Alternative Fuel Transit Bus Evaluation Program Results

Kevin Chandler, Norman Malcosky
Battelle

Robert Motta, Paul Norton, Kenneth Kelly
National Renewable Energy Laboratory

Leon Schumacher
University of Missouri - Columbia

Donald Lyons
West Virginia University

ABSTRACT

The objective of this program, which is supported by the U.S. Department of Energy (DOE) through the National Renewable Energy Laboratory (NREL), is to provide an unbiased and comprehensive comparison of alternative fuel and diesel transit buses. The information for this comparison has been collected from eight transit bus sites. The fuels studied are natural gas (CNG and LNG), alcohol (methanol and ethanol), biodiesel (20 percent blend), and diesel. The data collected include operations, maintenance, bus equipment configurations, emissions, bus duty cycle, and safety incidents data. Representative and actual capital costs have been collected for alternative fuels and have been used as estimates for conversion costs. Preliminary results are presented in this paper.

INTRODUCTION

Previous studies in alternative fuel transit bus applications have concentrated on one or two test fuels at a time with only a few vehicles. As part of their Clean Air Program, the Federal Transit Administration (FTA), formerly the Urban Mass Transit Administration (UMTA), collected data on alternative fuels such as methanol\(^1\) and compressed natural gas (CNG)\(^2\), and has summarized results of alternative fuels transit bus demonstrations in the U.S. Each transit agency that has tested alternative fuels also has performed data collection and analyses for their own purposes.

Over time, as more transit agencies and other fleet owners began to show interest in alternative fuels because of Federal and state clean air and energy policies, a need emerged to compare similar vehicles on different fuels. These comparisons were needed to evaluate the advancement of these new technologies and to make decisions about which fuels and technologies were mature enough to be used in normal transit service.

As the studies from the FTA and the different transit agencies demonstrating these new alternative fuels became available, there became a need for a multi-fuel, multi-site data collection program. This combined program would help to solve issues of standard data collection protocols and analyses, as well as standard data presentation for unbiased comparisons.

The Alternative Fuel Transit Bus Evaluation Program, supported by the U.S. Department of Energy (DOE) through the National Renewable Energy Laboratory (NREL), is intended to bridge this need of a multi-fuel, multi-site data collection program. This study examines currently active fleets of alternative fuel transit buses in the U.S. The alternative fuels studied are listed below:

- Liquefied Natural Gas (LNG) - natural gas (primarily composed of methane - 95+ percent) which is stored and dispensed as a cryogenic liquid (the engines receive the fuel in the gaseous state)
- Compressed Natural Gas (CNG) - natural gas (primarily composed of methane - 95+ percent) which is stored and dispensed in gaseous form stored at high pressures from 3,000 to 5,000 psi (20.7 to 34.5 MPa) and dispensed into the buses at 3,000 or 3,600 psi (20.7 or 24.8 MPa) - settled pressure
- Ethanol - ethanol is an alcohol (ethyl alcohol) derived from biomass (corn, sugar cane, grasses, trees, and agricultural waste). The ethanol blends used in this study were E93 (93 percent ethanol, 5 percent methanol, 2 percent kerosene by volume) and E95 (95 percent ethanol, 5 percent unleaded gasoline by volume)
- Methanol - methanol is an alcohol (methyl alcohol) produced primarily from natural gas, but can be derived from biomass or coal. The methanol buses
in this program have operated on 100 percent (neat) methanol.
  - Biodiesel Blend - biodiesel fuel can be derived from any plant- or animal-derived oil product. The biodiesel blend used in this program, called BD20, was 20 percent biodiesel from soybeans and 80 percent diesel #2 fuel by volume.

In-depth results are also available in other reports from NREL.4

**PROGRAM DESIGN**

This program was developed in response to the Alternative Motor Fuels Act (AMFA) of 1988, which required that the U.S. Department of Energy (DOE) collect alternative fuels data on vehicles in the U.S., including transit buses. NREL was designated the program manager for the DOE alternative fuels data collection programs. Battelle was selected to evaluate the operational impacts as well as the operating and facilities costs of alternative fuel usage in the transit industry. The University of Missouri at Columbia was asked to collect biodiesel blend operational data at the St. Louis, Missouri site. The West Virginia University (WVU) transportable heavy-duty vehicle emissions testing laboratory measured emissions from the buses in the program.

The individual transit agencies that have participated in this program own and operate the buses and have collected the data used to evaluate the buses. Table 1 summarizes the transit agencies, vehicles and fuels in the program. Note that none of the results for the data collection or the emissions testing for the St. Louis site have been included in this paper. Fuel blending issues surfaced midway through the data collection. The biodiesel blend was discovered to have been 4 percent lower (BD16) than the intended blend (BD20). Also, issues of proper mixing of the biodiesel blend were raised. Corrective measures for these issues have been taken. Future reporting will include the results of the data collection and emissions testing at this site.

**PROGRAM OBJECTIVE** - The objective of the program has been to provide an unbiased and comprehensive comparison of currently available alternative fuel and diesel control transit buses. The control buses listed in Table 1 provide a diesel operations baseline at each site to compare the alternative fuel operations against.

**SITE SELECTION** - The site selection criteria that define which transit agencies would be in the program are given below. These criteria have been used as a guideline to select each participating site.

<table>
<thead>
<tr>
<th>Transit Agency</th>
<th>City</th>
<th>Bus</th>
<th>Engines</th>
<th>Alternative Fuel (AF)</th>
<th>AF Buses</th>
<th>Control Buses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houston Metro</td>
<td>Houston, TX</td>
<td>40 ft. Stewart &amp; Stevenson</td>
<td>DDC Dual-Fuel 6V92TA PING(a)</td>
<td>LNG</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Tri-Met</td>
<td>Portland, OR</td>
<td>40 ft. Flexible</td>
<td>Cummins L-10</td>
<td>LNG</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Metro-Dade Transit Authority (MDTA)</td>
<td>Miami, FL</td>
<td>40 ft. Flexible</td>
<td>Cummins L-10</td>
<td>CNG</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Pierce Transit</td>
<td>Tacoma, WA</td>
<td>40 ft. BIA</td>
<td>Cummins L-10</td>
<td>CNG</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>GP Transit</td>
<td>Peoria, IL</td>
<td>35 ft. TMC</td>
<td>DDC 6V92TA</td>
<td>E95/E93 Trap</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Metropolitan Council of Transit Operations (MCTO)</td>
<td>Minneapolis/ St. Paul, MN</td>
<td>40 ft. Gillig</td>
<td>DDC 6V92TA</td>
<td>E95</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Triboro Coach Company (NYCDOT)</td>
<td>New York, NY</td>
<td>40 ft. TMC</td>
<td>DDC 6V92TA</td>
<td>M100</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Bi-State Development Agency</td>
<td>St. Louis, MO</td>
<td>40 ft. Flexible</td>
<td>DDC 6V92TA</td>
<td>BD20</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Note: Trap = diesel particulate trap, BIA=Bus Industries of America (now Orion Bus), TMC=Transportation Manufacturing Company (now NovaBus), DDC=Detroit Diesel Corporation, Cummins=Cummins Engine Company.  
(a) PING - pilot ignition natural gas. This engine is a dual-fuel engine, which operates on diesel and natural gas fuels in normal operation, but can also operate on diesel fuel alone if needed.
1. Engines in use at each transit agency were required to have used CNG, LNG, propane, methanol, ethanol, or biodiesel blends.
2. Engines in use must have been new original equipment manufacturer (OEM) engines (except biodiesel study at St. Louis - used older engines that were recently rebuilt for the test and control buses).
3. At least five buses using the alternative fuel must have been operated at any one transit agency (the program target was to have ten buses for each alternative fuel split between two different sites).
4. The alternative fuel buses must have been closely matched in equipment to the diesel fuel control buses (that is, the vehicles should have the same manufacturer and be the same model, and the engines should be similar models).
5. Diesel fueled and alternative fueled buses should have been close in age, both in odometer and model year.

