tends to travel along the ground to ignition sources. Methanol vapor is only slightly denser than air and disperses more rapidly to non-combustible concentrations. Methanol burns 25 percent as fast as gasoline and methanol fires release heat at only one-eighth the rate of gasoline fires.

Methanol's low vapor pressure and broad flammability range result in a condition where the vehicle fuel tank ullage vapors can be ignited by a flame or spark. Under most conditions, gasoline tank ullage vapors are too rich and diesel tank ullage vapors are too lean to be flammable. This is another reason M85 is used in light-duty vehicles, as previously discussed. However, EPA studies (*Methanol Fuel Safety: A Comparative Study of M100, M85, Gasoline, and Diesel as Motor Vehicle Fuels* - 1987, Paul Machiele) suggest that increased fuel volatility increases the incidence of car fires, and this risk may be more serious than the risk of having a flammable mixture in the fuel tank ullage.

2.1.4 Costs

Three different prices must be considered when examining the "costs" of methanol used as a motor vehicle fuel: (1) the actual fluctuating spot price of chemical methanol on the open market, (2) the price of fuel methanol purchased through the California Fuel Methanol Reserve, and (3) the projected price of methanol if it was commonly used as a vehicle fuel, and new large-scale production plants were built to support this market.

The spot price of methanol on the open market is driven almost entirely by supply and demand; it has very little to do with the cost of production. For the last few years, the price of methanol has been driven more by the MTBE market (and anticipated MTBE market) than any other factor. This has caused the spot price, which had fluctuated in the $0.35 to $0.65 per gallon range from 1990 through 1993, to shoot up to over $1.60 per gallon in late-1994, and then drop to approximately $0.50 per gallon (Gulf Coast spot price) in 1998. The recent price drop resulted from the realization that MTBE demand may be less than originally thought. This fluctuating price situation affects the adoption of methanol as a motor vehicle fuel. To be competitive with current gasoline and diesel fuel prices, the wholesale price of methanol needs to be in the range $0.35 to $0.40 per gallon (pre-tax).

To help dampen price fluctuations, and to ensure the lowest possible methanol price through large volume contracting capabilities, the State of California created the California Fuel Methanol Reserve (CFMR) in 1988. The CFMR has provided methanol to dealers at stabilized prices which have slowly increased from $0.40 per gallon in early-1990, to approximately $0.50 per gallon through 1993, and to $0.50 per gallon in 1998. Even though the CFMR benefitted methanol vehicle use in California by providing stabilized and lower prices for dealers and consumers, the recent $0.50 per methanol gallon CFMR price is not competitive with gasoline and diesel fuel prices. However, if MTBE use is banned as a gasoline, a large majority of the methanol demand would subside. Therefore the price of spot price of methanol would decrease because it would have to compete in a fuel market rather than a fuel additive market, causing the future CFMR prices to be more competitive.

There have been a number of studies that examined options for future methanol production to support massive use of methanol as a transportation fuel. A study authorized by

California Assembly Bill 234 in 1988 involved 100 experts from government and industry meeting in workshops that addressed future alternative fuel issues including economics. Although the various experts considered various scenarios, methanol prices as low as $0.54 per gallon were projected for the year 2007 if there are four million methanol vehicles on the road. A program sponsored by the NREL is researching methanol from biomass technology and economics, because this strategy has such attractive resource-conserving features. A program goal is to reduce the cost of biomass-produced methanol to $0.55 per gallon.

The Federal excise and energy tax on methanol (M100) is $0.114 per gallon, compared to $0.184 per gallon for gasoline. However, when adjusted for energy content (but not efficiency differences, etc.), the Federal tax is higher for methanol (M100) than gasoline ($0.23 versus $0.184 per gasoline gallon or equivalent). State fuel taxes vary. The California tax is less for methanol ($0.085 per M100 gallon) than gasoline ($0.18 per gallon), even when adjusted for energy-content.

A factor influencing the use of methanol as a motor vehicle fuel is its price. Methanol prices, expressed as gasoline or diesel fuel energy-equivalent prices, are more than gasoline prices and diesel fuel prices. Methanol prices (which are roughly 20 percent more than gasoline prices, at the present time) are also more than CNG prices (by a factor of two in some locations), LNG prices, and propane prices. It is uncertain whether future methanol prices will become less than energy-equivalent gasoline and diesel fuel prices by an amount adequate to amortize all extra capital costs.

2.1.5 Suppliers/Backers

Currently, Methanex Corporation of Vancouver, British Columbia, Canada is the only supplier of fuel based methanol in the United States. Methanex and previous suppliers have invested relatively limited resources to develop a motor vehicle fuel market for their product, and they have been less aggressive politically, relative to other alternative fuel producers. It appears that recently, methanol producers seemingly have been more interested in the near-term MTBE market than the longer-term M85 and M100 markets. However, interest in marketing M85 and M100 may be rekindled by the possible ban on MTBE as a gasoline oxygenate mentioned in Section 2.1.4 above.

The American Methanol Institute (AMI) is an organization that once represented the interests of a variety of methanol producers and promoted methanol use as a transportation fuel. Methanex's interest in the methanol fuel market, and its commitment to continued support of the CFMR appears to fluctuate.

The methanol industry's fluctuating or lukewarm interest in the alternative fuels market and the high price of methanol on an energy-equivalent basis (M85 currently costs approximately the same as high octane gasoline) has multiple effects: OEMs are less inclined to produce methanol vehicles because of methanol price uncertainty, the methanol industry is not standing behind methanol as an alternative fuel, and because the price of FFV production is great. These instabilities discourages fleets and the public from this fuel.

2.1.6 Availability

M85 is currently available at 52 public-access stations in California. However, this number may decline in the next few years because the ten-year commitment from the oil companies is ending. In addition, there are over 50 private fleet stations that dispense M85 and/or M100. Nearly all of these stations are concentrated in urban centers, and so Flexible Fuel Vehicles (to be discussed subsequently) must be refueled with gasoline when driven in some parts of the state.

All M85 and M100 stations in California obtain their fuel through the CFMR, and so fuel prices at the stations vary accordingly (i.e., the CFMR price plus transportation costs, gasoline costs for M85, additive costs for M100, blending costs, plus mark-up). Recent M85 prices at public-access stations have been approximately $1.00 per gallon.

Over the past few years, methanol fuel availability has been limited by the number of stations dispensing M85 and/or M100. In the future, methanol fuel availability may also be limited by the CFMR's ability to contract for methanol supply at stabilized price, as discussed in section 2.1.4.

2.2 LIGHT-DUTY METHANOL VEHICLES

Light-duty methanol vehicles are loosely defined here as vehicles whose counterparts are gasoline-fueled vehicles, and heavy-duty methanol vehicles (discussed subsequently) are defined as vehicles whose counterparts are diesel-fueled vehicles (disregarding the occasional diesel-fueled automobile or light-truck).

2.2.1 Vehicle Technology and Equipment

The methanol vehicles initially released by OEMs in 1981 (Volkswagen Rabbits and Ford Escorts, see Section 2.2.4) were dedicated-methanol vehicles, except that the methanol contained 5.5 percent isopentane (i.e., M94.5), and subsequently contained 10 percent gasoline (i.e., M90). M85 use began shortly after the initial delivery of 500 1983 Ford Escorts to California demonstration fleets; the 15 percent gasoline provided all the previously discussed benefits pertaining to flame luminosity, nonflammable fuel tank ullage vapors, and cold starting.

In the mid-1980s, attention began to focus on Flexible Fuel Vehicles (FFVs) — vehicles capable of being fueled with either M85 or gasoline, and capable of running on any mixture thereof.[2] The FFVs provide many advantages, and a few disadvantages. For example, the 15 percent gasoline provides all the previously discussed advantages pertaining to cold starting, flame luminosity, and non-flammable fuel tank ullage vapors. Also, an FFV can be refueled with gasoline and provide standard gasoline vehicle performance when there is no M85 station available, and this is an important advantage while the network of M85 stations is sparse. It is arguable whether FFVs are a transition technology or an end goal themselves. The main disadvantage of FFVs and M85 is that the engine compression ratio cannot be raised to take advantage of methanol's high octane rating, to increase fuel efficiency and power (since the engine must also run on gasoline).

It is relatively straightforward to make a spark-ignition gasoline engine run on methanol; the main changes required are to accommodate:

- Methanol's lower energy-density which requires higher flow rates through the fuel system
- Methanol's lower energy-density which also makes larger fuel tanks desirable
- Methanol's chemical-compatibility characteristics which require some different fuel system component materials
- Methanol's combustion characteristics which require colder spark plugs and slight engine retuning (e.g., spark advance)
- Methanol's toxicity which has motivated some OEMs to install special anti-siphoning devices in the fuel tank filler neck
- Methanol compatible lubricants need to be used to minimize wear.

---

[2] Different OEMs use different terminology for methanol vehicles with this capability, e.g.: Variable Fuel Vehicles (VFVs), Gasoline Tolerant Methanol Vehicles (GTMVs), and Flexible Fuel Vehicles (FFVs). For brevity, this report refers to these vehicles as FFVs, regardless of manufacturer.

- Catalytic convertors need to address formaldehyde as well as unburned hydrocarbons.

In addition, for dedicated methanol vehicles, the compression ratio can be raised because methanol has a higher octane rating than gasoline, and some means to enhance cold-starting is necessary if M100 is used. FFVs, on the other hand, have special engine control equipment made possible by the electronic control systems used on all recent light-duty vehicles. This equipment includes a sensing device, located in the fuel line, which continuously measures the methanol/gasoline content of the fuel, and a modified engine control computer capable of interpreting this signal and adjusting the engine operating conditions (e.g., fuel flow relative to air flow) accordingly. Most FFVs also include an additional dashboard gauge which displays the existing fuel methanol content.

2.2.2 Performance

FFV performance differences on M85, gasoline, or intermediate mixtures are essentially "invisible" to the driver. The only serious performance difference is vehicle range which is shorter with M85 than gasoline, thereby requiring more frequent refueling. However, because many FFVs are equipped with larger fuel tanks, FFV range with M85 approaches that of the counterpart gasoline vehicle.

FFV startability and driveability with M85 is generally very good, and indistinguishable from counterpart gasoline vehicle startability and driveability. Some drivers claim to be able to detect a slightly faster acceleration capability with M85, but the power difference is generally quite small because the compression ratios of FFV engines are limited by the requirement that they also operate satisfactorily with unleaded gasoline.

Current FFVs carry the same warranty coverage as their gasoline counterparts. Although the reliability and durability of the latest generation of FFVs appears to be very good, they have not accumulated enough mileage to make a precise statistical comparison. Earlier generation FFVs sometimes experienced minor reliability and durability problems due to things like fuel filter clogging (usually due to fuel contamination) and fuel pump failures.

2.2.3 Emissions

All FFV passenger cars currently and recently offered for sale to the public in California (the Ford Taurus, Chrysler Intrepid and Spirit/Acclaim, and GM Lumina — see Section 2.2.4 for the current availability) have been CARB certified to Transitional Low Emissions Vehicle (TLEV) standards. Methanol fueled vehicles (including FFVs) benefit under the CARB system because their non-methane organic gas (NMOG) emissions are adjusted downward by approximately 60 percent to account for their lower photochemical reactivity, and lower ozone-forming potential, relative to gasoline vehicle NMOG emissions. However, all vehicles and engine families must be EPA certified. Although some engine families are California only engine families, they must be issued a Certificate of Conformity by EPA prior to being introduced into commerce.

Two categories of emissions that were problems for some prior-generation methanol vehicles are formaldehyde (tailpipe) emissions and overall evaporative emissions. Formaldehyde is designated as a toxic air contaminant by both CARB and EPA, and it also has a high photochemical reactivity. Unfortunately, it is an intermediate product of combustion of methanol with air, and early-technology methanol vehicles had high formaldehyde emissions. However, current-generation FFVs meet the TLEV standard for formaldehyde (0.015 gram/mile) with M85, and methanol advocates point out that gasoline vehicles emit other, more reactive or toxic substances.

Evaporative emissions are of increased concern as tailpipe emissions have steadily decreased. FFVs present a special problem relative to evaporative emissions because the fuel vapor pressure can vary over such a broad range as the relative amounts of methanol and gasoline in the fuel tank changes. Early-generation FFVs were not equipped to manage this variation. However, recent FFVs are, and measurements of their diurnal and hot soak evaporative NMOG emissions show that they are approximately equal to those of current gasoline vehicles, and "ozone" emissions are less due to methanol's relative low reactivity.

It should be noted that the successful emissions performance discussed above is for M85 fueled FFVs. Dedicated methanol light-duty vehicles have a significantly lower emissions potential, although they present other problems, as previously discussed. Many experts feel that FFVs are an intermediate step to dedicated methanol vehicles. Consistent with this goal, EPA is sponsoring research to make dedicated methanol vehicles practical, and to realize their low-emissions potential.

2.2.4 Availability and Costs

There are approximately 12,700 methanol vehicles currently in service in California. Only one light-duty methanol vehicle is currently for sale to the public. The Ford Taurus M85 FFV mid-size passenger car with a 3.0-liter V-6 engine costs $560 more relative to equivalent gasoline vehicles. A Chrysler Intrepid FFV which was offered until 1996 cost $150 more than the equivalent gasoline vehicle. General Motors also offered a FFV for public sale — a Chevrolet Lumina FFV mid-size passenger car with a 3.1-liter V-6 engine, in 1991 and 1993. In addition to these current and recent FFV models, OEMs (including European and Japanese manufacturers) have tested various other light-duty methanol vehicles since the early-1980s.

As discussed above, the incremental price increase of OEM light-duty FFVs is quite small. But as discussed in the prior fuel section, the recent cost of methanol fuel is substantially higher than the price of gasoline (on an energy-equivalent basis), even when purchased through the CFMR. Nevertheless, for most applications, the life-cycle costs of methanol FFVs are less than those of any other available OEM alternative fuel light-duty vehicles. This is because most light-duty vehicles consume so little fuel that the extra cost of fuel (e.g., for methanol), or the fuel cost savings (e.g., for CNG), is small relative to the incremental initial cost of the vehicle .[3]

2.2.5 Summary

Light-duty methanol FFVs are more "transparent" than any other alternative fuel vehicles, i.e., their operation is more similar to gasoline vehicles so far as the driver is concerned. They are technologically advanced, their performance is good (except that their range is less than gasoline vehicles), they have low emissions, and their cost is only slightly above that of their gasoline counterparts. The only problem is the fuel — methanol recently and currently costs more than gasoline (on an energy-equivalent basis), and methanol producers' commitment to this market has fluctuated.

2.3 HEAVY-DUTY METHANOL VEHICLES

2.3.1 Engine Technology and Equipment

Heavy-duty vehicles are loosely defined here as trucks, buses, etc. which normally have diesel engines. Usually, the diesel engine manufacturer is separate from the vehicle chassis

[3] For example, consider a methanol FFV with an incremental cost of $500 consuming M85 costing $1.48/gge (gasoline gallon equivalent; current CFMR price), versus an OEM CNG vehicle with an incremental cost of $5,000 consuming CNG costing $0.66/gge (recent Sacramento price). If both vehicles get 25 mi/gge, have 10-year lives, are driven 10,000 mi/yr, and the cost of money is 10 percent, then the annualized fuel plus incremental vehicle cost is $673 for the FFV versus $1,078 for the CNG vehicle. Even if they are both driven 20,000 mi/yr, the FFV is cheaper ($1,265 versus $1,342 annualized plus incremental vehicle cost).

manufacturer. Also, diesel engines are more difficult than spark-ignition (gasoline) engines to run on methanol. For these two reasons, this discussion will focus primarily on heavy-duty methanol engines.

Diesel engines are technically defined compression-ignition (CI) engines. The fuel is injected into the combustion chamber and autoignited by the high temperature of the compressed air charge — no spark plugs are used. The ability of a fuel to be ignited in this fashion is characterized by its cetane number. Unlike diesel fuel, methanol has a very low cetane number, and therefore it is difficult to compression-ignite. For this reason, unlike gasoline engines, diesel engines cannot be converted to methanol operation by simply modifying the fuel system to accommodate the higher fuel flow rate, replacing some materials, and making some timing adjustments.

A number of approaches have been pursued for converting diesel engines to methanol operation:

- Conversion to spark-ignition — Conversion to spark-ignition involves the addition of an ignition system, modification (or replacement) of the injection system, and other adjustments (e.g., compression ratio). The resulting engine generally has a lower thermal efficiency than the original diesel.
- Cetane improvers — Various hydrocarbon nitrates increase the cetane rating of fuels when added in small proportions. Avocet is a brand name for such an additive, and Avocet has been demonstrated in a number of methanol-diesel conversions. While cetane improvers enable diesel engines to operate on methanol with a minimum of modifications (e.g., increased injector system fuel capacity, material changes), they increase the cost of an already-expensive fuel.

- Dual-fuel — Methanol can be introduced into the diesel engine air induction system (e.g., using a carburetor or low-pressure injector), and the diesel fuel direct-injection rate can be decreased accordingly. This approach is analogous to the pilot-ignition or fumigation approaches used to fuel diesel engines with natural gas. It is not considered to be very satisfactory, and it has not been pursued by any engine OEMs.
- Direct-injection of methanol — It has been found that, through subtle engine adjustments that are more easily implemented with 2-stroke diesels than 4-stroke diesels, direct-injected methanol will autoignite, in spite of its low cetane rating, over most of the engine operating map. For those operating conditions where autoignition does not occur reliably, glow plugs (which are already installed in many diesel engines to assist in cold-starting) are used to promote ignition. This approach is used in the most successful heavy-duty methanol engine to date, and the only one to be emission-certified and commercialized — the Detroit Diesel Corporation (DDC) methanol 6V-92TA. The engine adjustments that enable diesel operation on methanol consist primarily of air system modifications (e.g., increasing the blower-bypass schedule) that increase the fraction of exhaust residual remaining in the cylinder. This residual increases the charge temperature and provides free radicals, both of which promote ignition of the injected methanol.

Essentially all heavy-duty methanol engines are fueled with M100 (straight methanol, usually with a lubricant additive) rather than M85. The 15 percent gasoline is not needed for cold-start, and most of the other reasons for using M85 in light-duty applications are considered less critical for heavy-duty applications. One specific exception is the methanol-fueled California school buses which use DDC 6V-92TA engines. Most of these school buses are fueled with M85 because of safety concerns, and also because of the greater availability of M85 stations.

2.3.2 Performance

This discussion focuses on the DDC 6V-92TA because it is the only commercialized heavy-duty methanol engine, and the one most used. As a point of fact, the 6V-92TA is basically a transit bus engine, and that is by far the most common application, but it also has been demonstrated in other applications such as trucks. Power levels equivalent to diesel counterparts have been achieved. Fuel efficiencies (on an energy-equivalent basis) are slightly below that of diesel counterparts — a 5 percent deficit is typical. This exacerbates the biggest issues for heavy-duty (and light-duty) methanol vehicles, i.e., the decreased range (or need for increased fuel tank volume) and fuel cost.

Reported results regarding reliability and durability are mixed. Even though the problems with first-generation methanol 6V-92TA engines have been rectified, many fleet users [such as the Los Angeles County Metropolitan Transit Authority (LACMTA)] report that the engine reliability is still not up to diesel standards.

2.3.3 Emissions

Methanol fueling of diesel engines enables them to simultaneously achieve low NO_x and low particulate emissions; this is something very difficult for diesel-fueled engines to accomplish.

In the late-1980s, both CARB and EPA adopted transit bus engine emissions standards of 5.0 g/bhp-hp NO_x and 0.10 g/bhp-hr particulate which were scheduled to take effect in 1991. The DDC methanol 6V-92TA was certified to these standards, and this was anticipated to create an opportunity for substantial commercial sales of this engine. But the EPA decided to delay these standards until 1993 to satisfy concerns that they could be met only with methanol engines or particulate trap equipped diesel engines.

By 1993, diesel engines that could meet these standards without particulate traps were developed. DDC accomplished this by introducing a new line of 4-stroke diesels (the Series 50 for buses and Series 60 for Class 8 trucks), and this has the unfortunate effect of making the 2-stoke engines (including the methanol 6V-92TA) the "old line" with dim prospects for future on-road applications.

2.3.4 Availability and Costs

Various diesel engine manufacturers have engaged in methanol engine development work, and there have been a number of on-road demonstrations of methanol-fueled heavy-duty vehicles, but only one manufacturer has commercialized an engine — the DDC methanol 6V-92TA, as previously discussed.

Approximately 550 of the DDC methanol 6V-92TA engines have been built and delivered. Most of those are used in transit buses, the main application of the engine, as previously discussed. Of these, approximately 330 were in use in LACMTA buses, but these have since been converted to operate on ethanol. In addition to transit buses, 150 of the engines are used in school buses built by Crown Coach and Carpenter Corporation. These school buses are all being operated in California as part of the CEC Safe School Bus Clean Fuel Efficiency Demonstration Program (most of these are the buses fueled with M85 rather than M100, as previously discussed in Section 2.3.1). However, although the DDC 6V-92Ta was the most-used HDV methanol engine in the U.S. by a huge margin, DDC no longer actively markets this engine, and very few methanol HDVs (with any kind of engine) remain in operation in the U.S.

The DDC methanol engine is priced at roughly twice as much as the counterpart diesel engine, i.e., on the order of $10,000 more for a bus manufacturer purchasing a number of the engines. In addition, to use this engine in a heavy-duty vehicle (e.g., a transit bus), a somewhat different fuel system is required (i.e., a larger capacity tank fabricated from methanol compatible materials, and usually a heat exchanger in the fuel recirculation system). This typically adds at least another $2,000, so the total incremental cost of a methanol-fueled transit bus is in the vicinity of $12,000.

2.3.5 Summary

The economics of methanol-fueled heavy-duty vehicles are not good at this time. Both the fuel and the vehicle cost significantly more than diesel fuel and diesel vehicles. In spite of the fact that adoption of methanol-fueled heavy-duty vehicles could significantly reduce NO_x and particulate emissions (particularly in urban areas, in the case of transit buses), there are currently no production heavy-duty methanol engines available. In addition, the high cost of methanol on an energy-equivalent basis and the methanol industry's seemingly low interest in investing to build a methanol fuel market currently limit its possibilities. This is a stark contrast to the price of CNG and LNG, and the natural gas industry's commitment to CNG and LNG vehicles.

SECTION 3

ETHANOL

3.1 GENERAL DISCUSSION

3.1.1 Ethanol as a Motor Vehicle Fuel

Ethanol or ethyl alcohol (C_2H_5OH), is also called grain alcohol because it is usually made from grains such as corn, or from other agricultural products. Ethanol is the alcohol in intoxicating beverages. In fact, motor fuel ethanol is "200 proof" with a denaturant added to make it unfit to drink. Ethanol proponents point out that ethanol is the only truly "renewable resource" alternative fuel, because it is made from agricultural products and not from fossil fuels (the supply of which is limited). Ethanol detractors counter that ethanol usually competes with food (for humans or animals), and that nearly as much fossil fuel is consumed in its production (e.g., tractors to plant and harvest the grain) and in converting the feedstocks as is saved in its use as a fuel.

Because ethanol can be produced from biomass it is considered a renewable resource. Increasing demands on agricultural systems to produce more biomass requires land, fertilizers, pesticides, herbicides, farm machinery, and water with associated impacts. With current methods to process biomass into ethanol, high-oxygen-demand liquid wastes could be produced. The solid wastes produced would result from crop collection, processing residue, biotreatment of wastes (sludges), and combustion (ash). The effects of an ethanol spill on water sources are the same as that of methanol Section 2.1.1. Even though biomass is a renewable resource, fossil fuels still play a role in the ethanol life cycle. Fossil fuels power agricultural machinery (for planting and harvesting), fuel transportation equipment to move feedstock to processing facilities and to market, and industrial equipment used in feedstock conversion to ethanol.

Ethanol is the most-used alternative fuel in the world, and nearly all of its usage is in Brazil. Over 4 million ethanol vehicles (approximately one-third of the total) are in service in Brazil. Most of the ethanol is produced from sugar cane, and Brazil has a huge ethanol fuel infrastructure in place.

Ethanol would also be the most widely used alternative fuel in the United States if gasohol (ethanol blended with gasoline), were defined as an alternative fuel. According to EIA estimates from 1997, consumption of gasohol (defined as E10 or oxygenate) was 787,800 thousand/gasoline gallon equivalent (gge), as compared to E85 equaling 1416 thousand/gge and E95 equaling 2628 thousand /gge. However, in this discussion, we adopt a narrower definition of alternative fuel, i.e., the majority of the fuel must be something other than a petroleum distillate.

Ethanol is also probably the oldest alternative fuel. The Ford Model T had a carburetor adjustment which allowed it to run on either gasoline or ethanol. During WWI and WWII, gasohol was used as a vehicle fuel to conserve gasoline. Subsequent to both WWI and WWII, there were efforts (primarily from corn-growing states) to encourage the continued use of ethanol, but these were not successful. Current efforts to promote ethanol also originate primarily from the corn-growing states.

Ethanol falls roughly midway between methanol and gasoline in its energy density, octane rating, and materials compatibility. The energy density or volumetric heating value (e.g., Btus per gallon) of ethanol is approximately 65 percent that of gasoline. Therefore, assuming equal fuel energy efficiency and equal fuel tank sizes, an ethanol vehicle would have only 65 percent of the driving range of a gasoline vehicle. Or, inversely, the ethanol vehicle fuel tank would have to be approximately 50 percent larger to achieve the same driving range. The actual situation is a little more complicated because current light-duty ethanol vehicles use a blend of approximately 85 percent ethanol and 15 percent volatile gasoline components (E85), their energy-efficiency is slightly better, and many have larger fuel tanks (relative to gasoline vehicles).

There are advantages and disadvantages associated with using ethanol, instead of gasoline, in light-duty vehicles with spark-ignition engines. The advantages include ethanol's high octane rating (--which enables a higher compression ratio and therefore more power and improved fuel economy), low emissions potential (to be discussed in Sections 3.2.3 and 3.3.3), and the fact that the feedstock is domestically available and renewable. Key disadvantages include the difficulty that ethanol vehicles have starting in cold weather and the flammability of the vapors in the fuel tank ullage. Both of these problems are due to ethanol's low volatility, (methanol has the same two problems), and both are solved by using E85 instead of straight or neat ethanol. Unlike methanol, ethanol flames are readily visible.

Current original engine manufacturers (OEMs) light-duty ethanol vehicles are flexible-fuel vehicles (FFVs) which can be fueled with E85, gasoline, or any mixture of the two. In order to accomplish this, engine compression ratios are limited by gasoline octane ratings, and so most of the improved power and fuel economy benefit is lost. Ethanol FFV technology will be discussed further in Section 3.2, Light-Duty Ethanol Vehicles.

3.1.2 Infrastructure

Most fuel ethanol in the United States is currently made from corn through fermentation and distillation. Ethanol can also be made from other grains, or any starch-yielding agricultural product, or even from cellulose (although this process is not yet commercial, BC International is expected to open a plant in Jennings, Louisiana by end of 1998). Ethanol produced from biomass such as agricultural wastes or municipal wastes is of particular interest because these feedstocks are not also food sources. For this reason, the Department of Energy [through (NREL)] conducts research to reduce the cost of producing ethanol from biomass.

Ethanol is primarily produced, promoted, and used in the Midwest, i.e., the corn-growing states (see Section 3.1.5, Suppliers/Backers). The ethanol used as either E100 (primarily for heavy-duty vehicles) or E85 (for ethanol FFVs) is trucked from production or intermediate storage/distribution facilities to refueling stations. Ethanol refueling equipment is similar to gasoline equipment, except that some different materials must be used to be compatible with ethanol's properties. Revised gasoline components with materials proven in methanol service will provide ethanol compatibility.

The United States has a relatively small ethanol fuel infrastructure (e.g., compared to Brazil) consisting of roughly 70 refueling stations which support several hundred thousand ethanol flex-fueled vehicles.

The ethanol fuel infrastructure in California is currently very small. Roughly 10 million gallons of ethanol per year are produced in California, and most of this comes from agricultural and food-processing wastes (e.g., cheese whey). A small fraction of this ethanol is used as E85 fuel within the State.

3.1.3 Health and Safety Issues

Ethanol is perhaps the safest of the alternative fuels. However, ethanol is flammable and poisonous, and may contain additives that are harmful if inhaled or consumed. Relative to methanol, ethanol is less toxic and has a more visible flame. Relative to CNG, it does not have to be stored at high pressures, and because it is heavier than air it "leaks down" like gasoline. Relative to LNG and hydrogen, ethanol is not cryogenic and there is no venting issue. Relative to LPG, it does not have to be pressurized to be stored, and leaks are not as hazardous.

Because ethanol has a low vapor pressure and broad flammability range, vehicle fire susceptibility and severity characteristics (e.g., in case of a crash) are different than those of gasoline vehicles. In particular, the vapors in the fuel tank ullage are normally flammable if the fuel is E100, but they are not normally flammable if the fuel is E85. But it is not clear if the increased fuel volatility enhances the overall vehicle safety (this same uncertainty applies to methanol vehicles).

3.1.4 Costs

On the average, over the past few years, ethanol has been the most expensive alternative fuel, per Btu (except hydrogen). The retail price of ethanol (E85) is roughly $1.20 per gallon.

The Federal excise and energy tax for ethanol (E100) is $0.13 per gallon, which is less than the Federal tax for gasoline ($0.184 per gallon). However, when adjusted for energy content, the tax is $0.197 per gasoline gallon equivalent, i.e., more than gasoline.

However, ethanol used as a motor vehicle fuel receives special Federal government tax incentives (recently extended through 2007, gradually decreasing in amount) designed to make the price of ethanol fuels (gasohol through E85 and E100) comparable to the price of gasoline. This includes an income tax credit available to ethanol fuel producers, plus a partial excise tax exemption for fuels with at least 10 percent ethanol content. The specific rules for computing and applying this credit and exemption are complicated, e.g., the tax credit must be reduced by the amount of the partial excise tax exemption benefit. Some states also provide financial incentives or excise tax exemptions for ethanol used as a motor vehicle fuel.

Because ethanol is basically an agricultural product, agricultural economics and institutions dominate its production. For example, the price of ethanol is related to crop prices — when the weather is bad and crop yields are poor, the price of ethanol goes up. If ethanol use as a fuel substantially increases in the future, complex factors will probably affect its pricing. If, as is the case now, most ethanol is made from corn, ethanol prices will fluctuate with corn prices. On the other hand, if fuel ethanol is produced from biomass feedstock rich in cellulose, the production plants are more expensive and so a bigger portion of ethanol price must amortize these higher capital costs, but price fluctuations may be less.

Another effect on ethanol prices is the fact that there are three competing fuel uses of ethanol:

- Direct use as a vehicle fuel as E100 or E85 — the subject addressed here
- Gasohol, a blend of (typically) 10 percent ethanol plus 90 percent gasoline — various service stations in the Midwest dispense gasohol
- ETBE (ethyl tertiary butyl ether) — a fuel oxygenate (competing with MTBE, see Section 2, Methanol) used in reformulated gasoline

Legislation that mandated that 30 percent of gasoline oxygenates must come from renewable sources (i.e., ethanol as ETBE) was reversed by the U.S. Court of Appeals. This diminished the ETBE market outlook, because MTBE is cheaper, and it is not yet clear what, if any, effect the reversal will have on E100 and E85 prices.

3.1.5 Suppliers/Backers

Ethanol backers are primarily, but not entirely, agricultural interests in the Midwest. Ethanol use is also strongly supported by researchers who believe that its production from renewable resources is critically important (analogous to hydrogen backers who believe that its low emissions potential is critically important). Ethanol backers have been singularly successful in the political arena, e.g., the previously mentioned legislation providing tax incentives and mandating that 30 percent of gasoline oxygenates must come from the renewable resources (which was later overturned/reversed). Some observers suggest that these successes are related to the political power of farm states and farm interests.

Various ethanol producers supply ethanol as a motor vehicle fuel. The largest ethanol supplier is Archer Daniels Midland in Decatur, Illinois. Ethanol is also produced in California where its use as a fuel is promoted by the California Renewable Fuels Council.

3.1.6 Availability

The current ethanol production capacity in the United States is approximately 1.4 billion gallons per year. Only a small fraction of this production capacity is directly used as a vehicle fuel at this time. A much larger fraction is used for gasoline blending (Section 3.1.4). E85 and/or E100 is currently dispensed from approximately 70 (public and private) refueling stations in the United States.

In summary, ethanol backers are highly motivated to develop a motor vehicle fuel market for ethanol. Detractors question whether an adequate ethanol supply can be made available at a reasonable price if the ethanol fuel market grows to a significant fraction of the current gasoline or diesel fuel markets.

3.2 LIGHT-DUTY ETHANOL VEHICLES

Light-duty ethanol vehicles are loosely defined here as vehicles whose counterparts are gasoline-fueled vehicles, and heavy-duty ethanol vehicles are defined as vehicles whose counterparts are diesel-fueled vehicles (disregarding the occasional diesel-fueled automobile or light-truck).

3.2.1 Vehicle Technology and Equipment

In the mid-1980s, OEMs concluded that FFV technology was appropriate for both ethanol and methanol light-duty vehicles. Even when fueled with 100 percent E85, the 15 percent gasoline provided superior cold start capability and shifted the fuel tank ullage vapor mixture out of the flammable range. Also, and very important for the situation of a fledgling ethanol refueling station network, ethanol FFVs can be refueled with gasoline when there is no E85 station available. A disadvantage of the FFV approach is the fact that the engine cannot be optimized for operation on ethanol alone, e.g., a high compression ratio to increase power and decrease fuel consumption.

Modification of a spark-ignition gasoline engine for ethanol operation requires fewer changes than for any other alternative fuel:

- The fuel flowrate through the carburetor or fuel injection system must be increased to accommodate ethanol's lower heating value;
- Larger fuel tanks are desirable to maintain the same vehicle range;
- A few engine and fuel systems materials should be changed to be more compatible with ethanol's corrosivity characteristics (the material changes are not as extensive as those required for methanol vehicles); and
- Slightly colder spark plugs should be used and the spark advance should be adjusted.

Ethanol FFVs take advantage of modern microprocessor technology which continually adjusts the engine operation (e.g., fuel/air ratio) as required by the ratio of ethanol and gasoline in the fuel tank. OEMs use similar or identical FFV equipment for both ethanol (E85) and methanol (M85) vehicles, e.g., the materials, sensors, and engine control systems.

3.2.2 Performance

FFV performance differences on E85, gasoline, or intermediate mixtures are essentially "invisible" to the driver. The only noteworthy performance difference is vehicle range which is shorter with E85 than gasoline, thereby requiring more frequent refueling. However, as previously noted, many FFVs are equipped with larger fuel tanks so that FFV range is similar to that of the counterpart gasoline vehicle. FFV startability, power, and driveability with E85 is generally very good, and indistinguishable from counterpart gasoline vehicle startability, power, and driveability.

Current FFVs carry the same warranty coverage as their gasoline counterparts. Although the reliability and durability of the latest generation of FFVs appear to be very good, they have not accumulated enough mileage to make a precise statistical comparison.

3.2.3 Emissions

Ethanol (and methanol) has the potential of reducing exhaust emissions relative to gasoline, when used as a light-duty vehicle fuel. M85-fueled FFVs have been more completely emissions-tested than E85-fueled FFVs. Also, M85-fueled FFVs have been CARB Certified to Transitional Low Emissions Vehicle (TLEV) standards, but OEMs have neither sought nor attained this certification for E85 FFVs. This is related to the primary market focus of ethanol vehicles which is outside California.

The EPA has carried out emissions tests of Chevrolet Lumina and Ford Taurus FFVs using E85, M85, gasoline, and other fuels. These tests show that emission levels with E85 and M85 are similar, and these emissions levels are generally lower than those with gasoline. Specifically:

- OMHCE (organic material hydrocarbon equivalent) emissions are usually slightly higher with E85 than M85, and they are higher or lower than with gasoline, depending on the vehicle;
- CO emissions are very slightly lower with E85 than M85, and they are higher or lower than with gasoline, depending on the vehicle;
- NO_x emissions average very slightly lower with E85 than M85, and they are usually much lower than with gasoline; and
- The calculated "ozone potential" (considering reactivity) is higher for E85 than M85, and it is usually lower than the ozone potential with gasoline.

Note that superior emissions performance would be expected of dedicated ethanol vehicles, relative to FFVs, because they could be optimized for ethanol-only operation.

Ethanol detractors claim that the "fuel-cycle" emissions (from production of the fuel to tail pipe emissions) of ethanol are higher than those of other alternative fuels because of the fuel consumption required to plant, harvest, and process the agricultural feedstock used to produce ethanol. This claim should be balanced against the observation that this higher energy consumption is associated with the fact that ethanol is a renewable fuel, and that simple depletion of a fossil fuel will generally produce lower fuel-cycle emissions. Also, most fuel-cycle emissions comparisons have been carried out or commissioned by parties advocating a particular alternative fuel, and perhaps the results should be interpreted accordingly.

3.2.4 Availability and Costs

The Ford Taurus E85 FFV mid-sized passenger car with a 3.0-liter V-6 engine has been in production since 1996, and will continue to be available into 1999. However, the standard production models (engine and fuel delivery system) of both the Ford Taurus and the Ford

Ranger beginning in model year 1999 will be FFVs only. There will no longer be an option to purchase these vehicles without FFV capabilities. Also, all standard Chrysler minivans currently produced (which exist in various models) for model year 98 and beyond are FFVs only. Until 1995, General Motors offered a Chevrolet Lumina E85 FFV mid-sized passenger car with a 3.1-liter V-6 engine for public sale. GM is anticipated to resume production of E85 (and M85) vehicles in the future.

In addition to these current and future E85 FFV models, various OEM ethanol-fueled vehicles have been manufactured and tested in the past in the United States (but not offered for public sale), and a few million ethanol vehicles have been manufactured and sold in Brazil (these do not meet various U.S. standards, and therefore they cannot be sold in this country).

3.2.5 Summary

The technology for fueling light-duty vehicles with ethanol, particularly E85, is well developed. Ethanol is more like gasoline than any other alternative fuel (i.e., with respect to range, performance, and required vehicle modifications). Issues relevant to a substantial growth of ethanol fuel usage include emissions, costs, and availability. E85 FFV emissions are generally lower than those of gasoline vehicles, but not quite as low as those of methanol (M85) and natural gas vehicles, particularly when reactivity is considered. Ethanol fuel-cycle emissions of both criteria pollutants and greenhouse gases are relatively high compared to other alternative fuels. Current fuel ethanol prices may not reflect the cost of production, and current usage for E85 and E100 is a small fraction of total ethanol production capability. Therefore, there are uncertainties regarding both price and availability if ethanol fuel use grows to displace a significant fraction of gasoline use in the near future.

3.3 HEAVY-DUTY ETHANOL VEHICLES

3.3.1 Engine Technology and Equipment

Heavy-duty vehicles are loosely defined here as trucks, buses, etc. which normally have diesel engines. Usually, the diesel engine manufacturer is separate from the vehicle chassis manufacturer. Also, diesel engines are more difficult than spark-ignition (gasoline) engines to run on ethanol. For these reasons, this discussion will focus primarily on heavy-duty ethanol engines.

Diesel engines are technically defined as compression-ignition engines. The fuel is injected into the combustion chamber and autoignited by the high temperature of the compressed air charge — no spark plugs are used. The ability of a fuel to be ignited in this fashion is characterized by its cetane number. Unlike diesel fuel, ethanol has a very low cetane number, and therefore it is difficult to compression-ignite. For this reason, unlike gasoline engines, diesel engines cannot be converted to ethanol operation by simply modifying the fuel system to accommodate the higher fuel flow rate, replacing some materials, and making some timing adjustments.

A number of approaches have been pursued for converting diesel engines to ethanol operation:

- Conversion to spark-ignition — Conversion to spark-ignition involves the addition of an ignition system, modification (or replacement) of the injection system, and other adjustments (e.g., compression ratio). The resulting engine generally has a lower thermal efficiency than the original diesel.
- Cetane improvers — Various hydrocarbon nitrates increase the cetane rating of fuels such as ethanol when added in small proportions. While cetane improvers enable diesel engines to operate on ethanol with a minimum of modifications (e.g., increased

injector system fuel capacity, material changes), they increase the cost of an already-expensive fuel.

- Dual-fuel — Ethanol can be introduced into the diesel engine air induction system (e.g., using a carburetor or low-pressure injector), and the diesel fuel direct-injection rate can be decreased accordingly. This approach is analogous to the pilot-ignition or fumigation approaches used to fuel diesel engines with natural gas. It is not considered to be very satisfactory, and it has not been pursued by any engine OEMs.
- Direct-injection of ethanol — It has been found that, through subtle engine adjustments that are more easily implemented with 2-stroke diesels than 4-stroke diesels, direct-injected ethanol or methanol will autoignite, in spite of their low cetane ratings, over most of the engine operating map. For those operating conditions where autoignition does not occur reliably, glow plugs (which are already installed in many diesel engines to assist in cold-starting) are used to promote ignition. This approach is used in the most successful heavy-duty ethanol and methanol engine to date, and the only one to be emission-certified and commercialized — the Detroit Diesel Corporation (DDC) ethanol 6V-92TA. The engine adjustments that enable diesel operation on ethanol consist primarily of air system modifications (e.g., increasing the blower-bypass schedule) that increase the fraction of exhaust residual remaining in the cylinder. This residual increases the charge temperature and provides free radicals, both of which promote ignition of the injected ethanol.

Heavy-duty ethanol engines are fueled with a variety of high-percentage ethanol fuels including neat ethanol denatured with various chemicals (i.e., essentially E100), E95 (95 percent ethanol plus 5 percent gasoline components), and other blends of at least 90 percent ethanol plus gasoline and other hydrocarbons. The 15 percent gasoline used in E85 is not needed for cold-start, and most of the other reasons for using E85 is light-duty applications are considered less critical for heavy-duty applications.

3.3.2 Performance

This discussion focuses on the DDC 6V-92TA ethanol engine because it is the heavy-duty ethanol engine most used in the United States. This engine is basically a bus engine, but it has also been used in trucks (e.g., the Archer Daniels Midland Corporation has operated four E95-fueled 6V-92TA line-haul trucks since 1992).

In general, ethanol-fueled heavy-duty engines can provide power levels equivalent to diesel-fueled engines, but fuel efficiencies (on an energy-equivalent basis) are somewhat less. The Los Angeles County Metropolitan Transit Authority (LACMTA) reports that ethanol buses have slightly superior cold start capability and idle stability relative to methanol buses. Heavy-duty ethanol engine reliability and durability results are incomplete, but fundamentals suggest that heavy-duty ethanol engines should be at least as reliable and durable as heavy-duty methanol engines (see Section 2, Methanol).

