Alternative Fuel Transit Bus Evaluation Program Results

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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 transit buses operating on alternative fuels and diesel fuel. The information for this comparison was collected from eight transit bus sites. The fuels studied are natural gas (CNG and LNG), alcohol (methanol and ethanol), biodiesel (20 percent blend), propane (only projected capital costs; no sites with heavy-duty propane engines were available for studying operating experience), and diesel. Data was collected on operations, maintenance, bus equipment configurations, emissions, bus duty cycle, and safety incidents. Representative and actual capital costs were collected for alternative fuels and were used as estimates for conversion costs. This paper presents preliminary results.

INTRODUCTION

Previous studies in alternative fuel transit bus applications have concentrated on using one or two test fuels at a time in 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 United States. Each transit agency that has tested alternative fuels also has collected and analyzed data 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 standard transit service.

The available studies from the FTA and the transit agencies demonstrating these new alternative fuels clearly demonstrated 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), bridges this need of a multi-fuel, multi-site data collection program. This study examines currently active fleets of alternative fuel transit buses in the United States. 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 - 85 to 90 percent or higher) which is stored in bulk in gaseous form at high pressures from 3,000 to 5,000 psi (21 to 35 MPa) and dispensed in the same form at 3,000 or 3,600 psi (21 or 25 MPa) - settled pressure in the vehicle fuel tanks
- Ethanol - 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 - an alcohol (methyl alcohol) produced primarily from natural gas, but can be derived from biomass or coal. The 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.
- Liquefied Petroleum Gas (LPG) - LPG broadly refers to commercial propane, commercial butane, and mixtures of the two. LPG is derived from two sources: natural gas processing and petroleum refining. Most LPG sold in the United States, particularly in interstate commerce, contains 90 percent or more propane gas and is really commercial propane. A propane with tighter specifications, called HD-5, is intended to be a fuel for internal combustion engines. In Europe and Asia, LPG generally contains nearly equal parts propane and butane.

In-depth results from this program are also available in other reports from NREL[3,4].

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 United States, 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 operations data on buses running on BD20 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 participated in this program own and operate the buses and 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 are included in this discussion. Fuel blending issues surfaced midway through the data collection. The biodiesel blend was discovered to have been 4 percent

Table 1. Participating Transit Agencies, Engines, and Alternative Fuels

Transit Agency	City	Bus	Engines	Alternative Fuel (AF)	AF Buses	Control Buses
Houston Metro	Houston, TX	40 ft. Stewart & Stevenson	DDC Dual-Fuel 6V92TA PING(a)	LNG	10	5
Tri-Met	Portland, OR	40 ft. Flxible	Cummins L-10	LNG	8	5
Metro-Dade Transit Authority (MDTA)	Miami, FL	40 ft. Flxible	Cummins L-10 DDC 6V92TA	CNG M100	5 5	5 5
Pierce Transit	Tacoma, WA	40 ft. BIA	Cummins L-10	CNG	5	5
GP Transit	Peoria, IL	35 ft. TMC	DDC 6V92TA	E95/E93 Trap	5	 3
Metropolitan Council of Transit Operations (MCTO)	Minneapolis/ St. Paul, MN	40 ft. Gillig	DDC 6V92TA	E95	5	5
Triboro Coach Company (NYCDOT)	New York, NY	40 ft. TMC	DDC 6V92TA DDC Series 50(b)	M100	5	 5
Bi-State Development Agency	St. Louis, MO	40 ft. Flxible	DDC 6V92TA	BD20	5	5

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.

(b) The Series 50 engine was used for the diesel control vehicles in New York because the diesel 6V92TA was being phased out and was not available for new vehicles. The alcohol 6V92TA engine was the only methanol engine available for new vehicles.

lower (BD16) than the intended blend (BD20). Also, issues of proper mixing of the biodiesel blend were raised. Corrective measures for these issues were taken. Future reporting will include the results of the data collection and emissions testing at this site.

PROGRAM OBJECTIVE - The objective of the program is 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 against which to compare the alternative fuel operations.

SITE SELECTION - The following site selection criteria define the transit agencies selected to be in the program. These criteria were used as a guideline to select each participating site.

1. Engines in use at each transit agency were required to be using CNG, LNG, propane, methanol, ethanol, or biodiesel blends.
2. Engines in use must have been new original equipment manufacturer (OEM) engines. The biodiesel study at St. Louis, which used older engines that were recently rebuilt for the test and control buses is an exception.
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). The only exception to this was New York because the DDC 6V92TA diesel engine was not available as a new engine in a new vehicle, so the Series 50 diesel engine was used.
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 are grouped into four types: operating descriptions, bus operations, capital costs, and emissions testing results. Data collected (except for emissions testing) were completely dependent on the transit agencies collecting complete and accurate data. The source of most of the data collected in this program was from the existing data collection systems at each transit agency. Some information was 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[5] and data format plan[6], which are available from NREL. West Virginia University (WVU) performed emissions testing.

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, were 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. For each site, data are to be collected for 18 months.

The capital cost data include descriptions of facilities and the costs for any upgrades to existing facilities or new facilities built for the change to an alternative fuel. 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 was documented.

Chassis dynamometer emissions measurements were made at the transit sites by WVU's transportable chassis dynamometer. The transportable chassis dynamometer was designed and constructed by WVU's Department of Mechanical and Aerospace Engineering to test emissions levels from heavy-duty vehicles[7,8]. The transportability of this chassis dynamometer allows the program to perform a large number of on-site emissions tests on buses and heavy-duty vehicles around the country. Before the unit was built, other options were considered, such as transporting vehicles to existing stationary dynamometers, or removing engines and transporting them to existing facilities. Both options were rejected because of expense and vehicle down time.

WVU has prepared a detailed description of the test procedures and the facility design. Typically, the transportable chassis dynamometer is set up on the grounds of the local transit agency and the selected buses are tested using the fuel in the vehicle at the time of the test. The dynamometer may be set up to operate inside or outside depending on the space available at the transit agency. To test the transit buses in this program, WVU used the standard Central Business District (see Figure 1) test cycle, a driving cycle devised to simulate the speeds, loads, and conditions experienced by buses during a typical route through a city's Central Business District.

RESULTS AND DISCUSSION - RELIABILITY

For this program, reliability refers to the ability of the buses in the program to perform when and as needed. The reliability is measured directly by recording the road

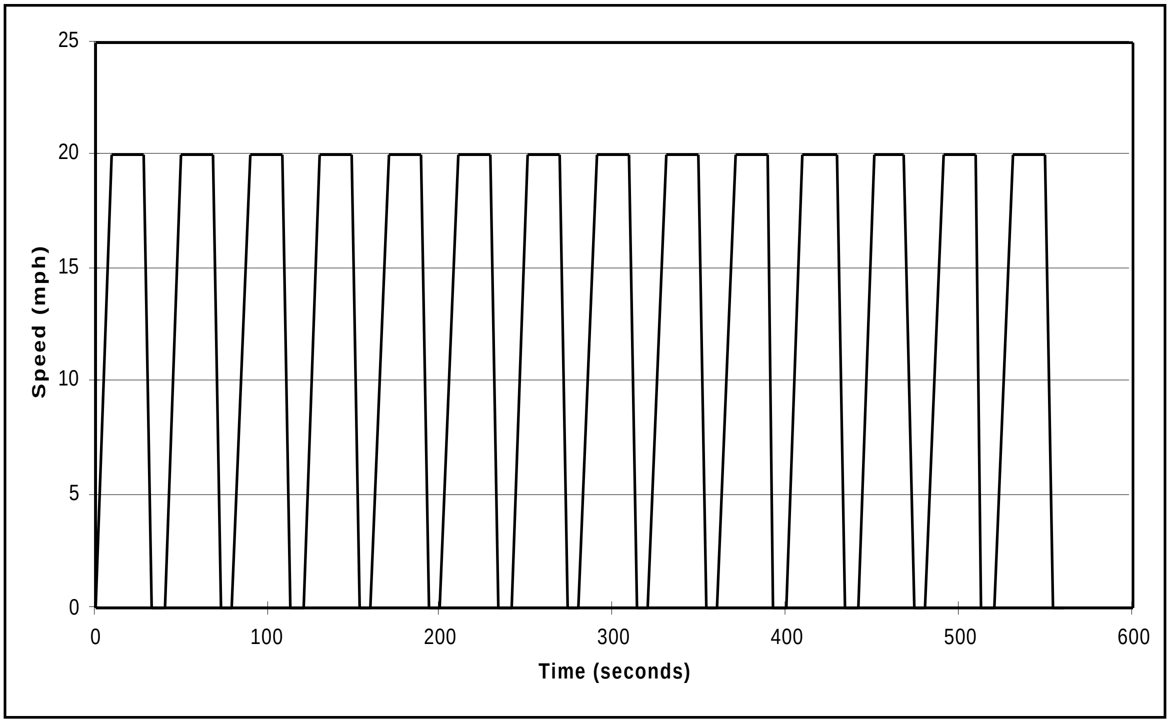


Figure 1. Chassis Dynamometer Driving Cycle Central Business District (CBD)

call rate - the average number of in-service failures per 1,000 miles (per 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 most sites has been completed, but at other sites the data collection may not be complete. In general, the fewer months of operations data available or the lower the fleet mileages from a given site, the less 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 repaired 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.

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 was 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.

Figure 2 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.