DATA COLLECTION - The data collected in this study have been grouped into three types: operating descriptions, bus operations, and capital costs. Data collected have been completely dependent on the transit agencies collecting complete and accurate data. The source of all data collected in this program has been from the existing data collection systems at each transit agency. Some information has been collected from the bus and engine manufacturers as well, but only for background on the vehicle configurations and capital costs. The data collection for this program was defined in a data collection plan and data format plan, which are available from NREL.

Operational data include the vehicle configurations and bus routes. These allow for comparisons of vehicle specifications and vehicle usage respectively. During the study, major equipment or design changes to the bus or engine, such as fuel injector design changes, have been documented in the vehicle configuration descriptions.

Bus operations data are made up of the fuel and engine oil consumption for each vehicle, as well as the maintenance detail, labor hours, and part costs by bus. Any safety incidents are described and any costs associated are also captured.

The capital cost data include facilities descriptions and the costs for any upgrades to existing facilities or new facilities built for the change to alternative fuels. These capital costs were developed from previous studies and are presented for comparison purposes only. Actual capital costs for facilities conversions are dependent on geographic location and climate as well as the age of the facilities to be converted. The original purchase price of the buses also is collected.

RESULTS AND DISCUSSION - RELIABILITY

For this program, reliability refers to the confidence that the buses in the program will perform when and as needed. The reliability is measured directly by recording the road call rate - the average number of in-service failures per 1,000 miles (1,600 kilometers). The vehicle usage and safety incidents are also used as indicators of reliability. Using these measures and indicators, the reliability of the alternative fuel buses is compared to the reliability of the diesel control buses at a given site. Comparisons across sites are limited because operating experience is so diverse from site-to-site. Some caution should be taken when using the data presented here. The data collection for some sites has been or has nearly been completed, while at other sites the data collection may not be complete. In general, the fewer months of operations data available from a given site, the lesser certain any conclusions will be for that site's operational experience.

ROAD CALL RATES - A road call is defined in this study as an on-road failure of an in-service transit bus that requires a replacement bus to be dispatched to finish the route of the failed bus. If the failed bus is fixed on the road and put back into service immediately, then this repair is not considered a road call even though some disruption of service may have been experienced. Also, failures of a bus while not in service are not considered road calls, even if the bus was away from the normal storage location.

Figure 1 shows the overall average road call rates for the alternative fuel and diesel control fleets in the program and a short discussion by site is given below. Major maintenance issues that indicate reliability problems are discussed separately following this discussion on road call rates.

- Houston (LNG) - The road call rate for the LNG buses has been nearly twice that of the diesel control buses on a per 1,000 mile basis. This site has had major problems with proper operation of the engines. Many of the road calls for the LNG buses were for running out of fuel and fuel system leakage problems. These issues are discussed in the next section.
- Portland (LNG) - The road call rate for the LNG buses has been more than twice that of the diesel control buses on a per 1,000 mile basis. The LNG buses have had a few running out of fuel and fuel system leak problems causing road calls similar to Houston.
- Miami (CNG) - The CNG buses experienced 60 percent more road calls than the diesel control buses on a per 1,000 mile basis. However, the CNG fleet has had very low mileage during the 18 months of data collection - 95,000 miles for the fleet or 19,000 miles per bus. Also, note that the CNG fleet
Figure 1. Road Call Rates By Site and Fleet

has one year older engines than the Tacoma site. The major problems causing road calls were for running out of fuel and the engine stalling and having low power. These issues are discussed in the next section.

- Tacoma (CNG) - The CNG and diesel control buses had essentially the same road call rates. No major issues (different from the diesel control buses) were reported which resulted in road calls for the CNG buses.
- Peoria (E95/E93) - During E95 operations, the ethanol buses had a 45 percent higher road call rate; however, during E93 operations, the diesel control buses had a 23 percent higher road call rate.
- Minn./St. Paul (E95) - The road call rate for the ethanol buses was less than 50 percent that for the diesel control buses.
- Miami (M100) - The methanol buses experienced 15 percent more road calls than the diesel control buses on a per 1,000 mile basis. Many of the road calls for the methanol buses were related to the engine stalling or low power. These issues have been related back to fuel system and fuel quality problems, which are discussed in the next section.
- New York (M100) - The methanol buses showed a road call rate nearly 45 percent more than the diesel control buses. Several of the road calls for the methanol buses were related to the fuel system and low engine power as with Miami.

SPECIFIC VEHICLE MAINTENANCE

ISSUES - Specific vehicle system reliability issues are discussed in this section. Some of these issues are fuel dependent and some are not. These issues are observations based on the data collected in this program and on discussions with the transit agency personnel as well as engine and vehicle manufacturer personnel. Most of these issues are for information and not intended to indicate that one fuel is better or worse than another.

Pilot Ignition Natural Gas (PING) Engine Problems at Houston - Unusually small LNG fuel consumption (14 percent LNG, 86 percent diesel #1 on an energy equivalent basis) was reported by Houston in this program. The reason for this low LNG use was determined to be “dirt in the fuel.” The LNG engines being used at Houston operate on LNG with some diesel fuel. At idle, these engines use only diesel fuel and at other speeds, these engines use some diesel fuel for proper ignition timing of the LNG. When problems develop with the PING engine, the engine can be operated on diesel fuel alone (without using any LNG). In this way, if LNG fuel system problems arise, the engine can be operated in a “limp home” mode, which allows the engine to operate properly at all speeds with diesel fuel alone. However, the diesel tank volume is only 43 gallons, which severely restricts vehicle range when operating only on diesel.
Houston's initial understanding of the "fuel cleanliness" problem was that "dirt" in the fuel system was the cause of the rash of PING engine failures that occurred. The investigation revealed that the gas injector was the primary problem as it "tends to stick open" due to the dirt in the fuel. Filters were added to the fuel system and the tanks were carefully cleaned by the fuel tank manufacturer. The gas injector was the focal point of the fuel dirt issue because, if it "sticks" open, it allows the engine to be overfed and subsequently causes both excessive power and overheating of the engine.