3.3.3 Emissions

Ethanol fueling of diesel engines enables them to simultaneously achieve low NO_x and low particulate emissions; this is something very difficult for diesel-fueled engines to accomplish. The DDC 6V-92TA engine fueled with E95 has been emissions-certified by both CARB and EPA. DDC test data show that 6V-92TA NO_x emissions with E95 are more than twice as much as with M100, but they are approximately the same as with M85 (although all are less than CARB standards for trucks and buses). 6V-92TA hydrocarbon emissions are also much

SECTION 4

COMPRESSED NATURAL GAS

4.1 GENERAL DISCUSSION

4.1.1 Natural Gas as a Motor Vehicle Fuel

Natural gas is a fossil fuel with greater domestic availability and lower cost relative to petroleum. A pipeline network that covers much of the United States supplies natural gas for home heating, electricity generation, and industrial processes. Pipeline natural gas is primarily methane (75 to 98 percent CH_4) plus heavier hydrocarbons and inert gases such as nitrogen.

Because of its low cost, domestic availability, and clean-burning combustion characteristics, natural gas is also an attractive alternative to gasoline and diesel as a motor vehicle fuel. The biggest problem with this application is how to store the fuel on the vehicle. Because methane is a gas at room temperature, it has a very low energy density (i.e., Btus per cubic foot). In order to boost its energy density so as to make it a practical transportation fuel (i.e., provide a reasonable vehicle range with practical-size fuel tanks), natural gas is either compressed or liquefied. Compressed natural gas (CNG) vehicles are discussed here, and liquefied natural gas (LNG) vehicles are discussed in Section 5. Storage of methane adsorbed in porous materials is also a possibility, but this method is still in the research stage.

Because methane is a greenhouse gas, direct releases of methane to the environment are of concern. Environmental impacts of using natural gas can occur during extraction and processing (natural gas and crude oil), from the accidental releases of gas in the distribution systems or at fueling hook-ups as well as through tail pipe emissions.

4.1.2 CNG Description

CNG is stored on the vehicle at a maximum pressure of 3,000 to 3,600 psi, and this provides roughly one-fourth the energy density of gasoline. The natural gas must be compressed prior to transferring it to the vehicle and special high-pressure tanks are used to safely contain the CNG on the vehicle. These cylindrical tanks may be constructed of high-strength steel, aluminum overwrapped with a composite material (e.g., fiberglass), or all-composite materials. This is an area of active R&D where an important goal is to minimize the weight and cost of the tanks. Additional discussion of CNG vehicle tanks and other equipment is provided in Sections 4.2 and 4.3 which address light-duty and heavy-duty CNG vehicles, respectively.

4.1.3 Infrastructure

The CNG infrastructure generally consists of natural gas provided by a local distribution company (LDC) to a refueling station owned by the LDC, a private fleet, or a public refueling company (e.g., Shell, Amoco). The LDC receives the gas from a producer company through a pipeline company.

CNG refueling station capabilities can range from very small slow-fill (suitable for home refueling of one or two private vehicles) to large fast-fill (suitable for refueling a fleet of heavy-duty vehicles). Slow-fill systems are relatively simple, but they require multi-hour (e.g., overnight) fill times. Fast-fill systems can refuel CNG vehicles in a few minutes.

The basic elements of fast-fill CNG refueling stations accomplish gas compression, drying and filtration, storage, and dispensing. The gas compressors are usually major capital equipment items that consume significant power (usually electric; occasionally gas engine).

There are multiple fast-fill CNG station design approaches involving smaller compressors and larger cascade gas storage tanks, or larger compressors with less storage capacity, depending on the fleet refueling schedule requirements. The CNG refueling dispenser resembles a gasoline or diesel dispenser; it has a hose and nozzle, but the nozzle is a positive-connect pressure fitting.

4.1.4 Health and Safety Issues

CNG has limited health concerns because it is non-toxic. However, there are safety issues associated with using CNG because of its high pressure (up to 3,600 psi). For example, concerns have been raised regarding the long-term durability and reliability of on-vehicle CNG fuel tanks, although CNG vehicle advocates assert that this is not a serious issue. Strict standards for CNG equipment have been established by the National Fire Protection Association (NFPA), American National Standards Institute (ANSI), and others. While mishaps have occurred (e.g., a few CNG tanks have ruptured after being corroded, and pressure relief devices have vented gas prematurely), there have been no major CNG vehicle accidents (e.g., involving loss-of-life) in the United States. One particular mishap was at Los Angeles County Metropolitan Transit Agency (LACMTA) in which a tank ruptured upon refueling. The tank was a Type IV EDO cylinder that was constructed of high density polyethylene with a carbon fiber over-wrap. The over-wrap was damaged (it is not certain how) and because LACMTA did not have a regular tank inspection program, the damage went undetected because the cylinders are on the underside of the bus. Since the over-wrap provides most of the structural integrity of the tank, the damage to the over-wrap caused the cylinder to fail upon refueling the bus. The cylinder broke through the bus floor and bounced around in the inside of the bus causing considerable damage. There was no fire, explosion or loss of life from this incident. LACMTA has since instituted a regular tank inspection program to prevent a similar occurrence.

CNG vehicles require some safety procedures that are different from gasoline and diesel vehicle procedures. For example, natural gas "leaks up" because it is lighter than air, whereas gasoline and diesel fuel "leak down." This usually requires modifications to vehicle maintenance facilities if they were originally designed to serve only gasoline and diesel vehicles.

4.1.5 Fuel Costs

The price of CNG is usually less than the price of gasoline and diesel fuel (on an equivalent-energy basis), even after amortization of the CNG compressor station costs are taken into account. For example, on April 3, 1995, the price of CNG dispensed by a Shell station in Sacramento was $0.66 per equivalent gasoline gallon which was approximately 60 percent of the price of gasoline from the same station. Note that care must be taken in interpreting the gasoline equivalence factor for rigorous economic analyses (e.g., comparison of higher heating values with lower heating values must be avoided, and differences in vehicle energy efficiency should be taken into account).

CNG is exempt from Federal excise tax, but it is subject to a Federal energy tax of $0.0485 per 100 scf which is approximately $0.056 per gasoline gallon equivalent (i.e., much less than the total Federal gasoline tax of $0.184 per gallon). States differ considerably in their taxation of CNG. California taxes CNG at approximately $0.07 per gasoline gallon equivalent (compared to $0.18 per gallon for gasoline).

While CNG is relatively inexpensive, light-duty and heavy-duty vehicles cost substantially more than corresponding gasoline and diesel vehicles (as will be quantitatively discussed in Sections 4.2.4 and 4.3.4). Life-cycle cost analyses show that the fuel cost savings are not enough to amortize these higher vehicle capital costs, except for a few very high-mileage fleet vehicle applications. However, this situation is anticipated to improve in the future as the incremental price of CNG vehicles decreases due to increased sales volume and improved technology.

4.1.6 Suppliers/Backers

It appears that CNG vehicle advocates are quite committed to success through the support of natural gas LDCs, pipeline companies, and producers. Proponents of other alternative fuels sometimes complain that these companies have an unfair advantage because part of their costs to develop CNG technology and purchase CNG vehicles and equipment can be rate-based (i.e., charged to all natural gas consumers as part of their gas bill). A large and committed community of CNG equipment companies (e.g., tanks, compressors) has also evolved. These firms have combined forces with the gas companies (e.g., as the Natural Gas Vehicle Coalition), and they have gained significant attention at the state and federal levels.

In California, Southern California Gas, Pacific Gas and Electric, and other gas companies have large and aggressive CNG vehicle programs. However, the scope of these programs was recently cut back in response to legislation which introduces more competition into the utilities' business, and these programs are being criticized by anti-utility groups such as Toward Utility Rate Normalization (TURN). California is also the home of many companies in the CNG equipment business (e.g., Structural Composites Industries manufactures CNG tanks, Wilson Technologies designs and installs CNG refueling station, and IMPCO manufactures CNG fuel induction systems).

4.1.7 Fuel Availability

The availability of CNG is limited by the number of refueling stations and not by the availability of the feedstock — natural gas. Nationwide, CNG is currently available at approximately 1300 refueling stations. Recently, there have been several instances where people have successfully driven dedicated CNG vehicles across the country without geographic restrictions. However, dual-fuel CNG vehicles (vehicles with both CNG and gasoline or diesel fuel system — to be discussed subsequently) can drive without geographic restrictions by simply switching to gasoline (or diesel) when they run out of CNG and there is no CNG refueling station in the vicinity.

4.2 LIGHT-DUTY CNG VEHICLES

4.2.1 Vehicle Technology and Equipment

Light-duty CNG vehicles are loosely defined here as vehicles whose counterparts use gasoline-fueled spark-ignition engines. Spark-ignition engines are simpler to convert to natural gas fueling than diesel engines which will be discussed in Section 4.3.

There are two types of light-duty CNG vehicles: dedicated, which operate exclusively on CNG, and dual fuel, which can operate on either CNG or gasoline.

CNG vehicles have fuel system components that are different than those used on gasoline vehicles. The previously discussed cylindrical CNG tanks may be mounted in various locations (e.g., underneath the vehicle, in the trunk of passenger cars, in the bed of pickup trucks). CNG vehicles have refueling receptacles which are compatible with the high-pressure nozzle fitting at the end of the dispenser hose. The CNG tank pressure is reduced to the pressure required by the engine by one or two pressure regulators.

There are two types of natural gas metering and induction systems for spark-ignition engines: mixers and fuel-injection. Mixers are analogous to gasoline carburetors because they rely on the venturi principle to meter the gas and mix it with the air. Fuel injectors can be throttle-body or port types, and they are analogous to gasoline injection systems except that gas valves replace the gasoline nozzles. Over the last few years, natural gas metering and induction systems have become increasingly integrated with OEM engine electronic controls.

It should be noted that a majority of the CNG vehicles in existence today were converted from gasoline and thus are not optimized. Many are dual fuel and perhaps rarely use CNG.

4.2.2 Performance

The most notable difference between CNG and gasoline vehicles is the shorter driving range of CNG vehicles. This results primarily from the previously discussed lower energy density of CNG and secondarily from the difficulty of packaging cylindrical CNG tanks relative to conformal gasoline tanks. Dedicated CNG vehicles typically have three or four fuel tanks that provide the energy equivalent of 10 to 12 gasoline gallons and a driving range of roughly 150 to 200 miles — approximately one-half that of gasoline vehicles. Sometimes the actual driving range can be even less than the "advertised" range, e.g., when refueling at fast-fill stations that cannot fill tanks to 100 percent capacity because the heat of compression decreases the gas density. Obviously, driving range is less of a problem with dual fuel vehicles, although they must be equipped with two separate fuel systems, and therefore cannot be optimized for maximum performance with both gasoline and CNG.

Another performance compromise is the slight power loss experienced by most light-duty CNG vehicles. This is primarily because the gas displaces some of the air in the intake charge, and engine power is ultimately limited by the rate at which the engine can process air (e.g., the amount of oxygen which can react with carbon and hydrogen).

Dedicated CNG engines can provide increased power and improved fuel economy relative to engines that must also operate on gasoline. The primary modification to accomplish this is to increase the compression ratio, which is possible because the octane rating of natural gas is much higher than that of gasoline. Other adjustments include optimized valve timing and spark advance. With or without optimization for natural gas, the relative (energy-based) fuel economy of light-duty CNG and gasoline vehicles has been subject to confusion and controversy. Some of the confusion derives from the previously mentioned tendency to mix up higher and lower heating values when comparing the two fuels — which arises because natural gas is sold based on its higher heating value, whereas engine efficiencies are usually calculated based on the lower heating values of various fuels.

Another factor affecting CNG vehicle performance, optimization, and fuel economy comparisons is the variable composition of pipeline natural gas fed to refueling stations by LDCs. As previously noted, the methane content of pipeline natural gas in the United States ranges from 75 to 98 percent. This variation affects fuel properties (e.g., density, energy content, octane number), and thwarts efforts to precisely calibrate the engine for good performance, high fuel efficiency, and low emissions.

4.2.3 Emissions

The simple chemistry of the methane molecule and the combustion properties of natural gas combine to enable engineers to achieve lower exhaust emissions with natural gas vehicles relative to gasoline vehicles. This is particularly true when the unburned hydrocarbon emissions are measured as non-methane organic gases (NMOG). In addition, dedicated CNG vehicles have even lower total emissions because evaporative, refueling, and running loss emissions, which are issues for gasoline vehicles, are zero.

Most OEM light-duty CNG vehicles have achieved emissions levels below their gasoline counterparts during CARB and EPA certification testing. A noteworthy example is Chrysler's Dodge Caravan and Plymouth Voyager CNG minivans that were certified by CARB to the ultra-low emission vehicle (ULEV) standards. The applicable ULEV exhaust standards and the Dodge/Plymouth CNG minivan measurements are summarized below (all in g/mile):

	ULEV Standard[3]	**Dodge/Plymouth CNG Minivan**
NMOG	0.050	0.021
CO	2.2	0.4
NO_x	0.4	0.04

Because of CNG's outstanding emissions performance, incentives and/or mandates to use natural gas vehicles have been considered as part of various plans to meet air quality standards (e.g., air district rules, state implementation plans).

Since the early 1970's, the emissions performance of retrofit (aftermarket conversions) has been an issue for EPA. The Clean Air Act §203(a)(3) defines a prohibited act as any time a person removes or renders inoperative any device or element of design installed on a motor vehicle engine. EPA published a policy document, MEMORANDUM 1A, in June of 1974 that provided a basis for aftermarket convertors to know whether or not their conversion could be defined as a prohibited act. This guidance was often ignored and EPA published two more addenda to this original policy. One was published in September of 1997 and the most recent in June of 1998. In summary, the EPA policy for conversion of any vehicle or engine is that data must exist showing that the process of conversion did not cause any adverse effect on the emissions of the vehicle. If the vehicle was a dual-fuel vehicle, data must be generated on both fuels. In those cases where the engine family being converted is a California only engine family, EPA has allowed the CARB to make some decisions separate from EPA policies.

[3] These are the CARB ULEV standards for light-duty trucks (3,751-5,750 lb. loaded vehicle weight) because these minivans are classified in this category. Note that the Dodge/Plymouth CNG minivans' emissions are also less than CARB passenger car ULEV standards of 0.040 NMOG, 1.7 CO, and 0.2 NO_x (all in g/mile)

It should be further noted that conversions must be certified by EPA or their emissions performance cannot be guaranteed. In recent DOE and other studies, converted CNG vehicles are often found to have higher emissions than the gasoline counterpart. The conversion of vehicles (originally designed to operate on gasoline) to operate on any other fuel is very challenging for aftermarket conversion entities to produce low emission vehicles.

4.2.4 Availability and Costs

Light-duty CNG vehicles are available as new vehicles from OEMs (in a few models), and existing gasoline vehicles can be retrofitted with CNG conversion equipment.

Chrysler was the first OEM to offer CNG vehicles (in 1992). All Chrysler vehicles are dedicated CNG with very low emissions. GM sold 2,500 dual fuel CNG Sierra pickup trucks, but all have been recalled following tank rupture incidents in two vehicles (which were subsequently found to be caused by tank exposure to corrosive materials). GM reportedly plans to resume CNG vehicle sales in the near future. Ford CNG vehicles are converted from gasoline vehicles by Ford-approved retrofitter companies (conversion installers) through their "Qualified Vehicle Modifier Program." For example, GM uses IMPCO Technologies for its conversion installations.

At current low production and sales levels, OEM CNG vehicles cost between approximately $4,000 and $5,000 more than corresponding gasoline vehicles. The cost of retrofitting a gasoline vehicle is also in the same range, or slightly more, depending on the equipment sophistication, number and type of tanks, and retrofitter. As previously discussed, except for rare cases, these costs cannot be amortized by the fuel cost savings, and so the life-cycle-costs of operating light-duty CNG vehicles is more than for gasoline vehicles. However, this situation will change in the future if the sales volume increases and vehicle costs decline.

Also, economic decisions regarding CNG vehicles (and all alternative fuel vehicles) are also affected by available incentives, applicable mandates, and other factors.

4.2.5 Summary

CNG is arguably a promising alternative fuel for light-duty vehicles because it is technologically feasible, domestically available in large quantities, reduces exhaust emissions, and has an active and well-financed constituency of advocates. While CNG fuel prices are low, vehicle prices are not. Keys to CNG's growth in the light-duty vehicle market will be public acceptance of reduced vehicle range, technology advances and increased sales volume to reduce equipment prices, and/or future legislation and rulemakings.

4.3 HEAVY-DUTY CNG VEHICLES

4.3.1 Engine Technology and Equipment

The heavy-duty vehicle category is defined here as vehicles normally equipped with diesel engines (e.g., line-haul and other heavy trucks, transit buses, most school buses, and many pickup-and-delivery trucks). More often than not, the diesel engine manufacturer is separate from the vehicle manufacturer. Also, the technology required to convert a diesel engine to natural gas is more complicated than that required to convert a spark-ignition (gasoline) engine. For these reasons, the discussion in this section will focus primarily on heavy-duty CNG engines.

Diesel engines are technically defined as compression-ignition engines. The fuel is injected into the combustion chamber and autoignited by the high temperature of the compressed air charge — no spark plugs are used. The ability of a fuel to be ignited in this fashion is characterized by its cetane number. Unlike diesel fuel, natural gas has a very low cetane number, and therefore it is difficult to compression-ignite. For this reason, most heavy-duty natural gas engines are simply diesel engines converted to spark-ignition (i.e., the diesel injection system is removed, gas induction and spark-ignition systems are added, and other modifications are made). Another approach is pilot-ignition or fumigation — the diesel injection system is left in place, and it is used to ignite a gas-air charge created by a mixer or gas injector. A third approach is direct-injection of the gas into the combustion chamber. For two-stroke engines, this has been shown to work with glow plugs used for some operating conditions. For four-stroke engines (which are much more common), this approach is still in the research stage, and it appears that glow plugs are required for ignition at nearly all operating conditions.

Diesel engines have very good fuel economy because, among other reasons, the intake air is not throttled and so there is no pumping loss. Conversion to spark-ignition includes installation of a throttle and other changes which tend to lower the fuel efficiency. On the other hand, the economics of many heavy-duty CNG vehicle applications is more attractive than light-duty applications, primarily because they consume much more fuel and therefore generate more cost savings with which to amortize capital costs.

4.3.2 Performance

As is the case for light-duty CNG vehicles, the driving range of heavy-duty CNG vehicles is much less than that of counterpart diesel vehicles because the fuel energy density is less. This can be a substantial problem for some applications (e.g., cross-country line-haul trucks) and less of a problem for other applications (e.g., municipal transit buses).

Heavy-duty vehicles generally have more room for CNG fuel tanks, and so 300-mile vehicle ranges are typical. There is usually a trade-off between vehicle range and the added weight, size, and number of CNG tanks. Some heavy-duty vehicles can accommodate multiple large CNG tanks with no problem. Other vehicles have less available space and/or they have weight restrictions (e.g., when added fuel tank weight reduces maximum payload weight). For these vehicles, LNG (discussed in Section 5) may be a better choice than CNG.

Another heavy-duty CNG vehicle performance problem is the reduced energy-based fuel economy due to lower engine efficiency, as previously discussed. Fuel economy data from many heavy-duty CNG (and LNG) vehicle projects indicate a range of energy-based fuel economy decrements (i.e., CNG relative to diesel), but a 15 percent loss is typical. Technology advances will undoubtedly reduce this decrement, but probably not to zero unless direct-injection natural gas "diesel" engines are developed.

Manufacturers have been successful in maintaining the same power output when converting diesel engines to heavy-duty natural gas engines. Engine durability and reliability experience is mixed. Many heavy-duty CNG engines have experienced durability problems. Some of these are the result of specific design changes (e.g., the exhaust gas temperature is hotter because the engine is less efficient, oil leakage at valve stems/guides increases because the engine is now throttled), but others are simply the result of the newness of the technology.

The natural gas fuel composition issue also affects engine performance. As previously noted, the methane composition in natural gas can vary from roughly 75 to 98 percent, and the remaining percentage usually consists of heavier hydrocarbons and nitrogen. This composition variation makes it difficult for the engine designer to calibrate the engine for optimum performance, particularly with respect to NO_x emissions. For example, operation of heavy-duty natural gas engines near the lean-limit has been shown to minimize NO_x and maximize efficiency. The engine designer must either calibrate the air-fuel ratio with a wide margin (with respect to the lean-limit) to account for the fuel composition variation, or incorporate a closed-loop control system (which is difficult because lean-burn oxygen sensors for heavy-duty natural gas engines are still developmental).

4.3.3 Emissions

Heavy-duty natural gas engines have achieved significantly lower emissions levels than counterpart diesels. In particular, they have been able to break through the PM-NO_x limit affecting most diesels, i.e., they can simultaneously achieve low particulate and low NO_x emissions.

For example, emissions test results for the Cummins L-10 240G bus engine are compared to 1993 and later standards below (all in g/bhp-hr):

	Cummins L-10 240G Emissions Test Results	**CARB Standard, for 1998 and Later Transit Buses**
NMHC	0.6	1.2
CO	0.4	15.5
NO_x	2.0	4.0
PM	0.02	0.10

The very low particulate emissions of heavy-duty natural gas engines is of special significance for two reasons. First, for some applications such as urban buses, visible particulates are especially offensive to the public — air pollution control agencies get more complaints regarding smoke than any other vehicle issue. Second, recent research reported by EPA and CARB suggest that diesel engine particulate emissions are more carcinogenic than previously believed.

The low exhaust emissions of heavy-duty natural gas vehicles has motivated strong interest in using vehicles such as CNG transit buses as the basis of mobile emissions reduction credit (MERC) sales. While the first MERC sales are yet to happen, this concept is supported by agencies such as the South Coast Air Quality Management District, and such sales could shift the CNG versus diesel economics trade-off strongly toward CNG.

4.3.4 Availability and Costs

Most U.S. diesel engine manufacturers are involved in heavy-duty natural gas engine projects including R&D, prototype engine demonstration, and commercial sales of certified engines. In addition, various other companies offer equipment and services to convert existing diesel engines to natural gas engines. Most of these conversions result in pilot-ignition (i.e., dual-fuel) natural gas engines, although a few are conversions to dedicated natural gas spark-ignition operation.

Four companies (Cummins, Detroit Diesel, Hercules, and Tecogen) currently offer commercialized CARB-certified heavy-duty natural gas engines for transit buses, school buses, and medium trucks. All are spark-ignition engines. Caterpillar, Detroit Diesel, and Cummins are demonstrating prototype high-horsepower (e.g., 300 hp - 350 hp) spark-ignition natural gas engines in large Class 8 trucks (greater than 33,000 lbs. gross vehicle weight). In addition, Caterpillar is developing direct-injection natural gas engine technology. Power Systems Associates is currently offering three pilot injected natural gas engines that have NOx emissions less than 2.5 g/bhp-hr. The prices of heavy-duty natural gas engines are variable, depending on the manufacturer, engine, and project. Manufacturers are charging a substantial premium to cover some of their costs for development, certification, warranty service, etc. As a rough rule of thumb, manufacturers price heavy-duty natural gas engines at nearly twice the price of counterpart diesels, e.g., approximately $25,000 for a CNG transit bus engine.

Conversion of buses to CNG is usually performed by the bus manufacturer, but conversion of large trucks is usually carried out by full-service truck and engine dealers. They design and install the fuel system (CNG tanks, plumbing, etc.) in addition to the natural gas engine. Incremental costs relative to diesel buses and trucks are highly situation-specific. The incremental price of heavy-duty CNG vehicles can be as low as $20,000 per vehicle (e.g., for a fleet of small buses) or as high as $60,000 per vehicle (for a large one-of-a-kind CNG demonstration truck).

4.3.5 Summary

Heavy-duty CNG vehicles have significantly lower emissions than diesel fueled vehicles. Natural gas is more abundant in the United States than petroleum, and CNG generally costs less (per Btu) than diesel fuel. However, heavy-duty CNG vehicles currently cost substantially more than counterpart diesel vehicles, but heavy-duty CNG vehicle life-cycle economics are usually superior to light-duty vehicle economics because they consume so much fuel that they can more nearly amortize additional capital costs. Emissions-certified OEM heavy-duty natural gas engines are not currently available in horsepower ranges suitable for all applications, and available engines are less efficient than diesel engines. Also, for many heavy-duty vehicle applications, the decreased range and added weight and space requirements associated with CNG fuel tanks are substantial problems. These factors become less of a problem if the natural gas is stored as LNG instead of CNG, although LNG introduces new problems (see Section 5).

SECTION 5

LIQUEFIED NATURAL GAS

5.1 GENERAL DISCUSSION

5.1.1 Natural Gas as a Motor Vehicle Fuel

Natural gas (which is primarily methane, CH_4) is a candidate alternative to gasoline and diesel fuel as a motor vehicle fuel. Its advantages include low cost, domestic availability, and clean-burning combustion characteristics. Its primary disadvantages derive from the fact that methane is a gas at room temperature, and therefore it has a very low energy density (i.e., Btus per cubic foot). In order to store adequate quantities of natural gas on motor vehicles (i.e., to provide a reasonable vehicle range with practical size fuel tanks), it is either pressurized or liquefied. Compressed natural gas (CNG), which is stored at a maximum pressure of 3,000 to 3,600 psi, was described in Section 4. Liquefied natural gas (LNG), which must be stored at cryogenic temperatures as low as -260°F, is described here. Certain aspects of LNG and CNG vehicles are identical (e.g., engine technologies); this discussion makes reference to Section 4 where this is the case.

Because LNG is primarily composed of methane, and since this is a greenhouse gas, direct releases of methane to the environment are of concern. Environmental impacts of using natural gas can occur during the extraction and processing of natural gas and crude oil, from accidental releases of pipeline gas in distribution systems or at fueling hook-ups, as well as tail pipe emissions.

5.1.2 LNG Description

LNG is stored on the vehicle as a saturated liquid (i.e., at its boiling point). Because boiling temperatures depend on pressures, the actual LNG temperature depends on the pressure in the fuel tank, and for fuel systems with no pump, there is a minimum pressure required to supply fuel to the engine. For example, at a typical storage pressure of 50 psig, the LNG temperature is -220°F. At this state, the energy density of LNG is approximately 55 percent that of diesel fuel and approximately 230 percent that of CNG (at 3,000 psi). This illustrates the advantage of storing natural gas as LNG instead of CNG — the vehicle range is more than doubled for the same fuel tank volume, or, conversely, less than half as much fuel volume is required for the same vehicle range.

LNG fueling requires the natural gas to be liquefied before transferring it to the vehicle and highly insulated tanks to store the fuel on the vehicle. Technology for LNG fuel tanks is well-developed. Tanks are fabricated as concentric stainless-steel vessels. The space between the inner and outer vessel is evacuated (like a thermos bottle), and it contains reflective foil-like insulation. A typical fuel tank "hold-time" (before heat transfer induced pressure build-up requires gas venting) is 1 week.

Fuel purity (i.e., percent methane content) is an issue for both CNG and LNG, but it is more of an issue for LNG. There are two reasons for this. First, the fact that LNG is perpetually boiling (albeit very slowly, in well-designed tanks) occasionally causes "enrichment" — the concentration of heavier hydrocarbons (e.g., ethane, propane, butane) in the liquid may increase to the point that they affect engine operation. Second, the liquefaction process provides an opportunity to purify the natural gas, and some LNG suppliers advertise the high purity of their LNG product.

5.1.3 Infrastructure

There is more of a variety of fuel supply scenarios for LNG than CNG. These include: onsite liquefaction, central liquefaction facilities, LNG from gas processing plants, use of peakshaving LNG, and imported LNG. Each of these has supplied fuel for LNG vehicle projects.

Onsite liquefaction is analogous to a CNG station, except the liquefier replaces the compressor. This is the only LNG supply infrastructure that doesn't require LNG trucking, but it is not generally believed to be the most economical. Large centrally located liquefaction plants (with LNG trucked to nearby users) benefit from an economy-of-scale. Liquid Carbonic has built a plant of this type in Willis, Texas to support LNG fleets such as Houston Metro and Sun Metro (El Paso).

Some existing gas-processing plants can easily produce LNG, but these are not always located near LNG vehicle fleets. For example, the Amoco gas plant near Evanston, Wyoming, can supply low-cost LNG. Approximately 56 gas utilities in North America liquefy gas and store it for reevaporation during periods of peak demand (i.e., peakshaving). Some of this LNG can obviously be used to fuel vehicles. In the late-1960s and through most of the 1970s, San Diego Gas and Electric had peakshaving plants which supplied LNG for fleets including the San Diego zoo buses. San Diego Gas and Electric dismantled their LNG plants in the late-1970s, and this ended these LNG vehicle projects. Currently, Baltimore Gas and Electric, Northern Indiana Public Service, and Northwest Natural Gas provide peakshaving LNG for vehicle fleets. There are two active LNG import terminals in the United States — in Everett, Massachusetts, and Lake Charles, Louisiana. Both of these have supplied LNG for vehicle projects, but it is uneconomical to truck LNG from these terminals to distant locations (e.g., California).

For most LNG supply scenarios, the LNG refueling station consists of an LNG storage tank (or tanks), a fuel transfer system, and dispenser equipment. Fuel transfer is generally via either pump or gas pressure, but there are many design variations. The dispenser includes a cryogenic hose (or hoses), a refueling coupling, and a metering and control system. Some dispensers use two hoses and a double-coupling (to on-load LNG and off-load vapor), and some use a single hose system which condenses the vapor in the tank ullage. A goal of all LNG transfer and dispensing system designs is to minimize or eliminate vapor venting to the atmosphere. In general, LNG refueling hoses and couplings are more cumbersome than those for CNG, but LNG refueling is faster.

A few LNG-to-CNG refueling stations have been installed, and more are planned. These stations store natural gas as LNG, pump it to 3,000+ psi (which takes much less power than CNG compression), and then vaporize and dispense it into the CNG vehicle. The advantages of this approach are: fuel supply flexibility, low power consumption, and convenience when both CNG and LNG vehicle refueling is required. Also, it is claimed that LNG-to-CNG facilities can eliminate the heat-of-compression underfill problem, but a very complex system is required to accomplish this.

5.1.4 Health and Safety Issues

There are few health issues related to LNG. LNG is non-toxic, however the low temperature of the fuel (either in liquid or gaseous form) can cause cryogenic burns (frostbite) if direct body contact occurs. It is recommended that refueling personnel are trained and they wear gloves and face shields.

There are concerns regarding the safety of LNG-fueled vehicles because LNG is a cryogenic liquid, and also because there is relatively little experience with LNG use as a transportation fuel. Perceptions of LNG safety are affected by residual publicity from an LNG peakshaving plant accident causing 128 deaths in Cleveland in 1944, and by highly publicized controversies associated with past efforts to site LNG import terminals at various locations in the United States (e.g., Point Concepcion in California).

Experts agree that the 1944 Cleveland accident and LNG import terminal issues have little relevance to LNG vehicle safety. The primary LNG vehicle safety issues are the same as CNG vehicle safety issues, e.g., concern that a vehicle parked indoors will have a fuel system leak which forms a flammable mixture in the vicinity of an ignition source. Care must be taken to ensure that both CNG (with pressures up to 3,600 psi) and LNG (with temperatures down to -260°F) fuel systems are leak-free. However, a safety issue unique to LNG (and liquid hydrogen) vehicles derives from the fact that they cannot be parked for long periods without venting some "boil-off" gases. Advocates point out that this should not be a problem for frequently driven fleet vehicles serviced by trained personnel in properly designed facilities (i.e., three levels of risk mitigation).

The experience database for LNG vehicles is too incomplete to support safety conclusions based on accident statistics. However, the limited experience to date indicates that cryogenic burn risks are not substantial. There is also controversy regarding the risks and consequences of a large LNG spill from a vehicle or refueling facility tank; small leaks and spills immediately vaporize, but big spills might form a "ground-hugging cloud" of flammable gas-air mixture. No such spill has occurred to date, and advocates suggest that such a large spill is unlikely due to the robust double-wall construction of LNG fuel tanks.

Analytical efforts to rate and compare the safety risks of various vehicle fuels are highly scenario-dependent and of arguable value. However, a gross generalization of a safety analysis performed by Los Alamos National Laboratories would rate LNG (and CNG) vehicles as more safe than gasoline vehicles, but not as safe as diesel vehicles, for most accident scenarios. While safety standards for LNG vehicles and refueling facilities have been drafted, they are not as mature as CNG safety standards. This is primarily because there has been a long delay in promulgating draft LNG vehicle codes due to disputes within the National Fire Protection Association (NFPA) regarding the authority of this standard relative to the NFPA standard for large LNG facilities such as peakshaving plants.

5.1.5 Fuel Costs

LNG is available from numerous sources (see Fuel Availability, Section 5.1.7) at a price less than gasoline and diesel fuel, on an energy-equivalent basis. For most all fuel sources, the price of LNG is highly dependent on the buyer's willingness to contract to purchase a given quantity over a given time period, and the transportation costs involved.

For example, Houston Metro is currently paying approximately $0.50 per gallon for LNG (roughly $0.85 per diesel gallon equivalent). However, LNG is available for approximately $0.30 per gallon (approximately $0.51 per diesel gallon equivalent) or less from peakshaving utilities, gas processing plants, and large liquefaction plants — although each source carries significant restrictions at this price, e.g., geographic location, quantity purchased, transportation, and purity.

An anomaly currently affecting the price of LNG is the fact that federal tax law regards LNG as a liquid fuel and taxes it at the same rate per gallon as gasoline — $0.141 and $0.043 per gallon excise and energy tax, respectively. Therefore, LNG is taxed much more than CNG, and even more than gasoline, on an energy basis. The Federal government has been petitioned to rectify this disparity.

State taxes for LNG vary considerably. California taxes LNG at $0.06 per gallon, or approximately $0.09 per gasoline equivalent gallon (compared to the California gasoline tax of $0.18 per gallon).

Like all alternative fuels (with the possible exception of propane), LNG prices are projected to be less if and when a substantial market for the fuel develops. This would enable economical utilization of large economy-of-scale liquefaction plants, for example. It would also ensure a more economical fully-utilized fuel transportation infrastructure. LNG is unique among alternative fuels in that a variety of private companies aspire to sell LNG for transportation applications, and they are making significant investments to develop this market (see Suppliers/Backers, Section 5.1.6).

As with CNG, even though LNG currently costs less than petroleum fuels on an energy-equivalent basis, the fuel cost savings is usually inadequate to amortize the additional capital equipment costs, at current prices. However, the situation may be better for LNG than for CNG because, as will be discussed subsequently, LNG is usually favored for heavy-duty vehicles such as large trucks, transit buses, and even railroad locomotives. These vehicles consume large amounts of fuel, and they can generally generate more fuel cost savings relative to the incremental capital costs for vehicles and facilities. This is the basic requirement for making alternative fuel vehicle life-cycle-costs superior to gasoline and diesel vehicle costs, and a key factor is reduced capital costs if a market develops and sales volumes increase.

5.1.6 Suppliers/Backers

A variety of companies aspire to sell LNG as a motor vehicle fuel, and many of these have made significant investments to achieve this goal. The types of companies include specialty gas and chemical companies, petroleum and natural gas companies, LNG importers, and certain natural gas local distribution companies (LDCs). Liquid Carbonic and Air Products are example companies in the first category. Liquid Carbonic has made substantial commitments to and investments in this market, e.g., they have built a liquefaction plant in Willis, Texas to supply LNG as fuel. Air Products has also made significant investments, and they have focused primarily on the railroad locomotive market.

Amoco, Exxon, and Chevron are examples of oil and natural gas companies able and willing to sell LNG. All three have significant natural gas reserves and existing gas processing plants that can produce LNG. Unfortunately, these plants are distant from most potential LNG vehicle fleets, so significant LNG transportation may be required. The two previously mentioned import terminals (in Louisiana and Massachusetts) also face significant transportation distances for any fleets not in their local geographic area.

As discussed in Section 4 (CNG), the involvement of LDCs in the natural gas vehicle market development is important because they have significant financial capabilities (although critics assert that most of these funds come from ratepayers more interested in heating their homes than supporting natural gas vehicles). LDCs fall into four categories with respect to their attitudes toward LNG: LDCs with peakshaving facilities who aspire to sell LNG (e.g., Minnegasco), LDCs with peakshaving facilities who do not aspire to sell LNG, LDCs without peakshaving facilities who are promoting the LNG vehicle market development (e.g., Southern California Gas), and LDCs without peakshaving facilities who are neutral to negative regarding LNG vehicles. Some LDCs in the last category are anxious to sell their gas for CNG vehicle fleets. They envision little or no competition in this regard, and they are concerned that fuel supplier competition would accompany development of any LNG vehicle fleets.

5.1.7 Fuel Availability

At the current time, LNG production capability substantially exceeds demand (although significant transportation distances may be applicable for some locations), but there are not many LNG refueling stations. There are essentially no public-access LNG stations because most all LNG applications are for heavy-duty vehicle fleets, and such fleets are usually refueled at private facilities and not public-access facilities. Note that the broad availability of fuel and the limitation due to expensive refueling stations is analogous to the situation with CNG.

A problem affecting LNG vehicle pilot projects (e.g., initial tests of two or three LNG vehicles) is that there is a minimum cost for an LNG refueling station, regardless of how small it is, and this often makes the economics of small pilot projects look very unattractive. This problem is partially solved by the recent availability of LNG storage and refueling facilities on a lease basis. Two of the facilities in California are of this type. They are portable skid-mounted units built by Cryenco and leased through Jack B. Kelley (a Texas trucking company). Other firms are also entering the LNG refueling facility leasing business, and this will increase the availability of LNG in small quantities on an economical basis.

5.2 LIGHT-DUTY LNG VEHICLES

LNG is more appropriate to heavy-duty fleet vehicles (preferably with centralized refueling) than to light-duty vehicles. LNG is especially inappropriate for privately-owned light-duty vehicles that may occasionally remain unused for weeks at a time. The reasons for this CNG-LNG application distinction are based on vehicle performance, economics, and safety. The fact that LNG provides longer vehicle range with smaller and lighter tanks (relative to CNG) is especially significant for heavy-duty vehicles where range and payload capability usually translates directly into economics.

LNG refueling requires more training than CNG refueling. While CNG refueling can be carried out by private owners/drivers with minimal training, this is not as easily done for LNG refueling. Also, as previously discussed, it is important that LNG vehicles not be parked indoors for long periods of time. It is easier to ensure appropriate vehicle refueling procedures and personnel training relative to parking and maintenance for heavy-duty centrally serviced fleet vehicles than it is for large numbers of light-duty vehicles in either private or fleet use environments.

The natural gas vehicle applications to date are consistent with this demarcation. Most all light-duty vehicles are CNG; the few existing light-duty LNG vehicles are usually associated with larger fleets of heavy-duty LNG vehicles where all the LNG facilities and training are already in place. Therefore, no detailed discussion of light-duty LNG vehicle technology is presented here.

Most large natural gas fueled trucks (e.g., Class 8) and all natural gas fueled locomotives are LNG, for the reasons discussed above. Heavy-duty LNG vehicle technology is discussed in the next section. The "grey area" includes transit buses and medium-duty truck fleets. Time will tell if these vehicles are best suited to LNG or CNG.

5.3 HEAVY-DUTY LNG VEHICLES

5.3.1 Engine Technology and Equipment

As explained in Section 4 (CNG), the heavy-duty vehicle category is defined here as vehicles normally equipped with diesel engines. In this category, the vehicle chassis and engine are usually manufactured by separate companies.

Diesel engines are more difficult to convert to natural gas than spark-ignition (gasoline) engines. There are three basic types of heavy-duty natural gas engines: spark-ignition, pilot-ignition, and direct-injection. Technical details of these three approaches were summarized in Section 4 (CNG). Nearly all currently available heavy-duty natural gas engines are converted diesel engines. The OEM natural gas engines are available as new warranted and emissions-certified natural gas engines, but they usually have the same block, crankshaft, etc. as one of the manufacturer's diesel engines. Retrofit conversion kits are also available from non-OEM companies.

LNG fuel tanks all have the same basic proven design, regardless of manufacturer. However, there are different design approaches for the fuel conditioning and delivery systems, and some of these components may actually be inside the fuel tank. For example, positive-displacement fuel pumps inside the fuel tanks must be used when high fuel supply pressure (e.g., over 200 psi) are required, and they are sometimes used with lower fuel supply pressure requirement. Intermediate fuel supply pressure requirements (e.g., 100 psi) are usually achieved by "conditioning" the fuel i.e., adding heat to increase its saturation temperature and pressure (and, unfortunately, decreasing its density as previously discussed). Some manufacturers advocate conditioning the LNG as part of the refueling process, and some advocate conditioning the LNG on the vehicle using a heat exchanger system in the fuel tank. Low fuel supply pressure requirements (e.g., 50 psi) can usually be met with no special equipment, because the LNG is already at or near this saturation pressure.

5.3.2 Performance

LNG vehicles have much better driving range than CNG vehicles, but not nearly as much as diesel vehicles, for the same fuel tank weight and space restrictions. From the other perspective, for the same vehicle driving range, the full fuel tanks on an LNG vehicle will weigh approximately half again as much, and the full fuel tanks on a CNG vehicle will weigh roughly four times as much, as the full fuel tanks on a diesel vehicle (exact comparison numbers depend on relative fuel efficiency, tank construction details, number of tanks, mounting hardware, etc.).

Heavy-duty LNG vehicles usually have an energy-based fuel economy somewhat less (typically 15 percent) than corresponding diesel trucks, because unthrottled compression-ignition (diesel) engines have higher thermal efficiencies than throttled spark-ignition engines, for the reasons discussed in Section 4 (CNG). Heavy-duty natural gas engines generally have the same power output as counterpart diesel engines (but somewhat different torque curves). But on the other hand, as discussed in Section 4 (CNG), heavy-duty natural gas engine reliability has not yet reached diesel levels.

5.3.3 Emissions

Heavy-duty natural gas engines (used in both CNG and LNG vehicles) have achieved significantly lower emissions levels than counterpart diesels. Example emissions test results are compared with CARB standards, and the importance of low heavy-duty vehicle emissions are discussed, in Section 4 (CNG).

5.3.4 Availability and Costs

Most heavy-duty LNG trucks are produced by replacing the diesel fuel tanks on an existing or new truck chassis with LNG tanks and fuel system components (i.e., vaporizer, pressure regulator, and other plumbing components), and either installing a new OEM natural gas engine or converting the existing diesel engine. This mechanical work is usually carried out by full-service truck or engine dealers, but a few OEM truck chassis dealers are showing interest in installing natural gas engines and LNG fuel systems as part of their new truck assembly process. LNG buses, on the other hand, are usually assembled by the bus manufacturer (i.e., with a natural gas engine and LNG fuel system).

At least six manufacturers currently sell heavy-duty natural gas engines (see Table 4-2 in Section 4). Approximately eight companies manufacture LNG fuel tanks and vehicle fuel system components. Various OEM transit and school bus companies are willing to sell factory-assembled and warranteed LNG buses (one, Gillig, is located in California). OEM truck companies have not been willing to do this in the past, but they are now showing an interest, and there are many full-service dealers willing to custom-install the required equipment.

Therefore, at this time, the availability of OEM-warranteed buses is good. The availability of LNG trucks, with the warranteed LNG engine and fuel system equipment installed by qualified truck dealers, is also good. Incremental costs (relative to counterpart diesel vehicles) depend on the quantity of vehicles purchased, their equipment, and other factors. To provide very approximate figures, the incremental price of LNG transit buses can be in the $30,000 to $40,000 range with quantity purchases, and the incremental price of a Class-8 tractor custom-fitted with an LNG engine and fuel system can be as much as $50,000. These prices are anticipated to decrease if and when the market develops and more sales are made.