- Houston (LNG) - The road call rate for the LNG buses was nearly twice that of the diesel control buses on a per 1,000 mile (per 1,600 kilometer) 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 was 2.4 times that of the diesel control buses on a per 1,000 mile (per 1,600 kilometer) basis. The LNG buses experienced problems related to the bus running out of fuel and fuel system leaks 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 (per 1,600 kilometer) basis. However, the CNG fleet had very low mileage during the 18 months of data collection - 95,000 miles (152,000 kilometers) for the fleet or 19,000 miles (30,000 kilometers) per bus. Also, note that the

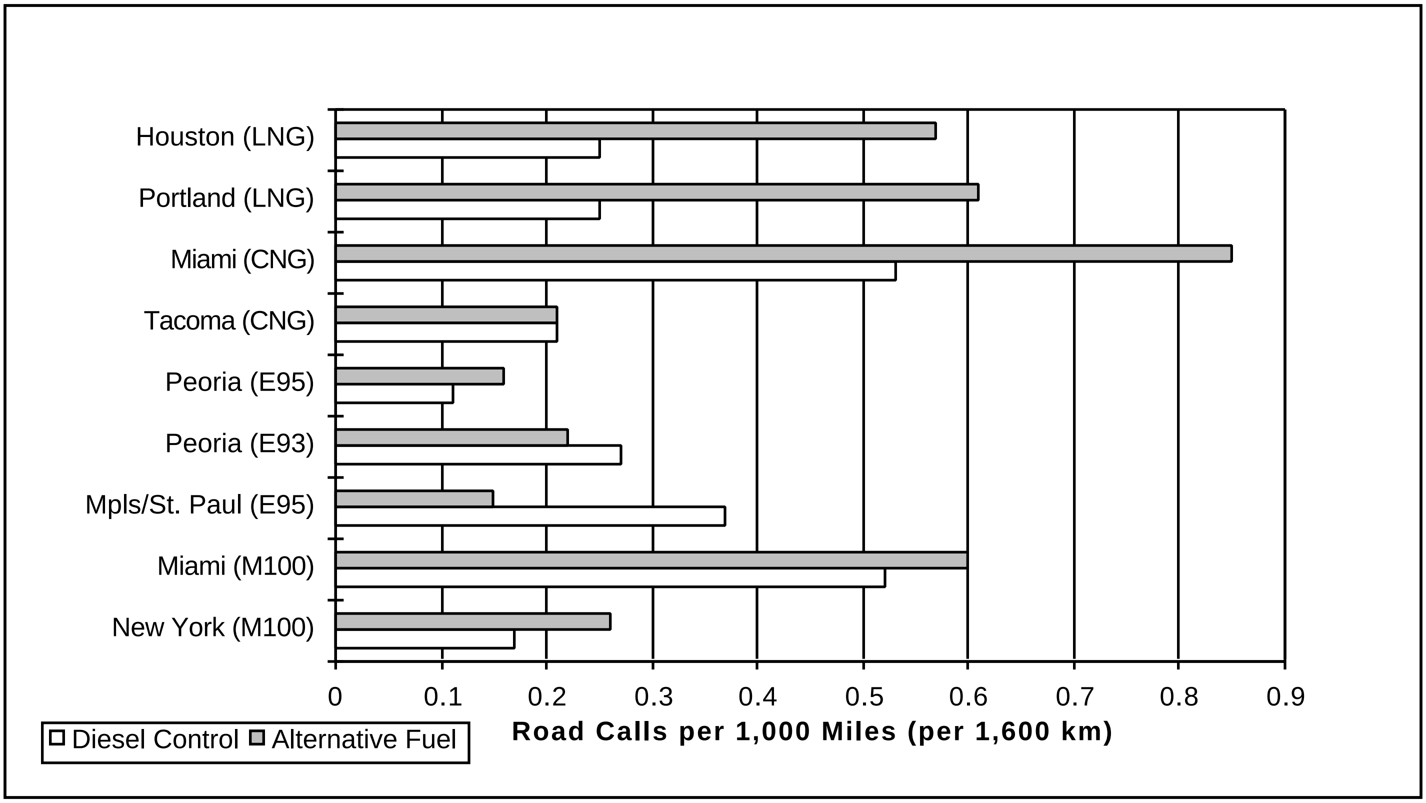


Figure 2. Vehicle Road Call Rates By Site and Fleet

Miami CNG fleet engines are one-year older than the Tacoma site engines. The major problems causing road calls were the bus running out of fuel and low power. These issues are discussed in the next section.

- Tacoma (CNG) - The CNG and diesel control buses had nearly 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.
- Mpls/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 (per 1,600 kilometer) basis. Many of the road calls for the methanol buses were related to the engine stalling or low power. These issues were related 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 53 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 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, are for information only and are not intended to indicate the superiority of any one fuel.

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 contaminants 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 contaminants in the fuel system were the cause of a 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 contaminants 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 system contaminants issue because, if it sticks open, it allows the engine to be overfueled 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 contaminants 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 contaminants 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 vehicle fuel systems used at Houston and Portland had many repairs for fuel leaks. This was 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 shut down 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 a problem exists 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.

Running Out of Fuel and Range Issues - Generally, fuel shortage and range issues are related to CNG; however, all of the alternative fuel bus fleets 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. Also, fuel level indicators have been and continue to be inaccurate for CNG and LNG and have contributed to running out of fuel and range problems.

Incompatible Materials Used with Alcohol Fuels (Methanol and Ethanol) - Contaminants in the fuel continue 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, which 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 - At the St. Louis site, it was learned that 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 requires some agitation to ensure that the biodiesel mixes properly with the diesel fuel (it is usually splash blended). Also, depending on the agitation method and how the fuel is pumped out of the tank, contaminants can be pumped into the buses. This will cause some fuel filter clogging and possible engine problems.

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 bus between test and control fleets at the same site (shown in last column of Table 2) gives an indication of whether the 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

Table 2. Vehicle Usage Summary

Site/Fuel	Fleet	Data Collection Status	No. Of Buses	Total Distance Traveled by Fleet (mi)	Average Monthly Distance Per Bus (mi)	Monthly Distance Ratio (DC/AF)
Houston LNG	AF DC	Complete	10 5	375,694 282,881	2,210 3,328	1.5
Portland LNG	AF DC	Nearly Complete[a]	8 5	232,186 364,088	2,073 3,833	1.8
Miami CNG	AF DC	Complete	5 5	95,098 330,342	1,057 3,670	3.5
Tacoma CNG	AF DC	Complete	5 5	407,778 451,337	4,531 5,015	1.1
Peoria E95	AF DC	Complete	5 3	209,702 106,118	3,600 3,509	1.0
Peoria E93	AF DC	Complete	5 3	118,688 67,491	2,967 2,812	0.9
Mpls/St. Paul E95	AF DC	Nearly Complete[a]	5 5	100,665 266,338	1,342 3,551	2.6
Miami M100	AF DC	Complete	5 5	208,660 380,453	2,318 4,227	1.8
New York M100	AF DC	Nearly Complete[a]	5 5	140,637 168,270	1,875 1,980	1.1

Note: AF - Alternative Fuel, DC - Diesel Control
(a) The data collection at these sites is not complete, but the data missing is 4 months or less out of the intended 18 months of data.

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 were 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 were restricted from the longer bus routes. As this site gained experience with the LNG buses, use increased significantly.
- Miami (CNG) - The diesel control buses accumulated approximately 3.5 times more distance than the CNG buses. At this site, the CNG buses were 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 caused this situation.
- Tacoma (CNG) - The monthly average distances per bus show that the test and control buses were essentially the same, with the diesel control buses accumulating about 10 percent more distance per month. This difference in distance is attributable to the slight differences between the duty cycles of the fleets. The CNG buses were not used on a small number of the longest routes because of insufficient driving range. However, this site has shown a high level of confidence in the CNG buses for all other routes.
- Peoria (E95/E93) - During operation 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.
- Mpls/St. Paul (E95) - The diesel control buses were traveling about 2.6 times farther per month than the ethanol buses. The ethanol buses were only used on limited “tripper” (service during only the morning and evening rush hours) 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 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 was a conscious decision by Miami because of cost of fuel and concern over vehicle capabilities.
- New York (M100) - The diesel control and methanol buses 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 were no major safety incidents or accidents involving the alternative fuels. At each transit agency, there were 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 program 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[9] (to two significant digits) used to calculate diesel equivalency are shown in the table.

High fuel efficiency may indicate good performance, 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. In general, a spark ignition engine at idle uses more fuel than a diesel compression ignition engine operating at idle. 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 (mpeg) when using more than 30 percent LNG (by volume). The diesel control buses had an average fuel efficiency of 3.63 mpeg. 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) - The LNG fleet showed a 30 percent lower fuel efficiency than the diesel control buses. This decrease is slightly more than was expected (15 to 25 percent is the expected decrease). Several issues could be causing the lower than expected fuel economy. For example, because the LNG buses are not operated in service on the weekend, they are started and idled in the yard for several hours on the weekend; there could be some fuel losses from overpressure in the fuel tanks; and the fuel measurement accuracy may play a role. The engine oil consumption for the LNG fleet was nearly twice as high as the control fleet.
- Miami (CNG) - The data showed 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.
- Mpls/St. Paul (E95) - The ethanol fleet showed nearly the same fuel efficiency (5 percent lower). 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

