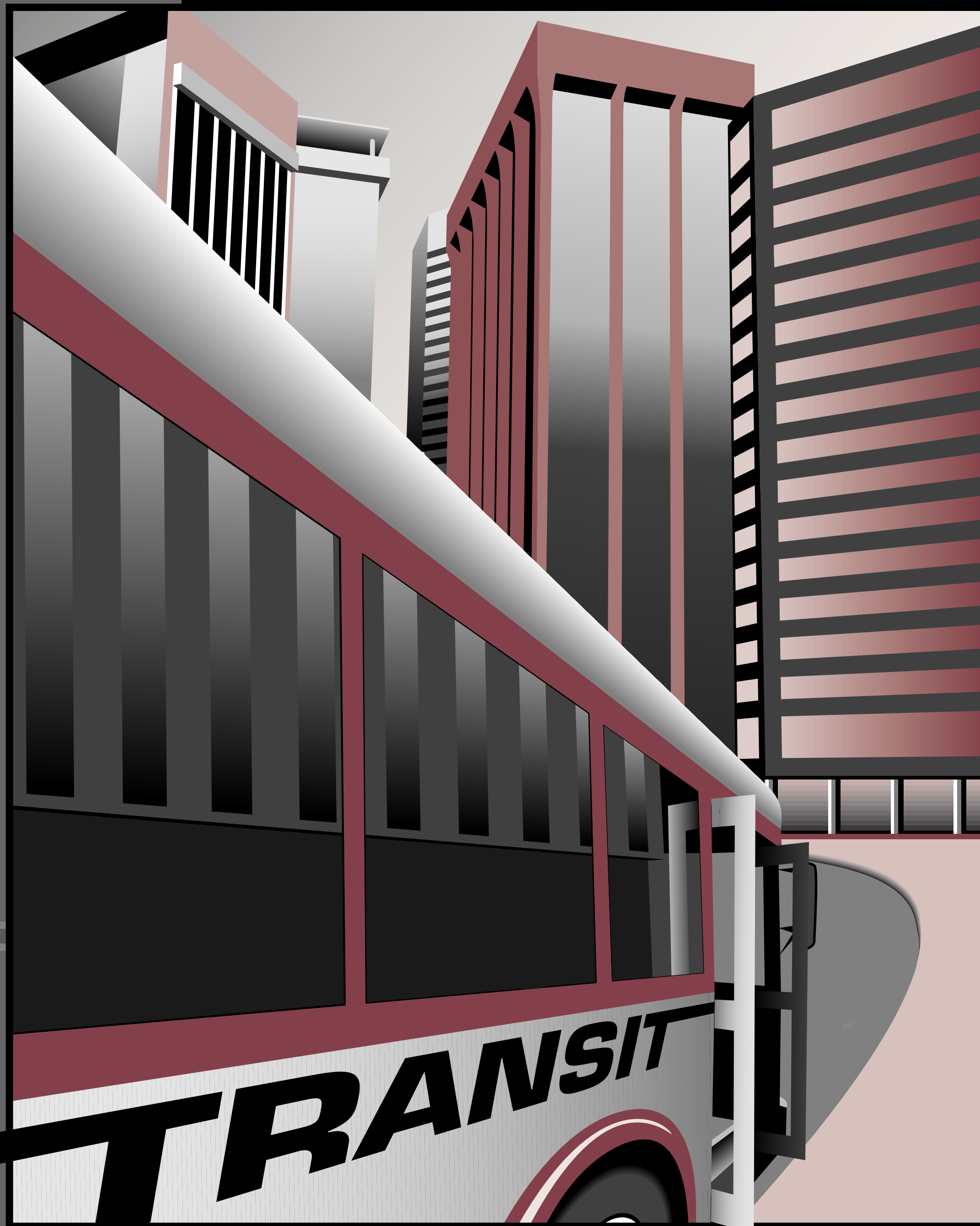
Alternative Fuel Transit Buses



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Final Results from the National Renewable Energy Laboratory Vehicle Evaluation Program

Alternative Fuel Transit Buses

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by

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The authors wish to thank all the transit agencies that participated in this program.

World Wide Web: http://www.afdc.doe.gov
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Executive Summary

Transit buses represent one of the best applications for alternative fuels, which have already made significant inroads into the transit bus market. As of January 1996, approximately 4% of the more than 50,000 transit buses in the United States surveyed by the American Public Transit Association ran on an alternative fuel such as ethanol, methanol, compressed natural gas (CNG), or liquefied petroleum gas (LPG). Even more significant, 1 out of every 5 new buses on order is an alternative fuel bus. These numbers do not include electric trolley buses.

The National Renewable Energy Laboratory, with funding from the U.S. Department of Energy, initiated a program to study the performance, reliability, costs, and emissions of alternative fuel transit buses versus conventional diesel buses (controls). The program involved collecting detailed operational and maintenance data from more than 100 buses at eight transit agencies across the country. A program goal was to have 10 test buses of each alternative fuel type, with 10 controls, split between two agencies, operating for 18 months. West Virginia University used its transportable chassis dynamometer to measure the emissions from the buses using a Central Business District (CBD) driving cycle.