An additional note is the LNG project currently underway, which is called the Interstate Clean Transportation Corridor (ICTC). The corridor will link West Coast locations (Las Vegas, Reno, Los Angeles, the San Joaquin Valley, Sacramento, San Francisco, and Salt Lake City) by providing LNG fueling infrastructures along the route to service approximately 800 heavy-duty and local delivery trucks.

5.3.5 Summary

LNG is better suited than CNG for very heavy-duty vehicles where range and payload are important, but CNG is best suited for most light-duty vehicles, and it is not yet clear which natural gas form is best for intermediate applications such as buses. Because LNG must be maintained at temperatures approximately 300°F below ambient, very specialized equipment and procedure are required (for both LNG vehicles and refueling facilities), but there doesn't appear to be any fundamental technology problems in this regard. Similarly, there does not appear to be any basic safety problems, but more research and pilot-project experience is needed to confidentially quantify LNG vehicle safety and risks.

LNG is available from a variety of highly motivated fuel suppliers, but long-distance transportation may be required for some locations. LNG vehicle equipment (engines, fuel systems, etc.) and LNG refueling stations are also readily available. While the current price of LNG is less than diesel fuel (on an energy-equivalent basis), the incremental price of vehicles and refueling facilities is high. Therefore, except in a few cases, the life-cycle costs of LNG vehicles are more than those for diesel counterparts, but this situation will change if and when a bigger market develops and/or emissions-based mandates or incentives are invoked.

SECTION 6

PROPANE

6.1 GENERAL DISCUSSION

6.1.1 Propane as a Motor Vehicle Fuel

There are far more propane vehicles in the United States than all other alternative fuel vehicles combined — estimates range up to 400,000, but no actual propane vehicle inventory exists. The propane used as a motor vehicle fuel is more properly called liquefied petroleum gas (LPG) because it is in fact a mixture of hydrocarbons (e.g., propane, ethane, butane) that are gaseous at ambient conditions but liquefy at moderate pressures. But, the more commonly used term is propane, which we will use throughout this section. Most motor vehicle fuel propane conforms to the "Propane HD-5" specification, which was developed by the Gas Processors Association (GPA) to determine the best commercial grade for propane HD-5 as a fuel suitable for internal combustion engines. Propane HD-5 is a varying mixture of such hydrocarbons as paraffins and olefins. The fuel's specifications define parameters for the amount of hydrocarbons and trace contaminants allowed to be present. Propane engines require a high paraffin content. Paraffins commonly found in propane HD-5 are ethane, propane, and butane, each of which have high octane value, allowing the engine to run without knocking. The remaining balance of the fuel is made up inert gases and olefins. The American Society for Testing Materials (ASTM) requires only 85-percent propane content. The specification stipulates that it must contain at least 90 percent propane (C_3H_8) by volume, and no more than 5 percent propene (which can form a gummy substance).

Propane is a non-renewable fossil fuel obtained from two resources, natural gas processing and crude oil refining. Propane does not pose environmental risk to water sources because of its volatility in air and insolubility in water. However, propane gas leaks can be extremely dangerous because propane is denser than air, and remains at ground level where it could combust. Propane gas may offer greenhouse gas reduction benefits in addition to the ozone formation benefits. Propane gas is a "clean" burning fuel because combustion produces only minor amounts of particulates and sulfur emissions.

The vapor pressure of propane at 70°F is 125 psia. This is the key to the economical storage of propane on a vehicle and at a refueling facility — it can be liquefied at ambient temperatures by pressurizing it to 25 to 250 psia, depending on the temperature. These pressures can be safely contained in simple thick-wall steel fuel tanks. This is in contrast to natural gas, for example, which must be pressurized to 3,000 psi and stored in reinforced tanks, or chilled to -260°F and stored in double-wall cryogenic tanks.

Propane has the highest energy density of all alternative fuels — approximately 83,000 Btu per gallon (based on lower heating value), depending on the constituents and pressure/ temperature, which is about 72 percent of the energy density of gasoline. Therefore, assuming equal thermal efficiency, a propane vehicle will have approximately 72 percent of the range of a gasoline vehicle if the fuel tanks are the same size, or it will have the same range if the propane vehicle's fuel tanks are about 40 percent larger. The octane rating of propane is significantly higher than gasoline, slightly higher than methanol and ethanol, but not as high as natural gas. Therefore, dedicated propane engines can operate at higher compression ratios to increase fuel economy and power, relative to gasoline engines. But on the other hand, the fact that gaseous propane displaces some of the air being processed by the engine limits peak power, so the maximum power level of propane engines is usually a little less than the maximum power level of gasoline engines (of the same size and type), particularly if they are dual fuel or not fully optimized for propane.

6.1.2 Infrastructure

Propane is produced as a byproduct of natural gas processing (approximately 60 percent) and petroleum refining (approximately 40 percent). Because so much propane production is associated with gasoline and diesel fuel production, some researchers and institutions do not classify propane as an "alternative" fuel.

Oil and gas wells produce a spectrum of hydrocarbons, and part of this spectrum is referred to as "natural gas liquids." The various natural gas liquids, including propane, are separated out by a process called "fractionation." From there, propane (plus the other light hydrocarbons contained in LPG) is transported by truck, railroad, or pipeline to propane sales and distribution centers. Propane has many uses in addition to its application as a motor vehicle fuel, e.g., for heating and cooking in rural areas where natural gas is not available, recreational vehicle appliances, and home barbecues. In fact, the so-called Propane Consumer's Coalition (which is primarily petrochemical companies that do not produce propane and must, therefore, buy it) has traditionally fought propane use as a transportation fuel because they are concerned that it would raise the price they pay for propane.

Propane can be purchased wholesale from distribution centers by fleet users with their own refueling stations, it can be purchased by fleet users at discounted prices from public-access refueling stations, and it can be purchased by the general public at retail prices from public-access refueling stations. The number of public-access propane refueling stations in the United States is variously reported as between 5,000 and 10,000 in the literature. There are approximately 700 public-access refueling stations in California set up to dispense propane in motor vehicles.

The basic elements of a propane refueling station consist of a propane storage tank, a transfer pump, metering and dispensing equipment, and a hose with a coupling which mates with the coupling on the vehicle fuel tank. A variety of coupling designs are used, and this sometimes creates an incompatibility problem.

It is important that propane vehicle fuel tanks not be filled beyond approximately 80 percent of their volume in order to allow room for liquid expansion if the temperature increases. The National Fire Protection Association (NFPA) Standard 58 requires that all propane vehicles have an automatic stop-fill device. This is usually a float-actuated valve, and there is controversy regarding the reliability of these devices.

California and some other states have not adopted NFPA 58. Propane vehicles in California use a device called an outage gage which is a small flow capacity tube, with a valve, which extends down to the 80 percent liquid level. This valve is opened during refueling, and refueling is terminated when liquid begins flowing from the valve. Most propane vehicles with automatic stop-fill devices also have outage valves. There are safety and emission issues associated with outage valve usage, and these will be discussed in subsequent sections.

6.1.3 Health and Safety Issues

Limited health data is available on propane and is therefore not documented in detail, however some safety issues overlap with health related issues discussed in this section. The relative safety of propane fueled vehicles is controversial. Propane proponents assert that it is a safe fuel, while proponents of other alternative fuels claim that it is not. An examination of fundamentals shows that there are factors that would make propane more safe, and factors that would make propane less safe, relative to other alternative fuels, gasoline, and diesel fuels.

Characteristics that make propane a relatively safe fuel include the fact that it is non-toxic and its flames have good luminosity (as compared to methanol), and it doesn't have to be stored at extremely high pressure or low temperatures (as compared to CNG and LNG, respectively). Propane advocates claim that, because propane vehicle fuel tanks have relatively thick-wall steel construction, they are much less prone to rupture and cause a fire in the event of a vehicle crash.

The main characteristics that makes propane relative unsafe is the fact that it is heavier than air — the weight of propane vapors at ambient temperatures is roughly 150 percent the weight of air. Therefore, in the event of a leak, propane vapors settle downward and form a flammable layer against the ground or floor (in contrast to natural gas which leaks upward and usually disperses if unconfined). The danger of propane leaks can be exacerbated because propane-air mixtures are flammable at only 2 percent concentration, and propane leaks are not obviously visible (in contrast with gasoline or diesel fuel leaks). To mitigate this last problem, propane is doped with an odorant (usually an ethyl mercaptan) to make leaks more detectable. Also, in some cases, propane is susceptible to contaminants such as hydrogen sulfide and moisture which can corrode metals and cause leaks.

Another possible source of propane leaks is the previously-mentioned outage valves, if they are used incorrectly during refueling. Various states and counties have different regulations affecting propane vehicle refueling stations, and some also have special safety restrictions on propane vehicle operations. For example, New York does not permit propane vehicles in tunnels, and Canada does not allow propane vehicles to be parked in enclosed garages.

6.1.4 Fuel Costs

It is difficult to be precise regarding the price of propane because its available purchase price depends on so many factors, such as: whether the purchase is at the wholesale (e.g., fleet) or retail level, the quantity being purchased, the timing relative to yearly and seasonal propane market fluctuations, the location within the United States, and the state tax treatment.

Historically, the pre-tax wholesale price of propane has been somewhat less than (e.g., typically 75 percent of) the price of gasoline, on an energy-equivalent basis (i.e., per Btu). Also, because propane production is associated with petroleum refining and natural gas processing, propane price fluctuations usually correlate with gasoline and diesel fuel price fluctuations, but there are occasional periods when they do not. On the average, since the early-1990s, the energy-equivalent price of propane has been increasing relative to gasoline prices, so that they are now more nearly equal.

Propane is available at significant discounts for vehicle fleet operators, from public-access propane refueling stations, and from bulk propane wholesalers (for fleets with their own propane refueling facilities). For example, a supplier estimated the price for 1,000-gallon propane deliveries at $0.65 per propane gallon which corresponds to approximately $0.90 per gasoline-equivalent gallon.

One reason that the price of propane is posted so high at public-access refueling stations is because these dealers usually also sell propane to fill barbecue grills, recreational vehicle appliance tanks, etc. Retail dealers require a substantial mark-up for these small-quantity sales, and they are reticent to post a large price differential for propane for these applications relative to vehicle refueling.

Propane is currently taxed as a liquid fuel: the combined Federal excise and energy tax is $0.183 per gallon, or approximately $0.25 per gasoline equivalent gallon (compared to the Federal gasoline tax of $0.18 per gallon). Therefore, on an energy-equivalent basis, propane is taxed more than gasoline, much more than CNG, slightly more than methanol and ethanol, but not as much as LNG.

States have many different taxation schedules from propane used as a motor vehicle fuel. California's tax (if the annual flat rate is not paid) is $0.04 per gallon, or approximately $0.055 per gasoline equivalent gallon.

6.1.5 Suppliers/Backers

Even though propane is the most-used alternative fuel, propane suppliers and backers have generally observed a "wait and see" strategy, and they are much less aggressive than CNG suppliers and backers, for example.

A variety of companies are involved in the propane supply infrastructure. In the United States, companies in the propane business include large integrated oil and gas companies (e.g., Conoco, Phillips), large national propane wholesalers/retailers (e.g., Amerigas, Suburban), and local independent propane suppliers (e.g., Mutual, Allied, and Coastgas in California). A separate category of companies also in the propane-fueled vehicle business are the vehicle equipment suppliers (e.g., Manchester for fuel tanks, and IMPCO for carburetor and fuel-injection systems) and vehicle conversion firms. There are and have been a few OEM propane vehicles, but the companies involved have not taken an aggressive position to promote propane relative to other motor fuels.

Propane interests have formed the first serious national-level organization to lobby for propane use as a motor vehicle fuel — the Propane Vehicle Council. In addition, various propane trade groups, such as the National Propane Gas Association, also have an interest in propane use as a motor fuel. The primary organization promoting propane vehicle fuel in California is the LPG Clean Fuels Coalition headquartered in Irvine. However, a group called Propane Consumers Coalition voiced concerns about increased transportation demands using a significant portion of the propane supply and causing increased prices for those existing propane consumers such as residential and petrochemical users. In response, the General Accounting Office (GAO), released a report (September 1998) entitled *Energy Policy Act Including Propane as an Alternative Motor Fuel will have Little Impact on Propane Market.* The report concludes that increased demand propane caused by EPAct requirements would not adversely effect existing propane consumers. Additional research conveyed that propane production is based on demand, and if the demand for propane due to transportation needs were to suddenly increase, the propane could be produced.

6.1.6 Fuel Availability

Propane is the most readily available of all alternative fuels — from 5,000 to 10,000 vehicle refueling stations in the United States, and approximately 700 stations in California. Almost 90 percent of all alternative fuel stations in the United States are propane stations. The fuel delivery infrastructure to provide propane to these stations is also well established and stable. Although there have been price fluctuations, propane has been readily available for many years, and its current availability is much better than that of any other alternative fuel.

The controversial issue is the future availability of propane if its use as a motor vehicle fuel should increase substantially. Some researchers observe that, because propane production is associated with petroleum refining and gas processing, and because there are already markets for propane (e.g., 52 percent is used for heating, 45 percent for industrial and other applications, and only 3 percent is currently used for motor vehicle fuel), then increased demand for propane will upset this balance. They conclude that either the price of propane would go up, or imports would have to increase above the current level of approximately 8 percent (net). Significant price increases would decrease the demand and make other alternative fuels more attractive. Increased fuel imports would defeat one of the main goals of an alternative fuel strategy for the United States and California.

Propane advocates suggest that potential availability problems are exaggerated, even if the demand for propane as a motor vehicle fuel significantly increases. They conclude that the potential exists for large production of propane for motor vehicles if the market and economics place a demand for the fuel to be produced. However, projections by the U.S. Department of Energy and some integrated energy companies show that a growth in propane demand would cause increased propane imports.

6.2 LIGHT-DUTY PROPANE VEHICLES

6.2.1 Vehicle Technology and Equipment

Light-duty propane vehicles are loosely defined here as vehicles whose counterparts use gasoline-fueled spark-ignition engines. The overwhelming majority of propane vehicles are in this category because spark-ignition engines are much easier to convert to propane than diesel (compression-ignition) engines.

There are two types of light-duty propane vehicles: dedicated, which operate exclusively on propane, and dual fuel, which can operate on either propane or gasoline.

The basic elements of a light-duty propane vehicle that differ from a gasoline vehicle are:

- The propane fuel tank and associated equipment (e.g., fill-coupling, over-pressure relief, outage gage)

- Propane fuel line, solenoid-operated shut-off valve, vaporizer and pressure regulator
- Either a propane carburetor or a fuel injection system

Propane carburetors (also called mixers) operate on the venturi principle and were used on propane vehicles from the 1920s through the 1980s, and they are still used on some vehicles (see Section 6.3, Heavy-Duty Propane Vehicles). With the advent of stricter emissions standards and electronic fuel injection systems on gasoline-fueled vehicles, similar technology has been developed for propane vehicles.

Computer-controlled propane fuel injection systems have been developed by specialty equipment companies such as IMPCO Technologies and GFI Control Systems, Inc., and by some vehicle original equipment manufacturers (OEMs) - e.g., Chrysler Canada, Ltd. These systems are quite sophisticated, and they incorporate a variety of technologies including throttle body or port injectors, open-loop or closed-loop (oxygen sensor) control, dual fueled or dedicated compatibility, air mass flow sensor or speed-density mixture control, and various diagnostics. This technology is analogous to natural gas fuel injection technology.

It should be noted that a majority of the propane vehicles in existence today were converted from gasoline and thus are not optimized. Many are dual fuel and perhaps rarely use propane.

6.2.2 Performance

The performance of propane-fueled light-duty vehicles is probably more similar to that of gasoline vehicles, relative to any other alternative fuel vehicles except methanol and ethanol FFVs. This is primarily because the range of propane vehicles is more than that of any other alternative fuel vehicles with the same size fuel tanks — approximately 72 percent of the range of gasoline vehicles.

The power of propane vehicles is usually slightly less than that of gasoline vehicles, particularly if they are dual fuel vehicles or they are not fully optimized for propane operation (e.g., increased compression ratio). This slight power loss is not usually a problem for light-duty vehicle fleet operators. Propane advocates assert that, because propane is so clean-burning, propane-fueled vehicles have substantially decreased maintenance requirements (e.g., more miles between oil changes and spark plug replacement) and increased engine durability. Some fleet users confirm reduced operating costs due to these factors.

6.2.3 Emissions

Emissions testing of light-duty propane vehicles has been limited, in spite of the relatively large number of propane vehicles in use in the United States. This is partially because no U.S. OEMs currently manufacture a light-duty propane vehicle (as will be discussed in Section 6.2.4, Availability and Costs). Therefore, the great majority of propane vehicles are conversions of gasoline vehicles (usually dual fuel, but sometimes dedicated) using aftermarket propane equipment.

Emissions reduction has not been a reason for converting vehicles to propane until recently. Early generation conversion equipment was not designed with reduced exhaust emissions as a key goal. More recent propane fuel injection systems, however, do include many features to minimize emissions.

Prior emissions testing of converted propane vehicles has produced somewhat mixed results. In some cases, substantial improvement over gasoline vehicles was shown, but other cases show worse results. Recent results of emissions tests conducted by propane fuel injection system manufacturers show reductions in non-methane hydrocarbons, CO, and NO_x emissions, relative to the counterpart gasoline vehicle. For example, GFI Control Systems anticipates that a

1995 Ford Contour will meet 1995 California ULEV emissions standards when equipped with their propane system. Fundamentals would suggest that the exhaust emissions of propane vehicles can be lower than those of gasoline vehicles, but probably not quite as low as those of natural gas vehicles (assuming that HC emissions are measured as non-methane HC in all cases).

A significant source of propane vehicle hydrocarbon emissions is the refueling operation when the previously described outage valve method is used. In fact, the new EPA procedures will require propane vehicles to meet the same evaporative and refueling emissions standards as other vehicles. This will preclude future use of outage valves, and it will limit the propane refueling coupling deadspace to 2 cm^3. Propane vehicle advocates say that this will be no problem because automatic stop-fill devices work well, although they are not yet commonly used in California.

EPA and CARB rules affecting vehicle conversions are complicated. As previously mentioned (Section 4.2.3), the emissions performance of retrofit (aftermarket conversions) has been a long-term issue for EPA. The Clean Air Act §203(a)(3) defines a prohibited act as any time person removes or renders inoperative any device or element of design installed on a motor vehicle engine. EPA published a policy document, MEMORANDUM 1A, in June of 1974 that provided a basis for aftermarket convertors to know whether or not their conversion could be defined as a prohibited act. This guidance was often ignored and EPA published two more addendums to this original policy. One was published in September of 1997 and the most recent in June of 1998. In summary, the EPA policy for conversion of any vehicle or engine is that data must exist showing that the process of conversion did not cause any adverse effect on the emissions of the vehicle. If, the vehicle was a dual-fuel vehicle, data must be generated on both fuels. In those cases where the engine family being converted is a California only engine family, EPA has allowed the CARB to make some decisions separate from EPA policies.

Also, conversions must be certified by EPA or their emissions performance cannot be guaranteed. In recent DOE and other studies, converted propane vehicles often have higher emissions than the gasoline counterpart. It is challenging for aftermarket conversion entities to convert vehicles originally designed to operate on gasoline to operate on any other fuel. EPA currently handles aftermarket conversions under the tampering policy (Memorandum 1A), unless the conversion is intended to generate emission reduction credits in which case the whole converted vehicle must be certified as a new vehicle. CARB previously "approved" certain retrofit conversion equipment (executive orders defined the conversion equipment application), but CARB is transitioning to a procedure involving conversion equipment certification for specific engine families (which requires emissions and durability testing). For example, CARB Executive Order B-16-13 approves the previously mentioned GFI Control Systems propane fuel injection system for seven 1995 engine families.

Analyses indicate that the overall fuel-cycle carbon emissions for propane vehicles usage is slightly less than those for gasoline vehicles. However, these should decrease as new refueling practices (without using outage gages) are adopted. Also, an accurate assessment of propane fuel-cycle emissions is difficult due to the ambiguity of how to allocate emissions at the gas processing or petroleum refining stage.

6.2.4 Availability and Costs

No OEM in the United States currently offers a light-duty propane vehicle for sale. Ford did offer a propane Granada from 1982 to 1985, however. Chrysler also previously produced a few propane vehicles. Ford recently produced some propane-fueled Crown Victoria sedans on an experimental basis for taxicab companies, and some of these are currently used by Yellow Cab in Las Vegas. Chrysler Canada Ltd. plans to produce and test some prototype full-size dedicated-propane Dodge Ram vans and wagons with 5.2-liter V-8 engines in 1995, and to sell these propane vehicles commercially (in Canada only) in 1996. News reports indicate that Ford will market a propane-fueled light-duty pickup truck in the United States in 1996.

As previously discussed, most light-duty propane vehicles are conversions of gasoline vehicles using aftermarket equipment. Conversion of a light-duty vehicle from gasoline to propane costs about $1,000 to $2,000, but this cost will probably increase as conversion equipment is becoming more sophisticated (e.g., electronic-controlled fuel injection) to be compatible with newer car equipment and to meet CARB certification requirements.

6.2.5 Summary

Propane is used to fuel more light-duty vehicles than all other alternative fuels combined. It is a relatively economical and convenient fuel, i.e., it costs a little less than gasoline when purchased wholesale, it has a high Btu content which translates into relatively good vehicle range, and the equipment required for propane conversion is much simpler than that required for CNG and LNG (but not as simple as that required for the liquid fuels methanol and ethanol).

Propane use can provide emissions reductions, but not to the extent of some other alternative fuels. Because propane is produced in association with petroleum refining and gas processing, there is some question as to whether propane is actually an "alternative" fuel, and there is concern regarding propane's price and availability if its demand as a motor fuel were to increase dramatically.

6.3 HEAVY-DUTY PROPANE VEHICLES

6.3.1 Engine Technology and Equipment

The heavy-duty vehicle category as loosely defined here includes all highway vehicles larger than light-duty passenger cars, vans, and pickup trucks. Most, but not all, vehicles in this heavy-duty category are normally equipped with diesel engines. Also, for most, but not all, of the vehicles in this category, the chassis is manufactured by a company separate from the company that manufactures the engine (particularly if it is a diesel engine). Therefore, this discussion will focus on propane engines produced by diesel engine manufacturers, and heavy-duty spark-ignition propane engines produced as part of a partial or complete vehicle package. The most noteworthy vehicle package in the latter category is the Ford F600 and F700 propane trucks, to be discussed subsequently.

Like most other alternative fuels, propane has a low cetane rating (i.e., it is difficult to compression-ignite), and this makes it a very difficult fuel to use in diesel engines. The technologies available to use propane in diesel engines include: conversion to spark-ignition, pilot-ignition or fumigation, and modification of the engine to permit direct-injection and compression-ignition. These technologies have been developed more for application of alcohols and natural gas than propane in diesel engines, and so more comprehensive discussions are contained in Sections 2, 3, 4, and 5 (Methanol, Ethanol, CNG, and LNG).

In summary, propane engines for heavy-duty vehicles can be of two distinct types, and each type can be manufactured in two ways:

- Heavy-duty spark-ignition gasoline engines with relatively minor modifications for propane operation
  - — Provided by an engine and chassis OEM (e.g., Ford F700)

— Conversion using aftermarket equipment (e.g., IMPCO Technologies' HD AFE system)

- Diesel-engine-derived heavy-duty propane engines

  — Provided by an engine OEM (e.g., DDC 50G)

  — Conversion using aftermarket equipment (e.g., Vinyard Engine Systems kit)

6.3.2 Performance

Reliable performance data for heavy-duty propane engines and vehicles is sparse, particularly for converted diesel engines. For the Ford 7-liter propane engine (which is a good example of an OEM-converted heavy-duty gasoline engine), factory test data shows about a 20 bhp loss (out of 210 bhp) at 3,000 rpm, but the propane engine is also rated at a higher rpm than the gasoline engine (3,500 rpm versus 3,000 rpm) in order to produce an equal power output. Propane fuel consumption test data is not available, but it is anticipated to be nearly the same as the gasoline engine, on a Btu-equivalent basis.

Fundamentals would suggest that heavy-duty propane engines derived from diesel engines would have similar power, but lower Btu-efficiency, relative to the baseline diesel engine.

Vehicle range is another performance issue. Heavy-duty propane vehicles, like light-duty propane vehicles, have driving ranges which are more than other alternative fuel vehicles, but less than gasoline or diesel-fueled vehicles, for equal-size fuel tanks. There are minor additional variations in relative driving range associated with the differences in Btu-equivalent fuel efficiency.

Fleet users report good durability and low maintenance costs for propane trucks, particularly as compared with gasoline trucks.

6.3.3 Emissions

Heavy-duty propane engines and vehicles generally have lower emissions than heavy-duty gasoline and diesel engines and vehicles, although the comparisons with gasoline and diesel emissions are somewhat different. Relative to diesel engines, propane-fueled heavy-duty engines can simultaneously achieve much lower particulate and NO_x emissions, although these emissions are anticipated to be not quite as low as those achievable with natural gas and methanol. The low particulate emissions of heavy-duty propane engines are especially relevant, because particulates are so visible and because recent research indicates that they are carcinogenic.

Heavy-duty gasoline engines converted to propane have also demonstrated lower exhaust emissions. For example, Ford test data indicates that their 7-liter propane truck engine will meet the 1998 California and Federal emissions standards for gasoline-fueled trucks over 14,000 pounds GVW (all data in g/bhp-hr):

	HC	CO	NO_x
Standard	1.9	37.1	4.0
Ford 7-L manual	0.53	20.54	2.84
Ford 7-L automatic	0.47	23.18	2.62

As another example of heavy-duty propane vehicle emissions, identical Orange County (California) Transit buses were equipped with experimental methanol, CNG, and propane engines, plus a diesel engine (all based on the Cummins L-10). Chassis dynamometer emissions tests indicated that the propane bus had the lowest emissions, and another bus with Caterpillar 3306 propane engine had even lower emissions.

6.3.4 Availability and Costs

A small variety of heavy-duty propane engines, vehicles, and conversion is available. Additionally, some OEMs are engaged in heavy-duty propane engine development projects.

The most significant OEM effort in this regard is Ford's commercially-available F600 and F700 dedicated propane trucks. These trucks use a simple IMPCO propane carburetor, EGR, a thermactor, no catalyst, and they are EPA- and CARB-certified. The buyer must add a permanent propane fuel tank. The "propane option" has a small incremental cost, but Ford has estimated that, with the Energy Policy Act of 1992 tax deduction provisions, the net cost of a propane truck is less than the cost of a gasoline truck.

GM has also produced "propane-ready" pickups, vans, and suburbans which required installation of fuel tanks, etc., subsequent to delivery. The incremental price from GM was reported to be $125 for these vehicles, although up to $1,000 additional would have to be added for post-delivery work.

A variety of diesel engine manufacturers are developing heavy-duty propane engines, but Caterpillar's 250-hp 3306 is the only propane engine in this category that is commercially available in the United States at this time. Caterpillar is developing a propane truck engine using sophisticated direct-injection technology, Detroit Diesel is reportedly developing a propane-fueled version of their Series 50 engine (which is commonly used for transit buses), and Cummins has developed and demonstrated propane-fueled L-10 engines on an experimental basis. Various European companies have also developed heavy-duty propane engines.

Heavy-duty propane engines also can be produced from gasoline and diesel engines using equipment available from companies such as IMPCO, GFI Control Systems, and Vinyard Engine Systems.

6.3.5 Summary

One OEM "light" heavy-duty propane vehicle series is well developed, certified, and commercially available: the Ford F600 and F700 trucks. Other OEMs also offer propane-ready "light" heavy-duty vehicles which are based on gasoline vehicles. In addition, aftermarket equipment is available to convert large gasoline engines to propane operation. There are a significant number of propane vehicles in this category (i.e., based on larger gasoline engines and vehicles) because the technology is straightforward, and the operators can sometimes realize economic benefits from the gasoline-to-propane price differential and EPACT tax deductions.

Use of "heavy" heavy-duty propane engines (e.g., in line-haul Class 8 trucks) is much less common, because the propane engines must be based on diesel engines, and this technology is not as straightforward. However, development work is in this area by diesel engine manufacturers is underway, and aftermarket conversion equipment is available.

Heavy-duty propane engines have potentially lower emissions than counterpart gasoline and diesel engines, and realization of this potential has been proven by tests in a few cases. However, as is the case for light-duty propane vehicles, key issues are the question of whether propane should be considered an "alternative" fuel, and the price and availability of propane if the demand increases substantially.

SECTION 7

HYDROGEN

7.1 GENERAL DISCUSSION

7.1.1 Hydrogen as a Motor Vehicle Fuel

Hydrogen has the potential to be the cleanest alternative fuel available for use in an internal combustion engine. It can be produced from a variety of feedstocks through several different processes. If it is derived from non-fossil fuel sources such as biomass, water, or photovoltaic cells (PV) it can be entirely renewable, and should produce virtually no tailpipe emissions other than NO_x when burned in an internal combustion (IC) engine. If produced by clean processes such as solar-water electrolysis, hydrogen will result in no net carbon emissions and only small amounts of greenhouse gas emissions. Presently hydrogen is made from natural gas through steam reformation, which produces carbon monoxide as a byproduct and could have an environmental impact effecting total carbon emissions. PV components used to generate hydrogen require raw material production (mining, drilling for petroleum, and/or harvesting), material processing (smelting and polymerization), and manufacturing (fabrication and assembly).

Unfortunately, hydrogen is still the farthest from commercialization of all alternative fuels. Although hydrogen vehicle fuel research has been conducted for over 100 years, there are still many obstacles that prevent it from being a practical vehicle fuel. It has the lowest heating value per volume of all combustion fuels (i.e., gasoline, natural gas, propane, and alcohols).

What this results in is lower vehicle range and bulkier storage on the vehicle. Hydrogen can be stored as a compressed gas (CH_2) at 3,000 to 4,000 psi or higher, as a cryogenic liquid (LH_2) at -423 °F, or as a solid bound in metal hydrides. Compressed hydrogen can be stored at higher pressures than natural gas because it does not suffer from the loss of effective storage at higher pressures due to molecular dimensions. These storage methods increase the energy density of the fuel, but still provide only a fraction of the energy storage allowed with gasoline, or even natural gas, while increasing the weight of the overall vehicle fuel system. More advanced storage techniques, such as higher pressure tanks, or hydrogen adsorption on activated carbon, are being explored.

7.1.2 Hydrogen Description

Despite hydrogen's promise of being such a clean fuel, many of its properties prevent it from being seriously competitive with gasoline or even natural gas, until a more satisfactory storage method is developed. Hydrogen is usually stored on-board a vehicle as a compressed gas in cylindrical tanks at 3,600 to 4,000 psi, as a cryogenic liquid in heavily insulated tanks at -423 °F, or bound in a metal-hydride powder. Because hydrogen is the lightest of all elements, H_2 has an energy/mass ratio (e.g. Btu/lb) higher than any other fuel, but an energy/volume ratio (e.g. Btu/ft^3) lower than any other fuel (about $^1/_3$ that of natural gas). Therefore, it is difficult to store enough hydrogen on-board a vehicle to provide the same energy and vehicle refueling range as gasoline. Consequently, hydrogen vehicles have either much shorter range than gasoline vehicles, or their fuel tanks take up much more space on the vehicle, or both. The range versus tank size problem is even worse than that for CNG and LNG vehicles (discussed in Sections 4 and 5). More advanced techniques of storing hydrogen as an adsorbent on activated carbon material are still in the early research phase.

7.1.3 Infrastructure

While hydrogen does have many industrial applications, for example as a chemical analytical gas or as an additive to natural gas (a practice employed in Germany), and has long been used as a rocket fuel by NASA, there is virtually no fueling infrastructure to speak of for motor vehicles. A few select research institutions and automotive research laboratories have their own private fueling stations, however, these are few and far between, and are not publicly accessible. Germany has extensive pipeline networks which have been used to distribute hydrogen since World War II. It has been speculated that hydrogen could be transported through existing natural gas pipelines in the U.S., but this may not be possible depending on what material the pipeline is made of. Because hydrogen is the lightest and smallest element, it has the ability to permeate surfaces that are impenetrable to most gases or liquids, including natural gas and air. Hydrogen exists most stably as a diatomic molecule, however, if provided with enough energy, it can dissociate to atomic hydrogen. Hydrogen atoms are small enough to permeate a metal surface and enter the metal lattice. This can cause structural damage to the metal, known as hydrogen embrittlement. The result is that the metal loses ductility and eventually fractures, resulting in a fuel leak. Highly alloyed stainless steels are generally resistant to such embrittlement, and could be used for hydrogen pipelines. Research on hydrogen distribution is focusing on finding an additive that can inhibit hydrogen embrittlement, so that hydrogen could be shipped in existing natural gas pipelines. Hydrogen can also be transported in liquid form. Cryogenic hydrogen is shipped in 13,000 gallon tankers, 35,000 gallon rail cars, or in vacuum-jacketed pipelines. The latter method can only be used for very short distances, and is only feasible for large-volume end-users such as airports. For the near-term, shipping hydrogen as a liquid in tankers will probably be more practical, since it will be easier to initiate such a system, as the vacuum tanker technology is already available. However, this would require stations to install LH_2 dears in order to store the hydrogen until it needs to vaporized (if it does indeed need to be vaporized). There would also be the added high costs of liquefaction versus compression. A gaseous hydrogen pipeline network may be more practical for the long-term, but will require a much longer time frame to lay the system in place such that it could provide service to a wide area such as the South Coast Air Basin or the Sacramento Valley Air Basin.

Experimental LH_2 refueling stations have been run in Germany by Messer-Griesheim, and in the U.S. at Los Alamos National Laboratory (LANL). Both of them employ clean break coupling systems for trouble-free fueling. At the LANL station, the operator simply connects the hoses, presses a "start" button, opens the vehicle tank valves, and fueling begins. A 32 to 40 gallon tank can be filled in 5 minutes or less. The Messer-Griesheim station is fully automatic, requiring no manual opening of valves. Boil-off gas is recovered through a second hose.

7.1.4 Health and Safety Issues

The real health danger from liquid (cryogenic) hydrogen (LH_2) is from the extreme cold temperatures of the fuel. Human skin can be easily frozen and torn if it comes into contact with surfaces or liquids maintained at sub-zero temperatures. Spills of LH_2 are not as much of a fire concern as they are a frostbite concern. If a spill of LH_2 were to occur, frostbite would be a more immediate concern than fire if the fuel spilled on the accident victim, although the likelihood of this is not great, given the location of the fuel tank with respect to the passenger. This is not to say that an LH_2 spill would not be a fire hazard, but the fire risk would diminish with time much faster than with LNG, propane or gasoline, since LH_2 has a higher evaporation rate than these other fuels.

The greatest safety concerns with hydrogen are fire and explosion. The fuel properties that make hydrogen such a safety concern are its wide flammability and detonability limits (4 to 75 percent and 18.3 to 59 percent by volume in air respectively), its high diffusion and buoyant velocities (2 cm/s and 1.2-9 m/s respectively), and its invisible flame. It is not generally considered a health hazard, since it contains no toxic or carcinogenic components, and the combustion products are only water vapor and NO_x. It is true that hydrogen is a fire hazard (as is any automotive fuel), because of its ability to leak due to embrittlement (mentioned above), and especially due to its wide flammability limits, as stated above, compared with 5.3 to 15 percent for natural gas, or 1 to 7.6 percent for gasoline. However, the lower flammability limit is usually the area of concern, since this is the concentration that will be attained first. Hydrogen's lower flammability limit of 4 percent by volume in air is higher than that for propane (2.1 percent) or gasoline (1 percent), which means that a greater concentration of hydrogen must accumulate in an enclosed area to form an ignitable mixture. However, since gasoline is a liquid at ambient temperatures and evaporates slowly, it is not likely that an ignitable vapor mixture will form, unless there is no ventilation. If there are no sources of ventilation, then it is quite possible that an ignitable vapor mixture of hydrogen could form, even an explosive mixture (at 18.3 percent) since hydrogen will quickly disperse to all parts of the enclosure. However, even the smallest vent is usually sufficient for hydrogen to escape, since it is very buoyant and evaporates so quickly. Natural gas is very similar to hydrogen in this respect. A study done at the University of Miami explored the formation of combustible fuel vapor clouds by hydrogen, natural gas, and propane leaks from a kitchen stove. The study showed that hydrogen and natural gas simply diffused straight up and out through the small vent over the stove, whereas propane formed a heavy combustible cloud that filled the kitchen. Because of hydrogen's high buoyant and diffusion velocities, it rapidly evaporates if spilled, and thus does not remain a fire hazard in open areas, as opposed to propane and gasoline, which are non-buoyant and will remain a fire hazard if spilled until they are removed. Propane, as noted, will form a heavy combustible vapor mixture, and gasoline will remain as an ignitable pool on the ground. In addition, hydrogen fires, unlike gasoline fires, are non-toxic and non-carcinogenic. The invisible flame is a problem that hydrogen shares with neat methanol. Suggested solutions to this have been non-toxic fuel additives or fuel tank coatings that would burn and lend color to the flame.

Cryogenic hydrogen does present some real safety hazards. The tanks themselves are not the concern, as cryogenic hydrogen tanks are well equipped with pressure relief devices to vent high pressure hydrogen which boils off inside the tank. Venting this gas only presents a real fire danger in a completely enclosed area. BMW has thoroughly crash tested their cryogenic tanks, and they have proven to be extremely safe. They have even improved the insulation on their tanks, such that a vehicle can be driven as little as two times a week with hardly any boil-off.

7.1.5 Suppliers/Backers

Support for hydrogen is still primarily at the research level, with funding coming largely from the DOE and the South Coast Air Quality Management District. Most research grants go towards national laboratories and universities. In Japan, the Ministry of International Trade and Industry is working on a global system of hydrogen transport and utilization, known as the World Energy Network (WENET).

There is little corporate support for hydrogen in the U.S., since there is not much profit to be gained from the sale of hydrogen in energy markets. In Canada, Electrolyser Corporation is an advocate of hydrogen, manufacturing solar-water electrolysis cells for hydrogen production. Perhaps the most corporate support for hydrogen lies in Germany, where research is backed by

Daimler-Benz AG, BMW AG, MAN, and Messer-Griesheim, a supplier of liquid hydrogen and developer of LH_2 refueling systems. Mazda Motor Corporation of Japan has undertaken a joint venture with Nippon Steel which produces hydrogen for making sheet steel. Nippon Steel has been providing Mazda with hydrogen since 1992 for their hydrogen version of the Mazda Miata (MX-5).

Colorado-based Hydrogen Consultants, Inc. (HCI) have developed a mixture of hydrogen and natural gas, called Hythane®, which is composed of 15 percent hydrogen by volume (5 percent energy content) and 85 percent natural gas by volume (95 percent energy content). HCI has tested a Chevy S-10 pickup converted to run on natural gas. The objective of the Hythane research was to find a near-term hydrogen technology that would provide leveraged benefits over pure hydrogen and pure natural gas. Preliminary test results show improved engine efficiency and power over natural gas and hydrogen vehicles, with both parameters improving with increasing hydrogen content. The addition of hydrogen allows for leaner combustion and reduced emissions of incomplete combustion products (CO and HC). In time, the hydrogen content can be increased to provide a cleaner, more renewable fuel. There is a marginal benefit on pre-catalyst NO_x emissions with up to 15 percent hydrogen by volume, but at greater than 15 percent hydrogen, pre-catalyst NO_x emissions increase at wide-open throttle. In 1992, HCI opened the first dedicated Hythane refueling station in Denver. Support for the Hythane project has come from the Urban Consortium, Air Products and Chemicals, Public Service Company of Colorado, Natural Fuels Corporation and the DOE.

7.1.6 Fuel Availability

Hydrogen, being the most abundant element on earth, is available from several different sources. It can be produced from any hydrocarbon molecule by a process known as cracking, to produce carbon and hydrogen, or, in the case of natural gas, by steam reformation. Steam reforming of natural gas produces carbon monoxide as a byproduct. Hydrogen can be produced from coal or biomass by gasification, which produces carbon dioxide as a byproduct. The cleanest method to produce hydrogen is through electrolysis of water to produce hydrogen and oxygen. Water can be electrolyzed by any of the following ways: (1) by applying a current to a water/electrolyte solution, (2) by thermochemical decomposition, (3) by high temperature steam electrolysis, or (4) by photolysis which employs light and a chemical similar to chlorophyll to remove the hydrogen. Coal gasification is likely to have negative environmental impacts due to coal mining, CO_2 emissions, and waste disposal of carcinogenic tars and residues. Currently, steam reformation of natural gas is the most economical method of hydrogen production, but this would not be considered a renewable feedstock. Biomass gasification will probably be the least expensive renewable process for the near- and mid-term. Some researchers expect solar-water electrolysis to become competitive with natural gas steam reforming in the early part of the 21st century.

7.1.7 Fuel Costs

Current hydrogen prices can be anywhere from 7 to 10 times higher than LNG or petroleum fuels. This price is of little relevance, however, since hydrogen is not actively sold as a fuel commodity. Attempts at predicting hydrogen fuel costs at this point are largely speculative, since it is not yet produced commercially as a motor vehicle fuel, and many of the hydrogen production techniques are in a state of rapid advancement, which could bring costs down significantly from their current levels. Any cost figures reported here are estimates, and should be viewed as such. For the near term, and most likely for the mid-term as well, it is highly improbable that hydrogen will be commercially competitive with fuels like natural gas, propane, alcohols, RFG, or diesel. A 1989 study performed by M. DeLuchi (University of California, Davis) estimates hydrogen prices in gasoline gallon equivalents (prices are estimated in 1985 US$) for coal gasification and solar-water electrolysis. From coal gasification, hydrogen prices range from $1.50 to $5.00 per equivalent gasoline gallon, whereas hydrogen from solar-water electrolysis ranges from $3.50 to $14.00 per equivalent gasoline gallon. Even this number is unjustly low, since the study assumes that electricity costs will be significantly lower than current levels. Photovoltaic hydrogen's high cost is due in large part to high module costs and poor module efficiency. The goals are to reduce module costs by 88 percent, to improve module efficiency up from 5 percent to 12-18 percent, and to bring the final price per equivalent gasoline gallon down to approximately $2.00. However, this is still a long time in the future. A study by J.M. Ogden (University of California, Davis) projects hydrogen costs out beyond the year 2000. Ogden predicts that biomass-hydrogen can be produced at a total delivered cost of $1.60 to $1.90 per equivalent gasoline gallon, whereas solar-hydrogen would range from $2.50 to $3.60 per equivalent gasoline gallon.

7.2 LIGHT-DUTY AND HEAVY-DUTY VEHICLES

7.2.1 Vehicle Technology and Equipment

German companies, Mercedes-Benz, BMW and MAN, and the Japanese auto maker, Mazda, have undertaken the most aggressive research of hydrogen vehicle technology. This research is partially motivated by the possibility of using hydrogen vehicles to satisfy California's ZEV mandate. Light-duty applications have included various sizes of passenger cars (including station wagons) and delivery vans. A heavy-duty hydrogen transit bus is also under development by MAN.