Houston Metro and their team of equipment suppliers studied the problem further and determined that internal injector clearances within a "batch" of injectors contributed to the problem. The other source of the dirt was related to operation of the PING engine exclusively on diesel fuel with the gas injectors inoperative. It is believed that this may have placed a "back pressure" on the gas injectors and caused dirt to be forced back into the gaseous fuel system. A stronger spring was used to fix this problem.

Natural Gas Fuel Leaks and Fuel Vapor Detection - The LNG fuel systems used at Houston and Portland had many repairs for fuel leaks. This has been a source of several road calls, as well as costly repairs, and appears to be a reliability issue for LNG as an alternative fuel. The cryogenic liquid in conjunction with the constant vibrations of transit bus operations are contributing factors.

Along with the issue of fuel leakage, fuel vapor detection systems have been suspect in several road calls and repairs. The role of the fuel vapor detection system for natural gas is to notify the engine control system computer that a fuel leak has occurred and shutdown the engine at the same time. In the case of LNG, there is very little odorant (if any) in it, so large concentrations of the fuel could be present without detection unless a fuel vapor detection system was used. However, if there is an engine shutdown by the fuel vapor detection system, there is no way to verify that there is a problem without another fuel vapor detector. Because of this fact, many road calls have occurred to avoid a hazardous situation even when there was no verifiable leak discovered during the repair investigation.

Also, in one instance, a CNG bus at Tacoma released its fire suppression chemical due to a false indication of a fire by the detection system. This chemical was released on the road during normal operations. When the chemical is released, a large white cloud billows out of the engine compartment. The billowing cloud raises concerns for the safety of other people on the road who might injure themselves or others while trying to avoid the bus.

Running Out of Fuel and Range Issues - In general, this has mostly been an issue with CNG; however, all of the alternative fuel bus fleets have had numerous road calls due to an out of fuel condition. This is most likely due to inexperience of the fleet operators with the alternative fuels. Even the diesel control vehicles usually have a few out of fuel road calls when they are new because the dispatchers have not learned the exact range of the vehicles.

Incompatible Materials Used with Alcohol Fuels (Methanol and Ethanol) - Contaminants in the fuel continues to be a problem for alcohol fueled buses. These contaminants have been reported to be caused by the breakdown of incompatible materials used in the fuel dispensing equipment (such as fuel dispenser hoses) as well as materials used in the engines. Alcohols such as methanol and ethanol are slightly acidic and can corrode some metal alloys (e.g., magnesium and aluminum) and other materials. Suppliers of "alcohol compatible" materials do not always understand that the intent is to use nearly pure or neat methanol or ethanol.

The contaminants are then passed on to the fuel filters and causes clogging of the filters and low fuel pressure to the engine. The result is a higher replacement rate for the fuel filters. Also, the alcohol compatible fuel filters are reported to be 15 to 20 times more expensive than their diesel filter counterparts. The reasons for the expense are the special compatible materials that have to be used with alcohol fuels and the low demand and volume sold. The high cost of the fuel filters in combination with the higher replacement rate makes this process very expensive.

Fuel Storage Tanks for Biodiesel Blends - When starting a biodiesel demonstration or conversion, the storage tanks intended to be used with the biodiesel blend should be cleaned thoroughly. A biodiesel blend needs some agitation to ensure that the biodiesel mixes properly with the diesel fuel (it is usually splashed blended). Also, depending on the agitation method and how the fuel is pumped out of the tank, dirt can be pumped into the buses. This will cause some fuel filter clogging and possible engine problems.

Reliability Problems Beyond the Alternative Fuel - In transit applications, buses experience many failures related to air conditioning, wheelchair lifts, and door systems. In nearly every fleet in this program, at least one (usually two or all three) of these systems were a major source of road calls and maintenance costs. In some of the diesel control fleets, air conditioning (HVAC) repairs even outweighed the engine and fuel system related repair costs.

VEHICLE USAGE - Table 2 shows vehicle usage by fleet and transit agency. This table presents the total distance in miles accumulated by each fleet during the data collection to date and the average monthly distance per bus for each fleet. In general, if a bus is running well, fuel is readily available, and the range is acceptable, the transit agency will use the bus as much as possible. Therefore, the ratio of the average monthly distance per
<table>
<thead>
<tr>
<th>Site/Fuel</th>
<th>Fleet</th>
<th>Data Collection Status</th>
<th>No. Of Buses</th>
<th>Total Distance Traveled by Fleet (mi)</th>
<th>Average Monthly Distance Per Bus (mi)</th>
<th>Monthly Distance Ratio (DC/AF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houston</td>
<td>AF</td>
<td>Complete</td>
<td>10</td>
<td>375,694</td>
<td>2,210</td>
<td>1.5</td>
</tr>
<tr>
<td>LNG</td>
<td>DC</td>
<td></td>
<td>5</td>
<td>282,881</td>
<td>3,328</td>
<td></td>
</tr>
<tr>
<td>Portland</td>
<td>AF</td>
<td>Just Started</td>
<td>8</td>
<td>116,032</td>
<td>2,072</td>
<td>1.9</td>
</tr>
<tr>
<td>LNG</td>
<td>DC</td>
<td></td>
<td>5</td>
<td>249,946</td>
<td>3,845</td>
<td></td>
</tr>
<tr>
<td>Miami</td>
<td>AF</td>
<td>Complete</td>
<td>5</td>
<td>95,098</td>
<td>1,057</td>
<td>3.5</td>
</tr>
<tr>
<td>CNG</td>
<td>DC</td>
<td></td>
<td>5</td>
<td>330,342</td>
<td>3,670</td>
<td></td>
</tr>
<tr>
<td>Tacoma</td>
<td>AF</td>
<td>Complete</td>
<td>5</td>
<td>407,778</td>
<td>4,531</td>
<td>1.1</td>
</tr>
<tr>
<td>CNG</td>
<td>DC</td>
<td></td>
<td>5</td>
<td>451,337</td>
<td>5,015</td>
<td></td>
</tr>
<tr>
<td>Peoria</td>
<td>AF</td>
<td>Complete</td>
<td>5</td>
<td>209,702</td>
<td>3,600</td>
<td>1.0</td>
</tr>
<tr>
<td>E95</td>
<td>DC</td>
<td></td>
<td>3</td>
<td>106,118</td>
<td>3,509</td>
<td></td>
</tr>
<tr>
<td>Peoria</td>
<td>AF</td>
<td>Complete</td>
<td>5</td>
<td>118,688</td>
<td>2,967</td>
<td>0.9</td>
</tr>
<tr>
<td>E93</td>
<td>DC</td>
<td></td>
<td>3</td>
<td>67,491</td>
<td>2,812</td>
<td></td>
</tr>
<tr>
<td>Minn./St. Paul</td>
<td>AF</td>
<td>Nearly Complete</td>
<td>5</td>
<td>100,665</td>
<td>1,342</td>
<td>2.6</td>
</tr>
<tr>
<td>E95</td>
<td>DC</td>
<td></td>
<td>5</td>
<td>266,338</td>
<td>3,551</td>
<td></td>
</tr>
<tr>
<td>Miami</td>
<td>AF</td>
<td>Complete</td>
<td>5</td>
<td>208,660</td>
<td>2,318</td>
<td>1.8</td>
</tr>
<tr>
<td>M100</td>
<td>DC</td>
<td></td>
<td>5</td>
<td>380,453</td>
<td>4,227</td>
<td></td>
</tr>
<tr>
<td>New York</td>
<td>AF</td>
<td>Nearly Complete</td>
<td>5</td>
<td>118,161</td>
<td>1,818</td>
<td>1.0</td>
</tr>
<tr>
<td>M100</td>
<td>DC</td>
<td></td>
<td>5</td>
<td>138,307</td>
<td>1,844</td>
<td></td>
</tr>
</tbody>
</table>