Transit properties involved in the program, and their alternative fuel buses, were:

- Houston Metro, in Houston, Texas (10 liquefied natural gas [LNG] buses with Detroit Diesel 6V92 pilot ignition natural gas engines)
- Tri-Met, in Portland, Oregon (eight LNG buses with Cummins L10 dedicated spark-ignited engines)
- Metro Dade, in Miami, Florida (five methanol buses with Detroit Diesel 6V92 engines and five CNG buses with Cummins L10 engines)
- Triboro in New York, New York (five methanol buses with Detroit Diesel 6V92 engines, and five CNG buses with Cummins L10 engines)
- Pierce Transit in Tacoma, Washington (10 CNG buses with Cummins L10 engines)
- Metropolitan Transit Commission, Minneapolis/St. Paul, Minnesota (five ethanol buses with Detroit Diesel 6V92 engines)
- Greater Peoria Transit in Peoria, Illinois (five ethanol buses with Detroit Diesel 6V92 engines)
- Bi-State in St. Louis, Missouri (five 20% biodiesel blend buses with Detroit Diesel 6V92 engines)

The alternative fuel engines in this program have only a few years of product development, versus decades for the diesel engine; however, the results show they are competing very well with diesels in many areas:

Vehicle Reliability. Road calls experienced per 1,000 miles of operation constitute one measure of a bus's reliability. A road call is defined as any event that prevents a driver from completing his or her route and results in a call for a backup bus. The program studied total road calls and those attributable to engine/fuel system-related components only—the areas most likely to be affected by alternative fuel use. The number of engine/fuel system-related road calls for the Tacoma CNG buses is the same as for the diesel buses. Most other sites show some reliability penalty, but in many cases the causes are either relatively minor (the buses running out of fuel because the driver is unfamiliar with the vehicle), or appear solvable (fuel filter plugging because of fuel quality problems at the alcohol sites).

Operating Costs. Operating costs of the buses are largely driven by the fuel cost. Fuel cost differences versus diesel far outweigh any differences in maintenance costs between the alternative fuel and diesel buses. Operating costs are lowest for the CNG buses, which are approximately equal to diesel bus operating costs. Operating costs are the highest for the alcohol and biodiesel buses because of high fuel prices.

Capital Costs. Capital costs consist of the extra cost to purchase an alternative fuel bus, and the extra cost (if any) to modify the facilities to fuel, service, and maintain them. Capital costs are the highest for CNG and LNG buses, and lowest for the alcohol and biodiesel buses—inverse to the operating costs. In the future, alternative fuel engine prices are expected to decrease as volumes increase, although whether they will be equal to or lower than diesel is unclear.

At the present time, no alternative fuel combines a low operating cost with a low up-front capital cost.

Vehicle Emissions. Emissions were measured on a transportable chassis dynamometer using the CBD driving cycle.

Natural gas and alcohol buses were shown to have the potential to significantly lower particulate matter (PM) and oxides of nitrogen (NO_x) emissions. With natural gas, PM emissions were virtually eliminated.

Test results also showed high variability in the emissions results from the alternative fuel vehicles. This probably results from the relative immaturity of the technology and from the different maintenance requirements of the alternative fuel engines. Investigative emissions testing showed substantial reductions in high-emitting vehicles after tune-ups and parts replacements.

Both diesel and alternative fuel technologies have changed substantially since we ran our emission tests. Newer generation CNG engines often feature closed-loop feedback control of air:fuel ratio, which should significantly reduce emissions variability between engines. Newer diesel engines are electronically managed and have lower PM emissions to meet the latest Environmental Protection Agency standards. We plan to test both types of engines in the future.

Looking to the future, newer, significantly more advanced alternative fuel engines than those in this program continue to be introduced, and they promise even better performance.

Introduction

Background

The National Renewable Energy Laboratory (NREL) is a U.S. Department of Energy (DOE) national laboratory; this project was funded by DOE.

One of NREL's missions is to objectively evaluate the performance, emissions, and operating costs of alternative fuel vehicles so fleet managers can make informed decisions when purchasing them. Alternative fuels have made greater inroads into the transit bus market than into any other. Each year, the American Public Transit Association (APTA) surveys its members on their inventory and buying plans. The latest APTA data show that about 4% of the 50,000 transit buses in its survey run on an alternative fuel. Furthermore, 1 in 5 of the new transit buses that members have on order are alternative fuel buses. This program was designed to comprehensively and objectively evaluate the alternative fuels in use in the industry.

In designing a program of this type, our most challenging problem was providing information on the latest products in a short period of time. Once a new product is introduced, we must find a suitable fleet that has ordered the vehicles, along with similar diesel controls. Next, we must collect, analyze, and report on 18 months of data. Because alternative fuel products are being rapidly improved, the information we present is often not on the latest generation of the engine or vehicle. Nevertheless, this information is far superior to none, and often reveals trends that continue to be true even with newer technology.

Some people may wonder why we included data on alcohol engines in this report, as the ethanol and methanol engines had been discontinued from production at the time of this writing. Because this is the only study of its kind, we decided to include the information to present an across-the-board comparison of alternative fuels. We believed that documenting the experience with all the fuels in one report was important. We also recently learned that one transit authority placed an order for the ethanol 6V92 engine, so this engine may again become available. The ethanol information may therefore be more relevant than we anticipated.

This report has data and results that are significantly updated from our previous reports, in which we stated that in some cases (such as with Miami) the diesel buses started the program at a higher mileage (odometer) reading than the alternative fuel buses. The data available to us were therefore not for comparable periods in the buses' life. We have since received back data on all the sites, so comparisons *at each site* are now made between buses with similar mileage accumulation.

Finally, we received valuable feedback—including written comments—on our last report. We appreciate the comments, and wherever possible have incorporated your suggestions.

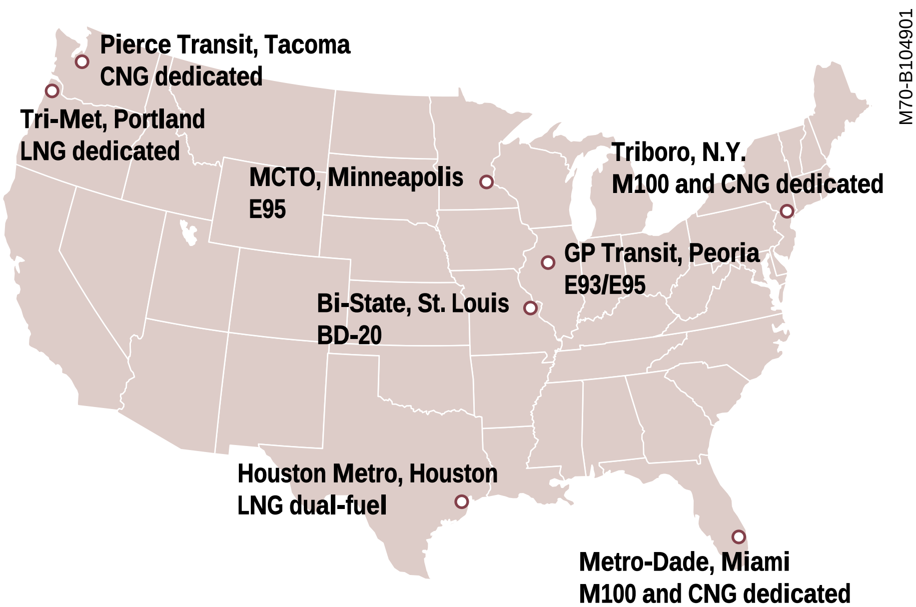

FIGURE 1. Buses were tested in eight metropolitan areas across the country.