The above original equipment manufacturers (OEMs) projects have successfully demonstrated the adaptability of conventional internal combustion automotive engines to hydrogen fueling. Hydrogen vehicle technology has been able to apply some of the same gaseous fuel system and fuel storage technology advances being developed for CNG and LNG vehicles. Several previous significant concerns regarding hydrogen's internal combustion engine adaptability, including fuel mixture pre-ignition and backfire, and engine power loss, appear to have been largely resolved in the German and Japanese vehicle demonstrations, although compensating for power loss is still necessary to maintain gasoline engine power output. Mazda's rotary engine technology looks to be especially effective at overcoming unsatisfactory engine operating conditions and resulting vehicle driveability problems commonly associated with hydrogen combustion, although advanced fuel injection system designs adapted to hydrogen have also been effective at overcoming such problems as preignition in conventional piston engines.

One of the major technical issues for hydrogen-fueled vehicles is on-board energy storage capacity and range. Hydrogen gas, even when compressed to the high pressures (e.g. 4,000 psi) allowed by current gaseous fuel storage cylinder technology, has only 1/10 or less the energy density per unit volume as gasoline. Thus, a vehicle running on compressed hydrogen gas would require ten times or more as much on-board fuel storage volume to have the same refueling range as a gasoline vehicle, or with triple the fuel storage volume of a gasoline vehicle, would have only one-third or less of the gasoline vehicle's refueling range. With the advent of "metal hydride" storage media, used by both Mercedes-Benz and Mazda, more hydrogen can be stored within the same space with the same pressure, allowing about a doubling of energy storage density of conventional compressed hydrogen tanks, but still representing only about 20 percent of the range of a gasoline vehicle. A typical compressed hydrogen vehicle can travel 100 miles between refueling events. Liquefied hydrogen storage, such as employed by BMW, requires the use of double-wall, vacuum super-insulated tank technology to maintain the low liquid temperature (-423 °F), allowing somewhat greater energy storage density than metal hydride storage, but still only about one-fourth of gasoline storage density. BMW's 745i model can store between 10 and 12 equivalent gasoline gallons, allowing it to achieve a range of 250 miles.

7.2.2 Performance

The biggest challenges facing hydrogen vehicle developers are achieving a driving range and acceleration comparable to that of a gasoline vehicle. Hydrogen suffers loss of range due to hydrogen's low energy per unit volume, as previously discussed. Because hydrogen is so light and bulky to store, it is difficult to store enough hydrogen on-board a typical passenger vehicle to provide the range of an equivalent gasoline vehicle. Overall, the fuel efficiency of a hydrogen vehicle, is comparable to that of a gasoline vehicle. Fuel economy is a function of the difference in weight and thermal efficiency between the vehicles. The weight differences result from differences in emission control systems, engine components and fuel storage systems. The thermal efficiency, which is a ratio of the work output over the heat supplied by the fuel, is even better, being 15 percent higher than that of a gasoline engine. This is due to hydrogen's ability to combust well in a lean mixture (excess air).

Engine power in hydrogen vehicles is lower than that of gasoline and all other alternative-fueled vehicles having the same engine displacement because of the lower volumetric heating value of hydrogen air/fuel mixtures. Gaseous hydrogen displaces more air in the combustion chamber than does gasoline, thus it has a lower charge density, causing a power loss of around 30 percent. Liquid hydrogen results in less power loss, because it displaces less air than does gaseous hydrogen. Some LH_2 vehicles actually show a slight increase in power over their gasoline counterparts.

Another problem experienced by hydrogen vehicles is preignition and backfiring. Because hydrogen's ignition temperature is an order of magnitude lower than gasoline's, hot surfaces or oil in the combustion chamber can prematurely ignite the charge, which causes backfiring into the intake manifold. Backfiring can lead to destruction of the entire fuel system. More advanced fuel delivery systems have been developed to overcome this problem.

7.2.3 Emissions

Limited emissions testing of hydrogen vehicles confirms the potential for achieving the lowest emissions levels of any combustion engine/fuel technology. Nevertheless, despite occasional references to "only water vapor" being emitted from hydrogen engines, there are emissions that require controls — primarily NO_x, and possibly traces of hydrocarbons from engine oil consumption. The UC-Riverside experimental hydrogen truck has been emission tested on a U.S 75 Federal Test Procedure. Baseline testing results before optimization (without a three-way catalyst) are shown in Table 7-1.

Mazda has indicated its belief that it may be able to establish low enough emission levels from its rotary engine hydrogen vehicles to qualify for consideration as "zero emission vehicles" under CARB's ZEV standard. This would presumably involve demonstrating that the hydrogen vehicle emissions would be no greater than emissions from electric power generation for electric vehicle charging, since EVs are currently considered the only ZEV option. Aside from the small amount of emissions from engine oil consumption, hydrogen-fueled vehicles would not directly emit (fuel-based) carbon emissions.

Table 7-1. Results of baseline emission testing at CARB

Measured Concentration			CARB Standards		
Pollutant	UCR Dodge RAM	Hythane Vehicle	TLEV	LEV	ULEV
CO	0.0 g/mile	0.7 g/mile	3.4 g/mile	3.4 g/mile	1.7 g/mile
NMHC	0.0	0.01	0.125	0.075	0.04
NO_x	0.37	0.2	0.4	0.2	0.2

Although vehicular emissions will be almost negligible, the entire hydrogen fuel cycle could contribute total carbon emissions comparable to natural gas-based fuel cycles, if natural gas or coal remains the feedstock. Even with the most advanced technologies, coal gasification plants emit large amounts of SO_x and NO_x, as well as other harmful, though unregulated, pollutants, such as carcinogenic polycyclic aromatic hydrocarbons. Coal gasification systems also emit large quantities of greenhouse gases, which are becoming more and more of a concern. On the other hand, if solar energy or another renewable form of energy is used to produce hydrogen from water, total net carbon emissions from hydrogen fuel use could be negligible.

7.2.4 Commercial Availability and Costs

Currently, no hydrogen vehicle model has yet been introduced in the international automotive marketplace. However, the previously mentioned R&D programs have produced experimental vehicles. The most extensive on-road demonstration of hydrogen vehicles to date has been conducted in Germany. Mercedes-Benz conducted a four-year fleet demonstration of ten hydrogen vehicles — five 280TE model station wagons and five 310 model vans — in Berlin from 1984 to 1988, accumulating about half a million miles of operation. The vans were dedicated gaseous hydrogen vehicles, while the station wagons employed a combination fuel system that allowed use of hydrogen/gasoline mixtures. Mercedes-Benz has demonstrated other individual hydrogen vehicle models as well, including a 230E model hydrogen research vehicle shown in Washington, D.C. in 1989. BMW's hydrogen vehicle development activities have concentrated on LH_2 fueling and have resulted in operation of at least three experimental vehicles, including a 520 model and two 745i models. BMW reports a 250 mile range on hydrogen, which is better than twice the most efficient electric vehicle. BMW also has a dual fueled 7 series model that can go back and forth between hydrogen and gasoline operation with the flip of a switch. Mazda has conducted hydrogen engine research with both conventional piston engines and with its rotary engines, testing and exhibiting several hydrogen vehicles including an experimental hydrogen-fueled, rotary engine-powered Miata. Mazda has discussed a possible U.S. hydrogen vehicle demonstration program that could begin by 1995. The German bus manufacturer MAN is developing a heavy-duty, hydrogen-fueled transit bus scheduled to begin an on-road demonstration in 1995. Incremental costs of hydrogen vehicles will probably be somewhat more than those of natural gas vehicles, since the fuel storage systems are similar, but the engines require more modifications relative to gasoline and diesel engines. Incremental costs for natural gas vehicles range from $4,000 to $5,000 for CNG passenger vehicles, and $20,000 to $50,000 for LNG heavy-duty trucks and buses.

7.2.5 Summary

Of all alternative fuels, hydrogen has the lowest tailpipe emissions, and may even have lower total fuel-cycle emissions than electricity produced for EVs. While hydrogen shows great promise in reducing vehicular tailpipe emissions to (or near) ZEV levels and increasing the thermal efficiency of internal combustion engines, the major inhibitors to hydrogen vehicle commercialization are cost, bulky storage, reduced power, and lack of fuel production, distribution and refueling infrastructure. Safety issues and engine backfiring issues appear to be largely resolved. Public acceptance of shortened range and loss of space in the vehicle will also be necessary, unless storage systems are advanced to the point that they can store an equal amount of energy in an equal amount of space as a conventional vehicle. Economics will be the most powerful driving force or hindrance to widespread hydrogen use. Until hydrogen fuel costs can be brought down to at least $2.00 to $3.00 per equivalent gasoline gallon (in 1995 US$), and even with the aid of tax incentives for ZEVs, it is not likely that the American consumer will be willing to pay the high price for such a clean fuel. However, in the push for a clean and ultimately renewable fuel, hydrogen continues to be a long-term option for study, research, and development into the 21st century.

SECTION 8

ELECTRIC AND HYBRID ELECTRIC VEHICLES

8.1 GENERAL DISCUSSION

8.1.1 Electric and Hybrid Electric Vehicle Overview

Several types of vehicles can be classified as electric vehicles, because electric motors are the means of propulsion. These include battery powered EVs, flywheel powered EVs, and hybrid EVs. The generation of electricity will not be discussed here, except to note that a diverse variety of fuels can be used to generate electricity, such as natural gas, coal, or biomass. Additionally, hybrid EVs use a supplemental fuel source to produce electricity on-board. This section will not discuss the various fuel technologies that can be used to produce on-board electricity, as they are explored in detail in Sections 2 through 7. In place of the fuel cell technology discussion, this section will deal with the various battery, and flywheel technologies.

Electric vehicles have been mandated in California and a few northeastern states as a means of reducing urban air pollution. They have the potential to be the lowest emitters of all vehicles, since battery and flywheel powered EVs will produce zero tailpipe emissions and hybrid EVs may have significantly lower emissions than internal combustion vehicles. Electricity to power EVs can be produced from clean fuels, such as natural gas, outside of heavily populated areas, cleaning up much of the air in city centers. However, many of the limitations of current EVs are likely to prevent these vehicles from replacing most conventional vehicle uses. Most EVs have less than a 100 mile range, due to low energy densities of the batteries, and they require many hours for a full charge. EV drivers will be motivated to be 'energy managers' to avoid unnecessary hard acceleration and higher speeds to stretch the available charge and reduce recharge time and expense. In addition, the high incremental costs of original equipment manufacturers' (OEM) EVs over gasoline and diesel vehicles may place them out of reach of most Americans, even with the aid of tax incentives, although many EV conversions and purpose-built EVs are available from specialty companies for under $30,000. Much development is needed to find a higher energy, longer lasting battery, and to bring costs down if electric vehicles are to compete successfully with conventional vehicles.

Disposal and recycling of EV batteries is one of the major environmental concerns relating to electric vehicles. Every battery considered commercially viable contains materials that are corrosive and toxic and which are classified as hazardous wastes by federal standards or California regulations. The impacts depend upon the electricity generating fuel source. Effects may also vary because emissions are generated by stationary rather than mobile sources perhaps creating spatial effects. The disposal and recycling impacts of batteries are further discussed in Sections 8.1.3 and 8.1.4.

8.1.2 Battery Technology Descriptions

The first generation of electric vehicle (EV) batteries, between 1998 and 2000, are likely to include advanced lead-acid and nickel-metal hydride. Nickel-cadmium batteries may also be commercially available during this time period, although they will probably not be used as heavily due to cadmium toxicity and nickel carcinogenicity. By 2000, available battery types could also include the high-energy zinc-air and high-temperature batteries such as sodium-nickel chloride and sodium-sulfur, although many major OEMs have switched their focus away from high temperature batteries. They are currently expensive and complicated due to their thermal management systems, and they are difficult to recycle due to undesirable or unmarketable products. Electric vehicle batteries that look promising for 2003 and beyond include lithium-ion, improved nickel-metal hydride, and lithium polymer for their ability to store more energy on-board and to provide extended range.

Traditional liquid electrolyte lead-acid batteries have been used in thousands of EV conversions, however they have numerous disadvantages for this application. Although lead content has been reduced over time, they are heavy and have low energy densities, they require frequent watering, they can generate gases when recharging, and they contain electrolyte in a liquid form that can be hazardous if spilled in a collision. They have short lifetimes (15,000 to 25,000 miles) and they can be severely damaged if they are allowed to drain to too low a charge too often. Advanced lead-acid batteries are commercially available. These batteries are lighter and maintenance free, have higher energy and power densities, can recharge much faster than conventional lead-acid batteries, and are sealed so that gases generated during recharging recombine with chemicals in the battery. Nickel-cadmium batteries offer improved performance and longer life relative to lead-acid batteries. However, they are expensive, highly toxic, and the amount of the cadmium reserves available to make these batteries may not be sufficient to supply a large niche in the EV market.

Nickel-metal hydride batteries have the advantage of high specific energy and long cycle life relative to lead-acid batteries. An important feature of nickel-metal hydride batteries is that they can be fully discharged with very little impact on battery life, unlike some versions of nickel-cadmium batteries. They operate at ambient temperature and do not require maintenance. CARB's recent tests of a converted vehicle with nickel-metal hydride batteries indicate dramatic improvements in range and performance over lead-acid batteries. In a converted gasoline vehicle, the range is extended to over 140 miles, combining both highway and urban driving cycles. The zinc-air battery is the focus of a large demonstration in Europe. The German postal service and telecommunications company, Sweden's largest utility and postal service, and the Italian utility will be converting part of their fleets to EVs powered with zinc-air batteries supplied by an Israeli company. The German postal fleet alone will run over 40,000 of these vehicles. The zinc-air battery, being developed by American and Israeli companies, has proven even better than the nickel-metal hydride, and comes closest to equaling gasoline-powered performance in terms of range and refueling. In tests of this battery in German postal fleet vehicles, the range has extended to over 400 miles on a single charge. The zinc-air has eight times the energy density of a lead-acid battery and is also lighter. By conventional charging methods, a zinc-air takes a full charge in 6 hours, however the Israeli developer has devised a method of recharging simply by replacing the cathodes, which can be accomplished in less than 2 minutes. The latter method will require an immediate recycling infrastructure for these batteries, the technology for which has already been developed.

Advanced lithium batteries, including lithium-ion and lithium-polymer, have the potential to meet many of the United States Advanced Battery Consortium's (USABC[4]) goals for mid- and long-term EV batteries. They have very high energy and power densities and can last for over 1,000 charge-discharge cycles. They are much lighter than lead-acid and promise a higher level of consumer safety, since lithium is non-toxic. The USABC has awarded four multi-million dollar research grants for developing advanced lithium battery technology for EVs. Many Japanese, as well as American, companies are devoting a great deal of research effort to these batteries.

Flywheel energy storage (FES) systems have been advertised to have the potential to rival chemical batteries in terms of performance, cycle life, charge time, range, life cycle costs, and

[4] The USABC is a consortium of representatives from the 'big three' U.S. automakers, the U.S. Department of Energy (DOE), and the Electric Power Research Institute (EPRI) which was formed to support the research, development, and testing of advanced electric vehicle batteries.

environmental friendliness, although no flywheel demonstration has yet proven these claims. A flywheel is an electromechanical energy storage system composed of composite rotors spinning at thousands of rpm on frictionless magnetic bearings, which can drive a generator to provide power for EVs. Energy stored in the flywheel increases quadratically with the rotational speed of the rotors. As energy is used up, the rotor slows. A first generation EV flywheel was unveiled by American Flywheel Systems (AFS) of Washington. AFS claims that their flywheel is the same size as a 6V lead-acid battery, but weighs much less, stores 3 times the energy, and can last 10 times longer. The AFS flywheel avoids gyroscopic effects by having the two adjoining wheels counter-rotating at identical speeds on a stationary shaft. Friction is reduced to negligible levels by suspending the wheels magnetically in a vacuum. If used in the GM lead-acid powered Impact, AFS speculates that their flywheel could theoretically increase the range of this vehicle from 80 miles to 300 miles on one charge. They add that the flywheel could theoretically last for the life of the vehicle, unlike a chemical battery pack which must be replaced several times in the life of the vehicle. Flywheels have yet to be sufficiently tested in vehicles to prove or disprove whether these predictions hold true.

8.1.3 Battery Charging/Recycling Infrastructure

In order for EVs to be successful, the necessary infrastructure must be in place. Critical components of the infrastructure include home-charging capabilities, as well as public recharging stations, reliable service centers, knowledgeable dealers, and a means of disposing of and/or recycling used batteries that does not inconvenience the consumer. California utilities and CALSTART, a consortium of automotive, aerospace, government, utility, labor, and environmental organizations, have joined efforts to develop a statewide EV infrastructure. The effort is focusing on six key issues: (1) installation of safe and convenient charging stations; (2) plans for recycling and disposal of batteries; (3) tool development and technician training for EV maintenance and service; (4) adaptation of standards and codes to accommodate EVs; (5) consumer education on EVs; and (6) EV impacts on utility energy supply systems. The plan calls for installation of 140 charging stations statewide, with 60 of these being in the Los Angeles area. The charging facilities should be able to accommodate different vehicle types, and will include EV charging parking lots. Utilities are expected to offer rate discounts to eligible users of EVs, such that a full night of charging will cost only $1.00, providing a range of 50 to 120 miles.

It is anticipated that most EV charging will take place at home, overnight, during off-peak hours. Homes can accommodate charging by installing the necessary wiring and a dedicated circuit breaker for a 240 V/40 A connection. Most EV conversions existing today can plug into a conventional 120 V/15 A outlet, however, this often requires over 8 hours of charging. Purpose-built EVs are expected to have different connections that may or may not fit into a standard outlet. U.S. automakers have yet to develop a standard interface for EV charging. GM and Toyota use an inductive charging interface, while Chrysler, Ford, Honda, Mazda, BMW, Mercedes-Benz and Volkswagen use conductive connectors. A national Infrastructure Working Council (IWC) is working to develop standardized EV charging, with standardized energy levels for slow charging (120 V/15 A), normal charging (240 V/40 A), and quick charging (75-200 kV); and two standards for charging connectors, one for conductive and one for inductive interfaces. During the ongoing GM PrEView Drive, in which utility customers were allowed to test drive the GM Impact, several homes in Los Angeles were equipped with home charging systems. The average installation cost was about $900. However the cost of the charging equipment alone can be several thousands of dollars, and some homes may require additional wiring that could cost thousands more. GM and

Power Control Systems, a division of Hughes, have developed a normal speed inductive charging system that could be used as a public charger or as a home charger.

Spin off organizations from utilities, such as Edison EV, are seeking customers for the placing and installation of public charging stations. While most charging will be done at home in private garages, public charging stations are necessary for places like shopping centers and business parking lots and garages, where vehicles may be parked for several hours, and urban residential neighborhoods, where private parking spaces are rare, making home charging difficult. The latter issue is more of a concern for European markets, where a larger percentage of the population resides in compact city dwellings. Public charging facilities are also likely to include quick charging stations and battery exchange facilities. Chrysler and a Canadian firm have developed a conductive quick charging system that monitors the battery state of charge in each module to prevent overcharge of the battery. Battery exchange is intended as a substitute for quick charging to avoid system overload during peak hours. The discharged battery can be replaced with a fresh one, allowing the discharged battery to be recharged during off-peak hours.

Recycling infrastructure in the state only exists for lead-acid batteries, with a total recycling capacity of about 200,000 tons/year. The infrastructure involves a deposit/trade-in system, which encourages consumers to return spent car batteries. Most states have lead-battery recycling laws, which prohibit disposal of these batteries in municipal landfills, but which also include exemptions from certain Resource Conservation and Recovery Act (RARA) regulations, allowing easier recycling for the consumer. No other battery yet enjoys this status. All are considered hazardous waste and must be treated as such during the recycling chain from consumer to recycler. A new EPA rule, the Universal Waste Rule, may soon allow other batteries to be treated in the same manner as lead-acid, which would facilitate an easier recycling process, pending adoption of the rule by the states. A nickel-cadmium battery recycling facility is located in Pennsylvania, which also handles nickel-iron and small amounts of nickel-metal hydride batteries. No recycling facilities exist for sodium-sulfur or sodium-nickel chloride, although a sodium-sulfur pilot plant, run by Asea Brown Boveri, was previously operating in Germany. AEG Corporation is developing recycling techniques for its sodium-nickel chloride batteries, but this is still in the laboratory stage. Since the recycled products of sodium-based batteries, with the exception of nickel, have very little market value, it is not likely that recycling these batteries will be economically feasible. One recycler of lithium batteries is located in British Columbia, Canada, with a relatively environmentally benign process. This facility has less than a 1,000 ton capacity. If lithium batteries capture a large percentage of the EV market, this facility would either need to be expanded, or additional facilities would need to be added. Studies are underway to determine how much recycling capacity the state will need of each battery type, as well as the environmental impacts of adding recycling facilities in-state.

8.1.4 Health and Safety Issues

A serious health hazard related to EV batteries would be associated with their disposal and recycling. Since all of the batteries under consideration for EV use contain some amount of hazardous chemicals, closed-loop recycling, in which the recycled metals and plastics are returned to the manufacture of new batteries, must be considered a necessary part of the development and life cycle of EV batteries. Lead-acid battery recycling is a good example of this, in which over 70 percent of the materials in a new battery come from recycled lead batteries, minimizing environmental impact from mining raw materials. In addition, there is ample data to assert that environmental controls on current lead recycling facilities are extremely effective. Even with the elimination of leaded gasoline, the per capita lead usage in the U.S. has increased from 4.48 kg in 1960 to 5.26 kg in 1990 due primarily to an increased number of cars which all use lead-acid batteries. Automotive batteries account for 75 percent of all domestic lead usage. However, the average blood lead concentrations have declined from 20 μg/dL to 2.8 μg/dL, well below the levels of concern of the U.S. Center for Disease Control (CDC). This is due to efficient emissions controls, and strict emissions standards, which cannot be increased, even if new facilities are added. The solid waste that is produced (about 8 ounces per 36 lb. battery) is 85 percent non-hazardous slag, which can be used as a construction aggregate or road pavement material. There are also cleaner processes to recycle batteries, such as electrowinning, which produce virtually no toxic air emissions. Such hydrometallurgical processes are more likely to be used in recycling other types of EV batteries, rather than pyrometallurgical processes.

There are safety concerns associated with EVs, relating to the hazardous battery contents, their health risks, and their potential to spill in a vehicle crash. Under normal operation, most EV batteries, in and of themselves, do not present inherent safety hazards over those of a conventional car battery, given that they are sealed. Many do contain corrosive metals and electrolytes, however there is insufficient crash test data to determine whether or not these materials could spill as a result of a vehicle crash. Some batteries have been reported to emit gases during discharging/charging, but the effects of these gases have not been determined. Additionally, since most batteries are sealed, offgasing should not be a problem during normal operation of the vehicle. High temperature batteries, such as sodium-sulfur, sodium-nickel chloride, and lithium-metal sulfides, have occasionally been the cause of vehicle fires, most notably sodium-sulfur. There is also the possibility of electrical fires, but again, there is insufficient data to indicate whether or not EVs will present a greater risk of electrical fires than the electrical system of conventional vehicles.

8.1.5 Battery/Flywheel Costs

Many of the more high performance electric vehicle batteries, such as the nickel-based batteries are currently much too expensive, ranging from $200/kWh to $300/kWh, to cost effectively power a vehicle. Current gasoline vehicles cost $30-$50/kWh. The high cost of these batteries is primarily due to high commodities prices for the metals used in the batteries. The USABC's mid- and long-term goals for battery cost are $150/kWh and $100/kWh respectively. While most advanced EV battery types are not in commercial production yet, developers are predicting economies of scale. Developers are also predicting that longer cycle lives of advanced batteries will bring down the vehicle costs-per-mile, but this remains to be seen. Early cost estimates attempt to account for mass production. Current advanced lead-acid and zinc-air batteries are available for around $75/kWh ($1,500 for a 20 kWh pack), while nickel-cadmium and nickel-metal hydride batteries are estimated at $200/kWh and $300/kWh respectively due to the high price of the rare metals in these batteries. Lithium-polymer costs are predicted to meet the USABC long-term goal. Cost information on lithium-ion batteries is not available, since this battery is still in a rapid state of development, and the batteries have only been tested at the cell level.

The first generation EV flywheel produced by AFS is anticipated to cost $5,500 to $6,000 for the complete system, but this will presumably last for the life of the vehicle, unlike the chemical batteries. A typical 20 kWh battery pack, typical for a passenger car, could cost between $1,500 and $6,000, but would need to be replaced more than once.

8.1.6 Suppliers/Backers

EV battery development is mainly supported by many sectors of the federal government, including the DOE, the DOT, and the EPA, as well as many state and foreign government agencies, including utilities and utility research organizations. The major U.S. supporters are the USABC and the Electric Power Research Institute (EPRI), providing research grants to national labs, universities, and private research companies for advanced battery development. In Japan, battery research is funded by the Ministry of International Trade and Industry (MITI), funding the Lithium Battery Energy Storage Technology Research Association. Developers of EV batteries are listed in Table 8-1.

Flywheel batteries are under commercial development by American Flywheel Systems. Other companies and laboratories working on flywheel development are the big three U.S. automakers, SatCon Technology Corporation, BMW, Advanced Controls Technology Inc., Flywheel Energy Systems Inc., Thortek Inc., Mechanical Technology Inc., Lawrence Livermore National Laboratory, and Oak Ridge National Laboratory.

8.1.7 Battery/Flywheel Availability

Most of the current EVs available run on lead-acid batteries. A few test fleets run on nickel-metal hydride and nickel-cadmium. These are the few EV batteries that are already commercially available, although there is some question as to the continued availability of cadmium reserves for battery manufacture. Nickel-cadmium batteries can, however, be produced from recycled cadmium. GM Ovonic will begin producing nickel-metal hydride batteries at the pilot level this year, and plans to manufacture them commercially before 2000. Electric Fuel, Ltd. is supplying zinc-air batteries to major government fleets in Germany and Italy's utility company, Edison Termoelettrica. Commercial production of high temperature batteries (sodium-sulfur and sodium nickel chloride) is not expected in the near term. Advanced lithium batteries will probably not be in full commercial production until after 2000. American Flywheel Systems has not made any statements regarding when they will begin producing their EV-flywheel.

Table 8-1. Battery performance specifications and USABC goals

Battery	Specific Energy (Wh/kg) (C/3)[1]	Peak Power (W/kg) (80% DOD[2])	Energy Efficiency (%)	Battery Life (cycles)	Self Discharge (% per 48 h)	Production Cost (US$/kWh)	Operating Temperature (°C)	Developer
Lead-acid	30-50	100-300	>80	500-1,500	0.6	70-150	ambient	Johnson Controls
Sealed-bipolar lead-acid	55	450	NA	1000+	<15	150	-30°C to 65°C	Johnson Controls
Nickel-cadmium	50-60	130-235	75	2,000	2	300	ambient	SAFT
Nickel-metal hydride	70-80	175	>70	800+	>10	200	-30°C to 60°C	Ovonic
Zinc-air	215	98	60	600+	NA	75	ambient	Electric Fuel, Ltd.
Sodium-sulfur	90-120	130-180	85	500+	0	250	350°C	ABB
Sodium-nickel chloride	90-130	60-130	NA	1,000+	NA	250	300°C	AEG
Lithium-polymer	85-130	80-85	80-85	1,000+	0.03	100	ambient to -120°C	3M, WR Grace
Lithium-ion	108	216	NA	800+	<1	NA	ambient to 60°C	Varta AG
USABC mid-term	80 to 100	150 to 200	75	600	<15	150	-30°C to 65°C	—
USABC long-term	200	400	80	1,000	<1	100	-40°C to 85°C	—

1. C/3 is the notation for current drain of discharge, a standard method for indicating the discharge current for a battery. Other C rates can also be specified by the following *equation:* $I = C_n/N$, *where* I is the discharge current in amperes, C_n is the capacity rating of the cell in Ah at the *n*-hour rate, and N is the hours of discharge.
2. DOD = Depth of Discharge

8.2 LIGHT-DUTY AND HEAVY-DUTY VEHICLES

8.2.1 Vehicle Technology and Equipment

Most light-duty electric automobile and van models demonstrated by OEMs to date (and supplied as conversions) are battery operated and utilize direct current (DC), variable-speed electric motor propulsion systems, employing advanced, compact electric motor technology developed in-house or by specialty manufacturers (such as Unique Mobility of Colorado). Alternating current (AC) EV technology is being applied in some experimental vehicles. Electric motors replacing the conventional internal combustion (IC) engine may utilize a conventional drive-train system (including automotive type transmission) or be positioned to drive individual wheels. Part of the underhood space normally occupied by the IC engine typically houses the electric motor controller system and associated electronics.

An interconnected system of storage batteries comprises the most substantial component of most EVs. Many manufacturers have compensated for this by using ultra lightweight composite materials in the body. In a battery EV, any remaining underhood space not required for motor and controller components, and usually a portion of the vehicle's normal cargo space, is occupied by batteries numbering as few as six to eight or as many as twenty or more. Some vehicle designs incorporate creative placement of batteries to minimize cargo space loss and/or better distribute the extra weight. GM's Impact, for example, incorporates a T-shaped battery compartment "tunnel" central in the vehicle chassis, while most EV van models have battery packs positioned beneath the floor.

Lead-acid batteries, both conventional types and newer improved technology types designed specifically for EV application, remain the battery of choice for most OEM EV projects, including those of GM, Chrysler, Toyota, Nissan, Fiat, and possibly Ford. Chrysler had, until recently, concentrated its EV efforts around nickel-iron and nickel-cadmium batteries, while Ford was using sodium-sulfur batteries, which are also being tried by Mercedes-Benz, BMW, Audi, VW and Fiat. Chrysler recently announced that it will employ an advanced lead-acid battery, The Horizon® battery, manufactured by Electrosource in Texas, rather than the nickel-iron or nickel-cadmium batteries that it had been testing. Ford indicated that they may follow Chrysler's lead in choosing the Horizon® battery. Other battery technologies being applied in various OEM electric vehicle development projects include nickel cadmium (Mercedes-Benz, Chrysler, Peugeot, Nissan, Toyota), lithium chloride (Opel), nickel metal hydride (Hyundai) and iron nickel aluminum (Nissan). Industry-sponsored battery technology research efforts, by organizations such as the USABC, are also pursuing various battery technologies in search of higher energy density and power density, and longer life to provide economical options for future EV use. Promising technologies are zinc-air, developed in Israel, and lithium-polymer and lithium-ion, which are being actively researched by the Japanese. Most EV models carry an integral battery charger on-board and incorporate a regenerative braking system that recovers a portion of braking energy for battery charging. A battery fluid replacement system is included for some battery technologies.

Hybrid electric vehicles employ less battery storage (virtually none on some designs) in favor of an on-board auxiliary power unit to supply the electricity or to provide alternate or supplementary propulsion power. The most common hybrid EV concept under development, the "series" hybrid EV, employs limited battery storage, with charging supplied alternately from the electricity grid or from an on-board combustion engine/generator, allowing partial battery-only operation, with the on-board generator available to provide charging when extended range or increased performance are needed. A less commonly known Hybrid technology is the "parallel" hybrid EV, which uses battery electric propulsion and IC propulsion simultaneously. Flywheel EV concepts replace some or all of the battery electricity storage with electro-mechanical energy storage in the flywheel system, some utilizing an on-board combustion engine/generator and some relying on grid-generated electricity to "charge" (spin) the flywheel.

Accessory features common to IC engine vehicles, including air conditioning, heater, power steering and power brakes, have required new engineering approaches for EVs (and most hybrid EVs), due to the absence (or reduction) of engine accessory drive power, waste heat, and engine vacuum. Electrically-powered systems employing electric motors or electric heat pumps to provide all of these functions are being incorporated on most OEM EV models. Minimizing the auxiliary electricity usage for these accessory functions and other traditionally electric accessories (i.e., windshield wipers, lights, power windows, etc.), which can contribute to a substantial reduction in EV driving range, remains an important challenge for EV technology development.

8.2.2 Performance

The most significant aspects of EV performance that vary from performance characteristics of comparable gasoline vehicles include:

- *Reduced driving range.* The much lower energy density of electric batteries versus gasoline fuel (less than one-tenth the energy storage per volume of gasoline for the best battery technologies), even when compensated by devoting additional storage space to batteries, results in limited driving ranges for current technology EVs. Typically 100 miles or less is required before charging. Operation of accessories, driving in hilly terrain or using maximum speed or acceleration capability, or driving with batteries at less than optimum charge or condition will significantly reduce driving range. Hybrid EVs allow longer driving ranges by carrying fuel on-board to produce electricity for battery recharging or (less commonly) to power an engine for supplementary propulsion.

Vehicle acceleration and top speed. Typical electric vehicle models demonstrated to date (including OEM and converted models) have exhibited slower acceleration and lower top speed than IC engine counterparts, due to lower horsepower output of the electric propulsion system and the extra battery weight. Zero-to-sixty mph acceleration times have typically been double or longer than those of comparable gasoline models, although some drivers report adequate acceleration for urban stop-and-go driving. Top speed limitations of around 70 mph are common, although again this may not be a factor in urban driving. Some EVs, most notably the GM Impact, have challenged the belief that EVs must be slow or underpowered vehicles. By incorporating sufficient power output to match the acceleration of gasoline counterparts, GM has proven that such performance capability is not exclusive to IC vehicles. However, the efficiency and range penalties for the use of such performance capabilities will continue to dictate some degree of compromise in the performance of production EV models.

Recharging/refueling procedure. EVs can typically be recharged wherever a compatible electric connection (typically 220 volt) is available, but the key consideration (as distinguished from gasoline or other alternative fuel refueling) is the time required. Full recharging is typically accomplished overnight, requiring from three to twelve hours depending on the number and type of batteries and the charger voltage. Conventional lead-acid batteries typically require 6 hours for a full recharge. Electrosource claims that their Horizon® battery can be fully recharged in 30 minutes, with a 50 percent charge possible in 8 minutes. A new zinc-air battery being developed by Electric Fuel of Israel can be recharged in less than 2 minutes, simply by replacing the spent cartridges with new ones. The spent cartridges are then sent to a facility for regeneration or recycling. Most current vehicle/battery technologies allow for partial recharging, sometimes sufficient for a required trip length, that can be accomplished in a fraction of the full-charge time, although this may still involve longer than IC refueling times. Allowing the battery charge to run low usually results in diminished vehicle performance and may adversely affect battery life. Hybrid EVs will require on-board fuel storage and refueling with whatever combustion fuel is required by the auxiliary power unit.

Other EV performance differences include the lack of IC engine noise (which is replaced by the quieter electric motor hum) and the "instant on" aspect of electric propulsion that substitutes for the idle aspect of IC engine operation. The ride and handling characteristics of EV models have had to be designed differently from gasoline vehicles, because these parameters are affected by the additional battery weight on EVs. OEM designs normally attempt to compensate for the extra weight with enhanced suspension features and the use of lightweight body materials. Hybrid electric vehicles may require driver interaction/selection of all-electric versus combustion engine/generator-assisted modes, although some designs accomplish this function via computer-controlled electronics.

8.2.2.1 Maintenance and Reliability Features

Electric vehicles clearly have fundamental technological differences that pose unique in-use maintenance and service considerations from those associated with IC engine vehicles. The lack of on-road experience with OEM electric vehicles to date prohibits any overall determination of the net result of such differences with respect to the comparative maintenance and reliability features of EVs versus gasoline vehicles or other alternative fuel vehicles. Taylor-Dunn, a manufacturer of off-road EVs, has acquired years of proven experience with their vehicles, which are primarily warehouse vehicles and "people movers" such as are found in amusement parks and college campuses. Customers, such as the San Diego Zoo and Huntington Memorial Hospital, have in fact reported lower maintenance costs after replacing their gasoline fleets with electric vehicles. However it is difficult to make that claim for EVs in all applications, particularly on-road EVs which will be subject to many different driving conditions. Among the significant differences likely to be encountered with electric vehicle versus internal combustion engine vehicle maintenance are:

- A need for different service/repair facilities, expertise, replacement parts, etc. for servicing electric propulsion systems (electric motors, controllers, electronics), in place of or in addition to current capabilities for IC engines and drivetrains (except for hybrid vehicles, which require both types of capability)
- Different (scheduled) maintenance procedures associated with the mechanical propulsion system (i.e. engine oil changes, cooling fluids, drive belts etc.), replaced with new procedures associated with maintenance of the battery pack, including battery pack replacement at several-year intervals
- An absence of maintenance, testing requirements etc. associated with emissions control systems (except for hybrid vehicles) may be replaced with battery maintenance, although battery manufacturers advertise their modules as maintenance-free.

8.2.2.2 Fuel Efficiency Features

Reported energy consumption rates vary widely among existing EVs currently in use and those under development. Reported values range from one-tenth of a kilowatt-hour per mile to over 1 kWh/mile. Only a limited number of actual test results directly compare EV energy usage with that of IC engine counterparts. Selection of an average projected EV electricity usage rate is thus subject to question. This becomes part of the uncertainty in projecting EV-related emissions (for ZEV equivalent determination), since the emissions caused by EV charging from the electricity supply grid will be directly proportional to electricity used, unlike combustion engine vehicles, which are all regulated and controlled to virtually the same grams-per-mile emissions levels independent of their fuel consumption rates.

CARB has undertaken limited testing of battery EVs using the same procedure used for determining gasoline (and alternative fuel) fuel economies (and emissions). Testing of several gasoline vehicles converted to EVs indicates an energy substitution ratio for EVs, compared to gasoline fuel economies measured for their gasoline counterparts using the same test cycle, of about 12 kWh/gasoline gallon. This means that an EV with a 20 kWh battery pack stores the energy equivalent of about 1.67 gallons of gasoline. This number appears to correlate well with some studies that indicate roughly the same net energy consumption per mile of travel for EVs using electricity generated by power plants using natural gas (or other fossil fuels) as for gasoline vehicles. Further work to develop more reliable estimates of future EV energy consumption relative to that of gasoline vehicles and other alternative fuel technologies is necessary. Hybrid EVs present more complex energy efficiency considerations, since all or part of their electricity requirements are produced via an on-board generation system (i.e. a small, mobile electric power plant). Whether the efficiencies of various auxiliary power units for hybrid EVs will match or exceed efficiencies of the electricity supply grid remains to be definitively determined, as does the relative efficiency advantage of hybrid EVs versus IC engine vehicles. In general, hybrid EV combustion engines are expected to operate at more constant, closer-to-optimum rpm ranges than IC engines in conventional vehicles, allowing for greater fuel efficiency.

8.2.3 Emissions

Battery-operated electric vehicles produce no engine exhaust or fuel vapor emissions, thus entitling them to CARB's designation as ZEVs. However, there are emissions from power plants to charge the electric vehicles. CARB has evaluated an equivalent ZEV (EZEV) standard, which allowed for vehicle and refueling emissions that are equivalent to those from power plants. Some types of EV batteries may produce off-gases, however definitive characterization and quantification of possible battery emissions has not been reported and, in general, battery emissions are not expected to be a significant concern. Hybrid electric vehicles produce emissions from operation of the combustion engine and from on-board fuel storage. Therefore it was previously thought that HEVs could not meet ZEV classification. However, CARB is reconsidering this position. An alternative ZEV equivalent would allow the manufacturer to demonstrate that the emissions from the HEV are not greater than the emissions from electricity generation for EVs. The small displacement, constant load and operating speed combustion engines typically adapted for use in hybrid EVs have demonstrated very low emissions output.

The charging of electric vehicles from the electricity supply grid is recognized to create the potential for increased electric generation emissions, however, the magnitude of such emission increases continues to be a controversial issue, subject to wide variation in analytical estimates and questions as to where these emissions will occur geographically. If a major part of the additional electricity for EV charging is generated by natural gas-fired power plants located in the same air basin as the EVs are operated, as studies in some cases predict, then the emissions levels of such power plants should provide the straightforward basis for determining the emissions associated with EV charging. Complicating this determination, however, is the considerable variability in emission factors from existing power plants, uncertainties in future emission improvements for both existing and new plants, and the extent to which other types of generation, both emissions-producing and emissions-free technologies, could also contribute. The average in-use electricity consumption rates of future EV fleets, which have a further important bearing on resulting emissions, also remain somewhat uncertain (see previous discussion in *Fuel Efficiency* section). Due to these and other factors, studies of the indirect emissions impacts of electric vehicle introduction thus have produced inconsistent results. The most favorable results for EV technology indicate that EVs likely to operate in Southern California (where power plant emissions are the best-controlled and likely to be reduced even further) would result in NOG and NO_x emissions in compliance with CARB's ULEV standards. Other results, however, indicate that higher EV-related power plant emissions are possible, suggesting that other conventional or alternative fuel vehicle technologies could potentially match or exceed the emission benefits of EVs. Clearly, more definitive analysis will be required to establish with certainty what the likely emissions associated with EV operation in different regions of California will be, and how these levels compare with low-emission vehicle standards and with emissions levels achievable with other potentially competing vehicular technologies.

Analyses of the greenhouse gas implications of battery EVs have also produced somewhat varied results, subject to some of the same uncertainties affecting comparisons of regulated emissions as discussed above. However, there appears to be general agreement that EVs offer a degree of total carbon emission reduction versus current technology gasoline or diesel fueled vehicles, perhaps on the order of a 20 to 30 percent reduction in carbon emissions even if all electricity for EV charging is supplied by natural gas-fired power plants. Hybrid EVs pose greater difficulty for greenhouse gas evaluation, since they may employ a variety of different fuel-consuming technologies.

8.2.4 Commercial Availability and Costs

Development of vehicles with electric propulsion is being pursued by the big three U.S. auto makers and by most of the major Japanese and European OEM companies, with most of the over 40 OEM electric vehicle (EV) projects reported to date involving light-duty vehicles. GM has been working with battery-electric passenger/cargo van technology, such as an electric version of the Lumina APV van, since acquiring Griffon Industries, a British manufacturer of electric vans in the early 1980's. GM's most well known EV activities include development of a two-passenger compact electric automobile, the EV1. Chrysler has also conducted a multi-year EV development program concentrating on passenger/cargo vans, the TEVan, and Ford has been pursuing development of EV models based on a compact van model, previously the Aerostar, currently the Ecostar, and a compact passenger car, the Ghia Connecta. CARB revised the dates for mandatory sales of ZEV until 2003. In return, the seven car manufacturers agreed to provide vehicles for sale prior to the 2003 date and share data on the results of EV commercialization. European companies BMW, Volkswagen, Mercedes-Benz, Peugeot and Fiat, and Asian companies Nissan, Toyota and Hyundai have undertaken compact EV passenger car development.

A few OEMs are beginning to offer EV models publicly in Europe and Japan. Several models of limited production electric vehicles from European manufacturers are available and being purchased in small numbers, primarily by electric utility companies and government fleets. Examples include the Danish-built City-El and Kewet El-Jet, both 3-wheeled, 1 or 2-passenger commuter vehicles (both technically classified as motorcycles); the Volkswagen CitySTROMer, and the Fiat Cinquecento Elettra and the Panda Eletras, both 2 or 3-passenger subcompact cars. In Japan, the Nissan Cedric/Gloria is already available. In the U.S., the Nordskog electric shuttle bus, and the Cushman 3-wheeled meter reader are available commercially, as well as many EV conversions such as the Solectria Force. The Ford Ecostar is available for fleet sales in the U.S. In addition to the big three automakers, several specialty companies in the U.S. have begun producing purpose-built EVs, rather than conversions of OEM vehicles. Examples are California Electric Cars, Inc. (the Monterey); Domino Cars, U.S.A. (the Minilight); Eco-Motion (the ION-1); Green Motorworks (the Kewet El-jet and Speedster); Herb Adams V.S E. (the Jackrabbit); Suntera (the Sunray); and VoltAge, Inc. (the Voltzvogon).