Note: AF - Alternative Fuel, DC - Diesel Control

Bus between test and control fleets at the same site (shown in last column of Table 2) gives an indication of whether or not that transit agency perceives the test fleet as reliable and capable of performing the required job. Differences in vehicle usage between test and control fleets can significantly impact fuel efficiency and maintenance costs. Some observations of vehicle usage at each site are listed below.

- Houston (LNG) - Both fleets of buses were randomly dispatched; however, the LNG buses have been restricted from some of the longer routes and were not used to the extent that the diesel buses were used. Problems with the engine and fuel system played a role in this situation as discussed in the previous section.
- Portland (LNG) - Both fleets of buses were randomly dispatched. The LNG buses were not used to the extent that the diesel buses were used and have been restricted from the longer bus routes. As this site has gained experience with the LNG buses, use has increased significantly.
- Miami (CNG) - The diesel control buses have accumulated approximately 3.5 times more distance than the CNG buses. At this site, the CNG buses have been used primarily to supplement peak service during the morning and evening rush (tripper service). At this site, the range of the CNG buses and concern over reliability has caused this situation.
- Tacoma (CNG) - The monthly average distances per bus show that the test and control buses have been essentially the same, with the diesel control buses accumulating about 10 percent more distance per month. This distance difference is attributable to the slight duty cycle differences between the fleets. The CNG buses have not been used on a small number of the longest routes because of range. However, this site has shown a high level of confidence in the CNG buses for all other routes.
- Peoria (E95/E93) - During each time period for which the ethanol buses were run on E95 and E93, the monthly average distances per bus were essentially the same as the diesel control buses (equipped with diesel particulate traps). This site has shown a high level of confidence in the ethanol buses for all routes.
- Minn./St. Paul (E95) - The diesel control buses have been operating 2.6 times more monthly distance per bus than the ethanol buses. The ethanol buses have only been used on limited "tripper" runs while
the diesel control buses were being used on all routes on a random basis. At this site, concern over vehicle capabilities and operating costs of the ethanol buses has caused this situation.

- Miami (M100) - The diesel control buses accumulated about 1.8 times more distance than the methanol buses on a monthly per bus basis. The methanol buses were not being used to the extent that the diesel control buses were being used. This difference in usage has been a conscious decision by Miami because of cost of fuel and concern over vehicle capabilities.

- New York (M100) - The diesel control and methanol buses have accumulated approximately the same distance on a monthly per bus basis. The monthly per bus distance is lower at this site (for the test and control buses) than at most of the other sites. This lower distance is due to the usage of both fleets on downtown routes. In general, this site appears to be as confident with the methanol buses on these routes as with the diesel control buses.

SAFETY INCIDENTS AND ACCIDENTS -
During this program, there have been no major safety incidents or accidents involving the alternative fuels. At each transit agency, there have been several minor accidents, which required minor body repairs such as painting. A few significant traffic accidents were reported at the Peoria and Miami sites. No major damage was reported, but some bumpers and body panels were replaced.

RESULTS AND DISCUSSION - FUEL EFFICIENCY AND ENGINE OIL CONSUMPTION

The fuel efficiencies in this study were calculated with respect to an energy equivalent gallon of diesel #2. Any comparisons between fleets in this study have been given with respect to the same reference. Table 3 shows the fuel efficiencies and engine oil consumption rates by site and fleet. The energy conversion factors (to two significant digits) used to calculate diesel equivalency are shown in the table.

High fuel efficiency may show good performance and reliability, a relatively easy duty cycle, or a combination of both. In the following summaries for Portland, Miami, and Tacoma, the natural gas engines are spark ignited. In previous demonstrations and engine manufacturer experience, the spark ignition engines running on natural gas show a fuel efficiency drop of 15 to 25 percent compared to diesel engines running in similar transit service. The duty cycle is the key. Transit bus service for this size vehicle has as much as 50 to 60 percent idle time. A summary for each site is given below based on the information given in Table 3.

- Houston (LNG) - The LNG fleet experienced a fuel efficiency average of 3.05 miles per equivalent gallon (mpg) when using more than 30 percent LNG (by volume). The diesel control buses had an average fuel efficiency of 3.85 mpg. The ratio of these two numbers, 0.84, gives an idea of how well the alternative fuel engines compare to the diesel control engines in service. The fuel efficiency was 16 percent lower for the alternative fuel engines. It would be expected that the LNG engines have a fuel efficiency much closer to the diesel control engines because of the compression ignition cycle. Most likely, the large difference was caused by the engine problems with the LNG vehicles (discussed earlier). The engine oil consumption rates for these fleets were very similar and as low or lower than the other fleets in this study.

- Portland (LNG) - At this time, the fueling data is incomplete for the LNG vehicles. The data will be updated as soon as the missing information is available. The engine oil consumption for the LNG fleet was 70 percent higher than the control fleet.

- Miami (CNG) - The data shows only an 11 percent loss in fuel efficiency as opposed to the 15 to 25 percent drop as would be expected from the above discussion. The CNG buses were not used to the extent and in as severe of service as that of the diesel buses as discussed in the vehicle usage section. Engine oil consumption for the CNG buses was slightly higher than the control buses.

- Tacoma (CNG) - The CNG fleet showed a 23 percent lower fuel efficiency than the diesel control buses as expected for this type of engine and in this type of service. The fuel efficiencies for both fleets were high compared to other sites. These vehicles do not have air conditioning and were used mostly on highway routes. The engine oil consumption rate for the CNG buses was significantly lower than the diesel control buses.

- Peoria (E95/E93) - During the entire data collection period, the diesel control and ethanol fleets had consistently similar fuel efficiencies.

- Minn./St. Paul (E95) - The ethanol fleet showed a 5 percent lower fuel efficiency. The engine oil consumption rates showed a 12 percent higher rate for the ethanol fleet.

- Miami (M100) - The methanol and diesel control fleets had similar fuel efficiencies with the diesel control buses having a slightly lower fuel efficiency. The diesel control buses had a higher engine oil consumption rate.