Program Objective

The objective of the program was to comprehensively and objectively evaluate the reliability, operating costs, and emissions levels of all alternative fuels currently in use in the transit bus industry. This included compressed natural gas (CNG), liquefied natural gas (LNG), 95% and 93% ethanol (E95 and E93), 100% methanol (M100), and a mixture of 80% diesel and 20% biodiesel (BD-20). Each fuel is briefly described in the sidebar on page 6. A future study will look at liquefied petroleum gas (LPG)-powered buses, which are not yet in production.

Program Design

The program was set up with the following guidelines:

- A program target was to evaluate 10 buses of each alternative fuel with 10 controls split between two sites. This would provide a sufficient sample size to draw conclusions and ensure that we did not "put all our eggs in one basket."
- We attempted to find transit agencies with the latest technology buses.
- Each transit agency had to have diesel control buses similar to the alternative fuel buses.
- Each transit agency had to have excellent maintenance records and be willing to supply detailed data on the vehicles for about 18 months.

Using these criteria, we tested buses in eight metropolitan areas: Houston, Texas; Miami, Florida; Minneapolis, Minnesota; New York, New York; Peoria, Illinois; St. Louis, Missouri; Tacoma, Washington; and Portland, Oregon (see Figure 1).

NREL contracted with Battelle to manage the program at each site, collect the detailed information, analyze the data, and write a report on the conclusions. Battelle performed this function for all sites, except one. The University of Missouri was contracted to perform similar functions for the biodiesel site at St. Louis.

Engines in the program included:

- Cummins L10-240G and L10-260G engines running on CNG
- Cummins L10-240G engines running on LNG
- Detroit Diesel Corporation (DDC) 6V92TA methanol engine
- DDC 6V92TA ethanol engine
- DDC 6V92TA pilot ignition natural gas (PING) dual-fuel engine
- The biodiesel buses use biodiesel fuel in an unaltered DDC 6V92TA diesel engine.

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

Transit Agency	City	Bus	Engines	Engine Model Year Alt. Fuel (AF)/Diesel	AF	AF Buses	Control Buses
Houston Metro	Houston, TX	40-ft Stewart & Stevenson	DDC dual-fuel 6V92TA PING[1]	1992/1992	LNG	10	5
Tri-Met	Portland, OR	40-ft Flxible	Cummins L10-240G	1993/1992	LNG	8	5
Metro-Dade Transit Authority (MDTA)	Miami, FL	40-ft Flxible	Cummins L10-240G	1991/1990	CNG	5	5
			DDC 6V92TA	1992/1990	M100	5	5
Pierce Transit	Tacoma, WA	40-ft BIA	Cummins L10-240G	1992/1991	CNG	5	5
			Cummins L10-260G[2]	1994	CNG	5	—
GP Transit	Peoria, IL	35-ft TMC	DDC 6V92TA	1992/1992	E95/E93[5]	5	3[3]
Metropolitan Council of Transit Operations (MCTO)	Minneapolis/ St. Paul, MN	40-ft Gillig	DDC 6V92TA	1991/1991	E95	5	5
							5[2,3]
Triboro Coach Company (NYCDOT)	New York, NY	40-ft TMC	DDC 6V92TA DDC Series 50[4]	1993/1993	M100	5	5
			Cummins L10-260G[2]	1993	CNG	4	
Bi-State Development Agency	St. Louis, MO	40-ft Flxible	DDC 6V92TA	1988 &1989	BD-20	5	5

Note: BIA = Bus Industries of America (now Orion Bus), TMC = Transportation Manufacturing Company (now NOVABus), DDC = Detroit Diesel Corporation.

[1] 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.

[2] Used for emissions testing only.

[3] Equipped with particulate trap.

[4] 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.

[5] GP Transit switched from E95 to E93 in early 1994 for fuel cost savings.

In a follow-up program being conducted now, we are evaluating the emissions performance of the new Cummins L10-280G or Cummins L10-300G, as well as the latest version of the DDC Series 50G.

A complete list of all sites, technologies evaluated, engine models, and bus models in the program appears in Table 1. For the New York M100 test fleet, the diesel control buses use the new DDC Series 50 engine, not a 6V92 engine. When New York ordered its 6V92 M100 engines, the 6V92 diesel engine was being phased out, so it ordered Series 50 diesel engines instead. We believe that even though the alternative fuel and control engines differed significantly at this site, this was still a valid comparison, because this is the realistic choice any transit agency would have to make.

Photo courtesy of Pierce Transit/PIX 04036

Pierce Transit in Tacoma, Washington, has had success running this bus on compressed natural gas.

Data Collected

The data collected in the program included:

- Records of all fuel and oil additions to the buses
- All maintenance records for the buses (the biodiesel site is an exception—only engine/fuel system-related data were collected because of the age of the bus chassis)
- Records of all road calls that resulted from a breakdown while the bus was in service
- Emissions data. West Virginia University (WVU) staff visited each site and used the university's transportable chassis dynamometer to conduct emissions tests on the buses.
- Capital cost information. A description of the alternative fuel facilities and facility cost was collected from each site. The incremental cost of the alternative fuel buses was also recorded.