OEMs with hybrid electric vehicle development projects, most involving compact passenger cars or vans, include GM and Chrysler, German companies Audi, Opel and BMW, Mercedes-Benz and VW, French auto maker Peugeot, and Japanese manufacturers Mazda and Mitsubishi. Heavy-duty EV development is being undertaken by Isuzu of Japan, with a 2-ton truck project, and by a California company, Norsdskog Electric Vehicles of Redlands (a division of Electricar Corp.), developers of the electric shuttle bus mentioned above. Toyota is selling a hybrid Prius in Japan. Sales have far exceeded expected production capacity with a price premium of $5,000 over a conventional Prius.

The market price differences between new electric vehicles and gasoline counterpart vehicles are not well established, since very few OEM EVs have yet to appear in the U.S. marketplace. EVs being supplied for limited pre-production demonstration programs typically carry purchase (or lease) prices double or even higher than comparable gasoline models. Chrysler has predicted that the incremental costs alone of its TEVan could be over $80,000. However, as with other alternative fuel vehicle technologies in their demonstration phases, these prices are set at levels intended to recover a portion of total manufacturer development costs, and cannot be considered representative of actual costs of ultimate commercial production of such vehicles.

Prices for EV conversions or purpose-built EVs, ranged from as low as $11,500 to $60,000 or more. Many of these are vehicles in full production, such as the Solectria Force. Solectria offers the Force RS, a Geo Metro conversion, at a base price of $26,000. This full-production vehicle has all the amenities of a gasoline vehicle, such as AM/FM stereo, air conditioning/heating, regenerative braking, has a top speed of 70 to 75 mph, and has achieved ranges well over 100 miles. It appears likely that initial commercial offerings of EVs from major OEM companies will carry significant price premiums, but the amount of these premiums cannot be reliably predicted in the absence of formal OEM announcements. Some manufacturers have cited general estimates of expected EV cost differentials of around $30,000 to $50,000 more than comparable gasoline models, however, such estimates cannot be considered definitive. Much remains to be determined about market acceptance of EVs, including what price premiums (if any) the market will bear, and whether the higher cost of EVs will require a form of subsidy.

Hybrid EVs, including concepts employing combustion engine/generators, or flywheel energy storage, remain in earlier development phases that make cost projections for such technologies even more uncertain than for battery-operated EVs.

Lower costs of electricity versus gasoline and anticipated lower maintenance costs are expected to help offset the initial purchase cost of EVs. CEC's most recent forecast of off-peak electricity rates for EV charging (about 6 cents per kilowatt-hour for the South Coast, with minimal taxation) represent about a 30 to 35 percent savings over forecast gasoline prices (using the previously noted energy substitution factor of 12 kWh electricity per gasoline gallon). Thus, a nominal EV consuming 0.4 kWh/mile (comparable to a 30 mpg gasoline vehicle) would save about

1.5 cents per mile in fuel expense, and in 15,000 miles of driving would realize a total fuel expenditure savings of $225.

Battery replacement costs for electric vehicles are expected to be the most significant operating cost difference. Current battery technologies require replacement every 2 to 5 years at a cost of $1,500 to $6,000 per replacement cycle, adding 4 cents per mile or more to vehicle operating costs. Any other differences in maintenance cost categories, including some maintenance items (e.g. oil changes) that favor EV technology, will likely be overshadowed by battery replacement costs, unless advances in battery technology produce a "lifetime EV battery", such as a flywheel battery, at a cost competitive with today's batteries.

8.2.5 Summary

Electric vehicle technology has undergone tremendous development in the last decade. The driveability and handling of many EVs, such as the GM EV1 and Ford Ecostar, have proven to be comparable to vehicles with internal combustion engines. However, current EVs are strongly limited by range, higher operating cost, low top speed, and long acceleration times from 0 mph to freeway speeds, thus restricting them to niche markets, such as downtown urban transport vehicles. They are extremely well suited for this application, not only because of their particular performance characteristics, but also because of their ability to eliminate vehicular tailpipe emissions in urban centers, where the problem of air pollution is most acute. In order for EVs to capture a greater portion of the transportation market, the vehicles require propulsion systems with adequate energy storage capabilities, whether they be chemical batteries, or flywheels. Although most chemical battery technologies are hindered by low energy density, low cycle life, and high cost, they will probably be the only propulsion systems available commercially in 1998 when the ZEV mandate begins. Flywheel technology could extend the range of EVs significantly, as well as lower overall life cycle costs, however, the timeframe for their commercial production is uncertain. Fuel cell systems are still very expensive, and there are still many complications with fuel storage and/or reforming equipment. If they are fossil-fueled, they are excluded from ZEV classification. If they are hydrogen-fueled, they can meet the ZEV classification, but will be limited, at least in the near term, by the lack of hydrogen infrastructure and high fuel costs. In the longer term, EVs could provide even further improvements in urban air quality, although the environmental effects of power generation and battery recycling should be carefully monitored and controlled so that a new regulatory environment to allow for the safe and effective use of EVs can be developed.

SECTION 9

FUEL CELLS

9.1 GENERAL DISCUSSION

Fuel cells provide a power source for electric vehicles that is replenished with chemical energy rather than electrical recharging. Fuel cell powered vehicles therefore share many of advantages of electric vehicles without the disadvantage of range limitations and battery replacements.

9.1.1 Fuel Cell Powered Vehicle Overview

A fuel cell is different from a battery because it does not store energy. It is an electrochemical energy conversion engine, that produces electric energy from a fuel (hydrogen) and an oxidant (oxygen). The fuel cell itself produces only water, heat, and electricity. Fuel cell systems can also operate on hydrogen that is produce from on-board reformers fueled with hydrocarbon fuels. Reformation systems are complex since they need to accomplish gas clean up steps and provide the hydrogen on demand for the vehicle. Reforming hydrocarbon fuels converts the carbon in the fuel to carbon dioxide. Trace pollutants can also be formed and are discussed in Section 9.1.2.

Fuel cells offer the advantage of higher efficiency and dramatically lower emissions than an internal combustion engine, and greater range than a battery-powered vehicle. Five types of fuel cells, each distinguished by its electrolytic conducting materials are considered for power generation applications: the alkaline fuel cell (AFC), the phosphoric acid fuel cell (PAFC), the polymer electrolyte membrane fuel cell (PEMFC), the molten carbonate fuel cell (MCFC), and the solid oxide fuel cell (SOFC). PEMFCs are the most suitable candidates for vehicle applications since they operate at relatively low temperatures (90 °C) and are not affected by atmospheric CO_2. These fuel cells have the disadvantage of being sensitive to CO contaminants. PAFCs operate at 200 °C and could be suitable for heavy-duty vehicle applications. PAFCs require long warm-up times before they are operational and can tolerate several percent CO in their fuel feed.

Fuel cells are already in use in stationary utility applications, but require significant cost reductions for vehicular applications. Obstacles that must also be overcome are on-board fuel storage; space restrictions; and vehicle weight.

Most of the emissions in the life cycle of a fuel cell occur in the manufacturing process. Even though hydrogen combusted in direct fuel cells is emission free, the processes that generate the hydrogen are not. Section 7.1.1 discusses the environmental impacts of hydrogen production. Sections 9.2.3 and 9.3.3 also discuss environmental impacts of hydrogen use.

9.1.2 Fuel Cell and Reformer Technology

The production, distribution, lack of fueling infrastructure, and the difficulties in storing sufficient quantities of hydrogen onboard a vehicle near a stationary facility are all obstacles that make the mass introduction of hydrogen-powered fuel cells difficult. As a result, considerable research has been directed towards developing technologies for the on-site or on-vehicle production of hydrogen. The addition of a fuel processor to generate hydrogen from existing liquid hydrocarbon fuels is an attractive alternative to hydrogen storage. Liquid hydrocarbon fuels have high energy densities, established storage and handling characteristics, and existing or easier to establish fueling infrastructures. The constraints imposed by vehicle operation and the fuel cell need to be incorporated into the design of on-board fuel processors.

PEMFCs are receiving the most attention for applications in passenger cars as well as buses. PEMFCs can operate on the gas generated from on-board reformers, however, CO must be reduced to below 50 ppm. Both low temperature methanol steam reformers and multi-fuel partial oxidation systems are undergoing development. The direct methanol fuel cell (DMFC) operates on an aqueous methanol solution and does not require a reformer.

Hydrogen has been produced from natural gas and other hydrocarbon fuels in methanol and chemical plants and oil refineries for decades. Two approaches are used for commercial hydrogen production.

- Steam Reforming (SR)
- Partial Oxidation (POX)

Steam reforming of methanol can also occur at lower temperatures with a copper/zinc catalyst. In a steam reformer system, a catalytic burner generates heat for the reformer catalyst. The catalyst temperature is 260°C. A mixture of methanol and steam enter the catalyst and is converted to hydrogen, carbon dioxide, and carbon monoxide. The carbon monoxide must be lowered below 50 ppm by reacting with steam and low levels of oxygen to allow the reformer product to be used in a PEMFC. The product gas is fed to the fuel cell and unreacted hydrogen is burned in the burner to provide heat energy for the reformer.

Partial oxidation reforming (POX) involves the substoichiometric burning of fuel with oxygen or air. An important advantage of POX over low temperature methanol steam reforming is that a POX system can operate on a variety of hydrocarbon feedstocks including natural gas, gasoline, ethanol, LPG, and methanol.

The hydrocarbon feedstock, water and air are fed into a reaction-chamber after vaporization, preheating, and pressurization. The required heat for the reaction in the reactor is supplied in-situ by oxidizing a fraction of the feedstock. The extent of the oxidation reaction is regulated by the mixture stoichiometry. The preheated and vaporized reactants are injected through a specially design burner into a combustion vessel, where partial oxidation occurs at 1000 - 1220°C. The oxygen content represents a rich or substoichiometric mixture, so all of the oxygen is consumed in the reaction. No NOx is produced under these conditions.

CO is converted to CO_2 in subsequent reaction steps and the gas mixture is fed through the fuel cell. Unreacted hydrogen is combusted in a catalytic burner and the energy is used to power a compressor/expander (turbocharger) which provides air for the fuel cell system. The catalytic burner operates at low temperatures so NOx emissions are extremely low. The exit gas from the fuel cell contains less than 50 ppm CO and less than 5 ppm HC which is carried over from the partial oxidation reformer. Since the inlet gas concentrations to the catalytic burner are low, CO and HC emissions are also very low.

9.1.3 Health and Safety Issues

There is limited data on health issues related to fuel cell powered vehicles. However, some health issues are combined with safety issues in this section. Safety issues related to fuel cell powered vehicles depend on the fuel supply options. For dedicated hydrogen vehicles, safety practices related to hydrogen storage need to be addressed. On-board reformer technologies do not store a significant quantity of hydrogen. Important fire safety issues will need to be addressed for hydrogen fueled vehicles as discussed in Section 7. Indoor parking and use of public garages may be limited. Safety precautions will also need to be implemented during refueling.

Different safety issues will need to be addressed for vehicles with on board reformers. Fuel will be combusted at temperatures as high as 1000°C inside a POX reactor. While these temperatures are not unusual for stationary burners and temperatures inside automotive combustion chambers are similarly high, the hardware will be a departure from standard automotive equipment. On board reformer systems will also generate steam or steam fuel mixtures at pressures as high as 4 atm. A steam leak could cause severe burns; however, it is likely that steam flows will be internal to the reformer system and not pose a health risk to vehicle drivers or mechanics.

Issues associated with battery use and disposal apply to a lesser extent to fuel cell powered vehicles. Some fuel cell vehicles, particularly buses, will be full hybrid configurations where the weight of the batteries will be substantial, about one-half of that of a battery powered vehicle. However, some passenger cars may not need substantial battery storage, particularly if ultracapacitors are available for energy storage. Ultracapacitors have the advantage of storing a relatively small amount of energy, however, the power during discharge is quite high compared to batteries. Therefore, ultracapacitors can provide peak power for vehicles with much lower weight than batteries since a hybrid vehicle primarily requires supplemental power rather than energy storage.

Methanol steam reformer systems and shift reactors for POX systems will contain nickel catalysts that are intended to operate under reducing conditions. Toxic gases could potentially be released if the catalysts are operated under conditions outside of their normal operating parameters. Safety systems on-board the vehicle will likely protect the catalysts from damage.

9.1.4 Suppliers/Backers

Fuel cell development is supported by the Department of Energy (DOE), the Department of Transportation (DOT), South Coast Air Quality Management District (SCAQMD), and several utility companies, as well as all major automakers. Major developers are Ballard Power Systems Inc., International Fuel Cells (PEMFC development), Allied Signal, Siemens, Fuji Electronic Corporation, Westinghouse Electric Corporation, and Energy Partners (PEMFC development in

LDVs). Fuel cell components are being developed by several companies and laboratories, including Los Alamos National Laboratory, Dow Chemical, and DuPont

In December 1997, Ford entered into a joint venture with Ballard Power Systems and Daimler- Benz. This venture established three companies that develop and manufacture fuel cells, fuel cell systems, and electric drivetrain systems. Ballard Power Systems retains majority ownership of the company that manufactures fuel cells. Daimler-Benz is the majority owner of dbb Fuel Cell Engines GMBH. This company will be responsible for fuel processors, air supply, and control subsystems. Ford is the majority owner of the company, ECo, which will further develop and commercialize electric drivetrains. An electric drive system consists of a traction inverter, electric motor, and transaxle which converts electric power from the batteries and fuel cell system to tractive power.

9.2 LIGHT-DUTY VEHICLES

9.2.1 Vehicle Technology and Equipment

All major automobile manufacturers are developing PEMFC systems for passenger cars. Each of the big three U.S. manufacturers is pursuing a cost-shared development program with the DOE. European and Japanese auto manufactures also have development programs and are building prototype vehicles. Table 9-1 shows on-going fuel cell development activities that have applications for light-duty vehicles.

Several vehicle manufacturers have built prototype vehicles equipped with low temperature methanol-steam reformers. This configuration does not allow the fuel flexibility of a POX system; however, the effluent from the reformer is more suitable as a feed gas for PEMFCs. GM/Delphi is building a low temperature reformer for a GM fuel cell powered car in a DOE program. Opel, the

German subsidiary of General Motors, unveiled a fuel cell powered Sintra at the Geneva Auto show in March 1998.

Table 9-1. Fuel Cell Development Efforts

Vehicle/System	Fuel Cell	Fuel	Power/Reformer/Storage[a]
GM PNGV, Opel Sintra	Ballard PEM	Methanol	Delphi steam reformer 50 kW FC
Ford PNGV	IFC, H-Power, Plug Power, Energy Partners, Ballard PEM	Hydrogen Gasoline	Compressed, 5000 psi (330 atm) storage Multi-fuel POX studies
Chrysler PNGV	Allied Signal, Ballard PEM	Gasoline Hydrogen	Multi-fuel POX Compressed H_2 10 kW FC
Mercedes Benz MDV NECAR I LDV NECAR II LDV NECAR 3	 Ballard PEM Ballard PEM Ballard PEM	 Hydrogen Hydrogen Methanol	 Compressed H_2, 33 kW FC Compressed H_2, 50 kW FC Steam Reformer, PROX 50 kW FC
Breadboard system	Siemens PEM	Methanol	TopsØe Steam Reformer, FZJ catalytic burner; AgPd membrane50 kW FC
Toyota RAV4 Prius	Toyota PEM	Hydrogen	Hydride storage, 20 kW FC 35 kW NiMH Battery
VW Joule III	Ballard PEM	Methanol	JM Hot-Spot POX, JM PROX, 50 kW FC planned
Laboratory Fuel Cell	JPL Direct PEM	Methanol	Currently < 1 kW
Laboratory Fuel Cell	LANL Direct PEM	Methanol	Currently < 1 kW
Laboratory Fuel Cell	Siemens DMFC	Methanol	Currently < 1 kW

[a] FC = Fuel Cell, JM = Johnson Matthey

Daimler Benz has attracted considerable attention with its prototype fuel cell vehicles NECAR I, NECAR II, and NECAR 3. The first two vehicles were configured for dedicated hydrogen operation. The NECAR 3 is based on a Mercedes-Benz A-Class car. This proof of concept prototype vehicle is equipped with a methanol steam reformer. The NECAR 3 uses a multi-stage selective CO oxidizer (PROX) to purify the gas mixture from the reformer. In the NECAR 3, the reformer/fuel cell system is sufficiently large that the vehicle does not require any battery storage for tractive power and produces hydrogen on-line. Mercedes-Benz announced that they will offer a fuel cell powered car for sale to the public by the year 2005.

Toyota has produced several concept cars for dedicated hydrogen operation with hydride storage. Both the RAV4 and Prius have been configured as hybrid fuel cell vehicles. Toyota also built a methanol fueled version of the Prius fuel cell hybrid. A low temperature steam reformer generates hydrogen to power the fuel cell.

The European Joule III project will use a Johnson Matthey Hot Spot™ catalytic autothermal reformer operating on methanol with a 50 kW Ballard PEMFC. The autothermal reformer approach offers the efficiency benefits of steam reforming combined with rapid start-up characteristics. The project will produce a prototype vehicle in the same size range as a Volkswagen Golf.

Other methanol fueled development projects include a PEMFC powered car with a steam reformer that has been built at Renault and a breadboard system at the FZJ. The FZJ system is unique because gas clean-up will be accomplished with a membrane, and the fuel cell will operate on pure hydrogen. Ford is developing a dedicated hydrogen PEMFC vehicle under the PNGV program. Several fuel cells were evaluated under this program including units from Energy Partners, IFC, H-Power, and Plug Power. IFC's ambient pressure fuel cell is particularly applicable for dedicated hydrogen systems where no waste anode gas must be burned. Ford has undertaken extensive studies with Directed Technologies Inc. (DTI) to evaluate hydrogen supply options and fuel cell efficiency. The advantages of hydrogen operation are zero emissions from the vehicle and an efficiency improvement of about 50 percent over a vehicle with an on-board fuel processor; however, some of the efficiency benefit is reduced when hydrogen compression is considered.

Many of the fuel cell developers in the Ford DOE program are also participating in the development of POX/PEMFC systems. IFC is also working on a 50 kW gasoline powered POX/PEMFC vehicle power plant. This project team includes DOE, A. D. Little (Epyx), Texaco, UOP, and Modine. Ford has also worked with Plug Power on PEM stacks and fuel processor systems. Plug Power acquired fuel cell technology from in a joint venture with Mechanical Technology Inc. (MTI). This team with A. D. Little assembled a gasoline fueled POX/PEMFC system in October 1997.

Chrysler is pursuing the development of a multi-fuel POX system for PEMFCs. They are teamed with Allied Signal who is developing a PEMFC module for vehicles. A. D. Little (Epyx) is participating in the effort with their multi-fuel POX system. The fuel cell stack is packaged in a cylinder that fits in the tunnel formerly occupied by the exhaust system and drivetrain. Delphi Energy and Engine Management systems is also integrating a Ballard PEMFC with a gasoline fuel processor for Chrysler (Lancaster). At the 1997 Detroit Auto Show, Chrysler announced plans to complete a gasoline powered prototype vehicle for on-road operation in 1999.

DMFC's are not ready for vehicle demonstrations within the next 2 years since the technology requires further scale-up work. A near term goal for DMFCs might be a hybrid utility vehicle with a small 5 kW fuel cell.

9.2.2 Performance

The performance of fuel cell powered vehicles is limited by trade offs in system power and weight as well as limitations on hydrogen production during transients. Fuel cell EVs require hydrogen fuel as input to the fuel cell. The hydrogen must either be stored directly on-board in liquid or gaseous form, or produced on-board in a separate reformer unit from another fuel (such as methanol, natural gas, or other hydrocarbon fuels). Projections for commercial passenger cars with on-board reformer systems indicate a weight increase of 200 kg for a vehicle to achieve similar acceleration performance. Therefore, some design tradeoffs may result in performance characteristics that are different than those for gasoline cars. In general, electric drive vehicles have superior acceleration at low speeds since electric motors can operate at full power at the beginning of acceleration. This advantage in acceleration at low speeds can offset an increase in vehicle weight.

9.2.3 Emissions

Fuel cell EVs produce only water from the fuel cell itself; however, operating an on-board reformer would result in emissions. Actual emissions testing of fuel cell EVs remains to be done. Thus, it remains uncertain how the emissions of hybrid EVs and fuel cell EVs may compare with low-emission vehicle standards or with other low-emission vehicle (LEV) or ultra-low emission vehicle (ULEV) technologies.

A partial oxidation fuel cell system would consist of a fuel processor, fuel cell, and anode gas burner. The primary parameters which affect whether the vehicles can meet EZEV standards are hydrocarbon emissions during start-up and the performance of the anode gas burner catalyst in controlling start up emissions. During start up, the fuel processor burns fuel at near stoichiometric conditions and emissions from the cold combustor are much higher than those from a system that is warmed up. Emissions can be controlled with the catalyst in the anode gas burner. During normal operation, the operating temperatures in the fuel processor are very high and most hydrocarbons are dissociated.

Reformer start-up is likely to result in the largest source of hydrocarbon emissions. Depending upon the degree of hydrocarbon control from the catalytic burner, HC emissions of about 0.003 g/mi can be expected from optimized vehicles with reformer systems. NOx emissions would be less than 0.005 g/mi.

Availability/Cost

Daimler Benz has announced plans to sell commercial fuel cell powered cars by the year 2003. Vehicle production volumes may be as high as 100,000 cars at this time. DOEs program for fuel cell development is paying careful attention to fuel cell and reformer cost. DOEs goals are for systems that are in the same cost range as conventional vehicles.

Fuel cell powered vehicles will result in an improvement in fuel economy compared to conventional vehicles. Goals of tripling the vehicle fuel economy or 80 mpg cars are stated by DOE. These improvements in fuel economy are not entirely attributed to the fuel cell power system but also to reductions in vehicle weight. Fuel consumption will likely be at least 30 percent below conventional vehicles for POX systems. Vehicles with methanol steam reformers will be more efficient, however, methanol fuel will also be more costly than gasoline.

9.3 HEAVY-DUTY VEHICLES

9.3.1 Vehicle Technology and Equipment

Several fuel cell powered transit bus development programs are underway. The longest running project is headed by Georgetown University. The project was initially funded by the U.S. DOE, U.S. Department of Transportation (DOT), through the Federal Transit Administration (FTA) and the SCAQMD. This project initially focused on the development of a PAFC with a methanol steam reformer.

With funding from FTA, the Georgetown fuel cell bus project has moved into Phase IV. This phase seeks to commercialize 40-foot transit buses with Ballard and IFC supplying both PEMFCs and PAFCs fuel cell and reformer systems. An IFC PAFC system was engineered into a Novabus RTS chassis. The reformer is a high temperature design based on IFC's stationary natural gas powered fuel cell. Ballard (ddb) is developing a low temperature methanol steam reformer for use with their PEMFC. The fuel cell will also deliver 100 kW, and it will power a hybrid bus.

Ballard Power Systems has built a series of prototype dedicated hydrogen buses leading to a commercial product. Direct hydrogen fueling eliminates the need for a reformer, and allows the fuel cell engine to follow load transients well enough that supplemental batteries are not needed. Their Phase 3 bus carries 60 passengers and has a range of 400 km (250 mi). The planned range for commercial buses is 560 km (350 mi) and will have a passenger carrying capacity of 75 passengers (Ballard) In May 1997, Daimler-Benz unveiled its first dedicated hydrogen bus, called the NEBUS (new electric bus). The bus is also powered by the 205 kW Ballard PEMFC engine. The bus operates at various transit agencies in Germany.

9.3.2 Performance

The power and weight of fuel cell systems for transit buses suggests that performance will be similar to diesel powered vehicles. The fuel cell engine for the Ballard hydrogen bus produces 205 kW which is similar to the power achieved by diesel bus engines. Hybrid buses will likely weigh 1000 kg more than conventional buses due to the weight of the batteries and fuel cell power plant. The batteries for the Phase IV Georgetown bus with the IFC PAFC power plant weigh 1800 kg and the fuel cell power plant weighs 1700 kg. Even with increases in weight, hybrid buses can achieve design acceleration performance.

Braking may be an issue with heavier vehicles. Hybrid vehicles are likely to be equipped with regenerative braking which will eliminate much of the energy absorbing requirement from the friction brakes.

9.3.3 Emissions

Emissions from heavy-duty fuel cell powered vehicles will be much lower than those from diesel vehicles. Combustion occurs under lean conditions and relatively low temperatures so NOx emissions will be low. The waste gas from the fuel cell is burned which consists of a mixture of carbon monoxide and hydrogen. This fuel is not a precursor to particulate emissions.

Table 9-2 shows the emissions from several PAFC fuel cell systems with methanol fuel. Both the Fuji PAFC and the IFC PAFC power plants were tested with emissions reported on a g/kWh basis. CO and TCH emissions from the Fuji system are relatively high since supplemental methanol is burned in the reformer to maintain flame stability. The IFC system has a more advanced control system that allows the reformer to operate primarily on waste gas from the fuel cell. A bus with the Fuji PAFC was also tested with g/mi results. The emission levels are consistent with those from stationary fuel cell power plant tests.

Table 9-2. Emissions from methanol fueled PAFC power plants for bus applications

System	NOx	CO	THC	PM
Fuji PAFC Power plant (mg/kWh)	10	1800	160	NM
IFC PAFC Power Plant (mg/kWh)	ND	20	10	13
Fuji PAFC Bus (g/mi)	0.02	8.5	0.25	NM

9.3.4 Commercial Availability and Costs

The hydrogen powered Ballard bus is well on its way towards being a commercial product with demonstration vehicles operating on in Chicago and Vancouver. Hybrid systems with on-board reformers are undergoing development with prototype vehicles operating on the road in 1999. Data on the price of fuel cell powered buses is not available. Experience with hybrid buses indicates that a price premium of $100,000 may be anticipated where a conventional bus costs $250,000.

Hydrogen is readily available for dedicated applications such as transit bus fleets. Small scale partial oxidation or steam reforming systems can convert natural gas to hydrogen. Hydrogen Burner Technology currently sells commercial hydrogen generation systems based on partial oxidation of natural gas. The cost of hydrogen from natural gas is about $1.00/100 scf. On a cost per mile basis, hydrogen is about 50 percent more than diesel fuel.

9.3.5 Summary

Fuel cell powered vehicles have the potential to operate with very low emissions. The emissions could be so low that fuel cell vehicles could be placed in the same category as battery powered electric vehicles for emissions certification. This classification would make manufacturing fuel cell powered vehicle very attractive for automotive manufacturers.

Fuel cell technology is advancing rapidly for vehicle applications. But dedicated hydrogen powered fuel cells as well as systems with on-board reformers are being investigated. Partial oxidation of multiple fuels as well as autothermal reforming and steam reforming of methanol are on-board hydrogen supply options. Dedicated hydrogen vehicles would be true zero emission vehicles while vehicles with on-board reformers would emit at very low levels.

Hydrogen powered fuel cell buses are available commercially today. Prototype light- and heavy-duty vehicles with on-board methanol steam reformers are being built in 1997 with active development in the area of multi-fuel partial oxidation reformers for passenger cars and buses.

SECTION 10

DIMETHYL ETHER

10.1 GENERAL DISCUSSION

10.1.1 DME as a Motor Vehicle Fuel

Dimethyl Ether (DME), an oxygenated hydrocarbon, is the simplest compound in the class of ethers. It is produced from the catalytic reaction of carbon monoxide and hydrogen under similar conditions as methanol production. The synthesis gas can be produced from almost any carbon based feedstock. These include natural gas, coal, crude oil, oil sands, wood, straw, or crop residues. Present production relies almost completely on the use of natural gas. The largest current use for DME is as a propellant in aerosol spray cans. Approximately 100,000 to 150,000 tons per year are produced throughout the world.

The chemical formula for dimethyl ether is CH_3OCH_3, which is the same molecular composition as ethanol (C_2H_5OH). DME has a molecular weight of 46 and unlike ethanol, DME is not a polar compound and not readily soluble in water. DME is a gas under standard pressure and temperature but under modest pressure becomes a liquid. The vapor pressure for dimethyl ether is eight bar at 38 degrees C, which is similar to propane (LPG) whose vapor pressure is five bar. For automotive applications DME is used, like LPG, in its liquid state. DME is colorless and almost odorless. Dimethyl ether also has a low viscosity and is a powerful solvent.

DME is a low molecular compound. Consequently, it has poor lubricity compared to diesel fuel and a low viscosity. The lack of viscosity can result in a wear of fuel system components such as fuel pumps, injector internals, and injection pump components. AVL Engineering is conducting research in this area and has investigated the use of lubricity additives such as castor oil. Castor oil has met short term needs for AVL research, but lacks the long term viability needed for DME commercialization. The National Renewable Energy Laboratory (NREL) is looking further into the development of low cost lubricity additives. Fuel injector leaks have also been reported with DME. Similar fuel system issues were experienced with the DDC methanol engines. Due to DME's relatively new use as a fuel in CI applications, it can be expected that more development work and field demonstrations will need to be completed before DME engines become a commercial technology.

DME burns readily through compression ignition in a diesel engine without combustion modifications. Engine developers estimate it would have a cetane rating of 55 to 60. Conventional diesel fuel has a cetane number ranging from 46 to 55. Research has focused on the use of DME as a diesel substitute, additive to methanol for compression ignition (CI) engines, and cold start additive for methanol CI engines. Efforts to use DME in conjunction with heavy-duty methanol engines has not led to great interest in commercialization or demonstrations. The clean burning properties of DME make it a very attractive diesel substitute. It contains no sulfur and produces very low particulate emissions.

DME has a higher energy density than methanol or ethanol, but significantly lower than diesel. To achieve similar power outputs to those from diesel volumetric fuel flow must be 1.8 times as large.

Dimethyl ether was initially considered as an additive to methanol to improve its ignition characteristics. Many research programs used DME in combination with methanol engines. DME was investigated as a cold start additive for both CI and SI engines. Most approaches added DME into the inlet air. Many laboratory experiments tested engine operation without developing an on-board fuel system that carried both methanol and DME. On-board catalytic production of DME from methanol was also tested. Tests on a DDC 6V-92TA engine operating on methanol with 1 percent DME did not indicate improved ignition qualities with low levels of DME. Low level DME can operate with a conventional fuel system since the fuel's vapor pressure is raised to about 7 psi.

In 1995, Amoco, AVL List, Halder Topsoe, Navistar, and the Technical University of Denmark published papers detailing the benefits of DME's use as a replacement for diesel. Recent interest in this gas as an alternative fuel stems from promising findings in the areas of performance, production costs and emission reductions.

Interest in DME is motivated by the fact that it can be produced from a clean, efficient and renewable source. Although current production relies on natural gas, DME can be produced from biomass inputs. Since nearly all of the current DME synthesized comes form natural gas, the environmental impacts will be dependent upon processing natural gas and crude oil, any gas leaks which may occur in the distribution system to the processing facility and any emissions from combustion. However, if coal or biomass were to be used, mining activities and agricultural activities would need to be examined for impacts to the environment.

10.1.2 Infrastructure

No infrastructure currently exists for large scale production, transportation, storage, or distribution of dimethyl ether. Beyond production, little information exists on the exact costs associated with developing this infrastructure. It is anticipated that the infrastructure requirements for DME will be similar to those of propane (LPG), because of LPG's similar physical properties and its flammability. The current pipeline network used to distribute diesel is not appropriate for DME use because DME must be pressurized (similar to propane), but it is possible to use existing propane distribution networks.

Current production of DME is achieved through a process called methanol dehydration. The production process relies upon a two-step synthesis conversion of natural gas into dimethyl ether. DME is produced by first converting natural gas to methanol and then methanol to DME. Current production uses natural gas as the energy feedstock because its use represents the lowest energy and investment alternative in near term development.

Researchers at Halder Topsoe, a Danish research and engineering firm, have developed a one step process for DME production. This process relies upon the direct conversion of the natural gas into DME. The Halder Topsoe process reduces the steps in production and thus increases efficiency. Because of the similarities between methanol and DME production it is assumed that production costs will be similar. In the methanol production process synthesis gas preparation accounts for 50% of the total investment. If DME production occurs in one, rather than two steps, overall production costs can decline by 50%.

Air Products and Chemicals is developing the Liquid Phase Methanol (LPMEOH) process for producing methanol. The process converts synthesis gas into methanol over a catalyst in an oil based slurry. Air Products is investigating the production of DME with the LPMEOH process. Another potential source for DME is integrating the synthesis of DME with methanol production. New methanol facilities are under consideration to take advantage of remote natural gas resources in areas such as Russia and the middle east. DME production could be integrated with these facilities to maximize the efficiency of DME production. However, transport of DME from remote locations would require special tanker ships. DME can also be produced from coal based gasification processes. The Air Products LPMEOH process is an example of a process that can readily be adapted to DME and methanol production.

DME can be transported, stored, and distributed in its liquid or gaseous state. Because the fuel is a solvent some rubber products will be weakened if they come into contact with DME. Dimethyl ether is a stronger solvent than LPG, therefore the typical rubber hose used in LPG vehicles would not be suitable. AVL has found elastomers that can be used with DME. Unlike CNG or LNG, there is no need to use chilled storage tanks. The storage tanks would be similar to those used to store propane, with slight modifications to the seals.

Refueling of DME is accomplished in the same manner as LPG. The fill nozzle is connected to the vehicle fuel tank and a pump fills the tank with DME. The vapors in the vehicle storage tank condense as the liquid is added to the tank. Current LPG hardware uses an outage valve to indicate when the tank is 80 percent full. Fuel vapor escapes from the valve until liquid reaches the 80 percent level and is visible as a white mist. This liquid fuel indicates that the tank is sufficiently full. The outage valve is a significant source of hydrocarbon emissions which is much greater than the vehicle exhaust. LPG vehicles in the Netherlands are equipped with an automatic shut off feature that eliminates the outage valve emissions. This technology would need to be implemented in order to assure that hydrocarbon emissions from DME vehicles are low. Because DME has a lower volumetric energy content, DME refueling will take approximately 80 percent more time or three additional minutes for a light-duty vehicle.

10.1.3 Health and Safety Issues

Given the relatively limited history of DME development, little work has been done on the health and safety issues associated with its use as a vehicle fuel. Its on-vehicle storage hardware, vapor pressure and molecular weight are similar to LPG. DME vapors are flammable in the range from 3.0 to 18.6 percent compared with about 1.3 to 8.0 percent for LPG. These data indicate that about twice the concentration of DME is required to initiate an ignition at the outer periphery of a spill.

DME will be stored on-board vehicles as a liquid at ambient temperature. The storage pressure varies from 100 to 190 psi depending upon pressure. As a point of comparison, the maximum storage pressure for CNG is between 3,000 and 3,600 psi. The storage tanks do not vent during normal operation and would only release fuel during emergency situations. Overfilling the fuel tank or a fire in the vehicle can cause the fuel tank to vent when the fuel expands. Vented fuel would be released to the atmosphere. Experience with propane vehicle fires includes instances where vented fuel ignites during a fire and burns like a flare from the vent. The vented fuel continues to burn without causing a significant hazard until the fuel tank is empty.

Dimethyl ether is stored as pressurized liquid and is highly volatile making its transport and distribution, and particularly refueling potentially dangerous. Its lower explosive limit is reported to be 3.4% by volume in air. The lower limits for diesel, propane and gasoline are 1%, 2.2%, and 1.4% respectively. Like propane, DME is heavier than air which allows it to settle in low spots creating the potential for explosion. These characteristics may make DME's use better suited for fleet use where personnel are trained in the handling of the fuel.

Dimethyl ether has a high flashpoint, 232 degrees F compared with petrodiesel, 171 degrees F. DME burns with a visible flame over a wide range of air/fuel ratios. DME is easily degraded in the troposphere and has a tropospheric lifetime that has been calculated to be about six or seven days. DME is non toxic. Its extensive use as an aerosol provides us with a variety of toxicological data that demonstrate no adverse impacts as a result of its use. With few exceptions, leaks and spills of DME will present little environmental hazard because DME evaporates rather than percolating into groundwater. DME can be stored in above ground storage tanks that are identical to LPG storage tanks. The fuel is stored under pressure at approximately 100 psi (7 atm). The storage tanks are typically surrounded with pipe barriers for crash protection. Any leaks from the tanks would result in the fuel vaporizing and being released into the atmosphere as vapor.

Like propane, DME would be stored on the vehicle in thick-wall steel tanks. Because of the similarities between propane and DME researchers believe that crash and fire tests would yield similar results. Because DME has been tested in very few protocol vehicles crash and fire tests for the fuel are unavailable. Propane has been shown to be safer than gasoline in these tests. A common concern when using ethers like DME is their tendency to form peroxides upon contact with air and light, leading to spontaneous explosion. This risk of spontaneous explosion is reduced because DME forms very few peroxides compared to diethyl ether and is stored in pressurized tanks where contact with light and air is limited.

10.1.4 Costs

There are a variety of issues which serve to keep current fuel costs high. These include limited production technology, a lack of infrastructure and limited demand. With DME production occurring in small quantities and demand for use in vehicles nonexistent, shipping costs are substantial. At current production levels of 100,000 to 150,000 tons per year one gallon of dimethyl ether sells for approximately $2.27 per real gallon. If DME were produced from remote natural gas, its production cost would be similar to that of methanol from remote natural gas, about $0.35 per gallon. Transportation and storage costs would make DME more expensive than methanol. DME must be shipped under pressure and stored in pressure vessels throughout the distribution chain. Consequently, the wholesale price of DME, including bulk plant storage, overseas shipping, and distribution terminal storage would be as high as $0.55 to 0.75 per gallon (excluding taxes) if produced on a large scale basis. Since diesel contains 1.8 times the energy of DME, the cost of DME produced from remote natural gas will be about twice that of diesel on a per mile basis.

As of August 10, 1998 the tax-excluded price of gasoline was $0.66 cents per gallon and $0.54 cents per gallon for #2 diesel. Also, the volumetric energy efficiency is only about half that of petroleum fuels.

10.1.5 Suppliers and Backers

DME research is supported by a small group of companies. These are Amoco, Halder Topsoe, AVL List (parent company of AVL Powertrain Engineering), and Navistar. In addition to these companies, Air Products of Allentown, PA has developed a liquid phase reactor process capable of DME production. Both the DOE and NREL have taken limited roles in supporting the development of dimethyl ether. DOE is supporting development of fuel injection systems for compression ignition diesel (CID) engines fueled with DME, and expects to demonstrate the developed technology by Spring of 2000. This project is being conducted in conjunction with the Partnership for a New Generation of Vehicles (PNGV). NREL is sponsoring the development of a DME fueled Navistar engine to be tested by AVL Powertrain. Both DOE and NREL have contracted with AVL to pursue their DME research projects. NREL considers development of a commercially viable DME-fueled engine to be a long-term prospect. AVL is considering a demonstration program in Los Angeles, CA, but additional secured funding is needed.

10.1.6 Availability

Currently, dimethyl ether is not commercially available as a vehicle fuel. A variety of companies produce the product for use in aerosols, but none have yet entered the fuel market.

10.2 LIGHT-DUTY AND HEAVY-DUTY VEHICLES

There are currently no commercially available light or heavy-duty vehicles that can run on DME. Limited bench tests have taken place but no demonstrations have been undertaken. There are significant technological hurdles inhibiting the commercialization of DME fueled vehicles. These include development of a fuel system capable of safely transporting the fuel and development of a fuel injection system that can handle the unique characteristics of DME. DME's lower volumetric energy content requires twice as much fuel to be injected to achieve similar power outputs. Its lower viscosity and poor lubricity result in low durability. In addition, the significant vapor pressure and low viscosity can cause leakage through injection needle valves and pump seals. The high compressibility of DME and its high variability with temperature along with low viscosity can cause pressure oscillations and variable injection pressures. These challenges lead NREL to conclude that DME is a fuel with long term potential, rather than short term commercial availability.

An advantage of DME is its high cetane number, good vaporization characteristics, and low tendency to form soot. Consequently, DME injection can be accomplished at relatively low pressures (100 bar (1500 psi)) with good combustion results and low particulate emissions. Diesel injection pressures range from 200 to 700 bar and ultra high pressure injection systems are now in the range of 1300 to 2100 bar. A more expensive and complicated injection system can be avoided with DME. However, the NOx -PM tradeoff for DME is virtually nonexistent compared to diesel engines and it has an extremely short ignition delay (in fact, by one account, the cetane number is well above the 55-60 reported), and good vaporization characteristics, one can inject at very low injection pressures (100 bar) compared to the usual diesel application (1000 bar or higher). For heavy duty engines (Class 7 and 8 trucks, urban buses), this can give quite a fuel consumption benefit. The prasitic losses from the cam-driven unit injectors on most of the current Class 7, Class 8, and the DDC Series 50 bus engine are quite high (30 to 50 hp in some cases) in order to achieve injection pressures in the 1800 to 2100 bar region needed primarily for emissions purposes.

Bench tests of a 0.27L single cylinder diesel engine, a 2.0L 4 cylinder passenger car engine and a Navistar 7.3L V-8 direct injected turbo diesel have demonstrated that DME fueled engines can reduce emissions. Tests show that DME fueled engines produce less engine noise, lower emissions, almost no particulates, lower carbon monoxide and less hydrocarbon emissions. Because DME lacks sulfur, SO_2 emissions are also low. All results discussed refer to performance and emission tests on engines only, rather than on protocol vehicles. These tests were completed by AVL and Amoco.

Tests of the single cylinder engine demonstrated that NOx emissions are reduced by 25% when compared to diesel emissions. Engine smoke was at or below the detection limit, therefore the mass of particulate emissions was estimated to be below 0.1 g/kwhr.

Petroleum fueled diesel engine design is limited by trade-offs between PM, NOx and power output. Such low PM emissions from these initial tests using DME indicates that better power output and even lower NOx emissions may be possible in future DME engines before PM emissions might become significant. It may also be possible that some of the PM currently seen from DME may be related to the lubricating oil being used, so that improved oils may be helpful.

Through testing of a 2.0L 4 cylinder AVL LEADER engine AVL List demonstrated the potential for a passenger car engine to meet California's ULEV standards. Results of this testing showed NOx emissions to be 1/3 of those from diesel, just meeting the ULEV standard. NOx was emitted at 0.2 g/mi (the ULEV standard is 0.2 g/mi), while particulate matter emissions were reduced to unmeasurable quantities. With use of an oxidation catalyst, hydrocarbon emissions decreased to 0.04 g/mi and carbon monoxide emissions were reduced to 0.6 g/mi. Combustion noise was about 10db lower than a comparable diesel fueled engine.