Table 3. Fuel Efficiency Summary

Site	Fleet	Houston	Portland	Miami	Tacoma	Peoria	Peoria	Mpls/St. Paul	Miami	New York
Fuel	AF DC	LNG Diesel #1	LNG Diesel #2	CNG Diesel #2	CNG Diesel #2	E95 Diesel #1	E93 Diesel #1	E95 Diesel #1	M100 Diesel #2	M100 Diesel #1
Total Distance Traveled by Fleet (mi)	AF DC	375,694 282,881	183,609 203,007	95,098 330,342	407,778 451,337	269,966 157,886	118,688 67,491	100,665 266,338	208,660 380,453	140,637 168,270
Energy Conversion to Diesel #2 (AF/D2)	AF DC	0.61 0.98	0.61 1.00	0.0070[b] 1.00	0.0070[b] 1.00	0.60 0.98	0.59 0.98	0.60 0.98	0.44 1.00	0.44 0.98
Fuel Usage in Diesel #2 gallons	AF DC	66,236 77,847	60,618 47,248	6,996 91,496	86,828 75,201	74,409 44,512	36,218 19,783	33,763 84,896	59,370 114,759	54,172 55,640
Representative Fleet Energy Equivalent MPG[a]	AF DC	3.05 3.63	3.03 4.30	3.22 3.61	4.48 5.80	3.63 3.55	3.28 3.41	2.99 3.14	3.42 3.32	2.60 2.94
Ratio of MPG (AF/DC)		0.84	0.70	0.89	0.77	1.02	0.96	0.95	1.03	0.88
Engine Oil Consumption Quarts per 1,000 miles (per 1,600 km)	AF DC	2.1 2.2	6.0 3.2	2.4 3.5	1.9 2.5	2.8 2.4	5.5 2.9	2.8 2.5	2.1 3.8	3.2 1.7

Note: AF - Alternative Fuel, DC - Diesel Control

(a) The representative mpg may or may not be based strictly on the total mileage and quantity of 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. For the alternative fuel fleets, mpg is referred to as miles per equivalent gallon (mpeg).

(b) The conversion from standard cubic feet (scf) to an energy equivalent diesel #2 gallon is 0.0070.

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.

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 (including driver labor), vehicle maintenance (including 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 (including labor), and fuels and lubes. In this program, only vehicle maintenance (which includes inspections, some cleaning, and rebuild costs but not administration or supporting activities such as rebuild shop, tire shop, paint shop, body shop, parts inventory, and others), facility maintenance, and fuels and lubes were studied and are discussed.

The average cost breakdowns for transit bus operations for the transit agencies reporting in this program[10] are shown in Figure 3. 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 these transit agencies.

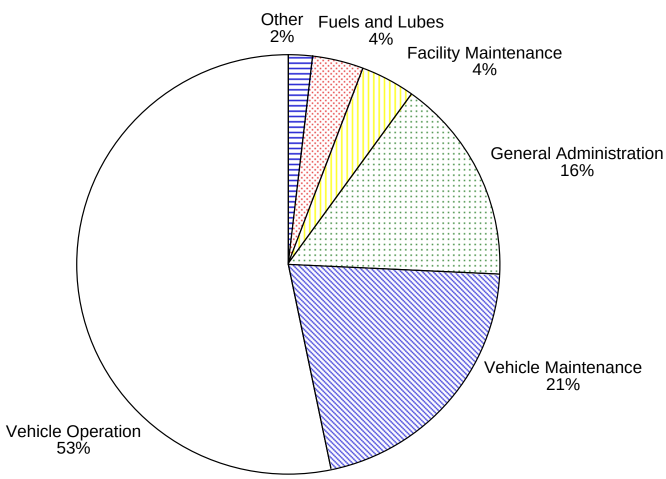
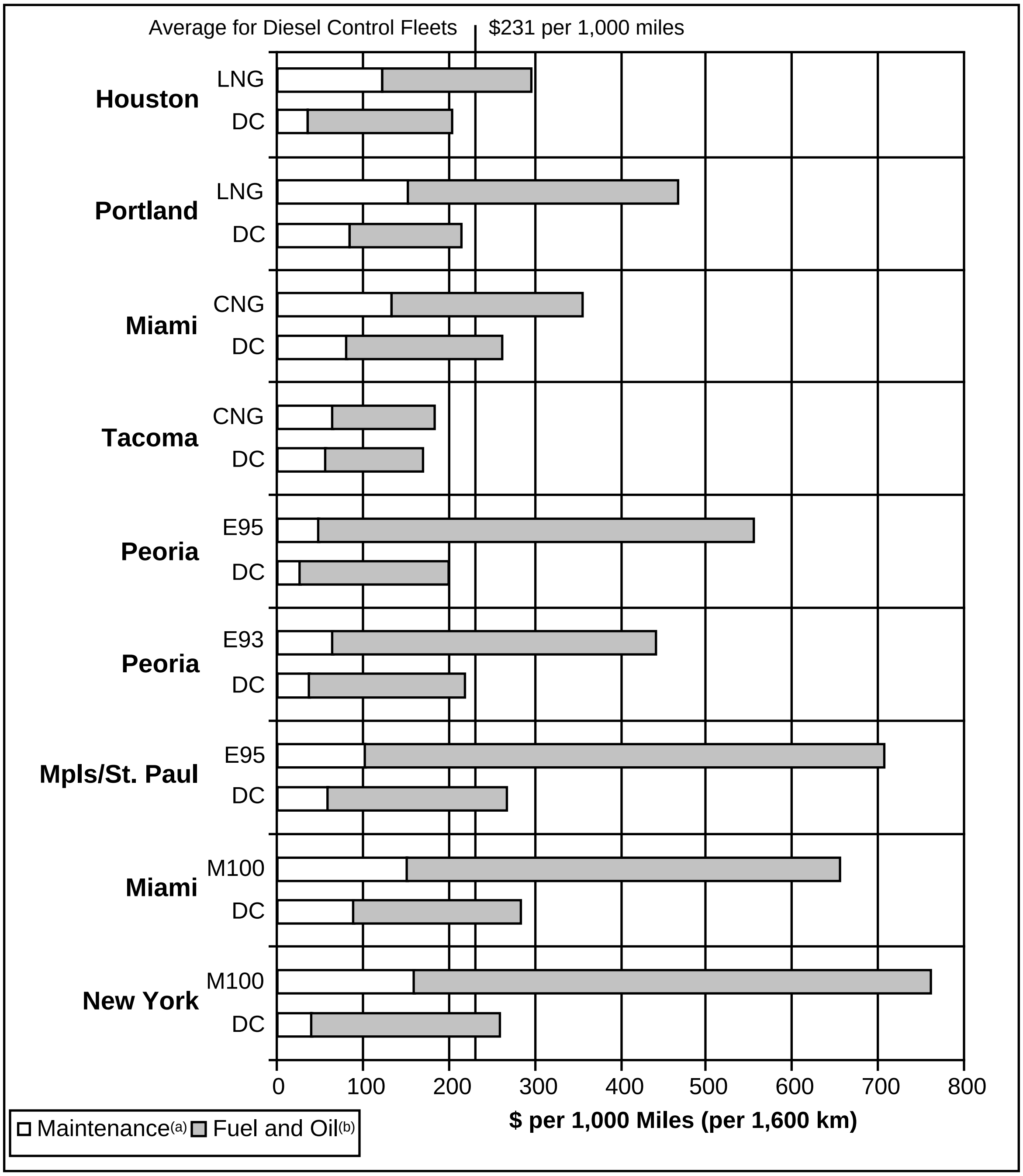


Figure 3. Overall Cost Breakdown for Transit Bus Operations

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[11] ranged from $8.40-$22.90, without fringe benefits or overhead costs. For the purposes of this study, a wage of $15 per hour was chosen as representative of labor costs for mechanics. Overhead costs for benefits (fringe) is an average of 53 percent for the transit agencies in this study. This overhead cost added to the wage makes the mechanic labor approximately $25 per hour. All maintenance costs presented here include this rate for the mechanic labor.

Figure 4 compares the bus maintenance, fuel, and engine oil costs per 1,000 miles (per 1,600 kilometers) among the test fleets as well as a comparison to other sites. 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 assess any increases in operating costs that could be directly related to the alternative fuel and related equipment. Additional maintenance costs for non-alternative fuel affected systems such as air conditioning, body repairs, and other repairs averaged $186 per 1,000 miles (per 1,600 kilometers) for these buses. Appendix A shows the numbers that comprise Figure 4. A summary for each site is given below:

- Houston (LNG) - The combined maintenance, fuel, and engine oil costs were 45 percent higher for the LNG buses. The majority of the cost difference between the test and control vehicles was in the maintenance costs. Also, because 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 2.2 times higher for the LNG buses. The major maintenance contributors were fuel leakage, natural gas sensing system, running out of fuel, and the cryogenic fuel pump.
- Miami (CNG) - The CNG buses showed a 35 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 were nearly the same, with the CNG buses being 8 percent higher. The maintenance cost for the CNG fleet was only slightly higher than the diesel control fleet, and the CNG fleet fuel and oil cost also was 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 was 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



(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 $186 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 $25 per hour.

(b) Fuel cost for LNG at Houston does not include maintenance or capital costs of the fueling station or costs associated with fuel losses during refueling. Fuel for LNG at Portland is purchased from a station owned and operated by the local utility. Fuel cost for CNG at Tacoma includes $0.06 per equivalent gallon of diesel to account for maintenance labor and parts used for the compression station. Fuel for CNG at Miami is purchased from a station owned by the local Airport Authority.

Figure 4. Bus Maintenance, Fuel, and Engine Oil Costs

fleet; however, the combined costs were still more than 2 times more expensive than the control buses.

- Mpls/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.
- 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 times more expensive than the diesel control fleet. The fuel costs were the major contributor to the high methanol fleet operations costs. Also, the maintenance costs were much higher for the methanol buses.

RESULTS AND DISCUSSION - CAPITAL COSTS

Capital costs presented in this paper differ from the other parts of the study because these costs are estimates based on knowledge gained from transit properties in this study as well as 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 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-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, no heavy-duty original engine manufacturer engines were available for transit bus operation on propane during this study. The new propane vehicle cost given in Table 4 is an estimate based on a bus order for a new pre-production DDC Series 50 engine optimized for operation on propane.