A program goal was to collect approximately 18 months of data on each site. Figure 2 shows the total mileage accumulation on the alternative fuel buses at each site. Data collection from all sites is now complete, and the following sections present the data analysis.

During the program, the biodiesel site encountered a problem that led us to exclude most of those data from the detailed analysis. When the site started up, biodiesel and diesel were splash blended in the on-site tank and agitated with a pump. After a few days, numerous problems occurred with clogged filters because contaminants were stirred up from the bottom of the tank. The agitation was stopped and the program continued. Later testing of fuel samples revealed that the biodiesel was not blending with the diesel during splash blending, but was forming a layer on the bottom that would cause the buses to run on blends other than the target blend of BD-20. Additional problems were uncovered: the fuel supplier was mixing one part biodiesel to five parts diesel (a 17% blend) instead of one part to four. The problems were rectified in October

The Alternative Fuels Being Tested

Methanol. An alcohol produced primarily from natural gas. Because it can also be derived from biomass or coal, the domestic resource base for methanol is vast. The methanol buses in this program run on 100% methanol.

Ethanol. An alcohol derived from biomass (corn, sugar cane, grasses, trees, and agricultural waste). The ethanol used in the test buses was E93 (93% ethanol, 5% methanol, and 2% kerosene) or E95 (95% ethanol and 5% unleaded gasoline).

Biodiesel. Can be produced from any plant- or animal-derived oil product. The biodiesel blend used in the test buses was 20% biodiesel (from soybeans) and 80% diesel fuel.

Natural Gas. Composed primarily of methane. It can be stored on the vehicle as either a compressed gas or a cryogenic liquid. The program is collecting data on vehicles that use both types of storage.

1995 and the program continued. Unfortunately, these problems prevented us from having enough data to conduct a detailed maintenance and reliability analysis. We have therefore included only that information we believe is reliable from that site. WVU reran the emissions tests after the problem was corrected, and the results are discussed in the emissions section. Also not to be overlooked is the lesson that splash blending biodiesel blends with diesel fuel is not effective. The fuel must be properly blended, preferably before delivery.

Photo courtesy of West Virginia University/PIX 04112

West Virginia University is able to transport this chassis dynamometer from site to site.

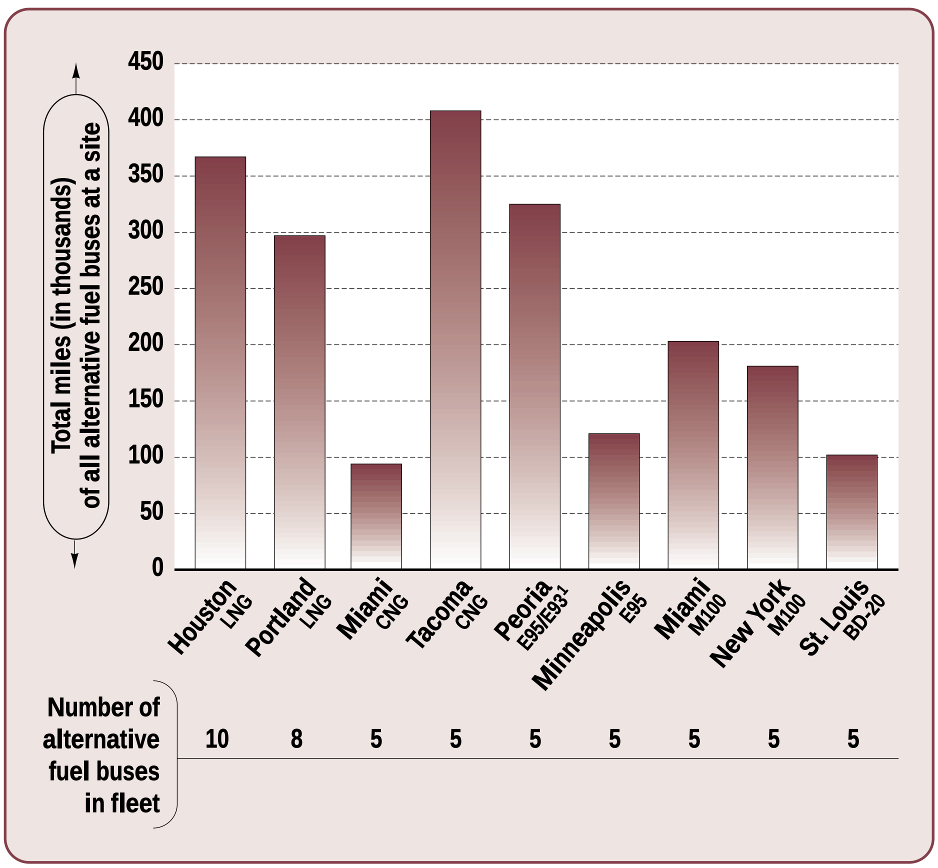

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FIGURE 2. Mileage accumulation on the alternative fuel buses by site

[1] 206,000 miles accumulated on E95, 119,000 miles on E93

Reliability

One measure of the reliability of a bus is the average number of road calls. When the driver cannot complete his or her route and calls for a replacement bus, a road call (which encompasses events from engine failure to running out of fuel) is recorded. For analysis, we divided these calls into two categories: (1) all road calls, including those caused by engine shutdowns, door failures, wheelchair lift failures or any other problem; and (2) calls that involve only the engine/fuel system-related components (specifically the engine, fuel system, electrical, ignition, engine cooling system, and exhaust systems). These are the systems most likely to show differences caused by the alternative fuel. We included "out of fuel" road calls in this group (even though these may not be caused by any mechanical or other problem with the alternative fuel system) because we believe this is a real issue being experienced as a result of alternative fuel use.

Figure 3 shows the road calls per 1,000 miles for the buses in the test program, displayed according to the two categories above. Below the chart is a schematic that shows the total mileage accumulation on the alternative fuel buses at that site. This helps provide a "weighting factor" for weighting the relative strength of the data from a site based on the number of miles accumulated.