Tests of the Navistar 7.3L engine reduced emissions to levels that were better than California's 1998 ULEV regulations for medium-duty vehicles. The engine produced full power while achieving totally smokeless operation (particulates 0.033 g-bhp/hr, the ULEV standard is 0.05). Emissions of non-methane hydrocarbons decreased to 0.21 g-bhp/hr (the ULEV standard is

1.3), carbon monoxide decreased to 3.2 g-bhp/hr (the ULEV standard is 7.2), NOx plus non methane hydrocarbons decreased to 2.4 g-bhp/hr (the ULEV standard is 2.5), and formaldehyde decreased to 0.022 g-bhp/hr (the ULEV standard is 0.025).

There are even fewer tests with published results detailing performance data. In those tests that discuss performance, it has been found to be largely unaffected with DME fuel. Tests of the 2.0 L engine showed a slight decrease in fuel consumption, from 36.0 mpg for diesel to 34.7 mpg for DME. Smooth compression ignition has been achieved in unmodified diesel engines that have been tested. Finally, dimethyl ether fueled engines have been successfully cold started at a temperature of -24 degrees C without ignition aids.

10.3 SUMMARY

There is a substantial amount of research to be done to bring dimethyl ether to the auto market. DME is a promising fuel for use in diesel engines but in order to become a realistic diesel alternative the infrastructure must begin to appear. Current capacity is almost non-existent relative to diesel consumption in America. For large-scale production to become economically feasible cheaper production technologies that are currently under development must be used. Demonstration projects using DME will also need to be undertaken before DME is widely accepted as diesel substitute. The use of DME in vehicle applications will not occur without changes to fuel injection system to accommodate the unique characteristics of the fuel. Given the relatively immature state of DME technology and research, much remains to be accomplished before the fuel will achieve large-scale commercial availability. Both DOE and NREL characterize DME as long-term prospects, unlikely to see widespread use in the next five to ten years.

SECTION 11

BIODIESEL

11.1 GENERAL DISCUSSION

11.1.1 Biodiesel as a Motor Vehicle Fuel

Biodiesel is the generic name for the family of diesel fuel alternatives produced primarily from seven agricultural feedstocks. Oil extracted from soybeans, rapeseeds, corn, cottonseeds, peanuts, and sunflower can be used to produce biodiesel. In addition, recycled cooking oil and animal fats may also be used. Research is currently under way to use oils created by aquatic plants to create biodiesel. Approximately 95% of biodiesel currently produced in the continental United States is derived from soybeans. Globally, producers choose the feedstock which is most abundant in the region. European and Canadian producers tend to use rapeseed as their feedstock. According to the DOE, world capacity for pure biodiesel production stood at 1.2 million tons in 1997.

The chemical definition for biodiesel is the mono alkyl esters of long chain fatty acids derived from renewable lipid sources. Chemical notation for biodiesel changes based upon the oil, alcohol and catalyst which are used. Biodiesel is produced through a catalytic chemical process called trans-esterfication using an alcohol, usually methanol, and a catalyst, typically sodium hydroxide. The alcohol is mixed with sodium hydroxide and the oil product. Mixing of these three ingredients produces glycerine, which settles, and fatty esters. These fatty esters are separated in two phases. Glycerol is removed in the first phase leaving an alcohol/ester mixture which is then separated. The alcohol is then recycled and the esters are purified creating pure biodiesel.

Use of agricultural feedstocks to meet diesel fuel needs is not a new development. Prior to World War II, South Africa produced biodiesel for its heavy-duty vehicles. South African production of biodiesel has been limited because of the abundance of cheap petroleum-based fuels. Agricultural crop production to make biodiesel requires land, fertilizers, pesticides, farm equipment, and water with the associated effects of fertilizer, pesticides and water. Cultivating oil producing crops can also decrease biodiversity found in local ecosystems if crops are grown in monocultures. If only one species of crop were grown in a large area, this could reduce the diversity of plant life in the region. After the crop has been grown and harvested it is then transported to a facility to be processed into oil, which is then turned into fuel. Most of the energy expended in biodiesel production occurs during the oil to fuel conversion process. This process requires alcohol which, in the U.S. is mostly methanol. Environmental impacts of methanol production should be taken into account and are specified in Section 2 of this report. Although hydrocarbon emissions from biodiesel fueled vehicles are reduced by 95% compared with conventionally fueled vehicles, total hydrocarbon levels are elevated compared with petroleum diesel because of agricultural and fuel processing. Biodiesel is four times faster to degrade than petroleum diesel and therefore, less of a threat to water resources.

Biodiesel offers several advantages, including: reduced emissions, biodegradability, and an abundance of homegrown, renewable sources for the creation of the fuel. Biodiesel has many fuel and combustions properties similar to those of diesel. The similarities to diesel allow this alternative fuel to use the same transportation, storage, and distribution infrastructure. Biodiesel is sold in its pure form, as a blended fuel with petrodiesel, or as an after market additive that diesel engine owners may add to their diesel fuel purchased at the pump. Blended biodiesel is referred to as B20, or 20% biodiesel and 80% petrodiesel. Pure biodiesel is commonly referred to as biodiesel, B20 is called blended biodiesel, and additives are referred to as additives. Currently, low-level biodiesel blends (5% or lower), known as premium diesel, are sold in the highest volume.

The similarities between diesel and biodiesel make biodiesel an alternative to diesel. Biodiesel can reduce emissions with no changes to vehicle engines, parts inventories, or refueling infrastructure. In order to achieve the reductions in carbon monoxide, particulate matter, hydrocarbons and sulfur oxides that are discussed in the following sections engines must be optimized through timing changes and use of an oxidation catalyst. No special training is required for mechanics who repair the engines running on biodiesel products. With minor changes to timing and possibly to fuel lines in older engines, vehicle operators using diesel fuel can substantially reduce their engine emissions. According to DOE, "biodiesel is a biodegradable transportation fuel that contributes little, if any, net CO_2 or sulfur to the atmosphere, and is low in particulate emissions."

The energy density, as measured by BTUs per gallon, of soy-based biodiesel is 132,902 BTUs which is similar to petrodiesel's energy content of 128,400 BTUs. Gasoline's content is 115,000 Btus. Energy content varies based on the type of oil used and the purity of the production process.

Biodiesel has a high flashpoint and therefore a low volatility, providing a high degree of handling safety. Through demonstration programs it appears that impacts upon performance are limited, and mostly related to differences in energy content of the fuels at the outset. Inconsistent biodiesel blend quality and production have resulted in performance impacts such as loss of engine torque and increase in fuel consumption, which vary from demonstration to demonstration. There is no consistent discrepancy in performance due to changes in the make-up of various biodiesel fuels used. Although testing of biodiesel has been successful much work remains to be done. This work includes improving production efficiency through reductions in production time, greater consistency of fuel quality across all biodiesel products, and studies of long-term performance.

Pure biodiesel is currently designated as an alternative fuel under EPAct, however blended biodiesel (B20) is not currently included in this fuel designation. Bills have been introduced in both the Senate and the House of Representatives to establish the status of B20. There have been two regulatory approaches put forth to handle B20 classification. One approach would give B20 "alternative fuel" status under EPAct. Another approach would provide fleet operators with AFV credits if they used specified threshold quantities of B20 in their fleets. In addition to congressional action, the Department of Energy has been considering a proposed rulemaking to add blended biodiesel to the list of "alternative fuels" under EPAct. Congressional legislation or the DOE rulemaking must occur for B20 to be considered for credits or inclusion under EPAct.

11.1.2 Infrastructure

The production process is hampered by the need to produce the fuel in batches that must be mixed for between 1 and 8 hours. The quantity produced is limited by the number of mixing vessels available for mixing of the oil, alcohol, and catalyst. Batch production leads to significantly higher capital investment for equipment than continuous, in the pipe, production. This raises production costs and reduces efficiency.

Researchers at the University of Toronto have begun to perfect an improved production process that would allow continuous production. This new process will allow the chemical reaction to occur continuously in the pipes of the production facility, rather than in reactor vessels. Without a reactor vessel process time and capital expenditures are reduced. This is a recent development and it is unlikely that it will be commercially feasible for some time.

Another technological development that should result in lower costs and improved market penetration of biodiesel products is the development of an automated technique for quantifying the quality of biodiesel produced. Current technology requires that samples of fuel be taken to a laboratory for analysis. This testing process is both expensive and cumbersome. Researchers at the USDA Peoria Laboratory have developed a technique that uses fiber optics to examine the quality of fuel produced instantaneously.

Production of biodiesel in the United States is concentrated in the Midwest and coastal regions. Biodiesel is predominantly used by boat owners, farmers, and bus operators. Farmers use biodiesel in expensive combines and other machinery where the lubricity enhances the life of the machines. Boating may be a good application for biodiesel because of its ability to degrade in aquatic environments and reduce smoke emissions. Most biodiesel marketing to consumers has taken place in the marine environment, where both pure and blended biodiesel is available at many marinas throughout the country. Two products, Soyguard and Soyshield, have been introduced in the Midwest as fuel additives that allow consumers to create their own blended biodiesel. Limited marketing tests of SoyGold, a biodiesel product blended at the pump, have begun to take place at Midwestern farm cooperatives. As of spring 1997, there were 10 Midwestern cities with SoyGold available at their pumps.

Transportation via truck and railcar, storage in tanks and distribution through the pump systems are the same for biodiesel and petrodiesel with one exception; biodiesel's solvent effect precludes its storage in concrete lined tanks. Because of biodiesel's compatibility with the existing infrastructure, one of the biggest challenges for market penetration is the provision of space for the product in tanks and at the pump by shippers and retailers. As a result biodiesel producers have sought to build their market through sales of additives to vehicle owners, which are sold through retail outlets.

11.1.3 Health and Safety Issues

Biodiesel is toxic and can cause health problems if ingested. However it can be considered less of a safety hazard, as compared to other alternative fuels, while maintaining the energy characteristics which make petrodiesel attractive. Biodiesel is biodegradable reducing the impacts of inadvertent release, has a high flashpoint increasing margins of safety in fuel handling, and a low toxicity lessening health risks.

In tests conducted at the University of Idaho pure biodiesel degraded in an aquatic environment four times faster than petrodiesel, while blended biodiesel degraded three times faster than diesel alone. After 28 days in an aquatic environment pure biodiesel was 85% degraded while petrodiesel was only 28% degraded. A California firm, Cytosol, has been marketing the use of biodiesel as a solvent to aid in the cleanup of oil spills, applying the fuel to spills to speed oil breakdown. Because of the biodegradable nature of this fuel the risks resulting from a fuel spill appear to be significantly reduced.

The flashpoint of biodiesel is substantially higher than that of petrodiesel. The flashpoint for pure biodiesel is 267 degrees F compared with 171 degrees F for #2 diesel (most common fuel used for diesel powered motor vehicles). When biodiesel is mixed with petrodiesel, the flashpoint is reduced proportionally. The high flashpoint is indicative of a fuel product that can provide a higher margin of safety for handling and storage because biodiesel does not produce explosive air/fuel vapors.

A review of toxicological tests undertaken by Southwest Research Institute (SwRI) has demonstrated that biodiesel's use represents a substantially lower toxic, mutagenic, and carcinogenic threat than diesel. The potential health impacts of using biodiesel are less than those associated with the use of petrodiesel because of the fuel's increased biodegradability and its lower toxicity.

11.1.4 Costs

The cost of biodiesel fuel is affected by the cost of the agricultural product being used as the feedstock. Production efficiency is limited by the need to use a batch process in order to allow for the chemical reactions of trans-esterfication which can take between 1 and 8 hours. Assuming large scale production there are no other cost differences between biodiesel and gasoline or petrodiesel beyond the production costs. Production costs include the cost of the feedstock, methanol and catalyst. Beyond costs of production biodiesel's shipment, storage and distribution costs would be the same as those costs associated with gasoline or diesel assuming large scale production.

Pure biodiesel currently costs about $3.00 per gallon primarily due to limited production capabilities and higher shipping costs associated with the small quantities being shipped. Blended biodiesel averages 20 to 40 cents more per gallon than petrodiesel. DOE and USDA estimate large-scale production would reduce the cost of pure biodiesel to $1.50 to $1.60 per gallon, using today's technology. In addition, researchers at the National Renewable Energy Laboratory (NREL) are hopeful that biodiesel produced from microalgae may cost as little as $1.00 per gallon. This is compared to a tax-excluded price of 66 cents per gallon for gasoline and 54 cents per gallon for #2 diesel as of August 10, 1998.

Producers are likely to choose feedstocks that can be used in biodiesel production so that costs can be somewhat controlled. According to the *Alternative to Traditional Transportation Fuels 1996*, producers can choose the "most economical feedstock dependent upon oil yield per acre, product quality, byproduct values, geography, and government policies."

11.1.5 Suppliers/Backers

Soybean growers associations and states in soy producing regions form the backbone of the coalition that supports the use of biodiesel. Support for biodiesel production is spearheaded by the National Biodiesel Board, headquartered in Jefferson City, MO.

Biodiesel is produced by five companies in the United States. These are NOPEC Corporation of Florida, Twin Rivers Technology of Massachusetts, Agricultural Environmental Products of Kansas, Columbus Foods of Illinois, and Pacific Biodiesel of Hawaii. Together NOPEC Corporation and Twin Rivers Technologies are capable of producing 60 million gallons per year, while the remainder are capable of producing a total of 7.65 million gallons per year. While biodiesel capacity for production stands at 67.65 million gallons, only 3.5 million gallons are produced each year. There are also regional operations, such as Columbus Foods, a cooking oil supplier, that recycles spent cooking oil at a biodiesel plant it helped to build in a disadvantaged section of Chicago. The plant created 120 jobs while giving the company a productive outlet for cooking oil that would otherwise be wasted. The biodiesel that is produced is then used in city transit buses. The project is a demonstration project under the Office of Transportation Technologies at DOE.

11.1.6 Availability

The United States capacity for biodiesel production is currently 67.65 million gallons per year. As a point of comparison 1996 U.S. consumption of #2 diesel was 38.5 billion gallons/ year. Biodiesel capacity will need to grow significantly before it can have a significant impact on overall diesel consumption, given the large discrepancy between biodiesel capacity and U.S. consumption of #2 diesel.

According to DOE, "up to ten percent of the total U.S. diesel fuel consumption could be replaced by biodiesel made from animal and vegetable oils." Currently, U.S. farmers produce about

2.7 billion bushels of soybeans each year. One bushel of soybeans produces about 1.5 gallons of biodiesel, therefore complete devotion of soybean crops would yield approximately 4 billion gallons of pure biodiesel or 20 billion gallons of blended fuel. More realistically, it is worth noting that current soybean surpluses stand at 200 million bushels per year, indicating that 1.5 billion gallons of B20 could be produced from use of surplus supply. The USDA 10-year outlook forecasts soybean production and surpluses to continue at these levels for the next ten years.

11.2 LIGHT-DUTY AND HEAVY-DUTY BIODIESEL VEHICLES

11.2.1 Vehicle Technology

Any light-duty or heavy-duty vehicle powered by a diesel engine could run on pure biodiesel with little or no engine modification. Therefore, there is little need for automakers to alter vehicle designs or to offer different engines in order to facilitate the operation of biodiesel fueled vehicles. Due to biodiesel's solvent characteristics engines in older model vehicles (prior to MY 1994-95) may need to change fuel lines and other rubber components which come into contact with the fuel. Most new model engines have installed rubber tubing, commonly Dupont Viton B, capable of handling fuels with biodiesel's solvent characteristics. However, in order to achieve the emissions reductions engines must be optimized by slightly adjusting the engine's timing and using a oxidation catalyst.

Although there have been numerous demonstration projects with heavy-duty vehicles, there have been relatively few demonstrations undertaken with light-duty cars and trucks. The National Biodiesel Board has contracted with SwRI to examine emissions and performance characteristics of both light-duty and heavy-duty trucks. Under 40 CFR part 79 subpart F a set of testing protocols for the fuel and fuel additive testing program are defined. SwRI conducted these tests to provide EPA with data to assess the impact of biodiesel use on potential emission risks posed by vehicle exhaust. SwRI utilized three engines, a Cummins N14 (rated power 276 kW), a Detroit Diesel Series

50 (rated power 205 kW) and a Cummins B5.9 (rated power 119 kW), in the tests while testing a variety of fuel compositions.

11.2.2 Performance

SwRI found that engine performance was only slightly affected through the use of biodiesel. The biodiesel used in the test had seven percent less volumetric energy content than diesel which resulted in a seven percent loss of available torque. Testing with blended biodiesel demonstrated a two percent decrease in available torque which corresponds with the improved energy content of the blend over pure biodiesel. Fuel consumption was also negatively affected with use of pure biodiesel. The N14 and Series 50 engines consumed 13% more fuel while the B5.9 consumed 17% more. In tests with blends the N14 and Series 50 showed no change in fuel consumption compared to diesel, while a six percent increase in consumption was observed with the B5.9 engine. The change in fuel consumption was most apparent in the Cummins B5.9 engine that was tested. Researchers speculate that this loss in efficiency could be related to fuel injection differences between the larger Detroit Diesel Series 50/ Cummins N14 and this engine. Finally, catalytic converter efficiency was improved due to biodiesel's decreased soot content.

Although biodiesel appears to have limited performance impact, there are shortcomings related to its use in colder climates. Biodiesel's cloud point is zero degrees Celsius versus petrodiesel which has a cloud point near negative 15 degrees Celsius. Blended biodiesel raises the cloud point of petrodiesel between one and three degrees Celsius. Biodiesel users in colder climates would need to alter fuel blends, use fuel heaters, or store the vehicles indoors in order to prevent frequent fuel flow problems. This reduced flow tendency is a potential added cost to users operating vehicles in colder climates.

The issue of cloud point is also of concern in terms of storage costs for biodiesel. The cost is similar to that of diesel storage. Petrodiesel storage in cold climates currently uses a heating mechanism to ensure that diesel stays warm, this mechanism would also be used for biodiesel.

The biodiesel industry, in partnership with government agencies and university researchers has sponsored more than 100 demonstrations, including three, one million mile tests and thirty 50,000 mile tests. Pure and blended biodiesel powered vehicles have logged over 10 million road miles. Engine wear has not been shown to be adversely affected.

11.2.3 Emissions

SwRI conducted tests of a Cummins N14 (rated power 276 kW), a Detroit Diesel Series 50 (rated power 205 kW) and a Cummins B5.9 (rated power 119 kW) in order to meet requirements under 40 CFR part 79 subpart F, which defines testing requirements for fuel registration. These engines were fueled with pure biodiesel, B20 and #2 diesel. Tests were conducted with and without catalysts. Emissions were measured over the U.S. EPA heavy-duty transient Federal Test Procedure. The results of SwRI's tests support the findings of other researchers who have undertaken similar testing using engines of varying size and make. Test results are on a pollutant by pollutant basis.

The chart below illustrates the baseline tests of the Cummins N14 running on #2 diesel, pure biodiesel, and B20. The Cummins N14 engine running on #2 diesel found hydrocarbon emissions to be 0.23 g/hp-hr, carbon monoxide to be 0.75 g/hp-hr, NOx to be 4.57 g/hp-hr and particulate matter to be 0.106 g/hp-hr. The same engine on pure biodiesel reduced hydrocarbon emissions to 0.01 g/hp-hr, carbon monoxide to 0.41 g/hp-hr and particulate matter to 0.076 g/hp-hr. NOx emissions increased to 5.17 g/hp-hr. When this engine was tested with B20 hydrocarbon emissions were 0.19 g/hp-hr, carbon monoxide were 0.64 g/hp-hr, particulate matter to 0.102 g/hp-hr and NOx emissions were 4.76 g/hp-hr. Comparisons between pure biodiesel and #2 diesel on the Cummins

N14 engine show a 95 percent reduction in hydrocarbons, a 45 percent reduction in carbon monoxide, a 28 percent reduction in particulate matter, and a 13 percent increase in NOx emissions.

Table 11-1. Cummins N14 Engine

	#2 Diesel	Pure Biodiesel	B20
Hydrocarbon	0.23 g/hp-hr.	0.01 g/hp-hr.	0.19 g/hp-hr.
CO	0.75 g/hp-hr.	0.41 g/hp-hr.	0.64 g/hp-hr.
NOx	**4.57 g/hp-hr.**	**5.17 g/hp-hr.**	**4.76 g/hp-hr.**
PM	0.106 g/hp-hr.	0.076 g/hp-hr.	0.102 g/hp-hr.

Baseline test results for the Detroit Diesel Series 50 engine with an oxidation catalyst produced hydrocarbon emissions of 0.03 g/hp-hr, carbon monoxide to be 1.43 g/hp-hr, NOx to be 4.51 g/hp-hr and particulate matter to be 0.075 g/hp-hr. When this engine was tested using pure biodiesel and a catalyst hydrocarbon emissions decreased to 0.02 g/hp-hr, carbon monoxide decreased to 0.76 g/hp-hr, particulate matter decreased to 0.03 g/hp-hr and NOx emissions increased to 4.90 g/hp-hr. Using B20 and an oxidation catalyst this engine's hydrocarbon emissions increased to 0.04 g/hp-hr, carbon monoxide decreased to 1.24 g/hp-hr, particulate matter decreased to 0.059 g/hp-hr and NOx emissions increased to 4.63 g/hp-hr. Comparisons between pure biodiesel and #2 diesel on the Detroit Diesel Series 50 engine show a 33 percent reduction in hydrocarbon, a 47 percent reduction in carbon monoxide, a 60 percent reduction in particulate matter, and a nine percent increase in NOx emissions.

The Cummins B5.9 running on #2 diesel with an oxidation catalyst produced hydrocarbon emissions of 0.19 g/hp-hr, carbon monoxide to be 1.52 g/hp-hr, NOx to be 4.75 g/hp-hr and particulate matter to be 0.077 g/hp-hr. On pure biodiesel with an oxidation catalyst this engine decreased hydrocarbon emissions to 0.06 g/hp-hr, carbon monoxide to 0.95 g/hp-hr, particulate matter to 0.04 g/hp-hr and increased NOx emissions to 4.91 g/hp-hr. Using B20 and an oxidation catalyst the Cummins B5.9 hydrocarbon emissions were 0.15 g/hp-hr, carbon monoxide were 1.21

g/hp-hr, particulate matter to 0.069 g/hp-hr and NOx emissions were 4.88 g/hp-hr. Comparisons between pure biodiesel and #2 diesel on the Cummins B5.9 engine show a 68 percent reduction in hydrocarbon, a 38 percent reduction in carbon monoxide, a 48 percent reduction in particulate matter, and a four percent increase in NOx emissions.

These test results demonstrate that biodiesel use was associated with lower emission of hydrocarbons, carbon monoxide and particulate matter compared to #2 diesel. According to SwRI these lower emission levels may be due to the fact that biodiesel contains about ten percent oxygen by weight. This oxygen helps to oxidize these combustion products in the cylinders. It is apparent that emission reductions vary with the type of fuel and engine used. Emission reductions can be achieved through the use of pure biodiesel or B20. Use of blended or pure biodiesel also increases NOx emissions.

11.2.4 Availability

Vehicles of all types are readily available to be operated with pure or blended biodiesel. The cost of these vehicles is not significantly different from their petrodiesel counterparts. As has been stated, most new automobiles contain rubber products capable of withstanding the solvent characteristics of biodiesel.

11.3 SUMMARY

Biodiesel currently costs 20 to 40 cents per gallon more than petrodiesel. But economies of scale should reduce the cost of biodiesel. Also the fuel must be readily available and a supply must be assured. The use of biodiesel can help reduce several emissions from heavy-duty vehicles and engine, fuel, and exhaust systems do not need to be redesigned. One current problem is the high clouding point of biodiesel which affects cold weather operation.

SECTION 12

FISCHER TROPSCH

12.1 GENERAL DISCUSSION

12.1.1 Fischer Tropsch Liquids as Motor Fuels

The Fischer Tropsch (FT) process (synthesis gas converted over a Fischer Tropsch catalyst) produces hydrocarbons which can be used as vehicle fuels. The FT process was originally developed in Germany in the 1920s to produce fuel from coal. FT plants are also operating in South Africa to make synthetic gasoline from coal. The FT process has three principal steps. First, a feedstock must be converted to synthesis gas, a mixture of carbon monoxide and hydrogen. Potential feedstocks include coal, biomass, and natural gas. A catalytic reactor converts the synthesis gas to hydrocarbons in the second step. The mixture of hydrocarbons consists of light hydrocarbons and heavier waxes. The majority of the hydrocarbons are saturated. In the third step, the mixture of hydrocarbons is converted to final products such as synthetic diesel fuel.

FT plants are currently being constructed to use remote natural gas as a feed stock. FT fuels can potentially be produced from renewable sources such as biomass. Currently, the most economically attractive production option for FT diesel fuel is chemical synthesis from remote natural gas. Natural gas is reformed to produce carbon monoxide and hydrogen which is converted to a liquid fuel with a FT catalyst.

FT diesel is a superior fuel for compression ignition engines. It contains virtually no sulfur or aromatics. Its cetane number is 75 compared to 50 for high quality diesel fuels. Both sulfur and aromatics are related to particulate production in diesel engines, while a high cetane number generally results in lower NOx emissions.

The volumetric heating value of FT diesel is slightly lower than that of conventional diesel fuel since it has a higher hydrogen to carbon ratio. Similarly, it has a higher energy content than conventional diesel fuels on a MJ/kg basis. The fuel is colorless and odorless and miscible with conventional diesel fuels.

12.1.2 Infrastructure

South Africa and Russia have been operating coal based FT plants since the 1950's. Typical units produce 5,000 to 13,000 bbl/day of synthetic fuel and provide a substantial portion of South Africa's fuel. Natural gas is converted to synthesis gas by reforming the feedstock with steam and oxygen. Natural gas is the simplest feedstock to convert to synthesis gas since it is gas and does not need to be processed in a gasifier. This synthesis gas is over 90 percent carbon monoxide and hydrogen with traces of methane and nitrogen. The FT reactor uses iron or cobalt catalysts in a fluidized bed reactor. Excess heat from the FT reactor produces steam for the reformer. Additional thermal energy can be used to generate steam to produce electric power or provide other process heat requirements such as powering desalinization plants. Wax is converted to liquid fuels by reacting with hydrogen in the final step of the process. The energy ratio (fuel output/feedstock input) for a natural gas to FT diesel plant is about 56 percent (HHV basis). This value does not include uses for excess thermal energy.

More recently, major oil companies have been constructing FT plants which operate on remote natural gas. Shell Malaysia completed at 10,000 bbl/day plant that produces middle distillates and paraffins in 1994. In 1997, ARCO announced plans to build a small scale gas to liquids plant on the West Coast of the U.S. Texaco also announced plans to build a mobile plant that will produce synthetic diesel on a commercial basis. Exxon is expected to site a 100,000 bbl/day plant in Qatar. FT plant capacity could be over 2 millions bbl/day by 2005. Plants operating on both remote natural gas as well as North American gas are possible. An FT diesel plant in Alaska could produce fuels that could be sent to market down the 800 mile trans-Alaska pipeline. The production of such fuels could make up for declining oil production. In 1997, Tosco and Paramount Petroleum also blended Shell's FT diesel to produce clean diesel for sale in California.

FT diesel fuel can be transported in conventional product tankers. Bulk storage, product blending, truck delivery, and local product dispensing can be accomplished with existing infrastructure. If pure FT diesel fuel is sold as a separate product, refueling stations will need to reallocate their inventory of local storage tanks or install additional storage and dispensing equipment.

FT diesel is likely compatible with existing dispensing equipment and vehicle fuel systems. However, fuel compatibility issues have not been widely documented. Some fuel compatibility problems were identified when low aromatic diesel fuels were introduced in California. Problems appeared to occur on older model diesel engines with a specific type of fuel system, but documentation on these types of engine problems is not comprehensive.

12.1.3 Health and Safety Issues

No health and safety issues are likely to be encountered with FT diesel fuels. The fuel meets diesel specifications. The vapor pressure will likely be similar to that of diesel thus resulting in similar flammability properties. Ingestion, dermal absorption, or other exposure effects are likely to be similar to that of diesel fuel. FT fuels may be less distasteful than conventional diesel which could potentially lead to increased accidental or intentional ingestion; however, such exposures are rare.

12.1.4 Costs

The cost of FT diesel fuels vary with geographic locations and other factors. Feedstock costs, capital and operating costs, facility size, and local conditions such as taxes and available uses for waste heat energy affect the cost of the fuel. Remote natural gas is sometimes valued at about $0.5/MMBtu to take into account collection costs. This cost component corresponds to $0.12/gal fuel. The total cost of FT diesel fuel is likely between $0.30 and $0.50/gal at the refinery (plant) gate depending upon the allocation of costs to other oil production activities as well as interest rate considerations. These are costs per gallon of FT fuel, wholesale terminal cost. Additional costs of transportation and storage would add another $0.10 to $0.15 per gallon. Therefore the wholesale price of FT diesel might be $0.40 to 0.65 per gallon. In 1998, the price of home heating oil (#1Diesel) ranged from $0.36 to $0.45 per gallon.

The cost of FT fuels could be similar to that of methanol and DME. Feedstock costs per gallon are lower for methanol and DME since the fuels have a lower energy density. Transportation costs for FT diesel would be the same or slightly cheaper than methanol. The plant equipment for methanol, DME, and FT fuels are similar.

12.1.5 Suppliers/Backers

Major oil companies are supporting the development of FT fuels or gas to liquids (GTL) products. Shell, Exxon, Texaco, and ARCO have built or are planning to build production facilities. Oil Companies own many of the natural gas fields in the world and are interested in finding a market for the fuel. Exxon included an article describing its GTL technology in their 1998 publication for shareholders which illustrates their interest in the technology.

FT fuels are attractive to oil companies since they improve the quality of diesel and make use of their natural gas resources. These fuels are also attractive since they can be used in existing vehicles.

12.1.6 Fuel Availability

FT fuels will become more widely available as more facilities are constructed to take advantage of low cost remote natural gas. The growth of the market may depend on the price of oil, since the cost of producing FT fuels does not drop significantly with a drop in the price of oil. FT fuels will likely be blended to produce high cetane, low aromatic diesel before they are sold as pure clean fuel alternatives. The blending approach allows for a build up of production and bulk storage capacity. Though some accommodation may be necessary, if a demand for pure FT fuels develops, the infrastructure will be in place.

12.2 LIGHT- AND HEAVY-DUTY VEHICLES

12.2.1 Vehicle Technology and Equipment

Existing compression ignition (CI) engines can operate on FT diesel without modification. Additional engine modifications could result in further emission reductions if the use of dedicated FT fuels is possible.

12.2.2 Performance

Since FT fuels are similar to conventional diesel, no significant difference in performance should be observed. Smoke emissions will be lower which may allow smoke limiting devices to be relaxed in order to achieve improved acceleration. The volumetric density of FT diesel is slightly lower than that of conventional diesel which may affect fuel economy and acceleration. The higher cetane number of FT diesel may result in improved combustion which could offset the effect of energy density on fuel economy and acceleration.

Many studies have been conducted on the effect of diesel fuel properties on performance and emissions. Substantial changes in fuel efficiency have not been observed.

12.2.3 Emissions

FT fuels provide a reduction in conventional CI engines without modifications. Increasing Cetane number has been shown to result in a linear reduction in NOx emissions while sulfur and aromatics are known to contribute to particulate emissions. PM reductions are likely related to the molecular structure of the fuel compounds (which affect cetane and distillation properties in addition to PM). The fuel is virtually aromatic-free, which could somewhat reduce soot agglomerate formation and might reduce formation of some air toxics (PAHs, n-PAH). The lack of aromatics also is part of the reason for high cetane number. The NOx decrease, however, is likely from the shorter ignition delay and reduced pre-mixed combustion and perhaps the PM and NOx results reported.

A comparison test of FT diesel with conventional #2 diesel on a heavy duty DDC Series 60 engine was performed by Southwest Research Institute (SwRI). Injection timing was not changed on the engine. The FT diesel resulted in 8 percent lower NOx emissions, 30 percent lower particulate emissions, 38 percent lower HC emissions, and 46 percent lower CO emissions when compared to the engine operating on a fuel representing the national average diesel fuel.

Engines modifications are also possible to provide further emission reductions. FT diesel enables many engine modifications since the fuel has no sulfur which affects catalyst performance and the low aromatics content and high cetane number result in low particulate.

Engine modifications could include injection timing changes, exhaust gas recirculation (EGR), and oxidation catalysts. Timing modifications allow for a reduction in NOx, however advancing injection timing is associated with an increase in particulate emissions which would be mitigated by the FT diesel fuel properties. EGR is generally thought to be challenging with conventional fuels since particulate formation affects the performance of EGR systems.

12.2.4 Availability and Costs

A fleet of existing CI engines can use FT diesel fuel without any cost for vehicle modifications. Research is also underway to reduce CI engine emissions with advanced technologies. The feasibility of most advanced diesel technologies might require an improvement in fuel quality which could be provided with FT diesel. Using pure FT diesel fuel may affect the fuel systems of some older engines. Some vehicles reportedly experienced problems with seals when clean diesel fuel was introduced in California; however, documentation on these problems is not thorough or comprehensive.

Advanced diesel technologies may be available by the year 2004 to meet new diesel emission standards. In 1996, the Engine Manufacturers Association signed a Statement of Principle which called for emission reductions for heavy-duty diesel engines for the year 2004. A target standard included a NOx limit of 2.5 g/bhp-hr if a clean diesel fuel is available and 3.5 g/bhp-hr if a clean fuel is not available. The improvements in fuel quality that contribute to the emissions reduction were expected to be reduced aromatics and increased cetane number.

The cost of low emission CI engines will include components such as high pressure fuel injection systems which are already being incorporated into diesel engines. Therefore there would be no incremental cost of this technology. More advanced technologies such as exhaust gas recirculation would likely be used in the largest class of heavy duty engines and may add additional cost to the engine. FT diesel fuels will also enable the use of oxidation catalysts to control unburned fuel in the exhaust. Such catalysts are already included on some diesel engines and may not represent an incremental cost.

12.3 SUMMARY

Conventional CI engines can operate on FT diesel without modifications. The fuel change resulted in an 8 percent reduction in NOx and a 30 percent reduction in particulate. FT diesel has superior properties (low sulfur, low aromatics, high cetane number) which allows for more advanced technologies for CI engines. NOx emissions as low as 2.5 g/bhp-hr are achievable with advanced engine technologies and clean fuels such as FT diesel.

Oil companies have recently invested in facilities to produce FT diesel from natural gas. These facilities take advantage of remote natural gas resources and also produce a fuel that improves the quality of current diesel fuels.

SECTION 13

FLEET EXPERIENCES

13.1 BACKGROUND

The total number of alternative-fueled vehicles (AFVs) in use is expected to reach nearly 403,000 by the end of 1998 representing a 6.9 percent increase from 1997. The total includes AFVs produced by original equipment manufacturers (OEM's) by converting vehicles that were originally designed to operate on gasoline or diesel fuel. The following table presents the distribution of light- and heavy-duty vehicles by fuel and year.

Table 13-1. Estimated Number of Alternative-Fueled Vehicles in Use in the United States, by Fuels and Weight Category, 1994, 1996, and 1998

	1994			1996			1998		
Fuel	Light Duty	Heavy Duty	**Total**	Light Duty	Heavy Duty	**Total**	Light Duty	Heavy Duty	**Total**
Liquefied Petroleum Gases [a] (LPG)	212,000	52,000	264,000	210,000	53,000	263,000	*223,000*	*56,000*	*279,000*
Compressed Natural Gas (CNG)	35,970	5,257	**41,227**	50,270	9,874	**60,144**	*68,734*	*16,388*	***85,122***
Liquefied Natural Gas (LNG)	94	390	**484**	127	536	**663**	*267*	*869*	***1,136***
Methanol, 85 Percent [b] (M85)	15,376	108	**15,484**	20,259	6	**20,265**	*21,364*	*6*	***21,370***
Methanol, Neat (M100)	0	415	**415**	0	172	**172**	*0*	*172*	***172***
Ethanol, 85 Percent [b] (E85)	605	0	**605**	4,536	0	**4,536**	*10,872*	*0*	***10,872***
Ethanol, 95 Percent [b] (E95)	2	31	**33**	0	361	**361**	*0*	*357*	***357***
Electricity	2,163	61	**2,224**	3,126	154	**3,280**	*4,562*	*199*	***4,761***
Non LPG Subtotal	54,210	6,262	**60,472**	78,318	11,103	**89,421**	*105,799*	*17,991*	***123,790***
TOTAL	**266,210**	**58,262**	**324,472**	**288,318**	**64,103**	**352,421**	***328,799***	***73,991***	***402,790***

[a] LPG values are rounded to thousands.
[b] The remaining portion of 85-percent methanol and both ethanol fuels is gasoline.
Note: Weight classes are based on Environmental Protection Agency definitions: light duty is less than or equal to 8500 pounds gross vehicle weight; heavy duty is greater than 8500 pounds gross vehicle weight. Estimates for historical years may be revised in future reports if new information becomes available. Estimates for 1998, in Italics, are based on plans or projections. Data for 1994 and 1996 have been revised.
Sources: 1994: Science Applications International Corporation, "Alternative Transportation Fuels and Vehicles Data Development," unpublished final report prepared for the Energy Information Administration (McLean, VA, August 1995) and Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels. 1996 and 1998: Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels.

Source: Alternatives to Traditional Transportation Fuels 1996, Energy Information Administration, December 1997.

LPG vehicles account for the largest share of AFVs, representing about 75 percent of the total number of AFVs, but are expected to decline to less than 70 percent by the end of 1998. CNG vehicles are expected to represent 21 percent of the total number of AFVs. Methanol vehicles will represent about five percent while ethanol (E85) vehicles are expected to represent slightly less than three percent of all AFVs. By the end of 1998 electric vehicles are expected to make up just over one percent of the AFVs on the road.

Based on the number of vehicles ordered the purchase of ethanol (E85) vehicles (operating on a mixture of 85 percent ethanol and 15 percent gasoline) are expected to increase by 51 percent. Although relatively small in number this represents the largest purchase growth among all AFV types. Purchase of methanol (M85) and liquefied petroleum gas (LPG) vehicles are expected to grow by three percent in 1998.

13.1.2 Federal Fleets

According to the Federal Motor Vehicle Fleet Report, the 1996 federal fleet is comprised of more than 575,000 vehicles. Approximately 24,000 of these vehicles are capable of operating with alternative fuels. The majority of these vehicles use M85, E85, or compressed natural gas (CNG). A large portion, 42 percent, of the Federal AFVs is part of the fleets of the General Services Administration (GSA), which leases AFVs to other agencies. In addition, the AFV fleets of the U.S. Postal Service and U.S. Department of Defense are substantial (30 percent and 28 percent respectively). These three federal fleets constitute the bulk of the AFVs owned and operated by the Federal government. GSA has purchased AFVs almost exclusively from the OEMs, while other agencies have also included after-market conversions in their AFV fleets.

Table 13-2. Estimated Number of Alternative-Fueled Vehicles in Use by the U.S. Federal Government, by Fuel and Weight Category, 1994, 1996 and 1998

	1994			1996			1998		
Fuel	Light Duty	Heavy Duty	**Total**	Light Duty	Heavy Duty	**Total**	Light Duty	Heavy Duty	**Total**
Liquefied Petroleum Gases (LPG)	33	2	**35**	193	2	**195**	*380*	*2*	***382***
Compressed Natural Gas (CNG)	7,022	0	**7,022**	13,945	0	**13,945**	*14,156*	*0*	***14,156***
Liquefied Natural Gas (LNG)	35	0	**35**	72	6	**78**	*181*	*6*	***187***
Methanol, 85 Percent[a] (M85)	9,291	0	**9,291**	7,668	0	**7,668**	*4,733*	*0*	***4,733***
Methanol, Neat (M100)	0	0	**0**	0	0	**0**	*0*	*0*	***0***
Ethanol, 85 Percent[a] (E85)	139	0	**139**	1,748	0	**1,748**	*4,136*	*0*	***4,136***
Ethanol, 95 Percent[a] (E95)	0	0	**0**	0	0	**0**	*0*	*0*	***0***
Electricity	102	0	**102**	188	9	**197**	*400*	*9*	***409***
Non LPG Subtotal	16,589	0	**16,589**	23,621	15	**23,636**	*23,606*	*15*	***23,621***
TOTAL	**16,622**	**2**	**16,624**	**23,814**	**17**	**23,831**	***23,986***	***17***	***24,003***

[a] The remaining portion of 85-percent methanol and both ethanol fuels is gasoline.
Note: Weight classes are based on Environmental Protection Agency definitions: light duty is less than or equal to 8500 pounds gross vehicle weight; heavy duty is greater than 8500 pounds gross vehicle weight. Estimates for historical years may be revised in future reports if new information becomes available. Estimates for 1998, in Italics, are based on plans or projections. Data for 1994 and 1996 have been revised.
Sources: Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels. Derived from Federal vehicle acquisition data from U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, supplemented with data from individual Federal agencies.
Source: Alternatives to Traditional Transportation Fuels 1996, Energy Information Administration, December 1997.

In addition to the requirements under the *Clean Air Act* (CAA) and the *Energy Policy Act of 1992* (EPACT), Executive Order 13031, *Federal Alternative Fueled Vehicle Leadership* was signed in December 1996. This Executive Order clarifies a Federal agency's responsibilities with regard to alternative fuel vehicle use. The order states that "each Federal agency shall develop and implement aggressive plans to fulfill the alternative-fueled vehicle acquisition requirements" of EPACT. In general, EPACT requires that in fiscal years 1996, 1997, 1998, 1999, and thereafter, 25, 33, 50, and 75 percent respectively, of the covered light-duty vehicles acquired by the Federal government must be alternative fuel vehicles (AFVs). EPACT also requires that each Federal agency file an annual report detailing its compliance with the requirement. EPACT allows agencies to receive extra credits for acquiring dedicated electric, medium-duty and heavy-duty AFVs, and states that agencies should use the appropriate alternative fuels in their AFVs to the extent practicable.

Table 13-3. New Fleet Vehicle Purchases Required By EPACT/CAA

	CAA			EPACT		
YEAR	GVWR less than 8,500 lbs. (% of CFVs)	GVWR less than 26,000 lbs. (% of CFVs)	Federal [a] (% or # of AFVs)	State [b] (% of AFVs)	Alternative-Fuel Provider [b] (% of AFVs)	Municipal/ Private (% of AFVs)
1993			5,000			
1994			7,500			
1995			10,000			
1996			25%			
1997			33%	10%	30%	
1998			50%	15%	50%	
1999	30%	50%	75%	25%	70%	
2000	50%	50%	75%	50%	90%	
2001	70%	50%	75%	75%	90%	
2002	70%	50%	75%	75%	90%	20%
2003	70%	50%	75%	75%	90%	40%
2004	70%	50%	75%	75%	90%	60%
2005	70%	50%	75%	75%	90%	70%
2006	70%	50%	75%	75%	90%	70%

[a] Fiscal year for federal fleet acquisition requirements; model year for all others.
[b] As required by 10 CFR part 490
[c] May be required by regulations if DOE finds these acquisitions are necessary.
Source: "Alternative Fuel Vehicles: For A Cleaner Environment," USPS, Issue 2, 1997.