- New York (M100) - The methanol fleet had a 12 percent lower fuel efficiency. Both the methanol and diesel fleets were used in severe downtown service. The engine oil consumption rate for the methanol fleet was more than double the rate for the diesel control fleet.
<table>
<thead>
<tr>
<th>Site</th>
<th>Fleet</th>
<th>Houston</th>
<th>Portland</th>
<th>Miami</th>
<th>Tacoma</th>
<th>Peoria</th>
<th>Peoria</th>
<th>Minn./St. Paul</th>
<th>Miami</th>
<th>New York</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>AF</td>
<td>LNG</td>
<td>LNG</td>
<td>CNG</td>
<td>CNG</td>
<td>E95</td>
<td>E93</td>
<td>E95</td>
<td>M100</td>
<td>M100</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>Diesel #1</td>
<td>Diesel #2</td>
<td>Diesel #2</td>
<td>Diesel #1</td>
<td>Diesel #1</td>
<td>Diesel #1</td>
<td>Diesel #1</td>
<td>Diesel #2</td>
<td>Diesel #1</td>
</tr>
<tr>
<td>Total Distance Traveled by Fleet (mi)</td>
<td>AF</td>
<td>375,694</td>
<td>116,032</td>
<td>95,098</td>
<td>407,778</td>
<td>269,966</td>
<td>118,688</td>
<td>100,665</td>
<td>208,660</td>
<td>118,161</td>
</tr>
<tr>
<td>Energy Conversion to Diesel #2 (AF/D2)</td>
<td>AF</td>
<td>0.61</td>
<td>0.61</td>
<td>0.0070(b)</td>
<td>0.0070(b)</td>
<td>0.60</td>
<td>0.59</td>
<td>0.60</td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>0.98</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>1.00</td>
<td>0.98</td>
</tr>
<tr>
<td>Fuel Usage in Diesel #2 gallons</td>
<td>AF</td>
<td>66,236</td>
<td>16,924</td>
<td>6,996</td>
<td>86,828</td>
<td>74,409</td>
<td>36,218</td>
<td>33,763</td>
<td>59,370</td>
<td>45,223</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>77,847</td>
<td>20,781</td>
<td>91,496</td>
<td>75,201</td>
<td>44,512</td>
<td>19,783</td>
<td>84,896</td>
<td>114,759</td>
<td>44,496</td>
</tr>
<tr>
<td>Representative Fleet Energy Equivalent MPG(a)</td>
<td>AF</td>
<td>3.05</td>
<td>N/A(c)</td>
<td>3.22</td>
<td>4.48</td>
<td>3.63</td>
<td>3.28</td>
<td>2.99</td>
<td>3.42</td>
<td>2.61</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>3.63</td>
<td>4.28</td>
<td>3.61</td>
<td>5.80</td>
<td>3.55</td>
<td>3.41</td>
<td>3.14</td>
<td>3.32</td>
<td>2.96</td>
</tr>
<tr>
<td>Ratio of MPG (AF/DC)</td>
<td></td>
<td>0.84</td>
<td>N/A(c)</td>
<td>0.89</td>
<td>0.77</td>
<td>1.02</td>
<td>0.96</td>
<td>0.95</td>
<td>1.03</td>
<td>0.88</td>
</tr>
<tr>
<td>Engine Oil Consumption Quarts per 1,000 miles</td>
<td>AF</td>
<td>2.1</td>
<td>5.1</td>
<td>2.4</td>
<td>1.9</td>
<td>2.8</td>
<td>5.5</td>
<td>2.8</td>
<td>2.1</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>2.2</td>
<td>3.0</td>
<td>3.5</td>
<td>2.5</td>
<td>2.4</td>
<td>2.9</td>
<td>2.5</td>
<td>3.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Note: AF - Alternative Fuel, DC - Diesel Control

(a) The representative mpg may or may not be based strictly on the total mileage and total fuel used. In some cases such as dual-fuel (use of two fuels at once, as opposed to bi-fuel, which is the ability to switch from one fuel to another), a period of time, when reliable data was collected, was chosen so that the fuel efficiency could be calculated with confidence and accuracy.

(b) 0.0070 has been used as the conversion from Standard cubic feet (scf).

(c) The fuel reported at this site for the LNG buses has not been complete to date. More information is being provided by the site to correct this issue.
RESULTS AND DISCUSSION - OPERATING COSTS

Before discussing operating costs for alternative fuels, it is important to put these costs into perspective. The overall operating costs for transit authorities running buses include vehicle operation (includes driver labor), vehicle maintenance (includes mechanic labor, maintenance administration, parts inventory, rebuild shop, tire shop, paint shop, body shop, revenue and non-revenue vehicle maintenance, cleaning, fueling, vandalism, and inspections), facility maintenance (includes labor), administration (includes labor), and fuels and lubes. In this program, only vehicle maintenance (revenue vehicle maintenance including inspections, some cleaning and rebuild costs; does not include administration or supporting activities such as rebuild shop, tire shop, paint shop, body shop, parts inventory, and others), facility maintenance, and fuels and lubes are studied and discussed.

The average cost breakdowns for transit bus operations for the transit agencies reporting in this program are shown in Figure 2. These costs are similar to those of most large transit agencies. The vehicle maintenance, facility maintenance, and fuels and lubes costs represent 29 percent of the overall operating budget for many transit agencies.

Figure 2. Overall Cost Breakdown for Transit Bus Operations

Mechanic labor costs vary tremendously depending on the size of city and area of the country in which a Transit agency is located. In reports from the American Public Transit Association (APTA) in July, 1995, bus mechanic labor wages ranged from $8.40-$22.90, without fringe benefits or overhead. For the purposes of this study, a wage of $15 per hour has been chosen as representative of mechanic labor costs. Overhead costs for benefits (fringe) is an average of 53 percent for the transit agencies in this study. This overhead added to the wage makes the mechanic labor $23 per hour. All maintenance costs presented here include this labor rate for the mechanic labor.

Figure 3 shows a comparison of the bus maintenance, fuel, and engine oil costs per 1,000 miles between the test fleets as well as a comparison to other sites. No capital costs or compression costs for CNG are included in these comparisons. Also, for the maintenance costs, only the alternative fuel affected systems (general electrical, charging, cranking, ignition, air intake, cooling, exhaust, fuel, and engine) are included. These systems were chosen to try to assess any increases in operating costs that could be directly related to the alternative fuel and related equipment. Appendix A shows the numbers that make up Figure 3. A summary for each site is given below:

- **Houston (LNG)** - The combined maintenance, fuel, and engine oil costs were 43 percent higher for the LNG buses. The majority of the cost difference between the test and control vehicles was in the maintenance costs. Also, since the engines are dual-fuel and have experienced problems running on LNG, much of the operating experience was using mostly diesel fuel and the fuel and engine oil costs have been correspondingly similar to the control fleet.
- **Portland (LNG)** - The combined maintenance, fuel, and engine oil costs were 78 percent higher for the LNG buses. The major maintenance contributors have been fuel leakage, natural gas sensing system, running out of fuel, and the cryogenic fuel pump.
- **Miami (CNG)** - The CNG buses show a 34 percent higher cost to operate. The fuel and oil as well as the maintenance costs for the CNG buses were all modestly higher than the diesel control buses.
- **Tacoma (CNG)** - The costs for the CNG and diesel control buses have been nearly the same, with the CNG buses being 11 percent higher. The maintenance cost for the CNG fleet has been only slightly higher than the diesel control fleet, and the CNG fleet fuel and oil cost has also been slightly higher.
- **Peoria (E95/E93)** - The ethanol buses during E95 operation showed a cost 2.8 times more to operate than the diesel control buses (particulate trap equipped). Most of this cost has been attributable to the high cost of the fuel; the maintenance cost was modestly higher for the ethanol vehicles when operating on E95. With the use of E93, the fuel and oil costs were reduced dramatically for the ethanol fleet; however, the combined costs were still more than 2 times more expensive than the control buses.
- **Minn./St. Paul (E95)** - The E95 fleet was 2.6 times more expensive than the diesel control buses for maintenance, fuel, and engine oil costs. The fuel costs were extremely high.
Figure 3. **Bus Maintenance, Fuel, and Engine Oil Costs**

- **Miami (M100)** - The methanol fleet had costs that were 2.3 times more expensive than the diesel control fleet. As for the other alcohol fleets in the program, the fuel costs were extremely high.

- **New York (M100)** - The methanol fleet had costs that were 3.6 times more expensive than the diesel control fleet. The fuel costs were the major contributor to the high methanol fleet operations costs.

---

(a) The maintenance costs shown here only include the alternative fuel-affected systems -- general electrical, charging, cranking, ignition, air intake, cooling, exhaust, fuel, and engine. The rest of the maintenance costs are an average of $167 per 1,000 miles, which includes inspections, air conditioning, transmission, body, door systems, air system, brakes, wheelchair lifts, and other repairs. Mechanic hourly labor rate is assumed to be $23 per hour.

(b) Fuel cost for only LNG and CNG do not include maintenance or capital costs of the fueling station, compression costs, or costs associated with fuel losses during refueling.
RESULTS AND DISCUSSION - CAPITAL COSTS

Capital costs presented in this program are different than the other parts of the study because these costs are estimates based on knowledge gained from transit properties in this study and others not included in this study. Also, some of the capital costs are estimates based on discussions with engine and vehicle manufacturers as well as information collected from previous studies where architect and engineering firms presented estimates for actual facilities at transit agencies planning to use alternative fuels. All costs presented here are intended to be for comparison purposes and are given only as an example. Actual capital costs experienced by a given fleet owner will vary dramatically depending on the intended alternative fuel, how the fuel will be introduced into the operation, local climate, local building codes, age of facilities, and other factors.

The addition of alternative fuel vehicles to a fleet may require changes that involve increased vehicle capital costs and facilities operating and capital costs in addition to vehicle operating costs. Table 4 shows representative prices (collected from vehicle and engine manufacturers) for purchasing new diesel and alternatively fueled standard (40-foot or 12.2-meter) buses. Specific prices vary with each transit property because of vehicle specifications and the size of the order. Propane is included in this section; however, there were no heavy-duty original engine manufacturer engines available for transit bus operation on propane during this study.

Several factors must be considered when a fleet owner begins using alternative fuels, because the vehicles use a relatively new technology. For alcohol, biodiesel blends, and propane fuels, ventilation and electrical facilities designs for gasoline vehicles are often acceptable to the fire marshal or other authority with jurisdiction (at most transit agencies in the U.S., some gasoline vehicles are used for revenue and non-revenue purposes). Propane may require more ventilation and sensors near the floor of buildings where the fuel could be present. Both CNG and LNG require modifications to existing bus maintenance and storage areas. Since each alternative fuel presents different physical and chemical challenges, a variety of facility modifications must be considered.

Capital costs for facilities can vary dramatically depending on the geographic location and the age of the facilities. Transit facilities in the colder climates usually include indoor storage facilities for the buses. These storage facilities would, in some cases, require major changes to accommodate alternative fuels. Also, since some alternative fuels require increased ventilation and more expensive electrical systems, the age of the facilities and whether or not the facilities will be built new may make a large impact on facility conversion costs.

In these estimates, conversion of facilities includes modifying fuel lanes, maintenance areas, and storage areas. These changes involve adding new equipment specific to each fuel and making changes to the electrical systems of the buildings to conform to appropriate building codes. To conduct this analysis, costs were broken out for fueling and maintenance facilities on a square-foot basis.

This analysis assumes that normal fleet operations are maintained during the facility conversion. With this assumption, the facilities were converted in three phases to allow normal operations to continue and to serve a mix of diesel, gasoline, and alternatively fueled vehicles. The estimated costs to convert a 170-bus facility (a typical size transit facility) with 84,850 ft² (7,883 m²) indoor storage, 19,250 ft² (1,788 m²) maintenance area, and 9,120 ft² (847 m²) fueling areas are shown in Table 5. These costs are for comparison purposes only.

Table 4. Alternative Fuel Transit Bus Price Comparison ($, 1995)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Price per Bus ($)</th>
<th>Difference from Diesel ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel (base case)</td>
<td>215,000</td>
<td>-</td>
</tr>
<tr>
<td>LNG</td>
<td>270,000</td>
<td>55,000</td>
</tr>
<tr>
<td>CNG</td>
<td>265,000</td>
<td>50,000</td>
</tr>
<tr>
<td>Methanol/Ethanol</td>
<td>235,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Biodiesel(a)</td>
<td>215,000</td>
<td>-</td>
</tr>
<tr>
<td>Propane</td>
<td>255,000</td>
<td>40,000</td>
</tr>
</tbody>
</table>

(a) There is no expected increase for biodiesel blend use because the engine and fuel system are the same as that used for the conventional diesel version. Note that problems with the engine and fuel system of vehicles operating on biodiesel blends attributed to the fuel may not be covered by the engine manufacturer.
Table 5. Facility Incremental Conversion Costs (170-Bus Facility) 
by Fuel Type (1994 $, Millions)

<table>
<thead>
<tr>
<th>Facility</th>
<th>LNG</th>
<th>CNG</th>
<th>Alcohol(a)</th>
<th>Biodiesel</th>
<th>Propane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fueling</td>
<td>0.9</td>
<td>1.5</td>
<td>0.1</td>
<td>N/C</td>
<td>0.2</td>
</tr>
<tr>
<td>Maintenance</td>
<td>1.2</td>
<td>1.1</td>
<td>N/C</td>
<td>N/C</td>
<td>N/C(b)</td>
</tr>
<tr>
<td>Storage</td>
<td>1.4</td>
<td>1.2</td>
<td>N/C</td>
<td>N/C</td>
<td>N/C(b)</td>
</tr>
<tr>
<td>Total</td>
<td>3.5</td>
<td>3.8</td>
<td>0.1</td>
<td>N/C</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Note: N/C - No change if facility is certified for gasoline 
(a) Methanol (M100) and ethanol (E95 or E85) 
(b) Increased ventilation and/or combustible gas sensors near the floor may be required by local officials.