Liquefied Natural Gas

Houston Pilot Ignition Natural Gas Dual-Fuel Engine

This figure indicates that the dual-fuel buses in Houston, which run on LNG and diesel, experienced considerably more road calls than the diesel controls. Comparing only road calls related to the engine/fuel system, there are about .39 road calls per 1,000 miles for the LNG buses, versus only .06 for the diesel, a ratio of greater than 6:1. The high rates are due mainly to either the buses running out of fuel (59 out of 210 calls), or the monitoring system detecting a fuel leak and shutting down the bus (24 calls). The dual-fuel buses have a very small diesel tank. If a fuel problem develops with the LNG system, the dual-fuel engines are designed to run on diesel as a backup. In this case, the bus would run out of diesel in a short time—the diesel fuel tank alone is not adequate to run the bus independently for long. The dual-fuel buses experienced nearly 15 times the rate of road calls for "out of fuel" as did the diesel controls. This engine is no longer in production, and to determine whether other sites using LNG were having similar problems, we added Portland, Oregon, as a site. Portland is running dedicated Cummins L10-240G engines in its LNG buses.

Portland Dedicated Spark-Ignited Engine

Portland is experiencing more road calls with its LNG buses than with its diesel buses, but the problems

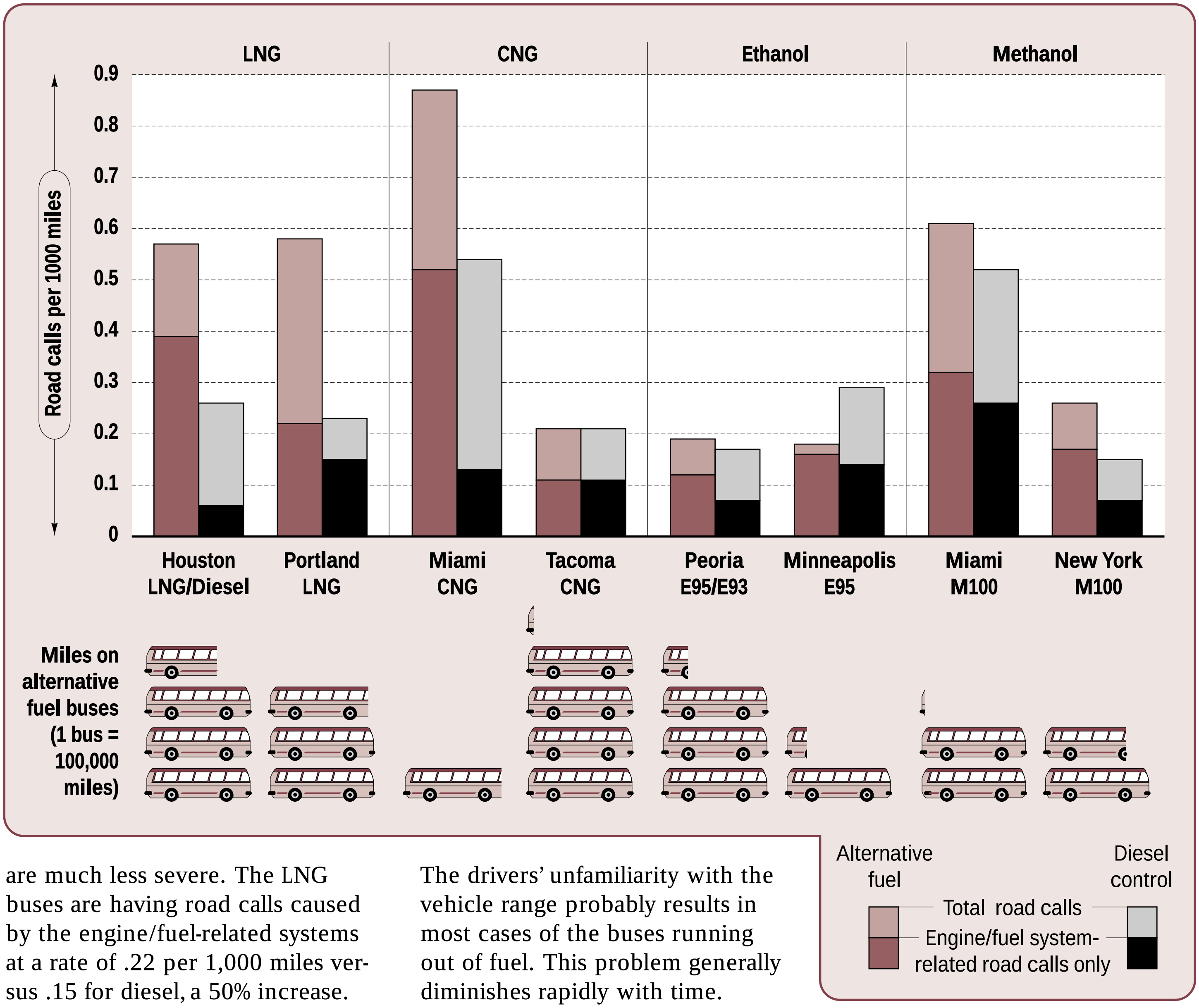

FIGURE 3. Number of road calls by site and category

are much less severe. The LNG buses are having road calls caused by the engine/fuel-related systems at a rate of .22 per 1,000 miles versus .15 for diesel, a 50% increase. Most alternative fuel-related road calls on the LNG buses are caused by the fuel leak detection system and/or fuel leaks (16 of 172 total calls), or the buses running out of fuel (6 out of 172 total calls). If the fuel leak detection system senses a leak, the bus is automatically shut down. However, a fuel leak was actually found in only 4 of the 16 cases. The reliability of the fuel sensors has been a problem, and Portland has reported much better performance with a new sensor design recently installed.

The drivers' unfamiliarity with the vehicle range probably results in most cases of the buses running out of fuel. This problem generally diminishes rapidly with time.