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 United States, 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

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

Fuel	Price per Bus ($)	Difference from Diesel ($)
Diesel (base case)	215,000	–
LNG	270,000	55,000
CNG	265,000	50,000
Methanol/Ethanol	235,000	20,000
Biodiesel	215,000	(a)
Propane	255,000	40,000

(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 are not currently covered by the engine manufacturer. Fuel system compatibility with a BD20 blend has not been proven, and none of the current heavy-duty engine manufacturers are currently offering BD20 specific engines.

major changes to accommodate alternative fuels. Also, because some alternative fuels require increased ventilation and more expensive electrical systems, the age of the facilities and whether the facilities will be built new may have a large impact on facility conversion costs.

In the estimates presented here, 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 ft^2 (7,883 m^2) indoor storage, 19,250 ft^2 (1,788 m^2) maintenance area, and 9,120 ft^2 (847 m^2) fueling areas are shown in Table 5. These costs are for comparison purposes only.

Table 5. Facility Incremental Conversion Costs (170-Bus Facility) by Fuel Type (1994 $, Millions)

Facility	LNG	CNG	Alcohols[(a)]	Biodiesel	Propane
Fueling	0.9	1.5	0.1	N/C	0.2
Maintenance	1.2	1.1	N/C	N/C	N/C[(b)]
Storage	1.4	1.2	N/C	N/C	N/C[(b)]
Total	3.5	3.8	0.1	N/C	0.2

Note: N/C - No change if facility is certified for gasoline
(a) Methanol (M100) and ethanol (E95 or E93)
(b) Increased ventilation and/or combustible gas sensors near the floor may be required by local officials.

RESULTS AND DISCUSSION - EMISSIONS TESTING

EMISSIONS TESTING OF ALCOHOL BUSES - The results of chassis dynamometer emissions testing on ethanol and methanol buses powered by DDC 6V92TA engines are summarized in Table 6 and illustrated in Figure 5. More detailed data are included in Appendix B. In 1994 and 1995, 10 buses in Peoria and Mpls/St. Paul were tested on ethanol, and 10 buses were tested on methanol in Miami and New York. Additionally, a total of 17 diesel control buses were tested in Peoria, Mpls/St. Paul, and Miami. Of the 17 diesel control buses, 8 were originally equipped with particulate traps. The buses with particulate traps were tested with the traps in place in 1994, and with the traps removed in 1995.

Figure 5 shows the test results plotted against odometer reading. This figure shows the range and variation of individual test results for a population of buses at various odometers, but are not intended to represent how emissions from a single bus deteriorate over time. Table 6 indicates the range of odometer readings for which buses were tested at a given site over the two-year period.

The results from the alcohol buses vary considerably from site to site and bus to bus. In general, the buses tested on ethanol and methanol appear to emit particulate matter (PM) levels similar to diesel buses equipped with particulate traps, and significantly less PM than diesel buses without traps. Although the particulate traps were effective in reducing PM levels from diesel vehicles, they were removed because of maintenance and durability problems. The majority of the ethanol and all of the methanol powered buses emitted lower levels of oxides of nitrogen (NOx) than the diesel controls. The ethanol and methanol buses emitted significantly higher amounts of hydrocarbons (HC) and carbon monoxide (CO). However, newer (tested at odometer readings between 6,700 and 42,000) methanol buses with DDC 6V92TA engines tested in New York City had consistently lower CO and HC emissions than either the diesel control or the older alcohol fueled buses.

The Environmental Protection Agency (EPA) engine certification data from the methanol (ethanol has not been certified) DDC 6V92TA has shown emissions reductions in all four components (HC, CO, NOx, and PM) versus the diesel 6V92TA. Recently, two of the buses in Peoria that showed high CO and HC emissions in previous tests underwent a series of diagnosis, repair, and retests. Several adjustments or repairs including blower bypass valve settings, new fuel injectors, and replacement of the catalytic convertor were studied.

Table 6. Average Chassis Dynamometer Emissions Results (g/mi) DDC 6V92 Engines

City	Test Fuel	Number of Buses	Number of Tests	Odometer Minimum	Odometer Maximum	PM	NOx	HC	CO
Peoria	Ethanol	5	8	60,000	104,000	0.63	13.4	8.86	37.1
Mpls/St. Paul	Ethanol	5	8	28,000	43,000	0.49	22	15.4	41.9
Miami	Methanol	5	9	38,000	87,000	0.39	11.6	37.5	25.1
New York	Methanol	5	10	6,700	42,000	0.11	6.84	2.09	8.4
Peoria	Diesel*	3	6	58,000	108,000	0.72	25.3	2.65	7.45
	Diesel**	3	3	58,000	69,000	0.44			
Mpls/St. Paul	Diesel	5	9	107,000	151,000	1.05	25.3	3.35	9.46
	Diesel*	5	10	26,000	69,000	0.81	26.4	2.11	6.68
	Diesel**	5	5	26,000	41,000	0.34			
Miami	Diesel	4	6	181,000	256,000	2.53	26.7	2.05	16

* average PM emissions calculated for buses tested **without** particulate traps in place
** average PM emissions calculated for buses **with** particulate traps in place

Tests on both buses performed before and after the catalytic convertor was replaced showed reductions in CO of approximately 85 percent (from approximately 40 g/mi to 6 g/mi) and reductions in HC of approximately 67 percent (from approximately 11 g/mi to 4 g/mi). A complete description of this series of tests will be the subject of a separate paper.

EMISSIONS TESTING OF COMPRESSED NATURAL GAS BUSES - Table 7 shows the number and location of buses with Cummins L10 engines tested in 1994 and 1995. The results of chassis dynamometer emissions tests on CNG and diesel buses powered by Cummins L10 engines are summarized in Table 7 and shown in Figure 6. More detailed data are included in Appendix C. The 5 CNG buses tested in Miami and 6 of the buses tested in Tacoma were equipped with early versions of the Cummins L10 engine (referred to as L10-240G) that did not require certification by the EPA or the California Air Resources Board (CARB). In 1994, Cummins made several enhancements to the engine. The later versions of this engine (referred to as L10-

Table 7. Average Chassis Dynamometer Emissions Results (g/mi) Cummins L10 Engines

City	Test Fuel	Number of Buses	Number of Tests	Odometer Minimum	Odometer Maximum	PM	NOx	HC	CO
Miami*	CNG	5	7	7,000	52,000	0.01	29.0	20.6	15.8
Tacoma*	CNG	6	10	103,000	170,000	0.01	30.1	9.26	20.6
New York**	CNG	5	10	3,000	20,000	0.03	12.0	16.1	1.56
Tacoma **	CNG	5	5	10,000	10,000	0.02	11.2	15.5	0.74
Miami	Diesel	9	10	65,000	250,000	1.77	23.9	1.80	21.9
Tacoma	Diesel	5	9	144,000	220,000	1.74	24.6	2.37	11.2

* L10-240G non-certified demonstration engines
** L10-260G CARB-certified version