RESULTS AND DISCUSSION - EMISSIONS TESTING

(to be provided by K. Kelly, NREL and D. Lyons, WVU)

SUMMARY AND CONCLUSIONS

In general, alternative fuel and diesel fuel technologies will continue to improve, especially in the area of reduced emissions and increased reliability. Any comparisons of alternative fuel to diesel fuel technologies in this program are intended to be used to evaluate the current in-use progress of alternative fuel technology development. The mission of this program has been to inform transit fleet operators about current alternative fuel vehicle operating experience with the intent of helping these fleet operators make informed decisions about moving to alternative fuels. Also, once the decision has been made to move to alternative fuel use, the intent of this program has been to provide information so the transition can be made as easily and efficiently as possible.

The data collection at all sites is not complete at this time and therefore the conclusions presented here are limited. The summary and conclusions are broken down into five major categories: reliability, fuel efficiency, operating costs, capital costs, and emissions. Under each major category, summaries and conclusions are given by alternative fuel.

RELIABILITY - The indicators used to look at reliability in this program have been road calls (in-service failures), specific vehicle reliability issues, vehicle usage, and safety incidents. There were no major safety incidents involving the program buses during the data collection period. The reliability indicators give both perceived and measured information about reliability. The following discussion summarizes reliability information by fuel.

LNG - The LNG buses have experienced around twice as many road calls. Both sites show that the LNG buses have been used 30 to 50 percent less than their diesel control buses. At the Houston site, the dual-fuel LNG buses experienced major engine problems, which were caused by injector design and other problems. At both sites, fuel system leaks and problems with cryogenic pumps were major issues. Running out of fuel has also been a major issue; however, learning the actual range of a new technology bus is an expected situation.

CNG - At the Miami site, the CNG buses have only been used in limited service (tripper - only during rush hours to supplement normal service and therefore the CNG fleet has not accumulated much mileage). The experience at Miami should not be considered normal for a transit bus; however, at Tacoma, the buses were used in what would be considered normal service. Therefore, results from the Tacoma site should be considered more representative of the expected in-service operation of CNG buses in transit service. The CNG buses at Tacoma were used nearly as much as the diesel control buses (CNG buses are only restricted from a few of the longest routes) and the road call rates were the same.

Ethanol - As with CNG, one ethanol site used the test buses in normal service and one site used the test buses in limited service. However, the results for the two ethanol sites were very similar other than for the vehicle usage. The ethanol buses at Peoria were used approximately the same amount as the diesel control buses and at the Minn./St. Paul site, the ethanol buses were used 50 percent less than the diesel control buses. At the Peoria site, the ethanol buses experienced as much as 45 percent higher rate of road calls and at the Minn./St. Paul site, the road call rate was 50 percent higher for the diesel control fleet. Most of the ethanol fleet road calls for both sites were related to fuel quality issues (contaminants in the fuel), which caused fuel filter clogging and low engine power problems.

Methanol - The Miami methanol site used the methanol fleet about 45 percent less than the diesel buses and the New York site used the methanol buses essentially the same as the diesel control buses. The
Miami methanol fleet experienced 15 percent more road calls and the New York methanol fleet experienced 45 percent more road calls than their respective diesel control fleets. As with ethanol, the major maintenance issue was fuel quality (contaminants in the fuel), which manifested itself in clogged fuel filters and low engine power.

**FUEL EFFICIENCY** - As noted earlier, all fuel efficiencies were calculated with respect to an energy equivalent gallon of diesel #2, so comparisons can be made between fleets. The following discussion summarizes fuel efficiencies by fuel. Vehicle usage is discussed in this section in addition to the discussion in the previous section, reliability, because of the cause and effect relationship between vehicle duty cycle and fuel efficiency.

Note that at Portland, Miami, and Tacoma, the natural gas vehicles use engines that operate on a spark ignition cycle rather than a compression ignition diesel cycle. This spark ignition cycle in conjunction with the transit duty cycle, which has been reported to have as high as 60 percent idle time, causes the fuel efficiencies of the natural gas vehicles to be 11 to 23 percent lower compared to diesel control vehicles operating in the same service.

**LNG** - The LNG buses at Houston showed significantly lower fuel efficiency than expected compared to the diesel control buses at this site. The engines used for LNG operation are dual-fuel and should have a fuel efficiency similar to the diesel control buses. However, due to problems with the gaseous fuel injectors, these engines did not perform up to expectation during the data collection period.

Significant effort was expended by Houston and the engine manufacturer to correct the problems with these vehicles and engines and get them back to operating on LNG. The fuel efficiency for the LNG fleet at Portland is not available at this time because of problems with collection of all of the fuel dispensed into the LNG vehicles.

**CNG** - The CNG buses at Miami showed an 11 percent decrease in fuel efficiency compared to the diesel control buses at this site. At the Tacoma site, the CNG fleet showed a 23 percent decrease in fuel efficiency as compared to the diesel control buses. The Miami site had chosen to operate the CNG buses in limited tripper service (and continue to operate these buses in limited service). Factors that led up to this situation include lack of easy access to a fast-fill fueling station and concerns over perceived reliability issues with the CNG buses.

At Tacoma, on the other hand, the CNG fleet has been used in the same service as the diesel control buses except for a few routes and the fuel efficiency has been 23 percent lower. This lower fuel efficiency is within the expected results for this type of service and engine design. Newer technology natural gas engines with lean-burn closed loop engine control systems are expected to increase fuel efficiency.

**Ethanol** - The fuel efficiencies for the ethanol vehicles at Peoria and Minn./St. Paul were similar to the diesel control buses at each respective site (within 5 percent).

**Methanol** - The fuel efficiency at the Miami site for the methanol fleet was nearly the same as the control fleet. At the New York site, the methanol fleet had a 12 percent lower fuel efficiency. The methanol buses in New York have operated in severe downtown service and this was probably a contributing factor to the lower fuel efficiency.

**BUS OPERATING COSTS** - Bus operating costs consist of vehicle operation, vehicle maintenance, general administration, facility maintenance, fuels and lubes, and other miscellaneous costs. In this program, only vehicle maintenance and fuels and lubes are collected for operating cost comparisons, no capital costs are included in this section. Also, for the maintenance costs, only the alternative fuel-affected systems (general electrical, charging, cranking, ignition, air intake, cooling, exhaust, fuel, and engine) are included. These systems were chosen to try to assess any increases in operating costs that could be directly related to the alternative fuel and related equipment. The fuel costs do not include the cost of compression for CNG or the capital costs and maintenance for the fueling and other facilities. A summary for each alternative fuel is given below.

**LNG** - The LNG buses at Houston and Portland have had significantly higher costs for maintenance, fuel, and engine oil. The higher maintenance costs at both sites were mostly due to fuel system problems as described in the reliability section. The fuel costs at Portland for the LNG fleet were much higher than at the Houston site. The LNG buses at Houston are dual-fuel buses that have run mostly on diesel fuel during the data collection period because of the engine and fuel system problems.