Looking at the bigger picture of all road calls at Portland, the LNG buses experienced even more than the diesel buses. The largest category of road calls for the LNG buses, however, related to body systems, (including the doors not working), rather than the alternative fuel system. This shows the importance of looking at the alternative fuel system in perspective of the entire vehicle. Overall the engine/fuel system reliability appears much better than that of Houston's buses, and not out of line with other systems on the buses.

Compressed Natural Gas

Buses that ran on CNG in Miami had about four times as many alternative fuel system-related road calls per 1,000 miles as their diesel counterparts. Most were engine or fuel system-related, including 9 out of 81 for running out of fuel. As shown in Figure 3, these buses have very low mileage because there is no convenient fuel station on the premises. In contrast, the buses at Tacoma have more than four times the mileage accumulation as the Miami buses. The Tacoma engines are also one model year newer. Their road call rates are identical for CNG and diesel. Because of the much greater mileage on the Tacoma buses, and the later model year engine, we have placed greater weight on these data. Overall, we can conclude that CNG buses are potentially as reliable as diesels. It is important to note that the manufacturer is now selling newer, more advanced CNG engines than the ones used at Miami or Tacoma.

Alcohol

All the alcohol sites had similar experience with road calls. At every site, fuel-quality problems were a significant issue, and account for a major portion of the difference observed between the alcohol and diesel control buses. Fuel filter plugging on the alcohol buses resulted in 5 of 61 total road calls in Peoria, 4 of 21 in Minneapolis, 18 of 123 in Miami, and 4 of 47 in New York. In addition, a few of these sites experienced many engine-related road calls, most of which were for lack of power and engine stalling. We believe these two problems are in many cases directly related to filter plugging, but were not recorded as such. These problems appear related to lingering material compatibility problems with the alcohol fuels that are probably occurring in the fuel delivery system, not on the buses.

Reliability Summary

In summary, except for Tacoma's CNG buses, all sites showed road call rates for the engine/fuel-related systems on the alternative fuel buses to be higher than on the diesel buses by varying degrees. Most of the problems are not insurmountable and are expected with relatively new technology. They can be divided into a few general categories: running out of fuel—a fairly minor issue, and one that seems to be largely concentrated in the first few months of operation; fuel leaks and leak detection shutdowns on the LNG buses—a problem that appears correctable with new improved leak detection sensors; and fuel filter plugging on the alcohol buses—a problem probably related more to fuel delivery to the buses than to what is happening on the bus.

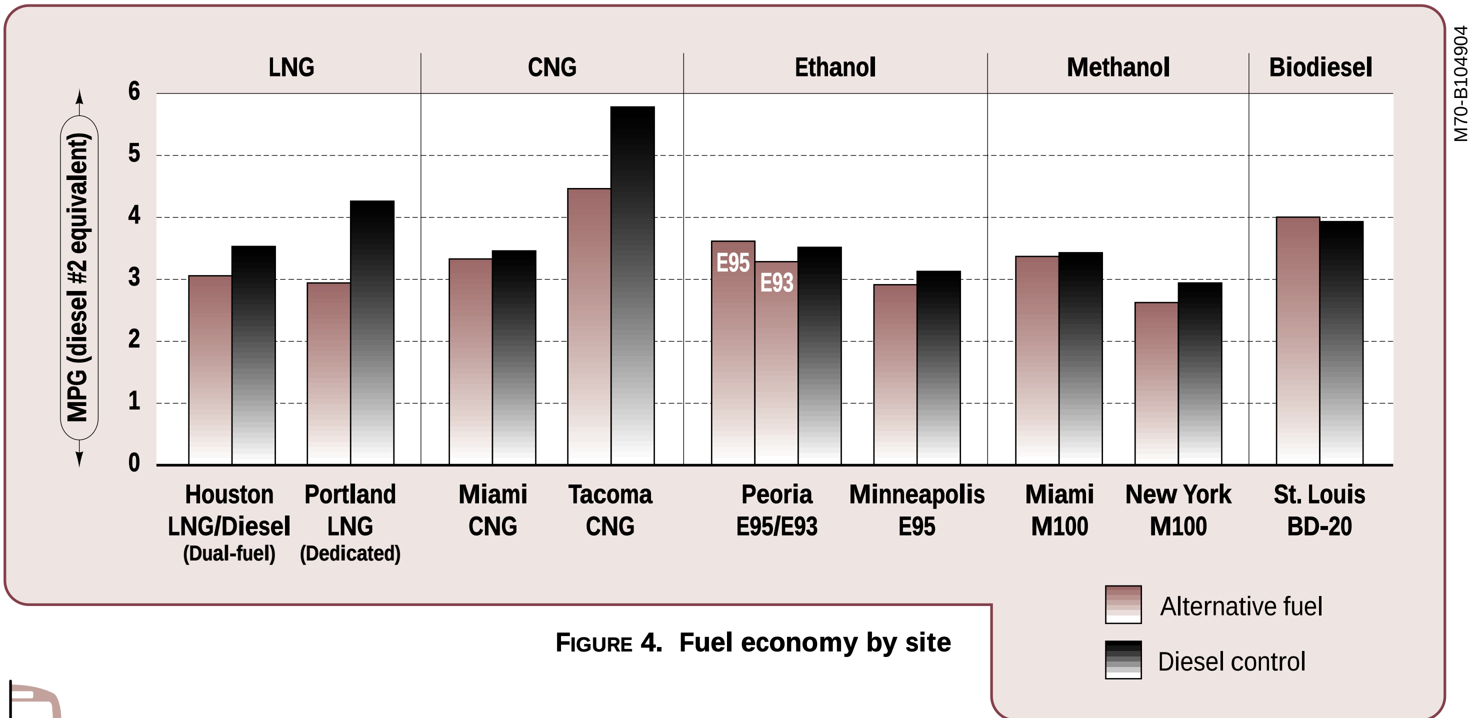

Figure 4. Fuel economy by site

Fuel Economy

Fuel economy and fuel costs are very important to transit agencies because they represent a significant part of the operating cost of a transit bus. Figure 4 shows the representative fuel economy for each site expressed as miles per diesel equivalent gallon, the quantity of alternative fuel that has the same energy content as one gallon of diesel fuel. The representative fuel economy is not always based on the total fuel consumed during the total data collection period. We selected a period of operation when we had good data and could accurately calculate the fuel economy. In the case of the Houston dual-fuel buses, we used a period of operation when the alternative fuel buses ran consistently on LNG (as opposed to running in their backup mode of diesel only). For comparison purposes, we have expressed all fuel economy in terms of #2 diesel equivalent gallons.