Figure 5. Chassis Dynamometer Emissions from Buses with DDC 6V92 Engines

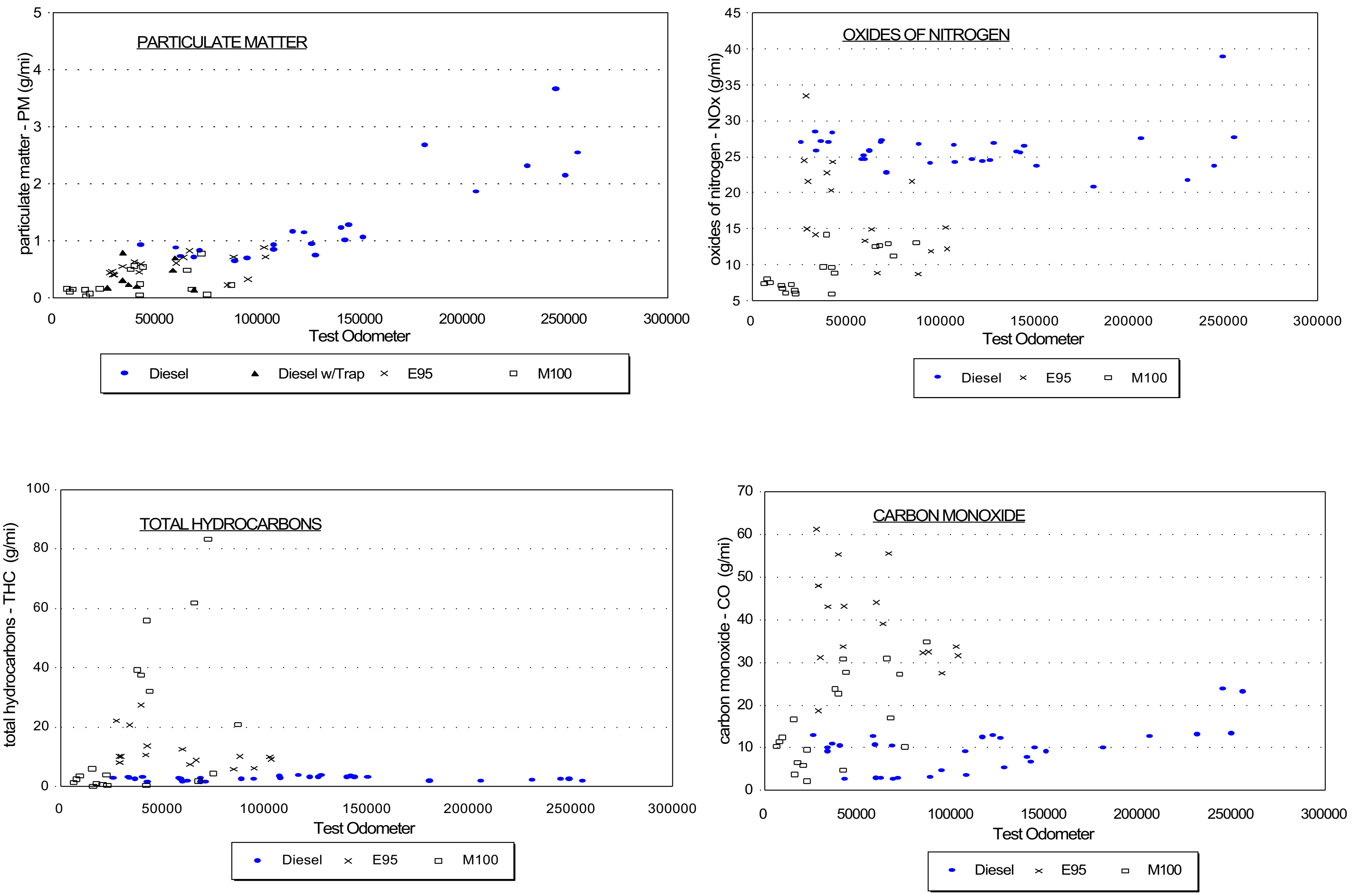
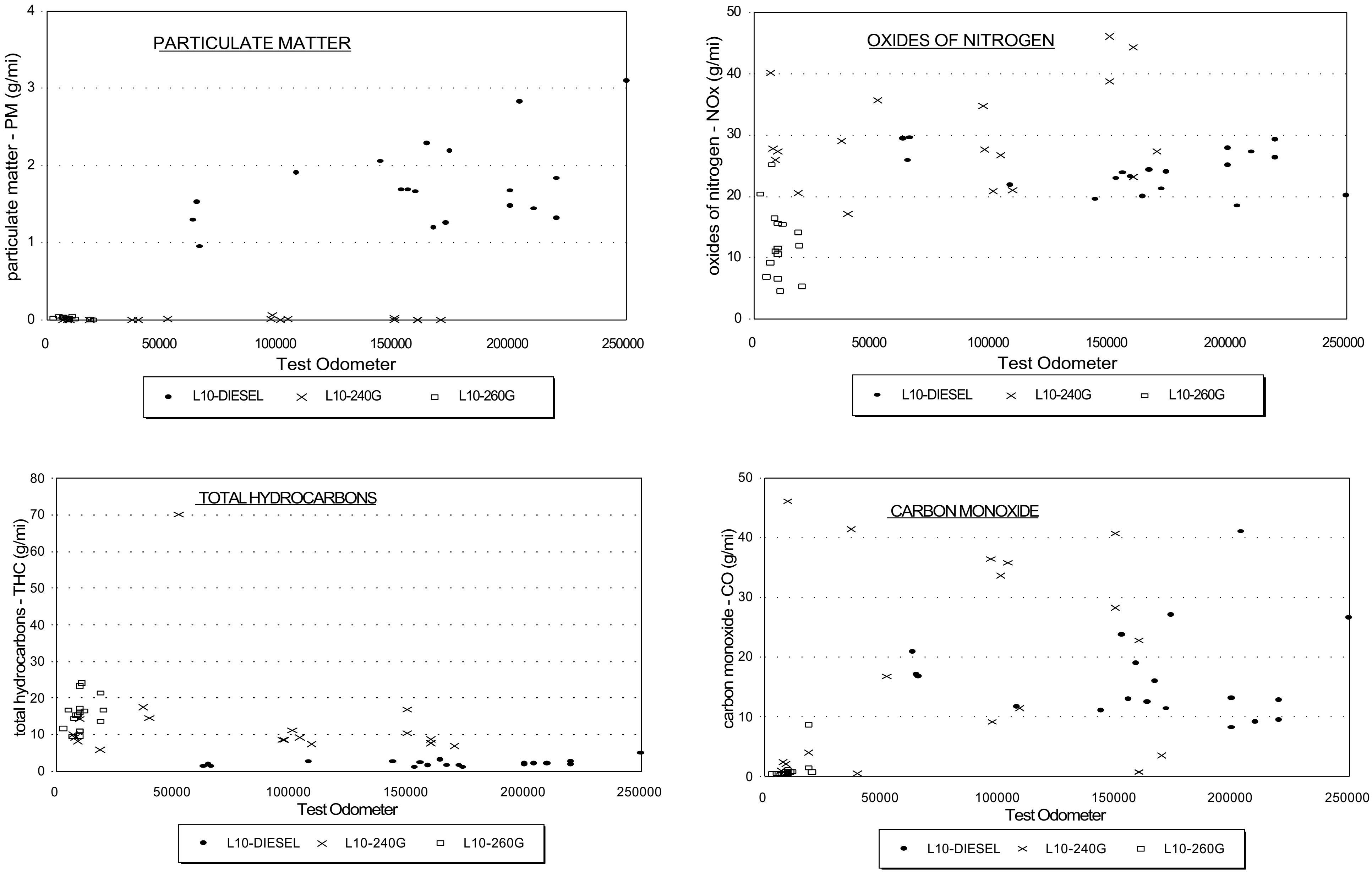


Figure 6. Chassis Dynamometer Emissions from Buses with Cummins L-10 Engines



260G) have been certified by CARB. Five buses with the newer engines were tested in Tacoma. Also, several L10 engines in New York City buses were upgraded to the certified configuration and 5 of these were also tested.

Although there is a substantial amount of scatter in the data, several general conclusions can be made. The most obvious result is that the PM emissions levels are reduced to nearly zero with CNG. Figure 6 shows that all of the CNG buses tested (including vehicles with odometers over 150,000 miles) had PM levels an order of magnitude lower than the diesel buses. Figure 6 also shows that buses equipped with the newer CARB-certified CNG Cummins L10-260G engines exhibited lower CO and NOx emissions than either the original CNG demonstration, or the diesel control buses. Note that the L10-260G tests were performed at 20,000 miles or less. The total HC emissions levels from the CNG buses are higher than the diesel buses. However, HC emissions from CNG vehicles are typically comprised of over 95 percent methane[12]. Both EPA and CARB regulations are written in terms of non-methane hydrocarbons (NMHC) because methane is considered to be non-reactive in the atmosphere. The NMHC levels from the CNG buses were not directly measured, but can be projected to be at similar or lower levels than from the diesel buses.

A series of diagnosis, repair, and retesting was recently completed in Tacoma on three buses with higher-than-expected CO emissions. The repairs included replacement of air/fuel mixing valve components and adjustments to the air/fuel ratio. All three buses showed reductions in CO which averaged approximately 93 percent (an average of 30 g/mi before repairs to 2 g/mi after repairs). A complete description of this work will be discussed in a separate paper.

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. The intent of this program also has been to provide information so that the transition to alternative fuels 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 presented in five major categories: reliability, fuel efficiency, bus 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.

<u>LNG</u> - The LNG buses experienced nearly twice as many road calls. Both sites show that the LNG buses were 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 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.

<u>CNG</u> - At the Miami site, the CNG buses were only used in limited service (tripper service only during rush hours to supplement normal service and therefore the CNG fleet did 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.

<u>Ethanol</u> - As with CNG, one ethanol site used the test buses in normal service and one site used the test buses in limited service. The ethanol buses at Peoria were used approximately the same amount as the diesel control buses and at the Mpls/St. Paul site, the ethanol buses were used 60 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 Mpls/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.

<u>Methanol</u> - 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 nearly the same as the diesel control buses. The Miami methanol fleet experienced 15 percent more road calls, and the New York methanol fleet experienced 53 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 among 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.

At Portland, Miami, and Tacoma, the natural gas vehicles have 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, caused 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 was 30 percent lower than the diesel control fleet. The LNG fleet was used in service that was somewhat less severe than the diesel fleet. The fuel efficiency for the LNG fleet was slightly lower than expected (15-25 percent lower than similar diesel vehicles was expected). Several issues could be causing the lower-than-expected fuel economy. For example, the LNG buses were not operated in service on the weekend. The LNG buses were started and idled in the yard for several hours, so the LNG tanks would not build up excessive pressure. There also could be some fuel losses from overpressure in the fuel tanks, and the fuel measurement accuracy also may play a role.

CNG - The CNG buses at Miami showed an 11 percent decrease in fuel efficiency compared to the diesel control buses at this site. 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 the Tacoma site, the CNG fleet showed a 23 percent decrease in fuel efficiency as compared to the diesel control buses. The CNG fleet was used in the same service as the diesel control buses except for a few routes. 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 improve fuel efficiency.

Ethanol - The fuel efficiencies for the ethanol vehicles at Peoria and Mpls/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. Both fleets in New York were operated in severe downtown service. The major contributing factor to the lower fuel efficiency was most likely the difference in engine model (methanol 6V92TA and diesel Series 50). The diesel buses have a newer and more advanced engine design.

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 costs for vehicle maintenance and fuels and lubes are collected for operating cost comparisons; no capital costs are included. Also, for the maintenance costs, only the following systems are included in this paper: general electrical, charging, cranking, ignition, air intake, cooling, exhaust, fuel, and engine. These systems were chosen to assess any increases in operating costs that could be directly related to the alternative fuel and related equipment. A summary for each alternative fuel is given below.