**CNG** - As discussed in the previous section, the CNG buses at Miami have not been used in normal service; therefore, the results were not comparable to the results from the Tacoma site. Also, since the Tacoma CNG buses have been used in normal service, operating cost results should be considered more representative of in-service CNG bus technology. At Tacoma, the CNG fleet had nearly the same maintenance costs and slightly higher fuel costs for an overall 11 percent higher operating cost. Note that the fuel cost does not include compression cost (this cost increase has been estimated to be as much as 12 percent of the cost of a diesel energy equivalent gallon of CNG - or about $0.07 per equivalent gallon).

**Ethanol** - The ethanol buses at Peoria and Minn./St. Paul showed significantly higher maintenance costs,
which were almost entirely due to the high cost for fuel filters and the higher rate of usage of the fuel filters. The fuel cost of the ethanol is 2 to 3 times the cost of diesel fuel use.

Methanol - The methanol results were very similar to the ethanol results in that the maintenance costs were significantly higher (Miami - 1.8, New York - 2.5 times) and influenced heavily by the fuel filter costs for the methanol buses. Also, the fuel costs at both sites were high (Miami - 2.6, New York - 3.8 times). Note that the price of methanol was volatile during the data collection period (as high as $1 - $2 per gallon). A cost of $0.75 per gallon of methanol ($1.72 per energy equivalent gallon of diesel #2) was used to calculate the fuel cost. In recent months (end of 1995), the spot market price of methanol settled considerably (under $0.40 per gallon of methanol).

CAPITAL COSTS - The addition of alternative fuel vehicles to a fleet may require significant changes that involve increased vehicle capital costs and facilities operating and capital costs in addition to increased vehicle operating costs. The following estimates of capital costs were developed from discussions with manufacturers and architect and engineering firms. Actual costs will depend on specific needs such as size of bus purchase, local building codes, and size of fleet. In general, the natural gas vehicles have the highest incremental capital costs for vehicle purchases, $50,000 to $5,000 from diesel, and facility conversions, $3.5 to 3.8 million for a 170-bus facility conversion. Propane has the next highest capital costs, $40,000 vehicle purchase and $200,000 for facility modifications for a 170-bus facility. The facility modifications for propane may be substantially more expensive if the local building code officials require increased ventilation and combustible gas sensors near the floor of the storage and maintenance facilities. Alcohol fuels (ethanol and methanol) require only a $20,000 premium for the vehicle and $100,000 for a fueling station for 170 buses. There may be no changes required for the maintenance and storage facilities for alcohol fuel use as long as the facilities conform to local gasoline building codes.

Current biodiesel blend demonstrations have not required a premium for vehicles (just put biodiesel blend in) and no facility modifications are required (at least at this time). However, there is an issue of warranty of the engines when operated on biodiesel blends. Problems with the engine and fuel system attributed to the fuel may not be covered by the engine manufacturer when a fuel other than the fuel specified by the manufacturer is used. The National Biodiesel Board has created a program where they will cover these warranty repairs as long as the biodiesel blend was purchased and mixed according to their specifications.

ACKNOWLEDGEMENTS

The authors wish to thank Richard N. Wares at the U.S. Department of Energy for direction and support of this program. Also, this program would not have been possible without the support and cooperation of the transit agency personnel at each participating site and the cooperation of Cummins Engine Company and Detroit Diesel Corporation.

REFERENCES

4. "Interim Alternative Fuel Transit Bus Assessment Results," Battelle, Columbus, Ohio, August, 1995
## Appendix A. Total Bus Maintenance, Fuel, and Engine Oil Costs

<table>
<thead>
<tr>
<th>Site</th>
<th>Fleet</th>
<th>Houston</th>
<th>Portland</th>
<th>Miami</th>
<th>Tacoma</th>
<th>Peoria</th>
<th>Peoria</th>
<th>Minn./St. Paul</th>
<th>Miami</th>
<th>New York</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel</strong></td>
<td>AF DC</td>
<td>LNG Diesel #1</td>
<td>LNG Diesel #2</td>
<td>CNG Diesel #2</td>
<td>CNG Diesel #2</td>
<td>E95 Diesel #1</td>
<td>E93 Diesel #1</td>
<td>E95 Diesel #1</td>
<td>M100 Diesel #2</td>
<td>M100 Diesel #1</td>
</tr>
<tr>
<td><strong>Total Distance Traveled by Fleet (mi)</strong></td>
<td>AF DC</td>
<td>375,694</td>
<td>116,032</td>
<td>95,098</td>
<td>407,778</td>
<td>269,966</td>
<td>67,491</td>
<td>100,665</td>
<td>208,660</td>
<td>118,161</td>
</tr>
<tr>
<td><strong>Maintenance Cost(a) per 1,000 mi. ($)</strong></td>
<td>AF DC</td>
<td>114</td>
<td>34</td>
<td>79</td>
<td>79</td>
<td>63</td>
<td>47</td>
<td>63</td>
<td>98</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td></td>
<td>138</td>
<td>79</td>
<td>79</td>
<td>59</td>
<td>26</td>
<td>37</td>
<td>58</td>
<td>86</td>
<td>91</td>
</tr>
<tr>
<td><strong>Fuel Cost per 1,000 mi. ($)</strong></td>
<td>AF DC</td>
<td>173(c)</td>
<td>229</td>
<td>220(b)</td>
<td>121(b)</td>
<td>504</td>
<td>369</td>
<td>601</td>
<td>502</td>
<td>659</td>
</tr>
<tr>
<td></td>
<td></td>
<td>166</td>
<td>128</td>
<td>177</td>
<td>112</td>
<td>171</td>
<td>178</td>
<td>207</td>
<td>193</td>
<td>173</td>
</tr>
<tr>
<td><strong>Engine Oil Consumption Cost per 1,000 mi. ($)</strong></td>
<td>AF DC</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Maint, Fuel, and Oil Cost per 1,000 mi. ($)</strong></td>
<td>AF DC</td>
<td>288</td>
<td>373</td>
<td>348</td>
<td>186</td>
<td>555</td>
<td>440</td>
<td>780</td>
<td>650</td>
<td>755</td>
</tr>
<tr>
<td></td>
<td></td>
<td>202</td>
<td>209</td>
<td>259</td>
<td>167</td>
<td>199</td>
<td>217</td>
<td>266</td>
<td>282</td>
<td>210</td>
</tr>
</tbody>
</table>

**Note:** AF - Alternative Fuel, DC - Diesel Control

(a) The maintenance costs shown here only include the alternative fuel-affected systems -- general electrical, charging, cranking, ignition, air intake, cooling, exhaust, fuel, and engine. The rest of the maintenance costs (not shown in table) are an average of $167 per 1,000 miles, which includes inspections, air conditioning, transmission, body, door systems, air system, brakes, wheelchair lifts, and other repairs. Mechanic hourly labor rate is assumed to be $23 per hour.

(b) Does not include compression cost, which could be as significant as 12 percent (without capital cost of the fueling station).

(c) This cost does not include a fuel loss due to storage over time and during transfer, which could be as significant as 25 percent. These are dual-fuel buses which were using 50-70 percent diesel fuel during the period used to calculate fuel economy and cost.