Liquefied Natural Gas—Houston Dual-Fuel Buses

The buses at Houston use PING engines, which operate on a compression-ignition cycle that uses diesel as the pilot ignition source to ignite the natural gas. The average fuel economy for these buses was calculated by adding the amount of LNG (in diesel equivalent gallons) and diesel burned in the buses over time, and dividing that sum by the total miles logged. The average fuel economy for the LNG buses (3.1 miles per diesel equivalent gallon) was approximately 13% less than that of their diesel counterparts. A small part of this reduction is due to the approximately 860 pounds of extra weight of the LNG/diesel dual-fuel buses, but the largest part is most likely attributable to the engine design, engine operating problems (see Reliability section), differences in driving cycles, or LNG measurement inaccuracies.

Liquefied Natural Gas and Compressed Natural Gas—Dedicated Spark-Ignited Engines

The natural gas engines that operated in Portland, Miami, and Tacoma were spark-ignited throttled engines; the diesel engines were unthrottled compression-ignition engines. When a diesel compression-ignition engine is redesigned into a spark-ignition engine to run on natural gas (the case with all natural gas engines in the program), there is an inherent loss of efficiency because of pumping losses. Pumping losses represent the amount of energy required for the engine to draw in air during the intake cycle. An unthrottled diesel engine has minimal pumping losses, whereas a spark-ignited engine with a throttle has significant pumping losses. In addition, natural gas engines have a lower compression ratio than their diesel counterparts (10.5:1 for natural gas engines versus 16.3:1 for diesel engines), which also tends to lower efficiency.

An added disadvantage for CNG buses is their weight—as much as 3,900 pounds more than their diesel counterparts. This weight penalty is largely due to the weight of the CNG tanks, and increases the curb weight by about 15% (the diesel control buses have a curb weight of approximately 27,000 pounds). Newer design all-composite tanks reduce this weight penalty significantly, but these tanks were not used on the buses in the program. These factors led to the expectation that energy efficiency might be significantly reduced.

At the two CNG sites, the fuel economy of CNG buses was reduced by 3% and 23% compared to diesel buses. At the Portland LNG site, the fuel economy was 30% lower on LNG buses than on diesel, greater than expected for this type of engine. This may be due to greater idling time for LNG buses on the weekends, because Portland personnel believed that this was necessary to control pressure buildup and venting of the tanks.

Alcohol

The alcohol buses also have weight penalties—1,000 to 1,500 pounds, depending on the fuel tank capacity. Also, the alcohol buses at the Miami site have an additional weight penalty of 1,200 pounds, which is attributed to options and specifications unrelated to the alcohol fuel engine. This extra weight was expected to reduce the fuel economy of the alcohol buses.

The alcohol buses also have very high compression ratios (more than 20:1), which were expected to lower fuel economy because of higher friction losses such as piston side loading. The results to date, however, indicate that the alcohol buses at all sites are performing very well, delivering fuel economy comparable to that of the diesels on an equivalent energy basis. (Two notes: first, the diesel control buses at Peoria are equipped with particulate traps, which lower fuel economy slightly; and second, the diesel control buses at New York are Series 50 4-stroke diesel engines, not 6V92s.)

Biodiesel

On a diesel #2 equivalent gallon basis, biodiesel buses exhibited approximately the same fuel economy as the diesel control buses.

Fuel Economy Summary

In summary, the fuel economy results are in line with expectations from the various engine technologies, with the possible exception of the LNG dual-fuel engine.

Cost

The cost of operating alternative fuel buses versus the diesel controls can be broken down into operating and capital costs. Capital costs consist of the additional cost of the alternative fuel bus and the cost of modifying the facilities for alternative fuel use.

Operating Costs

Figure 5 shows the breakdown of operating costs for the transit agencies in the program. The costs likely to be affected by the use of an alternative fuel include fuel and lubricant costs and vehicle maintenance costs. Together these comprise one-fourth of the total operating costs.

The vehicle maintenance costs (shown as 21% of the total) include the costs not only to perform actual repairs and maintenance on the buses, but also to staff the parts department, paint shop, body shop, vehicle cleaning facility, and fueling facility. In this study we recorded only the maintenance costs directly associated with the bus—repairs and maintenance on the buses, rebuild costs, and inspections, but not supporting activities such as costs associated with running the tire, paint, body, or parts shops. Finally, to calculate maintenance costs we used a standard mechanic labor rate of $25/hour for every site, and multiplied this by the hours spent on each job. This represents a typical mechanic's wage plus overhead costs of approximately 50%.