LNG - The LNG buses at Houston and Portland 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 ran 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 were not used in normal service; therefore, the results were not comparable to the results from the Tacoma site. Also, since the Tacoma CNG buses were used in normal service, operating cost results should be considered more representative of in-service CNG bus technology. At Tacoma, the CNG fleet had slightly higher maintenance costs and fuel costs for an overall 8 percent higher operating cost.

Ethanol - The ethanol buses at Peoria and Mpls/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 was 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 times, 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 times, New York - 3.0 times). Note that the price of methanol was volatile during the data collection period (as high as $1- $2 per gallon). For Miami, 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. For New York, an actual methanol cost of $0.57 per gallon was used ($1.31 per energy equivalent gallon of diesel #2). 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 $55,000, 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 (simply 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 are not 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 through them and mixed according to their specifications.

EMISSIONS - Results from WVU's testing showed high variability in emissions levels from the alternative fueled vehicles compared to standard diesel control buses. Comparing chassis dynamometer emissions levels among heavy-duty vehicle technologies is a complex and evolving matter. Both the engine certification and chassis dynamometer testing have shown that alternative fuels have a potential for substantially reducing emissions levels, but emissions are also highly dependent upon the engine technology, and the condition of the vehicle. Although NREL and WVU are attempting to select the latest technologies available, many of the vehicles tested over the past several years represent early versions of alternative fueled engines that were put on the road as part of a demonstration or to assist in the development of the technology.

The alternative fuel buses appear to be particularly well suited to reducing emissions of PM and NOx. This feature is quite important as the federal emissions standards for PM and NOx are becoming more stringent. Early testing showed that some of the alternative fuel buses exhibited high levels of HC and CO emissions. In cooperation with the engine manufacturers, the program discovered that many of these vehicles were either improperly tuned, or had problems with fuel injectors, catalytic convertors, mixing valves, and other engine components. Recently, dramatic reductions in HC and CO emissions were achieved on CNG buses in Miami and Tacoma, and ethanol buses in Peoria after manufacturer representatives performed problem diagnosis and repair on the high emitting vehicles.

Each of the manufacturers has continued to upgrade their alternative fuel engine designs including optimization for emissions. A key component of the latest CNG engines is electronic "feedback" control of the air/fuel ratio through measurement of the oxygen content in the exhaust. In order to monitor progress in technology development, NREL and WVU plan to pursue emissions testing of the latest CNG technology engines as they are put into service in transit buses.

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Appendix A. Total Bus Maintenance, Fuel, and Engine Oil Costs

Site	Fleet	Houston	Portland	Miami	Tacoma	Peoria	Peoria	Mpls/St. Paul	Miami	New York
Fuel	AF DC	LNG Diesel #1	LNG Diesel #2	CNG Diesel #2	CNG Diesel #2	E95 Diesel #1	E93 Diesel #1	E95 Diesel #1	M100 Diesel #2	M100 Diesel #1
Total Distance Traveled by Fleet (mi)	AF DC	375,694 282,881	232,186 364,088	95,098 330,342	407,778 451,337	269,966 157,886	67,491 118,688	100,665 266,338	208,660 380,453	118,161 138,307
Maintenance Cost[(a)] ($) per 1,000 mi. (per 1,600 km)	AF DC	121 36	152 84	132 82	66 56	49 27	65 39	102 60	151 90	159 41
Fuel Cost ($) per 1,000 mi. (per 1,600 km)	AF DC	173[(c)] 166	307[(d)] 128	220[(b)] 177	116[(b)] 112	504 171	369 178	601 207	502 193	599 216
Engine Oil Consumption Cost ($) per 1,000 mi. (per 1,600 km)	AF DC	1 2	8 2	3 3	2 2	4 2	8 2	4 1	3 3	5 1
Maint, Fuel, and Oil Cost ($) per 1,000 mi. (per 1,600 km)	AF DC	295 204	467 214	355 262	184 170	557 200	442 219	707 268	656 286	763 258

Note: AF - Alternative Fuel, DC - Diesel Control

(a) The maintenance costs shown here include only 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 $186 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 $25 per hour.

(b) For Miami, the CNG is purchased from the Airport Authority and therefore includes the fuel cost, compressor station maintenance labor and parts as well as capital costs for the station. For Tacoma, the CNG cost includes maintenance labor and parts for the compressor station, but does not include capital costs.

(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.

(d) At Portland, the LNG is purchased from the local utility, and therefore the purchase price includes the fuel cost, maintenance labor and parts for the station as well as capital costs for the station.

Appendix B. Chassis Dynamometer Emissions from Buses with DDC 6V92 Engines

Ethanol Buses - Peoria, IL

VEHICLE	BUS	BUS	ENGINE	ENGINE	ENGINE	TEST	TEST	TEST	**Emissions Test Results(g/mi)**			
NUMBER	MAKE	YEAR	MAKE	MODEL	YEAR	DATE	ODOM	FUEL	PM	NOx	HC	CO
GPT-1504E	TMC	1992	DDC	6V-92TA	1992	4/19/94	59925	E95	0.61	13.37	12.67	44.10
GPT-1504E	TMC	1992	DDC	6V-92TA	1992	4/18/95	94999	E95	0.33	11.90	6.13	27.55
GPT-1506E	TMC	1992	DDC	6V-92TA	1992	4/25/94	66567	E95	0.82	8.9	9	55.6
GPT-1506E	TMC	1992	DDC	6V-92TA	1992	4/10/95	103481	E95	0.72	12.2	9.22	31.6
GPT-1507E	TMC	1992	DDC	6V-92TA	1992	4/21/94	63588	E95	0.71	14.97	7.60	39.07
GPT-1507E	TMC	1992	DDC	6V-92TA	1992	4/6/95	102819	E95	0.88	15.2	10.08	33.8
GPT-1508E	TMC	1992	DDC	6V-92TA	1992	4/10/95	88049	E95	0.72	8.7	10.21	32.5
GPT-1516E	TMC	1992	DDC	6V-92TA	1992	4/20/94	84911	E95	0.22	21.60	5.97	32.30
							COUNT		8	8	8	8
							AVERAGE		0.63	13.35	8.86	37.06
							MAX		0.88	21.60	12.67	55.60
							MIN		0.22	8.70	5.97	27.55

Ethanol Buses - Mpls/St Paul, MN

VEHICLE	BUS	BUS	ENGINE	ENGINE	ENGINE	TEST	TEST	TEST	**Emissions Test Results(g/mi)**			
NUMBER	MAKE	YEAR	MAKE	MODEL	YEAR	DATE	ODOM	FUEL	PM	NOx	HC	CO
MTC-8000	GLG	1993	DDC	6V-92TA	1991	10/5/94	27605	E95	0.44	24.5	22.2	61.3
MTC-8000	GLG	1993	DDC	6V-92TA	1991	5/21/95	39609	E95	0.63	22.8	27.55	55.45
MTC-8001	GLG	1993	DDC	6V-92TA	1991	10/1/94	29694	E95	0.4	21.6	10.2	31.2
MTC-8001	GLG	1993	DDC	6V-92TA	1991	5/22/95	41979	E95	0.445	20.4	10.66	33.75
MTC-8002	GLG	1993	DDC	6V-92TA	1991	5/25/95	33831	E95	0.55	14.20	20.81	43.18
MTC-8003	GLG	1993	DDC	6V-92TA	1991	10/4/94	28722	E95	0.46	33.5	10.2	18.7
MTC-8003	GLG	1993	DDC	6V-92TA	1991	5/25/95	42581	E95	0.585	24.3	13.715	43.2
MTC-8004	GLG	1993	DDC	6V-92TA	1991	10/5/94	29119	E95	0.41	15	8.1	48.1
							COUNT		8	8	8	8
							AVERAGE		0.49	22.04	15.43	41.86
							MAX		0.63	33.50	27.55	61.30
							MIN		0.40	14.20	8.10	18.70

Methanol Buses - Miami, FL

VEHICLE	BUS	BUS	ENGINE	ENGINE	ENGINE	TEST	TEST	TEST	**Emissions Test Results(g/mi)**			
NUMBER	MAKE	YEAR	MAKE	MODEL	YEAR	DATE	ODOM	FUEL	PM	NOx	HC	CO
MDTA-9211	FLX	1992	DDC	6V-92TA	1992	1/21/94	42283	M100	0.24	9.6	55.9	30.9
MDTA-9211	FLX	1992	DDC	6V-92TA	1992	2/14/95	87000	M100	0.23	13.07	20.93	34.90
MDTA-9212	FLX	1992	DDC	6V-92TA	1992	1/22/94	37745	M100	0.5	9.7	39.3	23.9
MDTA-9212	FLX	1992	DDC	6V-92TA	1992	2/15/95	72364	M100	0.78	12.95	83.20	27.30
MDTA-9213	FLX	1992	DDC	6V-92TA	1992	1/24/94	39500	M100	0.56	14.2	37.5	22.7
MDTA-9213	FLX	1992	DDC	6V-92TA	1992	2/14/95	67697	M100	0.15	12.7	1.9	17.1
MDTA-9214	FLX	1992	DDC	6V-92TA	1992	1/25/94	65450	M100	0.48	12.5	61.8	31
MDTA-9215	FLX	1992	DDC	6V-92TA	1992	1/24/94	43800	M100	0.54	8.8	32.2	27.8
MDTA-9215	FLX	1992	DDC	6V-92TA	1992	2/16/95	75000	M100	0.06	11.25	4.50	10.30
							COUNT		9	9	9	9
							AVERAGE		0.39	11.64	37.47	25.10
							MAX		0.78	14.20	83.20	34.90
							MIN		0.06	8.80	1.90	10.30