The use of after-market conversion kits to meet EPACT guidelines was a popular technique to build AFV fleets. As OEMs began to offer factory built bi-fuel and dedicated AFVs this option has become less appealing. A NREL 1996 study, *Compressed Natural Gas and Liquefied Petroleum Gas Conversions,* investigated the effectiveness of after-market conversion kits. Emissions tests of a small fleet of converted AFVs showed that converted vehicles did not realize expected reductions in NOx and CO. Test results were inconsistent among the cars tested.

In 1996 NREL undertook surveys of federal fleet managers and their drivers. These surveys, *Perspectives on AFVs,* compile the experiences of 273 AFV fleet managers and 929 AFV fleet drivers whom use AFVs. These fleet managers operate over 45,000 vehicles, of which approximately 3,000 are AFVs (about 6.7 percent). The two surveys reached similar conclusions as discussed below.

The five most common vehicles in the fleets were the Dodge Spirit, Ford Taurus, Dodge Caravan, Dodge Ram Van, and Chevrolet Lumina. Approximately 88 percent of fleet managers indicated that one of these models was most prevalent in the fleet. About 84 percent of the fleets surveyed contain fewer than ten AFVs, while the overall median fleet size was seven. Almost 21 percent of fleet managers report operating more than one type of AFV. The most common fuels among the federal fleets surveyed were E85, M85, and CNG.

The most common reasons cited for drivers not wanting to use AFVs was limited range (primarily associated with CNG), starting difficulties in cold weather and lack of fueling convenience. Overall, approximately 43 percent of surveyed fleet managers and 45 percent of surveyed drivers reported that there are no fueling stations located within a reasonable distance. About 65 percent of fleet managers and 55 percent of drivers using M85 vehicles cited lack of access to fuel as an impediment to operation of AFVs. Almost 75 percent of managers using CNG reported CNG fueling facilities were available close to the location of their fleet, while 58 percent of those using E85 reported E85 fuel is conveniently accessible. Most drivers indicated that refueling stations needed to be less than one-half mile away to be convenient.

Most respondents indicated no difference in type or frequency of unscheduled maintenance required among the various types of AFVs. Vehicle range was cited by 65 percent of drivers of CNG AFVs as being marginal or inadequate. Approximately 80 percent of drivers indicated they were satisfied with AFV performance. For both fleet managers and drivers fuel availability and vehicle range are the key factors to gaining further acceptance of AFVs.

13.2 FLEET INFORMATION AND EXPERIENCES

13.2.1 United States Postal Service (USPS)

The USPS fleet consists of approximately 208,000 vehicles, making it the largest federal fleet. Of this number, the USPS operates approximately 7,400 AFVs. Over 95 percent of the AFVs operated by the USPS are bi-fuel vehicles capable of running on CNG and/or gasoline. Before placing the AFVs in operation, and in order to ensure alternative fuel use compliance, the postal service requires the local fleet manager and the postmaster to commit to operating their new vehicles as AFVs and using the appropriate alternative fuel. In addition, each USPS AFV is emblazoned with emblems indicating the vehicle's use of alternative fuels.

According to *Alternative Fuel Vehicles: For A Cleaner Environment,* the USPS considers natural gas to be one of the best alternative fuels available today. USPS supports the use of CNG vehicles due to the superior emission performance of natural gas. Natural gas reduces the cost of maintenance because it burns cleaner and more completely compare to gasoline. As a result less frequent oil changes are required, spark plug life is extended,and the number of engine tune-ups is reduced.

Table 13-4. USPS "By the Numbers"

Fuel Costs:	CNG -- $0.70 per gasoline gallon equivalent; *Gasoline -- $1.10 per gallon (nationwide avg.)*
Fuel Economy:	19 miles per gallon for both fuels
Operating Costs:	CNG -- $0.099 per mile; Gasoline -- $0.149 per mile

Source: "Taking an Alternative Route, Fueling the Future," Case Study: U.S. Postal Service, Argonne National Laboratory, August 1997.

In 1998, the USPS purchased over 660 light-duty alternative fuel vehicles that operate on CNG and E85. These non mail-hauling OEM vehicles include the Ethanol Flex-Fuel Taurus, the CNG Bi-Fuel Contour, CNG Bi-Fuel ½ ton and ¾ pickups, CNG Bi-Fuel 1 ton van, and the CNG Dedicated ¾ ton van.

The USPS operates approximately 143,000 Long-Life Vehicles (LLVs) built by Grumman with a 1000lb. cargo capacity and a 24 year life expectancy. They have converted over 7,300 of their gasoline-powered LLVs into bi-fuel vehicles by installing a compressed natural gas (CNG) conversion kit onto the vehicles, making the USPS the nation's largest fleet of CNG delivery vehicles. In 1998, plans call for the conversion of an additional 3,600 LLVs into bi-fuel vehicles. The USPS also has 74 two and two and a half-ton pickup trucks currently operating on alternative fuels.

In order to convert their LLVs, the postal service has used kits supplied by a variety of after-market producers. With varying rates of success these kits have performed well. Because the USPS is sometimes the major, or only, purchaser of a company's conversion kit, access to replacement parts *and consistent availability of supply is difficult. In one instance a conversion* kit supplier went out of business, leaving the USPS with no access to replacement parts. It was forced to convert those LLVs using two different conversion kits.

The USPS prefers not to build its own fueling stations, fueling over 50 percent of its vehicles at commercial stations. This is done to reduce capital expenditures and liability issues associated with creating a refueling infrastructure.

The USPS is currently has four special demonstration projects in progress:

TABLE 13-5. USPS Demonstration Projects in Process

Conversion Type	States
7 LLV Conversions to Propane	Florida & New Jersey
9 Tractor Conversions to LNG	Texas
6 LLV Conversions to Electric	California & Virginia
20 LLV Conversions to dedicated CNG	Connecticut & Texas

Source: "United States Postal Service: Market Sector," presented by Ron Robbins, 4th National Clean Cities Conference, June 1998.

13.2.1.2 Electric Vehicles in the Postal Service Fleet

According to *Alternative Fuel Vehicles: For A Cleaner Environment, Issue 2*, the USPS has been using a small number of electric vehicles (EVs) intermittently since 1899. As battery technology has improved over the years, the USPS continues to test and evaluate this AFV as a viable means to deliver the mail.

During the 1970's and the early 1980's the USPS tested more than 620 electric vehicles in their fleet. Due to the limited battery technology at that time and limited range, battery motor and controller failures were encountered.

In 1993 six electric Ford Ecostar vehicles were leased to the USPS. In 1995, six gasoline LLVs were converted to electric. Each conversion cost about $7,500. Although the operating cost of the EVs has proven to be slightly higher than gasoline vehicles, the EV's life cycle cost is less because of the lower maintenance requirements: EVs do not need tune-ups or oil changes.

In 1997, the USPS had 11 electric vehicles in service, and plans to deploy more. These EVs were placed in a variety of climates and driving conditions to evaluate their performance.

13.2.2 Department of Defense (DoD) Fleet Information and Experience

The Department of Defense operates a fairly extensive AFV program in all four branches of the Armed Forces. Of approximately 100,000 vehicles operated by DoD nearly 6,500 are AFVs. Studies evaluating the experiences of the various entities within the Armed Forces operating AFVs are not available. In conducting researching of DoD AFVs, it became apparent that the programs tend to operate in a disparate fashion making overall evaluation difficult. There is no documented information compiled on the experiences of fleet managers or drivers under the Department of Defense.

13.2.3 General Services Administration (GSA) Fleet Information and Experience

The U.S. GSA operates the largest fleet of alternative vehicles within the federal government. The total fleet of 160,000 vehicles has approximately 10,000 AFVs. GSA's fleet is difficult to evaluate because the majority of its vehicles are leased to other government entities. While the cars are technically owned by GSA, they are operated by fleet managers throughout the federal government and are hard to follow and evaluate.

GSA's Interagency Fleet Management System (IFMS) has completed its alternative fuel vehicle orders for 1998. The table below presents the breakdown of the number of vehicles ordered and fuel type.

Table 13-6. GSA AFV Orders for 1998

Vehicle Type	Fuel Type	Number Leased
Chrysler Minivan	Flexible-Fuel E85	1,994
E85 Ford Taurus	Flexible-Fuel E85	605
Ford Contour	Bi-Fuel CNG	441

Vehicle Type	Fuel Type	Number Leased
Ford CNG Pickup	CNG	298
Ford Club and Cargo Vans	Dedicated & Bi-Fuel CNG	62
M85 Ford Taurus	Flexible-Fuel	32
GMC Pickup	Bi-Fuel CNG	30
Ford LPG Pickup	Bi-Fuel CNG	23
Freightliner FL50	Dedicated CNG	19
Chevy S10 EV	Electric	15
Ford Crown Victoria	Dedicated CNG	2
Total AFVs Ordered		**3,521**

Source: Alternative Fuel News, Department of Energy, Vol. 2, No. 2, 1998.

E85 vehicles will make up approximately 74 percent of the AFVs purchased by GSA in 1998. Both dedicated and bi-fuel CNG vehicles will equal 25 percent of the AFVs, with M85 and electric (combined) vehicles equaling about one percent.

13.2.4 State and Local Transit Experiences

As of January 1997, approximately 5.6 percent of the 65,000 transit buses in the United States surveyed by the American Public Transit Authority ran on an alternative fuel. Currently, one out of every five new buses on order is an alternative fuel vehicle. NREL's study entitled Alternative Fuel Transit Buses of 1996 examined AFV powered buses in eight transit agencies (Houston, Portland, Miami, New York, Tacoma, Minneapolis, Peoria and St. Louis). This demonstration project showed that vehicle reliability as measured in road calls per 1000 miles was considered to be more of a problem with buses using alternative fuels. Most issues resulted from minor problems such as clogged fuel filters, overly sensitive vapor detectors and the inexperience of bus operators. Operating costs are higher because of substantially higher fuel and infrastructure costs for AFVs. Capital costs for infrastructure are highest for CNG and LNG powered vehicles, and lowest for biodiesel, methanol and ethanol.

Reliability, as measured by the number of engine and fuel related problems reported per 1000 miles, was an issue for all transit agencies included in the study. Forty of the 382 engine or fuel problems reported on CNG or LNG buses were the result of fuel vapor detectors that would automatically shut down the bus, despite the fact that no leak was present. Seventy-four of the 483 calls received for all demonstration buses studied by NREL in this study were the result of driver inexperience with alternative fuels which led to running out of fuel. Of the 252 calls received for buses running on E85 and M85, 31 were the result of fuel related problems resulting from poor fuel quality that clogged fuel filters.

The fuel economy, measured in miles per gallon, of the all of the alternative fuel powered demonstration buses was lower compared to conventional diesel fueled buses. CNG and LNG powered busses operated least efficiently as compared to their diesel fueled counterparts. LNG buses operated 13 percent less efficiently, while those buses fueled with CNG operated 20 to 30 percent less efficiently. A portion of this reduced fuel economy is due to the extra weight associated with the tanks used for fuel storage on each bus. In addition, reductions in fuel economy are also a result of engine designs that have yet to be optimized for AFV operation. Methanol and ethanol powered buses performed better than CNG or LNG buses, operating with fuel economies similar but still smaller than the diesel buses.

Larger costs of operation were experienced with the alternative fueled buses in this demonstration project. Vehicles purchase costs were higher, changes to transit facilities were needed to store and repair AFVs safely (particularly CNG and LNG vehicles), and additional fueling facilities were required for those transit agencies who chose to operate their own fueling stations.

13.2.5 Private Fleet Experiences

While AFVs are used by a variety of private sector enterprises there has been limited information published on the experiences of these users. The experiences of Federal Express, Raley's and Hertz present some insights.

13.2.5.1 Federal Express

Battelle completed a study (CleanFleet) of Federal Express vans operating on five alternative fuels in Southern California. Eighty-four AFVs and twenty-seven "control" vans were used in this study over a two-year demonstration period. The five fuels included in the study were CNG, propane (LPG), reformulated gasoline (RFG), M85 and electricity.

CNG vehicle range was limited by the size and weight of storage tanks on board coupled with reduced energy content of the fuel. After-market conversion vans required more maintenance than those vans purchased from OEMs. CNG powered vehicles emitted lower levels of most pollutants than those vans operating on the other fuels in the demonstration. Infrastructure to support the CNG fleet proved to be an expensive endeavor. Indoor storage of these vans was hindered by requirements of local fire marshals. In order to comply with local regulations, building modifications may be required, raising startup costs associated with operation of CNG vans.

At the time of testing there were no OEM produced LPG vehicles available, meaning that all vehicles used were converted using after-market kits. The reliability of these kits proved to be questionable and the performance that resulted was less than that of the control vans. LPG vehicles may also require building modifications to comply with fire safety regulations if indoor storage is desired. Based on 1996 estimates the cost to operate a 50-vehicle LPG fleet was higher than a similar gasoline fleet, but less than other alternative fuels (38.2 to 39.6 cents per mile).

Driving range of the M85 vans was about 57 percent of gasoline vans due to M85's reduced energy content. M85 may require changes in storage and dispensing equipment to handle the solvent characteristics of the fuel. The estimated cost to operate a fleet of 50 M85 vans in 1996 ranged from 38.3 to 44.7 cents per mile.

EVs were successfully used on city routes where mileage is short. CleanFleet vehicles demonstrated that further advances in battery technology are essential for achieving consistently reliable electric vehicle operation. These vehicles proved useful for local routes where range was less of a concern. This demonstration also highlighted the importance of using charging technology capable of providing both consistent and efficient charges. Some charging systems used tended to waste energy by inefficiently charging the batteries. Costs of operation were affected by the cost of electricity, the life of the battery pack and the efficiency of the EV.

13.2.5.2 Raley's LNG Truck Fleet

Raley's is a supermarket and drug store chain operating in Northern California and Northern Nevada. Raley's operates a 48-truck fleet that includes eight LNG-fueled tractor-trailers. The LNG fleet operates 16-hour days on local routes, 5 to 6 days each week. Raley's chose LNG because it met the range requirements, and had positive safety and environmental qualities. The use of LNG in the Raley's fleet is expected to replace about 100,000 gallons of diesel and reduce NOx emissions by about five tons annually. Raley's is building an on-site fueling facility because of the size of the fleet and the large fuel demands. Results of this demonstration are expected in the spring of 1999.

13.2.5.3 Hertz Methanol Fleet

Hertz began to purchase methanol fueled flexible-fueled vehicles (FFVs) for the Los Angeles Metro area in 1992. FFVs were chosen because fuel availability was inconsistent throughout the region. If needed these automobiles could also run on gasoline. In addition, these cars were available from several OEMs, including Ford, Hertz's owner. Hertz has purchased and operated the Dodge Intrepid and Ford Taurus FFVs since 1992, operating a total of 1,913 FFVs in the Los Angeles area. Hertz operates M85 fuel pumps at its five facilities in the Los Angeles area. In addition to fueling facilities Hertz has trained its mechanics to work on the FFVs. Maintenance costs have been higher due to use of a special motor oil which is over $5.00 per quart compared to $1 per quart for conventional motor oil. Hertz has also incurred costs waiting for parts, which has taken the FFVs out of service for longer periods than gasoline fueled vehicles. It is important to note that these FFVs run on M85 10 to 15 percent of the time due to lack of available fuel beyond the Hertz facilities.

APPENDIX A

EMISSIONS

A.1 Heavy-Duty Engine Emissions

Alternative fuels generally provide lower emissions than conventional diesel fueled engines as shown in Figure A-1. Several engines have been certified in the last few years to run on various alternative fuels and some produce emissions at or below the proposed 2004 diesel emission standards of 2.5 g/bhp-hr NOx + NMHC and 0.1 g/bhp-hr PM. Diesel engines listed in Table A-1 meet the 1996 diesel engine standard of 5.0 g/bhp-hr NOx and 0.1 g/bhp-hr PM. There is a lower PM standard for urban buses (0.05 g/bhp-hr). In 1998, the diesel truck standard dropped to 4.0 g/bhp-hr NOx and 0.1 g/bhp-hr PM. A representative set of engines shown in Table A-1 manufactured in 1998 would be certified at or below that standard.

The most commercialized alternative fuels at present are natural gas (either CNG or LNG) and LPG. Engines certified on natural gas are shown in Table A-2 and engines certified on LPG are shown in Table A-3. As can be seen from these tables, current model year offerings produce emissions that approach the proposed 2004 standards. Further development could result in engines producing emission levels in the 1 g/bhp-hr NOx region. Both fuels produce little PM emissions, with most of the PM coming from lubricating oil being burned in the cylinder.

DDC is the only manufacturer that produced commercial certified methanol and ethanol engines. The two-stroke engines that these alcohol engines were derived from were common in buses prior to 1994, but DDC has phased out their two stroke engine lines for on-highway use and due to lack of interest in these engines, discontinued production of these alcohol engines. The ethanol version of this engine was developed to run on E95, 95% ethanol and 5% gasoline for a denaturant. The engine was built to run on methanol but was also certified for ethanol. If the engine was retuned for ethanol usage, better emission results could be expected.

As yet there is no commercial DME heavy-duty engines offered. In experimental projects, DME has shown NOx levels about half that of comparable diesel engines and very low particulate emissions. It may require a lubricity additive to protect fuel injector life that may result in some particulate emissions.

There is no commercial heavy-duty engine that has been certified on biodiesel. In demonstration projects, biodiesel blends have shown up to a 30% reduction in particulate emissions and a 50% reduction in hydrocarbon emissions. Biodiesel has not shown any reductions in NOx emissions.

Fischer-Tropsch diesel fuel has not been certified in any commercial engine in the U.S. Experimental results have shown about an 8% reduction in NOx emissions, 30% reduction in PM, 38% reduction in HC and 46% reduction in CO over conventional diesel fuel.

Fuel cells perhaps have the lowest emissions, though no certified fuel cells exist for heavy-duty vehicle usage. In experimental studies, with fuel cells reformers running on methanol, NOx emission below 0.01 g/bhp-hr and PM emissions below 0.01 g/bhp-hr have been shown.

Table A-1. Certified Production Diesel Engine Emissions (Federal Test Procedure)

Manufacturer	Model Year	Engine Model	HP @ Speed	Torque @ Speed	Emissions (g/bhp-hr)			
					NOx	CO	HC	PM
Caterpillar	1996	3126	300@2200	860@1440	4.65	0.82	0.12	0.084
Caterpillar	1996	3176	365@1800	1350@1200	4.24	1.26	0.14	0.062
Caterpillar	1996	3306	300@1900	1150@1200	4.59	0.63	0.48	0.086
Caterpillar	1996	C-10	370@1800	1350@1200	4.33	1.19	0.12	0.071
Caterpillar	1997	C-12	424@1800	1550@1200	4.32	1.02	0.14	0.069
Cummins	1996	B5.9	215@2600	440@1600	4.12	0.53	0.16	0.061
Cummins	1996	C8.3	250@2200	660@1300	4.48	0.79	0.18	0.063
DDC	1996	50	250@2100	780@1200	4.67	1.18	0.05	0.05
DDC	1996	50	275@2100	890@1200	4.73	1.14	0.04	0.045
Mack	1996	E7	350@1800	1360@1250	4.52	N/A	0.08	0.076
Navistar	1966	7.3L	220@3000	450@2000	4.79	1.74	0.22	0.086

Table A-2. Certified Production Natural Gas Engine Emissions (Federal Test Procedure)

Manufacturer	Model Year	Engine Model	HP @ Speed	Torque @ Speed	Emissions (g/bhp-hr)			
					NOx	CO	HC	PM
Caterpillar	1996	3306	250@2100	820@1200	0.7	6.3	0.7	0.02
Cummins	1994	B5.9G	150-195@2800	375-420 @ 1600	0.9	5.4	0.6	0.02
Cummins	1994	L10	280-300@2100	900@1300	2.4	5.3	0.5	0.03
Cummins	1996	C8.3G	250@2400	660-750@1400	2.1	1.5	0.1	0.02
DDC	1995	30G	210@2400	485@1500	3.5	3.4	3.5	0.05
DDC	1994	50G	250-260@2100	780@1200	1.9	2.5	0.6	0.03
DDC	1994	50G	275@2100	890@1200	2.7	2.5	0.6	0.03
John Deere	1995	6081H	250@2200	800@1350	2.17	2.4	0.3	0.06
Mack	1997	E7G	350@1800	1370@1250	2.5	2.8	N/A	0.10
Power Systems	1997	3126G	190-250@2400	700@1500	2.8	7.8	0.9	0.08
Power Systems	1997	3176G	275-350@2100	1050@1200	2.4	8.2	1.1	0.07
Power Systems	1997	C-10	280-350@2100	1050@1200	2.4	8.2	1.1	0.07
Power Systems	1998	C-12	370-410@2100	1250@1200	2.4	4.1	0.5	0.10

Table A-3. Certified Production LPG Engine Emissions (Federal Test Procedure)

Manufacturer	Model Year	Engine Model	HP @ Speed	Torque @ Speed	Emissions (g/bhp-hr)			
					NOx	CO	HC	PM
Caterpillar	1996	3306	235@2100	800@1200	0.7	6.3	0.7	0.02
Cummins	1997	B5.9	195@2800	420@1600	2.3	1	0.8	0.01
Ford	1996	7.0L	235@3600	360@2800	2.43	17	0.3	0.01

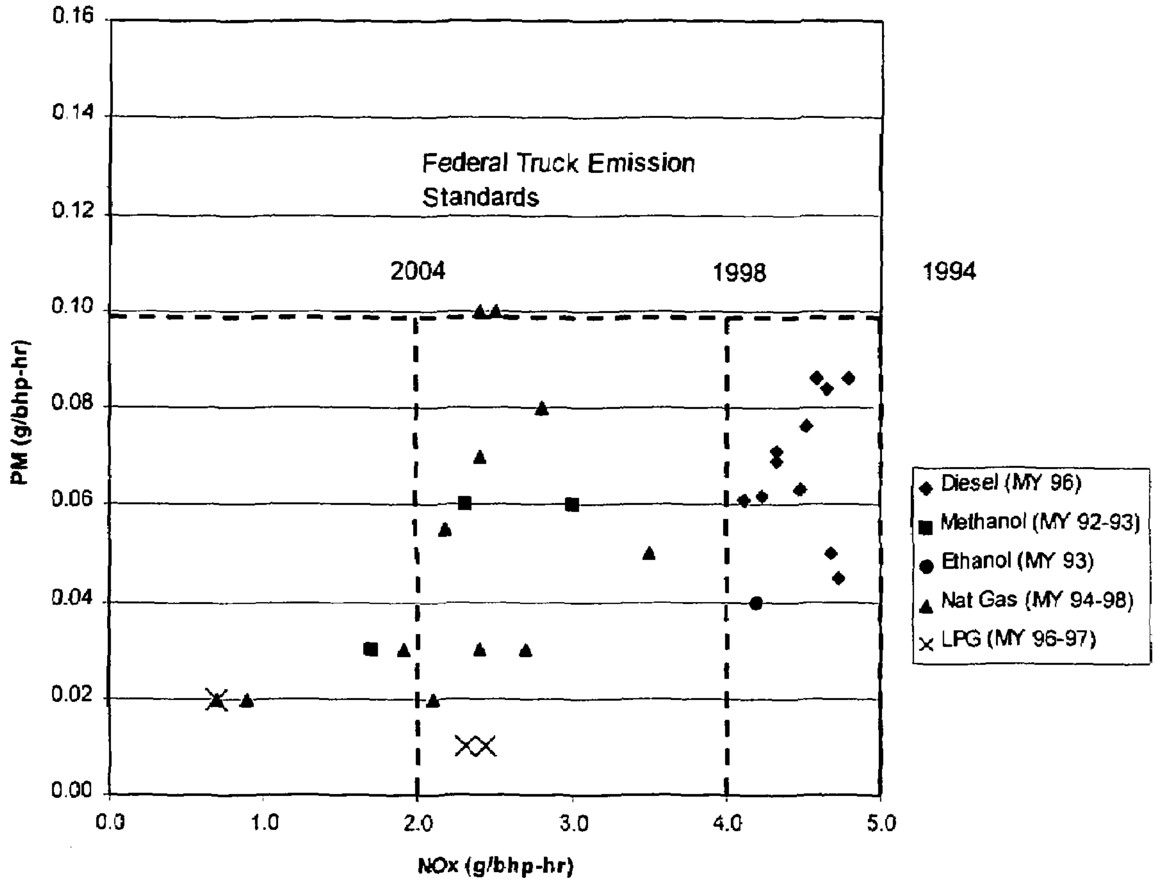
Table A-4. Certified Production Methanol Engine Emissions (Federal Test Procedure)

Manufacturer	Model Year	Engine Model	HP @ Speed	Torque @ Speed	Emissions (g/bhp-hr) NOx	CO	HC	PM
DDC	1992	6V-92TA	253@2100	775@1200	3	12	0.8	0.06
DDC	1992	6V-92TA	277@2100	880@1200	2.3	4.8	0.4	0.06
DDC	1993	6V-92TA	277@2100	880@1200	1.7	2.1	0.1	0.03

Table A-5. Certified Production Ethanol Engine Emissions (Federal Test Procedure)

Manufacturer	Model Year	Engine Model	HP @ Speed	Torque @ Speed	Emissions (g/bhp-hr) NOx	CO	HC	PM
DDC	1993	6V-92TA	277@2100	880@1200	4.2	1.7	0.7	0.04

Figure A-1. Certified Heavy-Duty Engine Emissions Comparisons



A.2. Light-Duty Engine Emisssions

Assessing the effect on air pollution from the use of alternative fuels entails consideration of two factors: total mass emissions and chemical composition of the emissions. The former is expressed as, in the case of VOCs, the grams per mile traveled of all emissions of volotile organic compounds. The latter is expressed as the mass of a specific chemical, such as formaldehyde of benzene, per mile traveled. The air pollution effects of current interest from light-duty vehicles are ozone formation and air toxic and fine particulate concentrations. One might also consider other environmental effects stemming from the use of alternative fuels ranging from potential impacts on ground water contamination to global warming. To illustrate the importance of total mass emissions, one can imagine an air pollution assessment of alternative fuels 40 years ago, before vehicle emissions controls were introduced. Large reductions in emissions would have been possible merely by switching to essentially any alternative fuel. However, as we approach the new century, emission control technology that can be used even on gasoline-fueled vehicles, let alone virtually any alternative-fueled vehicle, is resulting in near-zero levels of emissions for light-duty vehicles compared to 40 years ago. As the prospect of M85 a decade ago has been credited with inducing the reformulation of gasoline, now electric vehicle mandates may have inspired the latest advances towards a near-zero level of automobile emissions. For example, Honda will soon start production of a gasoline-fueled car, which in certification tests produced results so far below existing standards (such as the ultra low emitting vehicle or ULEV) that the California Air Resources Board (CARB) then introduced standards for yet a new category -- called the super ultra low emitting vehicle (SULEV). To provide some perspective on just how low the SULEV standards are, the latest CARB emissions estimates for an in-use, well-maintained, non-catalyst-equipped light-duty gasoline-fueled vehicle would be 29.3 grams per mile CO, 0.42 gm/mi. VOC, and 2.4 gm/mi. NO_x. The corresponding emissions from the new SULEV are 1.0 grams per mile CO, 0.01 gm/mi. VOC and 0.02 gm/mi. NO_x, respectively. These "super ultra low" emissions represent percentage reductions of 96.6, 99.8, and 99.2 percent, respectively. Even when compared to the California standards for transitional low-emitting vehicles or TLEVs in effect for 1998, the SULEV still can achieve percentage reductions of CO, VOC and NOx emissions of 76, 94, and 97 percent, respectively..

If one assumes that SULEV technology is compatible with virtually any alternative fuel, then it could be argued first that the emission differences should not be important because the levels would already be so low in mass, and second that there would be no significant differences in total mass emissions anyway because the control technology would probably be adjusted to meet the same mass emission levels expressed by the standards themselves.

For alternative fuels, however, the emissions impacts per unit mass emitted may still need to be considered even at such low overall mass emissions levels. Methanol makes a good illustrative example for discussion of this impact per unit mass emitted factor. As an alternate fuel, methanol, has gone through a series of stages, starting with promising studies in the early eighties[1] and a book promoting its use written in 1985[2], through production and sales by major auto makers into the mid-

---

[1] Systems Applications, Inc., "Impact of Methanol on Smog: A Preliminary Estimate," Prepared for ARCO Petroleum Products Co., February 1983: Jet Propulsion Laboratory and California Institute of Technology, " California Methanol Assessment," Vol. 2, prepared for the Electric Power Research Institute and the California Energy Commission, March 1983, Chap. 6.

[2] Gray, C.L., Jr. and J.A. Alson *Moving America to Methanol*, University of Michigan Press, Ann Arbor, MI, 1985.

nineties, to a recent decline in interest during the late nineties. Exhaust emissions from methanol fuel have reduced ozone-forming potential when compared with gasoline. CARB has given methanol vehicles a reactivity adjustment factor (RAF) of 0.41. This means that 1 gram/mile of methanol exhaust hydrocarbons in the exhaust are deemed equivalent to 0.41 gram/mile of gasoline exhaust hydrocarbons in the amount of ozone they produce. While methanol emissions include higher formaldehyde emissions (a toxic emission), toxic emissions of benzene, 1,3-butadiene and acetaldehyde are much lower than that from gasoline and generally result in a lower carcinogenic risk than gasoline emissions. However, because CARB allows use of the RAF in certifying vehicles, a methanol vehicle will generally emit higher non-methane organic gas (NMOG) emissions than an equivalently certified gasoline vehicle. Manufacturers can thus use less sophisticated emissions control equipment on a methanol vehicle to meet the same standards as a gasoline vehicle.

Each of the other alternative fuels may also have its own unique emissions issues. For example, E85 is made with 85 percent ethanol plus 15 percent gasoline. Some emissions and smog chamber tests[3] have shown the acetaldehyde and the emissions associates with the 15 percent portion of gasoline that is in E85 can dominate the ozone formation potential of E85 exhaust emission, thereby reducing the potential for the low-reactivity of ethanol itself to provide a significant ozone reduction, on a per mass emissions basis, compared to normal or even reformulated gasoline. Another example is natural gas vehicles, which have low NMOG emissions but can have high methane emissions. While methane is considered to have a very low reactivity to produce ozone in

---

[3] Technical Bulletin No. 16, "Exhaust Emissions of E85 Ethanol Fuel and Gasoline in Flexible/Variabale Fuel Vehicles," Auto/Oil Air Quality Improvement Research Program, July 1995.

the atmosphere, it is a greenhouse gas and needs to be considered in the total emissions picture.

In summary, the mass of emissions from vehicles that use alternative fuels can, as first approximation, be expected to have little difference compared to those using gasoline because control technology is often designed to meet identical mass emissions standards, i.e. all vehicles must meet the same emission standards regardless of fuels used. Further, there will soon exist vehicles operating on gasoline using significant new developments in control technology that are capable of near-zero levels of emissions even when compared to present standards. It should be possible to utilize at least some of these new control technology developments in vehicles operating on alternative fuels in order that they meet such near-zero standards. At such low levels of emissions any actual differences in emissions between fuels in terms of meeting the standards may be judged trivial.

APPENDIX B

Table B-1. Light and Medium-Duty Alternative Fuel Vehicles Available or Nearing Completion: All Alternative Fuels

Fuel Type	OEM	Vehicle Description	MY[1]	US[2]	Federal[3,5]	California[3]
CNG	Chrysler	Ram Van/Wagon	95, 96, 99	Y	*	ULEV/LEV
		Dedicated Dodge Grand Caravan/Grand Voyager	95, 96	Y	*	ULEV
	Ford	Bi-fuel F-Series Gaseous Fuel Prep Vehicle	95	Y	*	*
		Bi-fuel Econoline Gaseous Fuel Prep Vehicle	95	Y	*	*
		Dedicated Crown Victoria	96 - 99	Y	Tier 1	ULEV on CNG
		Bi-fuel F150/F250 Vehicles	96	Y	*	*
		Bi-fuel Econoline Prep Vehicle	96	Y	*	*
		Bi-fuel Contour	97, 98, 99	Y	Tier 1	TLEV
		Dedicated or Bi-fuel Econoline	97, 98	Y	Tier 1	SULEV/ ULEV on CNG
		Dedicated or Bi-fuel F150 Pickup	97, 98, 99	Y	Tier 1	LEV
		Dedicated or Bi-fuel F250 Pickup	97, 98, 99	Y	Tier 1	SULEV/ ULEV on CNG
		Dedicated Econoline (Super Club, E-350)	99	Y	*	*
	GM	Bi-fuel GMC Sierra 2500	97, 98, 99	Y	Tier 1	
		Bi-fuel Chevrolet Cavalier	98, 99	Y	Tier1	LEV/TLEV
	Honda	Dedicated Honda Civic GX	98, 99	Y		ULEV on CNG
Electric	Chrysler	NiCd or NiFe Dodge TE Van	95	Y	ZEV	ZEV
		Lead Acid EPIC Minivan	97	Y	ZEV	ZEV
		NiMH EPIC Minivan	99	Y	ZEV	ZEV
	Ford	Sodium Sulfur Ecostar	95	Y	ZEV	ZEV
		NiMH Ranger (Calif. only)	99	Y	ZEV	ZEV
		Lead Acid Ranger	97, 98, 99	Y	ZEV	ZEV
	GM	Lead Acid EV1	97	Y	ZEV	ZEV
		Lead Acid Chevrolet S10	97, 98, 99	Y	ZEV	ZEV
		Lead Acid or NiMH EV1	98	Y	ZEV	ZEV

	Honda	NiMH Honda EV Plus	97, 98, 99	Y	ZEV	ZEV
	Hyundai	NiMH Accent	99	Y	ZEV	ZEV
	Nissan	Lithium-Ion Nissan Altra	98	Y	ZEV	ZEV
		Lithium-Ion Nissan Prairie	98	Y	ZEV	ZEV
	Solectria	Lead Acid or NiMH Force	99	Y	ZEV	ZEV
		Lead Acid CitiVan	99	Y	ZEV	ZEV
		Lead Acid Flash	99	Y	ZEV	ZEV
	Toyota	Lead Acid or NiMH Toyota RAV4EV	98	Y	ZEV	ZEV
		Hybrid-electric Toyota Prius	98	Intl.	*	*

Ethanol (E85)	Chrysler	Dodge Caravan/Plymouth Voyager FFV	98, 99	Y	Tier 1	LEV/TLEV
	Ford	Taurus FFV	95 - 99	Y	Tier 1	LEV
		Ranger FFV	99	Y	*	*
Methanol (M85)	Chrysler	Dodge Intrepid	95	Y	*	TLEV
	Ford	Taurus FFV	95 - 98	Y	Tier 1	LEV
LPG	Ford	Dedicated F600/F700 Medium Duty Chassis	95, 96	Y	*	*
		Bi-fuel F150/F250 Vehicles	96	Y	*	*
		Dedicated or Bi-fuel Econoline	97, 98, 99	Y	Tier 1	SULEV/ ULEV on CNG
		Dedicated or Bi-fuel F150 Pickup	97, 98	Y	Tier 1	LEV
		Dedicated or Bi-fuel F250 Pickup	97, 98	Y	Tier 1	SULEV/ ULEV on CNG
		Bi-fuel F-Series	99	Y	*	*

1 MY95-98 vehicles data source: Alternative Fuels Data Center maintained by the National Renewable Energy Laboratory. MY99 vehicles data source: OEM company representatives (Chrysler, Ford, Honda, Solectria, Volvo) and the New Fuels and Vehicles Report (7-98). Vehicle availability subject to change. MY99 vehicle offerings have not been finalized by OEMs.

2 Intl. = International. Prius currently available in Japan only.

3 Federal (EPA) and California (CARB) emissions standards only for MY98 vehicles from the Green Guide to Cars and Trucks. Ratings for flex-fuel and bi-fuel vehicles are based on gasoline emissions unless otherwise noted. All others sourced from the California Air Resources Board (CARB).

4 * = We were unable to collect this data.

5 Emissions standards as defined from the Green Guide to Cars and Trucks.

- Tier 1 The prevailing Federal (EPA) standard.
- TLEV Transitional Low Emission Vehicle, an intermediate California standard about twice as stringent as Tier 1.
- LEV Low Emissions Vehicle, a stronger California standard emphasizing very low HC emissions.
- ULEV Ultra Low Emission Vehicle, a stronger California standard emphasizing very low HC emissions.
- SULEV Super Low Emission Vehicle, a California standard even tighter than ULEV and prohibiting emissions of fuel vapors.
- ZEV Zero Emission Vehicle, a California standard prohibiting any tailpipe emissions.

Table B-2. Heavy and Medium-Duty Alternative Fuel Vehicles Available or Nearing Completion: All Alternative Fuels Except Electric[1]

Fuel Type	OEM	Vehicle Description, Model	Engine Used	Available Since
CNG or LNG	Blue Bird	School Bus TC/2000 FE (front engine) TC/2000 RE (rear engine) All American FE & RE	John Deere 8.1-L (CNG only) Cummins B5.9G	N/A
		Transit Q-Bus (rear engine) CSFE (front engine) CSRE (rear engine)	Cummins B5.9G John Deere 8.1L (CNG only) John Deere 6.8L (CNG only)	1997
	Champion Bus, Inc.	Transit Shuttle, Solo, Contender	Cummins B5.9G	N/A
	Chance Coach, Inc.	Transit Trolley	Cummins B5.9G	N/A
	Crane Carrier Company	Refuse Hauler	Cummins L10G Cummins C8.3G Cummins B5.9G	1996
		Spotting Truck, Model M1000G	Cummins B5.9G	N/A
	El Dorado National Company	Transit, Escort RE-29, Transmark RE-29 & RE-32, EZ Rider 30	Cummins C8.3G Cummins B5.9G	N/A
	Elgin	Street Sweeper, Series E&F	Cummins B5.9G	N/A
	Freightliner	Heavy Truck	Cummins C8.3G Cummins B5.9G	TBD
		Medium Truck FL50, FL60, FL70	Cummins B5.9G	1996
		Step Van Custom, MT-10NG, MT-12NG, MT-13NG, MT-14-19NG	Cummins B5.9G Cummins C8.3G	1996
		Step Van Chassis Custom, MT-45	Cummins B5.9G	N/A
		Transit Shuttle, Custom MB SHuttle Bus	Cummins B5.9G	N/A
	Goshen Coach	Transit Shuttle, Sentry	Cummins B5.9G	
	Kenworth	Medium Truck T300	Cummins C8.3G	1996

	Magnum Terminal Tractors	Spotting Truck TT100	Cummins B5.9G	1996
Fuel Type	**OEM**	**Vehicle Description, Model**	**Engine Used**	**Available Since**
	Matthews Buses, Navistar Chassis, Thomas Built Buses[2]	School Bus	Cummins B5.9G	1996
	Metrotrans Corporation	Transit Shuttle, Eurotrans	Cummins B5.9G	N/A
	Navistar International	Heavy Truck 8100, 9200	Cummins L10G	(Prototype)
		School Bus 3800	Detroit Diesel 30G	(Prototype)
	NeoPlan USA	Transit, Transliner AN 440/440L, AN 460, Metroliner AN340, AN345	Cummins L10G, Detroit Diesel S-50G	N/A
	New Flyer Industries, Ltd.	Transit, Standard and Lowfloor (under development)	Cummins L10G, C8.3G, Detroit Diesel S-50G	N/A
	North American Transit, Inc.	Transit Shuttle, Unique Design Transit Vehicle (UDTV)	Cummins B5.9G	N/A
	Ottawa Truck Division	Medium Truck YT-50	Cummins B5.9G	1996
		Spotting Truck, Models C-30, C-50, C-60T and Commando	Cummins B5.9G	N/A
	Peterbilt	Refuse Hauler 320	Cummins L10G	1996
	Spartan Motors	SP Sample	Cummins B5.9G, C8.3G	N/A
		Transit Shuttle Low	Cummins B5.9G	1996
	Specialty Vehicles, Inc.	Transit Trolley	Cummins B5.9G	1996
	Thomas Built	School Bus Saf-T-Liner MVP	Cummins B5.9G, C8.3G	1996
	Trolley	Trolley	Cummins B5.9G	N/A
	TYMCO	Street Sweeper	Cummins B5.9G	N/A
	Volvo-GM	Refuse Hauler WXLL64, WX, WXR	Cummins L10G	1996
		Heavy Truck	Cummins L10G	TBD
	Western Star	Heavy Truck 4964S	Cummins L10G	N/A

Table B-2. Heavy and Medium-Duty Alternative Fuel Vehicles Available or Nearing Completion: All Alternative Fuels Except Electric[1]

Fuel Type	OEM	Vehicle Description, Model	Engine Used	Available Since
CNG/LNG or LPG	North American Bus Industry	Transit Nabi 416, Nabi 436, Nabi 40LFW	Cummins L10G Cummins C8.3G Detroit Diesel 50G	1997
	Orion Bus Company	Transit Orion 5/CNG (30-ft., 35-ft. &40-ft.) Orion 2/CNG 26-ft. Para-transit, handicapped accessible	Cummins L10G Cummins C8.3G Cummins B5.9G Detroit Diesel 50G	1996
LNG	Mack Truck, Inc.	Refuse Hauler	Mack E-7 12-L Mack E7G 12-L	Late 1997
LPG	Ottawa Truck Division	Spotting Truck, Models C-30, C-50, C-60T and Commando	Cummins B5.9	N/A
	Western Star	Heavy Truck, 4964S	Caterpillar 3306	N/A

[1] Vehicles data source: Heavy Vehicle and Engine Resource Guide, National Alternative Fuels Hotline.
[2] Parts for this bus provided by all three OEMs.