Methanol Buses - New York City

VEHICLE	BUS	BUS	ENGINE	ENGINE	ENGINE	TEST	TEST	TEST	**Emissions Test Results(g/mi)**			
NUMBER	MAKE	YEAR	MAKE	MODEL	YEAR	DATE	ODOM	FUEL	PM	NOx	HC	CO
TBCC-2136	TMC	1994	DDC	6V-92TA	1993	11/12/94	22582	M100	0.16	6.4	4	9.6
TBCC-2136	TMC	1994	DDC	6V-92TA	1993	6/19/95	42100	M100	0.05	5.9	0.49	4.8
TBCC-2137	TMC	1994	DDC	6V-92TA	1993	11/16/94	9484	M100	0.15	7.5	3.7	12.5
TBCC-2137	TMC	1994	DDC	6V-92TA	1993	6/19/95	17854	M100	0.07	6.1	1.06	6.6
TBCC-2138	TMC	1994	DDC	6V-92TA	1993	11/14/94	6674	M100	0.16	7.4	1.5	10.4
TBCC-2138	TMC	1994	DDC	6V-92TA	1993	7/11/95	16067	M100	0.035	6.7	0.22	3.75
TBCC-2139	TMC	1994	DDC	6V-92TA	1993	11/15/94	7979	M100	0.11	8	2.5	11.5
TBCC-2139	TMC	1994	DDC	6V-92TA	1993	6/21/95	20765	M100		7.3	0.79	5.9
TBCC-2140	TMC	1994	DDC	6V-92TA	1993	11/17/94	15561	M100	0.14	7.1	6.1	16.7
TBCC-2140	TMC	1994	DDC	6V-92TA	1993	6/21/95	23036	M100		6	0.53	2.2
							COUNT		8	10	10	10
							AVERAGE		0.11	6.84	2.09	8.40
							MAX		0.16	8.00	6.10	16.70
							MIN		0.04	5.90	0.22	2.20

Appendix B. Chassis Dynamometer Emissions from Buses with DDC 6V92 Engines

Diesel Buses with Particulate Traps (removed in 1995) - Peoria, IL

VEHICLE	BUS	BUS	ENGINE	ENGINE	ENGINE	TEST	TEST	TEST	**Emissions Test Results(g/mi)**			
NUMBER	MAKE	YEAR	MAKE	MODEL	YEAR	DATE	ODOM	FUEL	PM	NOx	HC	CO
GPT-1501	TMC	1992	DDC	6V-92TA	1992	4/15/94	68721	D1	0.14	27	2.8	10.4
GPT-1501	TMC	1992	DDC	6V-92TA	1992	4/4/95	107954	D1	0.84	24.2	2.83	3.4
GPT-1502	TMC	1992	DDC	6V-92TA	1992	4/15/94	59373	D1	0.7	25.1	2.5	10.7
GPT-1502	TMC	1992	DDC	6V-92TA	1992	4/18/95	95032	D1	0.69	24	2.46	4.6
GPT-1503	TMC	1992	DDC	6V-92TA	1992	4/27/94	58287	D1	0.48	24.6	2.8	12.6
GPT-1503	TMC	1992	DDC	6V-92TA	1992	4/19/95	88913	D1	0.64	26.7	2.48	3
							COUNT		3			
							AVERAGE	w/traps	0.44			
							MAX		0.70			
							MIN		0.14			
							COUNT		3	6	6	6
							AVERAGE	w/o traps	0.72	25.27	2.65	7.45
							MAX		0.84	27.00	2.83	12.60
							MIN		0.64	24.00	2.46	3.00

Diesel Buses without Particulate Traps - St. Paul, MN

VEHICLE	BUS	BUS	ENGINE	ENGINE	ENGINE	TEST	TEST	TEST	**Emissions Test Results(g/mi)**			
NUMBER	MAKE	YEAR	MAKE	MODEL	YEAR	DATE	ODOM	FUEL	PM	NOx	HC	CO
MTC-2207	GLG	1993	DDC	6V-92TA	1991	9/13/94	116911	D1	1.16	24.6	3.7	12.5
MTC-2207	GLG	1993	DDC	6V-92TA	1991	5/19/95	142835	D1	1.01	25.55	3.55	6.55
MTC-2208	GLG	1993	DDC	6V-92TA	1991	5/17/95	140678	D1	1.23	25.6	3.2	7.7
MTC-2209	GLG	1993	DDC	6V-92TA	1991	9/15/94	126622	D1	0.94	24.4	3.2	12.2
MTC-2209	GLG	1993	DDC	6V-92TA	1991	5/17/95	144612	D1	1.27	26.4	3.17	9.9
MTC-2210	GLG	1993	DDC	6V-92TA	1991	9/17/94	122545	D1	1.13	24.3	3.2	12.8
MTC-2210	GLG	1993	DDC	6V-92TA	1991	5/16/95	151201	D1	1.06	23.7	2.99	9.2
MTC-2211	GLG	1993	DDC	6V-92TA	1991	9/16/94	107614	D1	0.92	26.5	3.5	9.1
MTC-2211	GLG	1993	DDC	6V-92TA	1991	5/17/95	128418	D1	0.74	26.8	3.63	5.2
							COUNT		9	9	9	9
							AVERAGE		1.05	25.32	3.35	9.46
							MAX		1.27	26.80	3.70	12.80
							MIN		0.74	23.70	2.99	5.20

Diesel Buses with Particulate Traps (removed in 1996) - St. Paul, MN

VEHICLE	BUS	BUS	ENGINE	ENGINE	ENGINE	TEST	TEST	TEST	**Emissions Test Results(g/mi)**			
NUMBER	MAKE	YEAR	MAKE	MODEL	YEAR	DATE	ODOM	FUEL	PM	NOx	HC	CO
MTC-2222	GLG	1993	DDC	6V-92TA	1993	9/23/94	36670	D1	0.23	27.1	2.5	10.8
MTC-2222	GLG	1993	DDC	6V-92TA	1993	5/18/95	62561	D1	0.72	25.85	1.67	2.80
MTC-2223	GLG	1993	DDC	6V-92TA	1993	9/26/94	34101	D1	0.79	25.8	2.7	9.9
MTC-2223	GLG	1993	DDC	6V-92TA	1993	5/19/94	60000	D1	0.87	24.55	1.39	2.90
MTC-2224	GLG	1993	DDC	6V-92TA	1993	9/27/94	40812	D1	0.2	27	2.9	10.5
MTC-2224	GLG	1993	DDC	6V-92TA	1993	5/20/95	68890	D1	0.71	27.25	1.55	2.55
MTC-2225	GLG	1993	DDC	6V-92TA	1993	9/28/94	33720	D1	0.31	28.4	2.9	9.2
MTC-2225	GLG	1993	DDC	6V-92TA	1993	5/12/95	71583	D1	0.83	22.8	1.33	2.8
MTC-2226	GLG	1993	DDC	6V-92TA	1993	9/29/94	26370	D1	0.18	26.9	2.8	12.8
MTC-2226	GLG	1993	DDC	6V-92TA	1993	5/15/95	43043	D1	0.92	28.3	1.39	2.5
							COUNT		5	10	10	10
							AVERAGE	w/o trap	0.81	26.40	2.11	6.68
							MAX		0.92	28.40	2.90	12.80
							MIN		0.71	22.80	1.33	2.50
							COUNT		5			
							AVERAGE	w/ trap	0.34			
							MAX		0.79			
							MIN		0.18			

Diesel Buses without Particulate Traps - Miami, FL

VEHICLE	BUS	BUS	ENGINE	ENGINE	ENGINE	TEST	TEST	TEST	**Emissions Test Results(g/mi)**			
NUMBER	MAKE	YEAR	MAKE	MODEL	YEAR	DATE	ODOM	FUEL	PM	NOx	HC	CO
MDTA-9067	FLX	1990	DDC	6V-92TA	1990	1/18/94	181385	D2	2.68	20.7	1.9	9.9
MDTA-9067	FLX	1990	DDC	6V-92TA	1990	2/6/95	231619	D1	2.31	21.7	2.1	13.2
MDTA-9068	FLX	1990	DDC	6V-92TA	1990	1/19/94	206506	D2	1.85	27.5	1.7	12.6
MDTA-9068	FLX	1990	DDC	6V-92TA	1990	2/23/95	256087	D1	2.53	27.6	1.8	23.2
MDTA-9070	FLX	1990	DDC	6V-92TA	1990	2/22/95	250000	D1	2.14	38.9	2.5	13.4
MDTA-9071	FLX	1990	DDC	6V-92TA	1990	2/22/95	245674	D1	3.66	23.6	2.3	23.8
							COUNT		6	6	6	6
							AVERAGE		2.53	26.67	2.05	16.02
							MAX		3.66	38.90	2.50	23.80
							MIN		1.85	20.70	1.70	9.90

Appendix C. Chassis Dynamometer Emissions From Buses With Cummins L10 Engines

CNG Buses - Cummins L10-240G - Miami, FL

VEHICLE	BUS	BUS	ENGINE	ENGINE	ENGINE	TEST	TEST	TEST	**Emissions Test Results(g/mi)**			
NUMBER	MAKE	YEAR	MAKE	MODEL	YEAR	DATE	ODOM	FUEL	PM	NOx	HC	CO
MDTA-9201	FLX	1992	Cummins	L-10 240G	1991	1/26/94	10000	CNG	0	27.4	14.3	46.1
MDTA-9202	FLX	1992	Cummins	L-10 240G	1991	1/28/94	9018	CNG	0	25.9	8.3	2.1
MDTA-9202	FLX	1992	Cummins	L-10 240G	1991	2/18/95	39670	CNG	0	17.1	14.5	0.6
MDTA-9203	FLX	1990	Cummins	L-10 240G	1991	1/26/94	7004	CNG	0	40.1	10	1
MDTA-9204	FLX	1990	Cummins	L-10 240G	1991	1/27/94	36973	CNG	0	29	17.5	41.4
MDTA-9204	FLX	1990	Cummins	L-10 240G	1991	2/20/95	52182	CNG	0.02	35.7	70.2	16.8
MDTA-9205	FLX	1990	Cummins	L-10 240G	1991	2/3/94	7944	CNG	0.02	27.8	9.3	2.4
							COUNT		7	7	7	7
							AVERAGE		0.006	29.00	20.59	15.77
							MAX		0.02	40.1	70.2	46.1
							MIN		0	17.1	8.3	0.6

CNG Buses - Cummins L10-240G - Tacoma, WA

VEHICLE	BUS	BUS	ENGINE	ENGINE	ENGINE	TEST	TEST	TEST	**Emissions Test Results(g/mi)**			
NUMBER	MAKE	YEAR	MAKE	MODEL	YEAR	DATE	ODOM	FUEL	PM	NOx	HC	CO
PT-484	BIA	1992	Cummins	L-10 240G	1992	8/13/94	97278	CNG	0.06	27.7	8.6	9.2
PT-478	BIA	1992	Cummins	L-10 240G	1992	8/12/94	104000	CNG	0.01	26.8	9.2	35.8
PT-478	BIA	1992	Cummins	L-10 240G	1992	7/4/95	160000	CNG	0	44.3	8.83	22.8
PT-479	BIA	1992	Cummins	L-10 240G	1992	8/5/94	109010	CNG		21	7.4	11.5
PT-479	BIA	1992	Cummins	L-10 240G	1992	7/5/95	170000	CNG	0	27.3	6.98	3.6
PT-480	BIA	1992	Cummins	L-10 240G	1992	8/9/94	96730	CNG	0.02	34.7	8.6	36.4
PT-480	BIA	1992	Cummins	L-10 240G	1992	7/6/95	150000	CNG	0.03	46.1	10.47	40.7
PT-481	BIA	1992	Cummins	L-10 240G	1992	8/11/94	100800	CNG	0	20.85	11.2	33.7
PT-481	BIA	1992	Cummins	L-10 240G	1992	7/7/95	150000	CNG	0	38.8	16.88	28.3
PT-482	BIA	1992	Cummins	L-10 240G	1992	8/15/94	18654	CNG	0	20.6	6	4
PT-482	BIA	1992	Cummins	L-10 240G	1992	7/8/95	160000	CNG	0	23.2	7.67	0.8
							COUNT		10	11	11	11
							AVERAGE		0.012	30.12	9.26	20.62
							MAX		0.06	46.1	16.88	40.7
							MIN		0	20.6	6	0.8

CNG Buses - Cummins L10-260G - New York, NY

VEHICLE	BUS	BUS	ENGINE	ENGINE	ENGINE	TEST	TEST	TEST	**Emissions Test Results(g/mi)**			
NUMBER	MAKE	YEAR	MAKE	MODEL	YEAR	DATE	ODOM	FUEL	PM	NOx	HC	CO
CBC-4903	TMC	1994	Cummins	L-10 260G	1993	12/10/94	8517	CNG	0.04	20.85	14.85	0.60
CBC-4903	TMC	1994	Cummins	L-10 260G	1993	7/25/95	18872	CNG	0.01	12	21.35	1.5
CBC-4904	TMC	1994	Cummins	L-10 260G	1993	11/20/94	6764	CNG	0.04	9.2	9.5	0.4
CBC-4904	TMC	1994	Cummins	L-10 260G	1993	7/25/95	18666	CNG	0.01	14.2	13.7	8.7
CBC-4907	TMC	1994	Cummins	L-10 260G	1993	11/29/94	9048	CNG	0.01	11.1	15.5	0.8
CBC-4907	TMC	1994	Cummins	L-10 260G	1993	7/26/95	20091	CNG	0	5.4	16.74	0.8
TBCC-2051	TMC	1994	Cummins	L-10 260G	1993	11/17/94	5223	CNG	0.05	6.9	16.7	0.6
TBCC-2051	TMC	1994	Cummins	L-10 260G	1993	6/24/95	10871	CNG	0.05	4.6	24.12	0.8
TBCC-2054	TMC	1994	Cummins	L-10 260G	1993	11/19/94	2774	CNG	0.03	20.4	11.7	0.5
TBCC-2054	TMC	1994	Cummins	L-10 260G	1993	6/23/95	11993	CNG	0.02	15.5	16.45	0.9
							COUNT		10	10	10	10
							AVERAGE		0.03	12.02	16.06	1.56
							MAX		0.05	20.85	24.12	8.70
							MIN		0.00	4.60	9.50	0.40

CNG Buses - Cummins L10-260G - Tacoma, WA

VEHICLE	BUS	BUS	ENGINE	ENGINE	ENGINE	TEST	TEST	TEST	**Emissions Test Results(g/mi)**			
NUMBER	MAKE	YEAR	MAKE	MODEL	YEAR	DATE	ODOM	FUEL	PM	NOx	HC	CO
PT-803	BIA	1994	Cummins	L-10 260G	1994	7/10/95	10000	CNG	0.03	11.6	9.67	0.7
PT-804	BIA	1994	Cummins	L-10 260G	1994	7/13/95	10000	CNG	0.01	6.6	16.12	0.4
PT-806	BIA	1994	Cummins	L-10 260G	1994	7/10/95	10000	CNG	0.03	15.6	17.16	0.6
PT-807	BIA	1994	Cummins	L-10 260G	1994	7/14/95	10000	CNG	0	11.6	23.33	0.9
PT-811	BIA	1993	Cummins	L-10 260G	1993	7/13/95	10000	CNG	0.01	10.6	11.07	1.1
							COUNT		5	5	5	5
							AVERAGE		0.016	11.20	15.47	0.74
							MAX		0.03	15.6	23.33	1.1
							MIN		0	6.6	9.67	0.4

Appendix C. Chassis Dynamometer Emissions From Buses With Cummins L10 Engines

Diesel Buses - Cummins L10 - Miami, FL

VEHICLE NUMBER	BUS MAKE	BUS YEAR	ENGINE MAKE	ENGINE MODEL	ENGINE YEAR	TEST DATE	TEST ODOM	TEST FUEL	**Emissions Test Results(g/mi)** PM	NOx	HC	CO
MDTA-9001	FLX	1990	Cummins	L-10	1990	2/7/94	204000	D2	2.83	18.4	2.1	40.9
MDTA-9001	FLX	1990	Cummins	L-10	1990	2/24/95	250000	D1	3.1	20.2	4.9	26.6
MDTA-9003	FLX	1990	Cummins	L-10	1990	2/7/94	153000	D2	1.68	22.9	1	23.8
MDTA-9004	FLX	1990	Cummins	L-10	1990	2/8/94	174000	D2	2.19	24	1	27.1
MDTA-9081	FLX	1990	Cummins	L-10	1990	2/8/94	167000	D2	1.2	24.3	1.5	16
MDTA-9082	FLX	1990	Cummins	L-10	1990	2/9/94	172000	D2	1.26	21.2	1.5	11.3
MDTA-9083	FLX	1990	Cummins	L-10	1990	2/9/94	159000	D2	1.66	23.2	1.6	19
MDTA-9206	FLX	1992	Cummins	L-10		2/3/94	63126	D2	1.29	29.4	1.2	20.9
MDTA-9208	FLX	1992	Cummins	L-10	1992	2/1/94	65000	D2	1.53	25.8	1.9	17.1
MDTA-9209	FLX	1992	Cummins	L-10	1992	2/10/94	66000	D2	0.95	29.5	1.3	16.8
							COUNT		10	10	10	10
							AVERAGE		1.77	23.89	1.8	21.95
							MAX		3.1	29.5	4.9	40.9
							MIN		0.95	18.4	1	11.3

Diesel Buses - Cummins L10 - Tacoma, WA

VEHICLE NUMBER	BUS MAKE	BUS YEAR	ENGINE MAKE	ENGINE MODEL	ENGINE YEAR	TEST DATE	TEST ODOM	TEST FUEL	**Emissions Test Results(g/mi)** PM	NOx	HC	CO
PT-464	BIA	1991	Cummins	L-10	1991	7/3/95	200000	D2	1.48	27.9	1.89	13.1
PT-465	BIA	1991	Cummins	L-10	1991	8/18/94	164006	D2	2.29	20	3.2	12.5
PT-465	BIA	1991	Cummins	L-10	1991	7/15/95	220000	D2	1.83	26.3	2.63	9.5
PT-466	BIA	1991	Cummins	L-10	1991	8/19/94	107943	D2	1.91	21.9	2.6	11.7
PT-466	BIA	1991	Cummins	L-10	1991	7/17/95	210000	D2	1.44	27.2	2.12	9.2
PT-467	BIA	1991	Cummins	L-10	1991	8/20/94	155815	D2	1.68	23.8	2.3	13
PT-467	BIA	1991	Cummins	L-10	1991	7/18/95	220000	D2	1.32	29.3	1.89	12.8
PT-468	BIA	1991	Cummins	L-10	1991	8/22/94	144051	D2	2.05	19.5	2.5	11.1
PT-468	BIA	1991	Cummins	L-10	1991	7/20/95	200000	D2	1.67	25.1	2.17	8.1
							COUNT		9	9	9	9
							AVERAGE		1.74	24.56	2.37	11.22
							MAX		2.29	29.3	3.2	13.1
							MIN		1.32	19.5	1.89	8.1