Table B-3. Heavy and Medium-Duty Vehicles Available or Nearing Completion: Electric Vehicles[1]

Fuel Type	OEM	Vehicle Description, Model	Batteries	Propulsion System	Available Since
Electric	Advanced Vehicle Systems	Transit Bus, 22 foot	Chloride/Fulmen Trojan *Advanced chemistry batteries available*	Solectria AC Drive Nelco/Chloride DC Drive *Hybrid option available*	1996 --
	APS System	School Bus	Nickel-Cadmium SAFT	AC induction motor	TBD
		Transit Bus, 22-Foot	Nickel-Cadmium	Chloride traction controller, DC motor	TBD
		Transit Bus, 35-Foot	SAFT Nickel-Cadmium 112 volt 360 amps per hour	Hughes controller	1996
		Transit Bus, Villager	320 volt DC 78 kWh	AC Rexroth Motors	TBD
	Ballard Power Systems	Transit Bus	N/A	Hydrogen Fuel Cell	1996 Prototype
	Blue Bird Corp.	School Bus	Lead Acid	AC induction motor	1997
		Transit Bus	Lead Acid	AC induction motor	1997
	Bus Manufacturing USA	Transit Bus, 22-Foot battery/hybrid bus	Chloride Motive Power 325 amps per hour	Chloride controller Nelco DC traction motor	1996
	El Dorado National	Transit Bus	Concord Lead Acid 576 volts	Siemens Power Control System high speed AC induction motors	Demonstration
	Matthews	Transit Bus, ETAF	Lead Acid	Advanced DC	1997
	Orion	Transit Bus, 6 Low Floor	Lead Acid	Lockheed Martin HybriDrive propulsion system	TBD

	Specialty Vehicle Manufacturing *Corporation*	Transit Bus, 5131	Trojan Industrial Lead Acid; 160 *volts*	Hughes Power Control System	1996
		Transit Bus, 5122	Trojan Industrial Lead Acid	Nelco traction motor	1996
	Thomas Built Buses, Inc.	School Bus	Sealed Lead Acid, 320 volts	Hughes Power Control System	1996
	U.S. Electricar	Transit Bus, 22 Foot	Lead Acid 120 volts	Advanced DC motors	1997
		Transit Bus, 25 Foot	Lead Acid 320 volts	Panther 120 AC System	1997

[1] **Vehicles data source: Heavy Vehicle and Engine Resource Guide, National Alternative Fuels Hotline.**

Table B-4. Alternative Fuels for Light- and Heavy-Duty Vehicles: Status Summary & Outlook

Fuel	Emissions Performance	Commercial Heavy-duty Engines	Commercial Light-duty Vehicles	Current Cost Competitiveness	Prospects for Future Cost Competitiveness	Key Issues
LNG	Excellent	Enough	None	Poor	Fair	Press now or wait for tax reduction? Need infrastructure
CNG	Excellent	Enough	Some	Varies	OK	Link to LNG through L/CNG stations
LPG	Good	Spotty	Yes	Varies	OK	Need engines, infrastructure
Methanol	Excellent	None currently offered	Being phased-out	Poor	Fair	Why not wait for fuel cell opportunities?
DME	Good	Easy	None	Poor	Fair	Big investment needed
Ethanol	Good	None currently offered	Yes	Poor - depends upon tax subsidy	Fair	Timing - wait for lower cost technologies
Biodiesel Blends	Only small benefits	Easy	None	Poor	Poor	Need cost reduction
FISCHER TROPSCH	Good	Easy	Easily Done	Varies	OK	Cost reduction
Electric-ity	Excellent	Some	Yes	Poor	OK (some niches)	Energy storage, cost reduction
Hybrid-Electric	Excellent	None currently offered	Yes - not currently available in US	Poor	OK	Cost reduction
Hydro-gen	Excellent	None currently offered	None	Poor	Poor	Need engine, hydrogen storage
Fuel Cell	Excellent	None currently offered	None	Poor	Fair	Cost reduction

APPENDIX C

C. Alternative Fuel Resources:
C.1 Annotated Bibliography

ABCs of AFVs: A Guide to Alternative Fuels (Fourth Addition)
Publication Date: Jun 10, 1997
Publisher: California Energy Commission
Contact: Bob Aldrich at the California Energy Commission (boba@energy.ca.gov) or http://www.energy.ca.gov
Abstract: This source covers all of the designated alternative fuels, national and California state regulations, heavy-duty vehicles and engines, as well as future technologies. The fuels are covered in individual chapters that outline emissions, common questions and answers, available vehicles, industry contacts and a history of the fuel.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
✓Hydrogen	Dimethyl Ether (DME)	✓Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	✓Fuel Cell

Alternative Fuel Light-Duty Vehicles: Summary of Results from the National Renewable Energy Laboratory's Vehicle Evaluation Data Collection Efforts
Publication Date: May 01, 1996
Publisher: National Renewable Energy Lab
Contact: Alternative Fuels Data Center (800-423-1363)
Abstract: This study conducted by the U.S. Department of Energy's National Renewable Energy Laboratory focuses on OEM and converted light-duty vehicles. The study includes performance and reliability, fuel economy, and emissions data.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Alternative Fuel News
Publication Date: Bimonthly
Publisher: National Renewable Energy Lab
Contact: Alternative Fuels Data Center (800-423-1363)
Abstract: A bimonthly newsletter that covers the alternative fuel industry and the DOE's Clean Cities Program. Topics include Clean Cities (projects, designations conferences), as well as AFV legislation, OEM activity, market development, and information about new technologies in the alternative fuels and transportation industries.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
✓Hydrogen	Dimethyl Ether (DME)	✓Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	✓Fuel Cell

Alternative Fueled Vehicles for State Government and Fuel Provider Fleets: A Guide for Meeting EPACT 1992 Requirements

Publication Date: Feb 01, 1996
Publisher: US Department of Energy, Office of Transportation Technologies
Contact: Alternative Fuels Data Center (800-423-1363)
Abstract: This booklet outlines the main compliance requirements for state and fuel provider fleets covered by EPAct. Decision trees and definitions are provided to clarify the mandate.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Alternatives to Traditional Transportation Fuels - An Overview

Publication Date: Jun 01, 1994
Publisher: DOE, Energy Information Administration
Contact: National Energy Information Center (202-586-8800)
Abstract: This overview is one of the most comprehensive reports in the industry, and provides technical information about all of the alternative fuels using gasoline and diesel as a baseline. Topics include status of AFVs, fuel consumption, greenhouse gas emissions, legislation, as well as fuel characteristics, properties, production, and distribution.

✓Ethanol	✓Compressed Natural Gas (CNG)	✓Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
✓Hydrogen	✓Dimethyl Ether (DME)	✓Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	✓Fuel Cell

Alternatives to Traditional Transportation Fuels 1994
Volume 2: Greenhouse Gas Emissions

Publication Date: Aug 01, 1996
Publisher: DOE, Energy Information Administration
Contact: National Energy Information Center (202-586-8800)
Abstract: This report estimates greenhouse gas emissions resulting from conventional gasoline, methanol, ethanol, natural gas and propane. The overview also includes the chemistry and physics of global warming, the stability of ozone and the combustion chemistry of transportation fuels.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Alternatives to Traditional Transportation Fuels 1996

Publication Date: Dec 01, 1997
Publisher: DOE, Energy Information Administration
Contact: National Energy Information Center (202-586-8800)
Abstract: This report provides current statistical information about alternative transportation fuels and AFVs. The main focus of the report is quantifying AFVs in use, fuel consumption, and AFVs made available for onroad and nonroad use.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Applying for and Using CMAQ Funds: Putting the Pieces Together
Publication Date: May 01, 1997
Publisher: Enveco of Texas
Contact: National Technical Information Service (703-487-4650)
Abstract: CMAQ is a 6-year, $6 billion federal program formed by the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). This guide outlines the process for securing CMAQ funds for AFV research and demonstration projects.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Biofuels for Transportation: The Road from Research to the Marketplace
Publication Date: Aug 01, 1997
Publisher: National Renewable Energy Lab.
Contact: NREL Biofuels Information Center (303-275-4347)
Abstract: A folder containing a series of fact sheets that cover the topics of methanol production, ethanol production, biodiesel production, thermochemical conversion of biomass, and global warming and biofuels emissions. Outlines available biomass feedstocks, emerging production technologies, and environmental effects.

✓Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
✓Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Biofuels News
Publication Date: Quarterly
Publisher: National Renewable Energy Lab
Contact: Alternative Fuels Data Center (800-423-1363)
Abstract: A quarterly newsletter that covers the biofuels industry including legislation, feedstock development, production technologies and infrastructure for ethanol and methanol produced from biomass.

✓Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Clean Air Program: Summary Assessment of the Safety, Health, Environmental and System Risks of Alternative Fuels
Publication Date: Aug 01, 1995
Publisher: U.S. Department of Transportation
Contact: National Technical Information Service (703-487-4650)
Abstract: This summary covers the areas of safety, health, environmental issues, production, bulk transport, and bulk storage of alternative fuels. Safety risks of the alternative fuels in fleet applications are covered and comparisons are made to gasoline and diesel.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
✓Hydrogen	Dimethyl Ether (DME)	Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Clean Cities Guide to Alternative Fuel Vehicle Incentives & Laws (2nd Edition)
Publication Date: Nov 01, 1996
Publisher: U.S. Department of Energy
Contact: Alternative Fuels Data Center (800-423-1363)
Abstract: This guide provides a listing of federal and state incentives and laws as well as private incentives for purchasing alternative fuel vehicles. Industry and transportation contacts are listed for each state.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Conversion of Natural Gas to Hydrocarbons by Fischer-Tropsch (Prepared for Eurogas '96, Trondheim, Norway)

Publication Date: Jun 3, 1996

Publisher: Sastech R&D

Contact: B. Jager PO Box 1, Sasolburg, 9570, Republic of South Africa

Abstract: *This report covers the production of syngas, the Fischer-Tropsch Process, reactor* developments, catalysts, and the integration of the Fischer Tropsch process with the production of syngas.

Ethanol	Compressed Natural Gas (CNG)	✓Fischer Tropsch
Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Dimethyl Ether as a Transportation Fuel: A State-Of-The-Art Survey

Publication Date: Jun 01, 1997

Publisher: J.E Sinor Consultants Inc.

Contact: Alternative Fuels Data Center (800-423-1363)

Abstract: This report was compiled by conducting a literature review and interviews with companies and individuals that are directly involved with DME. The contents include physical and chemical properties, a history, engine performance, emissions, safety and health, distribution and dispensing, fuel storage, fuel production, and an environmental life cycle analysis.

Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	✓Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Federal Alternative Motor Fuels Programs - Fifth Annual Report to Congress

Publication Date: Sep 01, 1996

Publisher: U.S. Department of Energy

Contact: Alternative Fuels Data Center (800-423-1363)

Abstract: This document reports the current data that the DOE has collected during AFV demonstrations nationwide. It summarizes test results for light-duty vehicles, heavy-duty vehicles, transit buses, and aftermarket conversions in the areas of safety, infrastructure, vehicle availability, emissions, cost, fuel economy, performance and reliability.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Final Alternative Fuel Transit Bus Evaluation Results
Publication Date: Dec 01, 1996
Publisher: Battelle
Contact: Battelle, 505 King Avenue, Columbus, OH 43201
Abstract: The transit bus evaluation reports detailed operations information on alternative fuel and diesel buses including reliability, fuel economy, operating costs, capital costs, emissions testing results, operational issues including safety and training. The report is based on diesel transit buses currently in use as a basis for comparison.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Fuel-Cycle Fossil Energy Use and Greenhouse Gas Emissions of Fuel Ethanol Produced from US Midwest Corn
Publication Date: Dec 19, 1997
Publisher: Argonne National Laboratory
Contact: Center for Transportation Research Energy Systems Division Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439 or (630-252-2000)
Abstract: An analysis of the corn to ethanol production cycle and how it contributes to the production of greenhouse gas emissions. The report concludes that corn-based ethanol does have net energy savings and greenhouse gas reductions when compared to reformulated gasoline.

✓Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Green Car Guide
Publication Date: 1998
Publisher: American Council for an Energy Efficient Economy (ACE^3)
Contact: ACE^3 Publications Office (202-429-0063)
Abstract: The purpose of the green car guide is to help consumers buy cars that are cleaner and more fuel efficient in order to minimize adverse environmental effects. Each car is ranked by federal and California emissions standards, fuel cost per year, tons of greenhouse gas emissions per year, environmental damage index, green score based on the environmental damage index, class comparison form superior to inferior, and the estimated health cost per year based on the damaging effects of CO, HC, NO_x, and PM. The guide covers all 1998 conventional gas vehicles as well as the OEM alternative fuel vehicles. Rating for bi-fuels and flex-fuels are based on the gasoline emissions.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Guidebook for Handling, Storing, & Dispensing Fuel Ethanol

Publication Date: Jan 01, 1996

Publisher: Argonne National Laboratory

Contact: Center for Transportation Research Energy Systems Division Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439 or (630-252-2000)

Abstract: This guidebook contains information about alcohol fuel vehicles, production, fuel properties, environmental impacts, specification and standards, storage and dispensing, transport and delivery, and safety procedures. A comparison of E85 fuel properties to methanol, ethanol, and gasoline is also included.

✓Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

A Guide to the Emissions Certification Procedures for Alternative Fuel Aftermarket Conversions

Publication Date: Jan 30, 1998

Publisher: National Renewable Energy Laboratory

Contact: Alternative Fuels Data Center (800-423-1363)

Abstract: A reference guide that outlines the process of emissions certification procedure followed by the US Environmental Protection Agency and the California Air Resources Board for aftermarket conversion kits. The guide includes a history of Memo 1A and the Addendum, an explanation of engine family names, emissions testing procedures, FAQs, a glossary of abbreviations and definitions, schematics of commercial conversion systems, and a chart of federal and California emission standards. The guide also provides important contacts, websites, and documents for more information.

Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Harnessing Hydrogen: the Key to Sustainable Transportation

Publication Date: 1995

Publisher: INFORM

Contact: INFORM Inc. (212-361-2400)

Abstract: This book covers hydrogen engine and fuel cell technologies, fuel storage, production, distribution, efficiency, environmental impact and safety.

Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	Liquefied Natural Gas (LNG)	Battery
✓Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	✓Fuel Cell

Heavy Vehicle and Engine Resource GuideVehicle and Engine Resource Guide
Publication Date: Apr 30, 1997
Publisher: National Alternative Fuels Hotline
Contact: Alternative Fuels Data Center (800-423-1363)
Abstract: This resource guide provides information about heavy-duty engines and OEM models including medium and heavy trucks, refuse haulers, school buses, transit buses and shuttles, and street sweepers. The guide contains a chart that reflects the emissions, horsepower, displacement and torque for each of the heavy engines. A list of industry suppliers and contacts is also included.

Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Light-Duty Vehicle Resource Guide
Publication Date: Mar 30, 1998
Publisher: National Alternative Fuels Hotline
Contact: Alternative Fuels Data Center (800-423-1363)
Abstract: This document lists the Original Equipment Manufacturer's (OEM) light duty offerings for 1998. The guide includes the emissions class, powertrain, fuel capacity and range for each model. A contact phone number and website is listed for each OEM as well as a glossary of commonly used acronyms. The guide is updated annually to reflect the new model year offerings.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Liquefied Natural Gas as a Transportation Fuel for Heavy Duty Trucks: Volume 1
Publication Date: Dec 1997
Publisher: National Renewable Energy Laboratory
Contact: Paul Norton (303-275-4424)
Abstract: Designed as a training manual for executives, planners and engineers, volume one covers the physics and chemistry of LNG, economics of fleet conversion, summary of ongoing projects, federal government programs that encourage conversion to LNG, refueling station technology, as well as production and distribution infrastructure. The report also covers the available medium and heavy-duty vehicles, fuel systems and engines that are currently available.

Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	✓Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Looking Beyond the Internal Combustion Engine: The Promise of Methanol Fuel Cell Vehicles
Publication Date: Jun 01,
Publisher: American Methanol institute
Contact: Greg Dolan (202-467-5050)
Abstract: The American Methanol Institute has prepared this report to introduce readers to methanol fuel cell technology. The report reviews the types of fuel cells that are being developed, safety and health impacts, emissions, effect on the environment, and a comparison with gasoline fuel cells and hybrid vehicles.

Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	✓Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	✓Fuel Cell

Partners for Cleaner Air: Clean Cities and Natural Gas Vehicles
Publisher: NGVC and DOE
Contact: Natural Gas Vehicle Coalition (703-527-3022)
Abstract: The Natural Gas Vehicle Coalition promotes the use of NGVs and this publication outlines information that consumers and fleets need to know about purchasing and using NGVs. OEM offerings and several types of conversion options are covered. Information about initial cost, paybacks, and refueling are also described in detail.

Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	✓Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Perspectives on AFVs: 1996 Federal Fleet Driver Survey
Publication Date: Sep 15, 1997
Publisher: National Renewable Energy Lab.
Contact: Alternative Fuels Data Center (800-423-1363)
Abstract: This report summarizes the results of NREL's survey of Federal fleet drivers using AFVs. Survey topics cover the driver's fueling practices, vehicle use, and a comparison of the responses from the drivers and fleet managers. Performance evaluations include a comparison to gasoline vehicles, acceleration, range, and overall satisfaction.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Perspectives on AFVs: 1996 Federal Fleet Manager Surveyon AFVs
Publication Date: Jul 01, 1997
Publisher: National Renewable Energy Lab.
Contact: Alternative Fuels Data Center (800-423-1363)
Abstract: This report summarizes the results of NREL's survey of Federal fleet managers using AFVs. Survey topics cover driver acceptability, fuel availability, fueling practices, vehicle performance, maintenance, and a comparison with the gasoline vehicles in the fleet.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Replacement Fuel and Alternative Fuel Vehicle Technical and Policy Analysis Pursuant to Section 506 of the Energy Policy Act of 1992
Publication Date: Jul 01, 1997
Publisher: Department of Energy
Contact: Alternative Fuels Data Center (800-423-1363)
Abstract: This report is the first of two technical and policy analyses required by EPACT section 506. It evaluates the progress made in achieving the fuel displacement goals mandated by EPAct, the role of transportation and specifically the role of replacement fuels and AFVs, availability of fuels and vehicles and the important role of fleets.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
✓Hydrogen	Dimethyl Ether (DME)	Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Taking an Alternative Route: Alternative Fuels Fueling the Future
Publication Date: Jun 01, 1997
Publisher: Argonne National Lab
Contact: Alternative Fuels Data Center (800-423-1363)
Abstract: This report was compiled as an introduction for fleet managers to alternative fuels and federal mandates. The report contains a decision tree for determining coverage under EPAct and the CAA, a listing of MSAs and CMSAs, purchasing incentives, and a section designed to help fleet managers determine which fuels and vehicles will best meet the needs of their fleet.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Transportation Energy Data Book: Edition 16
Publication Date: Jul 1996
Publisher: Oak Ridge National Laboratory
Contact: Stacy Davis at ORNL (423-574-5957)
Abstract: This book is designed to be a desktop reference for statistics related to transportation. Includes a chapter on alternative fuels that covers fleets using AFVs, consumption, OEM offerings, as well as fuel prices, taxation and incentives.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Transportation Statistics Annual Report 1996
Publication Date: 1996
Publisher: US Department of Transportation, Bureau of Transportation Statistics
Contact: Bureau of Transportation Statistics (202-554-3564)
Abstract: The document is produced to reflect the nation's transportation system on an annual basis. The first major area includes transportation and the economy, energy and transportation, and safety. The second addresses how transportation effects the environment and specifically air quality.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

C.2 Websites

Alternative Fuels Data Center
http://www.afdc.doe.gov/
Abstract: A comprehensive website maintained by NREL that covers all of the alternative fuels as recognized by DOE. The site includes downloadable documents including refueling stations address locator and mapping, legislative information, OEM offerings, the *Alternative Fuel News* publication, and provides links to many alternative fuel websites.

✓Ethanol	✓Compressed Natural Gas (CNG)	✓Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
✓Hydrogen	✓Dimethyl Ether (DME)	✓Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	✓Fuel Cell

Alternative Fuel Vehicle Fleet Buyer's Guide

http://www.fleets.doe.gov/

Abstract: Includes cost comparisons of fleets and private alternative fuel vehicles to conventional gasoline vehicles. Provides updated information about laws and incentives for alternative fueled vehicles, and contains tools to help fleets determine if they are covered by EPAct. Lists of state contacts and information about alternative fuel vehicles are also included.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

American Methanol Institute

http://www.methanol.org/

Abstract: Provides information about the use of methanol and the development of methanol powered fuel cells. Contains press releases, fact sheets and speeches about methanol and related technologies.

Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	✓Fuel Cell

Bioenergy Information Network

http://www.esd.ornl.gov/bfdp/

Abstract: Sponsored by Oak Ridge National Laboratory (ORNL) and National Renewable Energy Laboratory (NREL). The web site contains information about the domestic production, recovery, and conversion of energy crops. Provides economic analysis of fuel conversion methods, environmental benefits, and power generation.

✓Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Biofuels Information Center

http://www.biofuels.nrel.gov/

Abstract: This web site is maintained by NREL, and provides technical information on biofuels conversion research conducted under U.S. DOE supervision from 1980 to the present. Allows access to *Biofuels News* and a searchable database of documents.

✓Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

California Air Resources Board
http://www.arb.ca.gov/homepage.htm
Abstract: Covers air quality requirements, legislation and regulations pertaining to the reduction of emissions from vehicles. The site also contains air quality data that is used for modeling, a section about low emission vehicles, and information on the different California and national vehicle standards (LEV, TLEV, ULEV, SULEV, etc.).

Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

California Energy Commission -Alternative Fuel Vehicles
http://www.energy.ca.gov/afvs/index.html
Abstract: This site contains general information about each of the alternative fuels as well as demonstrations and research programs in the state of California. Many reports are available to download.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
✓Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Calstart
http://www.calstart.org/
Abstract: Provides daily industry and government updates, EV recharge maps, the Clean Fuel Vehicle Fleet Resource Center, as well as industry reports and press releases.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	✓Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Energy Efficiency and Renewable Energy Network
http://www.eren.doe.gov/
Abstract: DOE web site that includes energy efficiency and renewable energy information, including alternative fuels. Provides links to all DOE sites that have alternative fuel information.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Energy Information Administration

http://www.eia.doe.gov/

Abstract: Includes statistical data about production and consumption of renewable and alternative fuels. Also provides links to documents about industry markets.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

EPA - Clean Fuel Fleets (Alternative Fuels, Calif. Pilot Program)

http://www.epa.gov/orcdizux/cff.htm

Abstract: Covers certified alternative fuel and/or clean-fuel fleet vehicles, as well as regulatory information related to Memo 1A and Clean Fuel Fleets.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

Fuel Cells 2000

http://www.fuelcells.org/

Abstract: Includes all fuel cell information, including fuel cells for transportation, types of fuel cells, developers, pictures and benefits of fuel cell technology.

Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	Liquefied Natural Gas (LNG)	Battery
✓Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	✓Fuel Cell

Gas Research Institute

http://www.gri.org/

Abstract: Many technical reports about natural gas can be obtained from this site. Documents about refueling, storage, and vehicle technologies are all available.

Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	✓Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Hydrogen InfoNet

http://www.eren.doe.gov/hydrogen/infonet.html

Abstract: This site was created for DOE. It covers information about hydrogen including many publications, status of current technology, as well as basic fact sheet about hydrogen power.

Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	Liquefied Natural Gas (LNG)	Battery
✓Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

Idaho National Engineering and Environmental Laboratory
http://www.inel.gov/ and/or **http://ev.inel.gov/**
Abstract: Includes hybrid and electrical research program information, and testing results from the laboratory field operations program.

Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	Liquefied Natural Gas (LNG)	✓Battery
Hydrogen	Dimethyl Ether (DME)	✓Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

LNG Express
http://www.lngexpress.com/
Abstract: Includes the monthly *LNG Express* publication, emerging market data and a directory of LNG products and services.

Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	✓Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

National Biodiesel Board
http://www.biodiesel.org/
Abstract: A searchable database of Biodiesel documents, *Biodiesel Report* newsletter, the latest information about biodiesel legislation, and how the fuel can be used in fleet, transit, marine, and mining applications.

Ethanol	Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
✓Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

National Renewable Energy Laboratory
http://www.nrel.gov/
Abstract: The site contains information about alternative fuels technology, refueling stations and biofuels production. NREL conducts studies and has a searchable database of reports related to alternative fuels.

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
✓Hydrogen	Dimethyl Ether (DME)	✓Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	✓Fuel Cell

Natural Gas Vehicle Coalition
http://www.ngvc.org/home.html
Abstract: This web site describes the objectives of the coalition that represents the natural gas vehicle industry. In addition to public and fleet information on natural gas vehicles, there is a section for NGVC members only.

Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	✓Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	Liquefied Petroleum Gas (LPG)	Fuel Cell

RP Publishing
http://www.rppublishing.com/
Abstract: This site provides a list of documents published by RP Publishing related to natural gas and propane. Includes periodicals and directories.

Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
Methanol	Liquefied Natural Gas (LNG)	Battery
Hydrogen	Dimethyl Ether (DME)	Hybrid
Biodiesel	✓Liquefied Petroleum Gas (LPG)	Fuel Cell

SAE International
http://www.sae.org/index.htm
Abstract: The Society of Automotive Engineers provides alternative fuel vehicle information and standards. The web site allows you to access summaries and search for specific documents. (There is a fee for downloading and ordering information.)

✓Ethanol	✓Compressed Natural Gas (CNG)	Fischer Tropsch
✓Methanol	✓Liquefied Natural Gas (LNG)	✓Battery
✓Hydrogen	✓Dimethyl Ether (DME)	✓Hybrid
✓Biodiesel	✓Liquefied Petroleum Gas (LPG)	✓Fuel Cell

APPENDIX D

REFERENCES

GENERAL

Newman, M. and Grey, J. (editors), *Utilization of Alternative Fuels for Transportation,* American Institute of Aeronautics and Astronautics, New York, 1979.

Fuel Alcohol, An Energy Alternative for the 1980's, Final Report by the U.S. National Alcohol Fuels Commission, U.S. Government Printing Office, Washington, DC, 1981.

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

Sperling, D. (Editor), *Alternative Transportation Fuels,* Quorum, New York, 1989.

"Prospect Specifications for Alternative Fuels for Motor Vehicles," California Air Resources Board Staff Report, October 1991.

Black, F., "An Overview of the Technical Implications of Methanol and Ethanol as Highway Motor Vehicle Fuels," SAE Paper 912413.

Gushee, D. E. and Lazzari, S., "Disparate Impacts of Federal and State Highway Taxes on Alternative Motor Fuels," Congressional Research Service Report 93-330E, The Library of Congress, December 1993.

Unnasch, S., et al., "Performance and Emissions of Clean Fuels in Transit Buses with Cummins L10 Engines," SAE Paper 931782.

Sinor, J. E., "What are the Alternative Fuels?" presented at the International Alternative Fuels and Clean Cities Conference, Milwaukee, Wisconsin, June 1994.

Imbrecht, C. R., "California's Clean, Alternative Fuel Vehicle Programs," presented at the International Alternative Fuels and Clean Cities Conference, Milwaukee, Wisconsin, June 1994.

"Alternatives to Traditional Transportation Fuels: An Overview," U.S. Department of Energy, Energy Information Administration Report DOE/EIA-0585/0, June 1994.

"ABCs of AFVs — A Guide to Alternative Fuel Vehicles," Second Edition, P180-95-001, California Energy Commission, Sacramento, California, January 1995.

"Evaluation of Fuel-Cycle Emissions on a Reactivity Basis," Acurex Environmental Report TR-95-8522-1 for the

California Air Resources Board, July 1995.

METHANOL

Ecklund, E. and Pefley, R., "Characterization and Research Investigation of Alcohol Fuels in Automobile Engines," Report ME-81-1 for the U.S. Department of Energy, University of Santa Clara, Santa Clara, California, April 1981.

Nichols, R. J., Buist, D. R., "Ford's Development of Alcohol-Fueled Vehicles," presented at the First International Conference on Fuel Methanol, New York, New York, May 9-10, 1983.

Toepel, R. R. and Bennethum, J. E., "Development of Detroit Diesel Allison 6V-92TA Methanol Fueled Coach Engine," SAE Paper 831744.

Wiens, F. J., et al., "California's Alcohol Fleet Test Programs — Final Results," presented at the IV International Symposium on Alcohol Fuels Technology, Ottawa, Canada, May 21-25, 1984.

Browning, L. H. and McCormack, M. C., "A Technology Assessment of Light-Duty Methanol Vehicles," presented at the X International Symposium on Alcohol Fuels, Colorado Springs, Colorado, November 7-10, 1993.

Alternative Motor Fuels Agreement: Comparison of Relative Environmental Impacts of Alternative and Conventional Motor Fuels (Final Report), International Engergy Agency, September 1995.

ETHANOL

Pischinger, G. and Pinto, N. L. M., "Experiences with Utilization of Ethanol/Gasoline and Pure Ethanol in Brazilian Passenger Cars," presented at the III International Symposium on Alcohol Fuels Technology, Asilomar, California, April 1980.

"Analysis of the Economic and Environmental Effects of Ethanol as an Automotive Fuel," U.S. Environmental Protection Agency, Special Report by the Office of Mobile Sources, April 1990.

Brown, M., King, L., Prakash, C., and Flavelle, C., "Operation and Emissions Experience of Ethanol Buses in Regina," 1992 Windsor Workshop on Alternative Fuels, Toronto, Ontario, Canada, June 15-17, 1992.

Marek, N. J., Stamper, K. R., and Miller, S., "The Ethanol Heavy Duty Truck Fleet Demonstration Program," presented at the X International Symposium on Alcohol Fuels Technology, Colorado Springs, Colorado, November 7-10, 1993.

Dodge, L. G., et al., "Dedicated Ethanol Ultra-Low Emission Vehicle," presented at the Alcohol Fuel and Cold-Start Emissions SAE TOPTEC, Golden, Colorado, January 12-13, 1995.

"Fuel Cycle Evaluations of Biomass - Ethanol and Reformulated Gasoline, Department of Energy," July 1994.

COMPRESSED NATURAL GAS

Weaver, C. S., "Natural Gas Vehicles — A Review of the State of the Art," SAE Paper 892133.

Liss, W. E. and Thrasher, W. H., "Natural Gas as a Stationary Engine and Vehicular Fuel," SAE Paper 912364.

Geiss, R. O., Burkmyre, W. M., and Lonigan, J. W., "Technical Highlights of the Dodge Compressed Natural Gas Ram Van/Wagon," SAE Paper 921551.

"OEMs and NGVs: Putting the Pieces Together," *Natural Gas Fuels*, V.3, N.11, Nov 1994, p. 15.

Lawson, A., "Emissions Durability of Bifuel Vehicles," presented at the Natural Gas Engine and Vehicle Technology SAE TOPTEC, Austin, Texas, April 30-May 2, 1995.

Sverdrup, G. M., "Experience with CNG in the CleanFleet Project," presented at the Natural Gas Engine and Vehicle Technology SAE TOPTEC, Austin, Texas, April 30-May 2, 1995.

Blazek, C. F., et al., "Evaluation of Aftermarket CNG Conversion Kits in Light-Duty Vehicle Applications," NREL/TP-425-6550, National Renewable Energy Laboratory, Golden, Colorado, July 1995.

LIQUEFIED NATURAL GAS

Gibson, C. J., "Four Years of LNG Vehicle Experience," presented at the Cryogenic Society of America Annual Symposium, Los Angeles, California, October 3-5, 1973.

Liss, W. E., Okazaki, S., Acker, G. H., and Moulton, D. S., "Fuel Issues for Liquefied Natural Gas Vehicles," SAE Paper 922360.

Nimocks, R. M., "Usage of LNG as a Transportation Fuel," presented at LNG as a Transportation Fuel SAE TOPTEC meeting, Houston, Texas, January 25-27, 1993.

Powars, C. A., Moyer, C. G., and Lowell, D. D., "LNG Vehicle Technology, Economics, and Safety Assessment," GRI-94/0051, Gas Research Institute, Chicago, Illinois, February 1994.

Jayaraman, J., "LNG as a Transportation Fuel: Outstanding Technical Issues," National Gas Fuels, V. 3, N. 9, Sept. 1994, P. 17.

Beale, J., "First Dedicated LNG Fuel Plant Online," National Gas Fuels, V. 4, N. 2, Feb. 1995, p. 28.

CH-IV Cryogenics. LNG Fact Sheet, September 1998. Web site: www.ch-iv.com.

"Alternatives to Traditional Transportation Fuels: An Overview," U.S. Department of Energy, June 1994.

"Clean Air Program: Summary Assessment of the Safety, Health, Environmental and System Risks of Alternative Fuel," U.S. Department of Transportation, August 1995.

COMPRESSED AND LIQUEFIED NATURAL GAS

"Assessment of Methane-Related Fuels For Automotive Fleet Vehicles," DOE/CE/50179, Volumes 1, 2, and 3, U.S. Department of Energy, Washington, D.C., February 1982.

Vinyard, S., "The Economics of Heavy-Duty Natural Gas Vehicles," *National Gas Fuels*, V. 3, N. 6, June 1994, p. 17.

Piasecki, J. L., "Heavy-Duty CNG and LNG Vehicle Programs," presented at the Natural Gas Engine and Vehicle Technology TOPTEC, Austin, Texas, April 30-May 7, 1995.

Piellisch, R., "CARB Eases Way for Converters," *Natural Gas Fuels,* V. 4, N. 9, Sept. 1995, p. 6.

PROPANE

Karim, G. A. and Wierzba, I., "Comparative Study of Methane and Propane as Fuels for Spark Ignition and Compression Ignition Engines," SAE Paper 831196.

Monster, R. and Topaloglu, T., "Assessment of Fuel Consumption and Exhaust Emissions of In-Use Propane Vehicles," presented at the Third Windsor Workshop on Alternative Fuels, Windsor, Ontario, Canada, June 24-26, 1987.

Webb, R. F. and Delmas, P. J., "New Perspectives on Auto Propane as a Mass-Scale Motor Vehicle Fuel," SAE Paper 911667.

Yates, S., "Chrysler's LEV LPG Vehicle Concept," presented at the 1994 Windsor Workshop on Alternative Fuels, Toronto, Ontario, Canada, June 13-15, 1994.

Vedlitz, S. E., "Propane Supply and Economics," presented at the Propane Technology SAE TOPTEC, Toronto, Ontario, Canada, June 14-15, 1995.

Hubbard, P., "Performance of Ford LPG Trucks," presented at the Propane Technology SAE TOPTEC, Toronto, Ontario, Canada, June 14-15, 1995.

"Chrysler Canada Propane-Fueled Ram Van Delivered in Ottawa," *Butane-Propane News,* V. 27, N. 9, Sept. 1995, p. 33.

"Energy Policy Act Including Propane as an Alternative Motor Fuel Will Have Little Impact on Propane Market," General Accounting Office, September 1998.

Hewitt, Jess., *HD-5 Fuel Specificaton Allows FuelBuyers to Know What They are Putting in the Tank,* Hydrocarbon Processing Inc. Web site www.ati-intl.com/hd5.htm.

"Alternatives to Tranditional Transportation Fuels: An Overview," U.S. Departmetn of Energy. June 1994.

"Clean Fuels: Paving the Way for America's Future (Second Edition)," Clean Fuels Development Coalition, Governor's Ethanol Coalition, U.S. Department of Energy, 1995.

HYDROGEN

"The Clean Fuels Report: Comprehensive Coverage of Business, Government and Technology Issues for Transportation Fuels," J. E. Sinor Consultants, Inc., April 1992.

"The Clean Fuels Report: Comprehensive Coverage of Business, Government and Technology Issues for Transportation Fuels", J. E. Sinor Consultants, Inc., November 1993.

DeLuchi, M, "Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, Environmental Impacts, and Cost," *International Journal of Hydrogen Energy*, 14(2), pp. 81-130, 1989.

Heffel, J., J. M. Norbeck, "Preliminary Evaluation of UC Riverside's Hydrogen Powered Truck," Presented at the National Hydrogen Association's Sixth Annual U.S. Hydrogen Meeting, March 7-9, 1995.

Kukkonen, C. A., M. S. Shelef, "Hydrogen as an Alternative Automotive Fuel: 1993 Update," SAE 940766.

Montano, M., T. Durbin, B. Tabarra, J. Bowden, *Hydrogen as a Fuel for Surface Transportation*, to be published by SAE, forthcoming.

Peschka, W., W. D. Escher, "Germany's Contribution to the Demonstrated Technical Feasibility of the Liquid-Hydrogen Fueled Passenger Automobile," SAE 931812

"Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles," Congress of the United States, Office of Technology Assessment, September 1993.

Winter, D., "Is Hydrogen the Ultimate Fuel?" *Ward's Auto World*, April 1995, pp. 50-51.

"Hydrogen Energy," U.S. Department of Energy, National Renewable Energy Laboratory.

Keoleian GA, Lewis G. McD., *Application of Life-cycle Energy Analysis to Photovoltaic Moduel Desgin. Progress in Photo Voltaics: Research and Applications*, 1997.

ELECTRIC VEHICLES

"The Clean Fuels Report: Comprehensive Coverage of Business, Government and Technology Issues for Transportation Fuels," J. E. Sinor Consultants, Inc., April 1992.

"The Clean Fuels Report: Comprehensive Coverage of Business, Government and Technology Issues for Transportation Fuels," J. E. Sinor Consultants, Inc., November 1993.

McCoy, G. A., J. K. Lyons, *Electric Vehicles: An Alternative Fuels Vehicle, Emissions, and Refueling Infrastructure Technology Assessment*, Washington State Energy Office, June 1993.

Montano, M., S. Unnasch, P. Franklin, G. Nowell, C. Martin, E. Craig, *Reclamation of Automotive Batteries: Assessment of Health Impacts and Recycling Technology*, Prepared by Acurex Environmental Corporation for the California Air Resources Board, March 1995.

Raitt, H., "The Calfuels EV Infrastructure Study: The Status of Electric Vehicles in California," California Energy Commission, Presented at the Twelfth International Electric Vehicle Symposium, December 5-7, 1994.

"Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles," Congress of the United States, Office of Technology Assessment, September 1993.

De Sabata G., *The Dilemma of Motorized Vehicles; Electric Cars Scarcely the Environmental Solution. Environmental Conservation*, 1995.

Steele NLC, Allen DT., *An Abridged Life-Cycle Assessment of ElectricVehicle Batteries*, Environmental Science & Technology, 1998.

"Comparison of Relative Environmental Impacts of Alternative and Conventional Motor Fuels (Final Report)," International Energy Agency, September 1995.

"Clean Fuels Paving the Way for America's Future (Second Addition)," Clean Fuels Development Coaltion, Governor's Ethanol Coalition, U.S. Department of Energy, 1995.

FUEL CELLS

Borroni-Bird, C.E., *Fuel Cell Commercialization Issues for Light-Duty Vehicle Applications*, Proceedings of the Fourth Grove Fuel Cell Symposium, September 1995, Journal of Power Sources, Vol. 61, July 1996.

Ballard Power Systems, Web Page and 1996 Annual Report.

Heller, F., *Mercedes-Benz Fuel Cell Research Car Debuts at Frankfurt Show*, Media Information, Daimler-Benz, September 1997.

Wimmer, R., *Integration Issues and Test Results of an FC/Battery System*, SAE Fuel Cells for Transportation TOPTEC, March, 1998.

Adams, VW., *Environmental Life Cycle Analyses of Transport Systems*, International Journal of Vehicle Design, 1996.

Kordesch KV, Simader GR., *Environmetnal Impact of Fuel Cell Technology*, Chemical Review, 1995.

DIMETHYL ETHER

Basu, A., Charbonneau, P., Fleisch, T., McCandless, J., McCarthy, C., Mikkelsen, S., Slodowske, W., and Udovich, C., "A New Clean Diesel Technology: Demonstration of ULEV Emissions on an Navistar Diesel Engine Fueled with Dimethyl Ether." SAE Paper 950061, 1995.

Cartellieri, W.P. and Kapus, P.E. "ULEV Potential of a DI/TCI Diesel Passenger Car Engine Operated on Dimethyl Ether," SAE Papers 952754, 1995.

Gill, D.W., Krotscheck, C. and Ofner, H. "Dimethyl Ether as Fuel for CI Engines - A New Technology and Its Environmental Potential," SAE Paper 981158, 1998.

Wilson, Rob., *DME Shows Promise as Drop-in Replacement for Diesel Fuel. Diesel Progress Engines and Drives*, June 1995.

"Development of a Production-Feasible, Common Rail Fuel Injection System for Liquid Dimethyl Ether (DME) for Use in Heavy-Duty Vehicles," National Renewable Energy Laboratory, 1996.

"Dimethyl Ether Offers Diesels ULEV Performance," Centre for Alternative Transportation Fuels Review, April 1995.

"Fuels Technologies, Fuels for Advanced Engines", U.S. Department of Energy, Office of Transportation Technologies (web site), Fact Sheet.

"Dimethyl Ether as a Transportation Fuel: A State of the Art Survey," J.E. Sinor Consultants, Inc., June 1997.

BIODIESEL

Howell, S., Marshall, W., Schumacher, L., *Engine Exhaust Emissions Evaluation of a Cummings Biodiesel Blend*, SAE Paper 952363, 1995.

Romig, C., Spataru, A., *Emissions and Engine Performance from Blends of Soya and Canola Methyl Esters with ARB #2 Diesel in a DCC 6V92TA MUI Engine*, SAE Paper 952388, 1995.

Peterson, C., Reece, D., *Biodiesel Testing in On-Road Pickups*, SAE Paper 952757, 1995.

Sharp, Christopher A., *Exhaust Emissions and Performance of Diesel Engines with Biodiesel Fuels*, Southwest Research Institute, 1998.

"Biodiesel Use in Urban Transits," National Biodiesel Board (web site), 1998.

"Farmers Now Offered Soy-Based Biodiesel at the Pump." *Biofuels Update*, Vol. V Issue 2, Spring 1997.

"Summary Results from Tier I Health Effects Testing for Biodiesel," Southwest Research Institute, March 1998..

"USDA Agricultural Baseline Projections to 2007," U.S. Department of Agriculture, Staff Report WAOB-98-1, February 1998.

"Used Cooking Oil Into Clean Biodiesel," U.S. Department of Energy, Office of Transportation Technologies, Fact Sheet, August, 1996.

"An Overview of Biodiesel and Petroleum Diesel Life Cycles," U.S. Department of Energy, May 1998.

"Clean Air Program: Summary Assessment of the Safety, Health, Environmental and Systme Risks of Alternative Fuel," U.S. Department of Transportation, August 1995.

Franke B, *Reinhardt G., Econoligcial Impacts of Biofuels in Europe*, Prepared for the Interantional Liquid Biofuels Congress, Brazil, July 18-22, 1998.

FISCHER TROPSCH

"AGC-21 Product for a New Century." Exxon Corporation, In the Lamp Vol.80, No.2, Summer 1998.

"Emissions Performance of Fischer-Tropch Diesel Fuels," Southwest Research Insitute, presented at the AIChE Spring Meeting, March 1997.

"Conversion of Natural Gas to Hydrocarbons by Discher Tropsch," Sastech R&D, prepared for Eurogas 96 Symposium, Trondheim, Norwya, June 1996.

FLEET EXPERIENCE

"Alternative Fuel Transit Buses, Final Results from the National Renewable Energy Laboratory Vehicle Evaluation Program," National Renewable Energy Laboratory for the U.S. Department of Energy, October 1996.

"Alternative Fuel Vehicles For a Cleaner Environment," United States Postal Service, Issue 2, 1997

"Alternatives to Traditional Transportation Fuels 1996." Energy Information Administration, U.S. Department of Energy, December 1997.

"CleanFleet Final Report," Battelle Memorial Institute, Columbia Operations, through sponsorship from South Coast Air Quality Management District and the California Energy Commission, December 1995.

"Compressed Natural Gas and Liquefied Petroleum Gas Conversions: The National Renewable Energy Laboratory's Experience," National Renewable Energy Laboratory, April 1996.

"Hertz Puts You In The Driver's Seat - And Methanol In Your Tank," Case Study, Argonne National Laboratory for the U.S. Department of Energy, April 1997.

"Nation's Largest Alternative Fuel Fleet Delivers the Goods for the U.S. Postal Service, " Case Study, Argonne National Laboratory for the U.S. Department of Energy, August 1997.

"Perspectives on AFVs: 1996 Federal Fleet Manager Survey," National Renewable Energy Laboratory for the U.S. Department of Energy, July 1997.

"Perspectives on AFVs: 1996 Federal Fleet Driver Survey," National Renewable Energy Laboratory for the U.S. Department of Energy, September 1997.

"Raley's LNG Truck Fleet Start-Up Experience - Alternative Fuel Truck Evaluation Project," Center for Transportation Technologies and Systems at the National Renewable Energy Laboratory, October 1997.