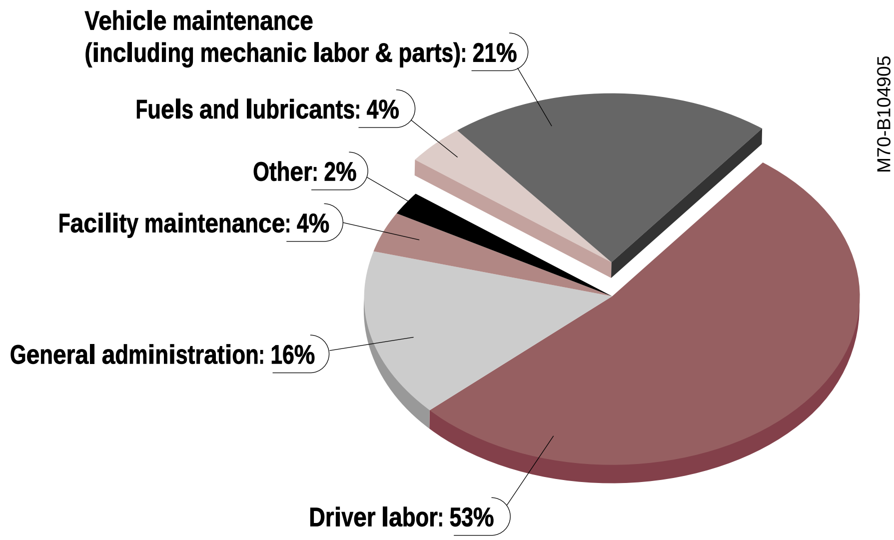

FIGURE 5. Operating costs for the transit agencies by category

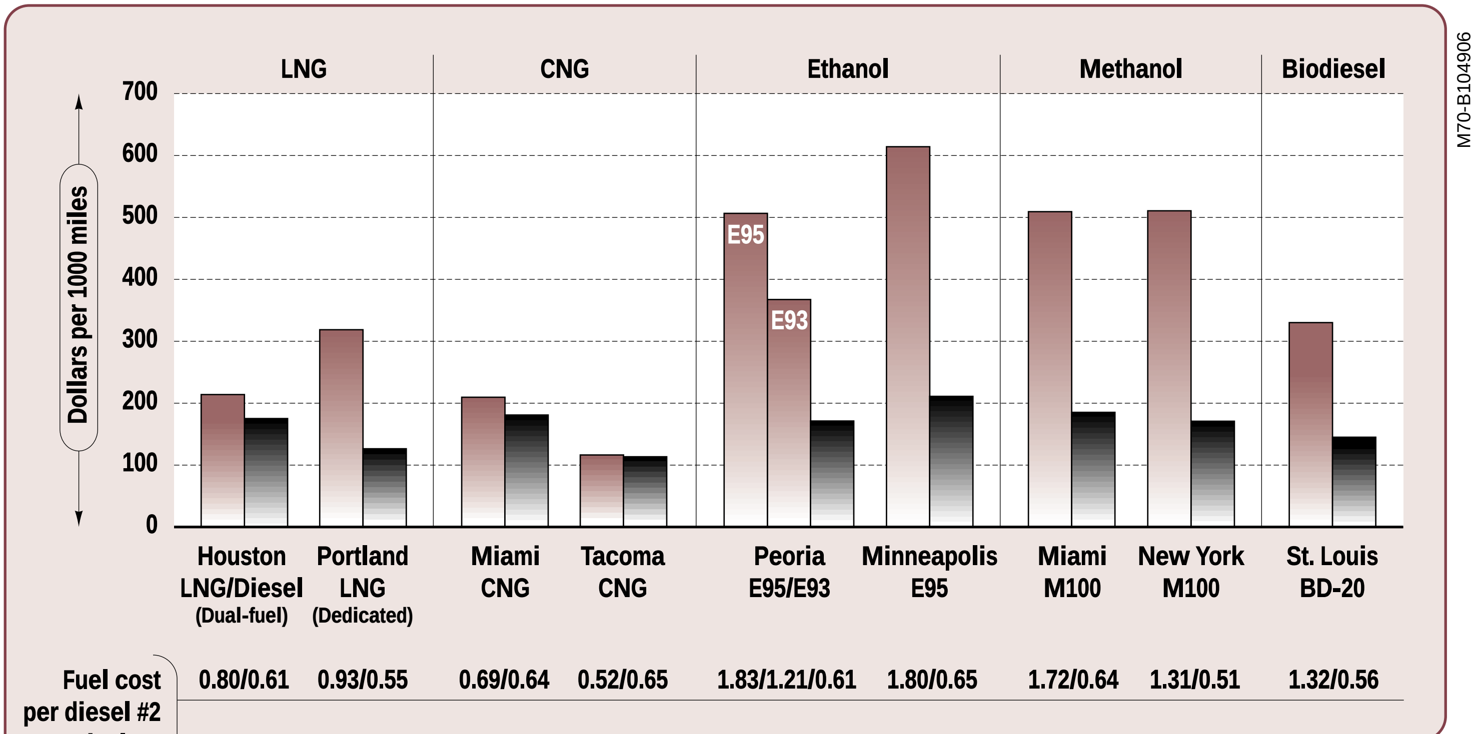

FIGURE 6. Fuel costs per 1,000 miles of operation

Fuel Costs

Fuel costs per 1,000 miles of operation for each transit agency are shown in Figure 6. These costs were calculated based on the representative fuel economy of the buses at the site and the prices paid for the fuel during the data collection period.

At the bottom of the figure, the fuel costs used to make these calculations are shown. In general, the prices of alternative fuels have been more variable than those of diesel fuel, both regionally and over time. For example, CNG prices differ significantly from region to region and methanol prices nationwide have been very volatile. The LNG prices at Portland are relatively high. LNG prices in other locations across the country are lower, in some cases much lower.

What Are the Fuel Prices in Your Area?

Fuel prices have a dramatic effect on operating costs. The fuel prices used to calculate operating costs in this report were the prices actually paid by the agencies while we were collecting data. For example, Pierce Transit was paying $0.52 per diesel #2 equivalent gallon for CNG and $0.65 for diesel. Since that time, the prices have changed significantly. Pierce Transit now pays $0.29 per gallon for CNG (because the agency buys it directly from the wholesaler as a commodity) and $0.76 for diesel, changing the economics considerably in favor of CNG. You might want to check on the fuel prices in your area to see what the current economics would be for your fleet.

Maintenance Costs

Maintenance costs were tracked on all the buses. Each transit agency provided copies of all work orders and lists of parts replaced. The work performed and parts replaced were coded by type of work (scheduled maintenance, unscheduled maintenance, road calls, and configuration changes to the buses), as well as by vehicle subsystem.

To show the effects of the alternative fuel system on costs, Figure 7 shows the maintenance costs for the engine/fuel-related systems only,

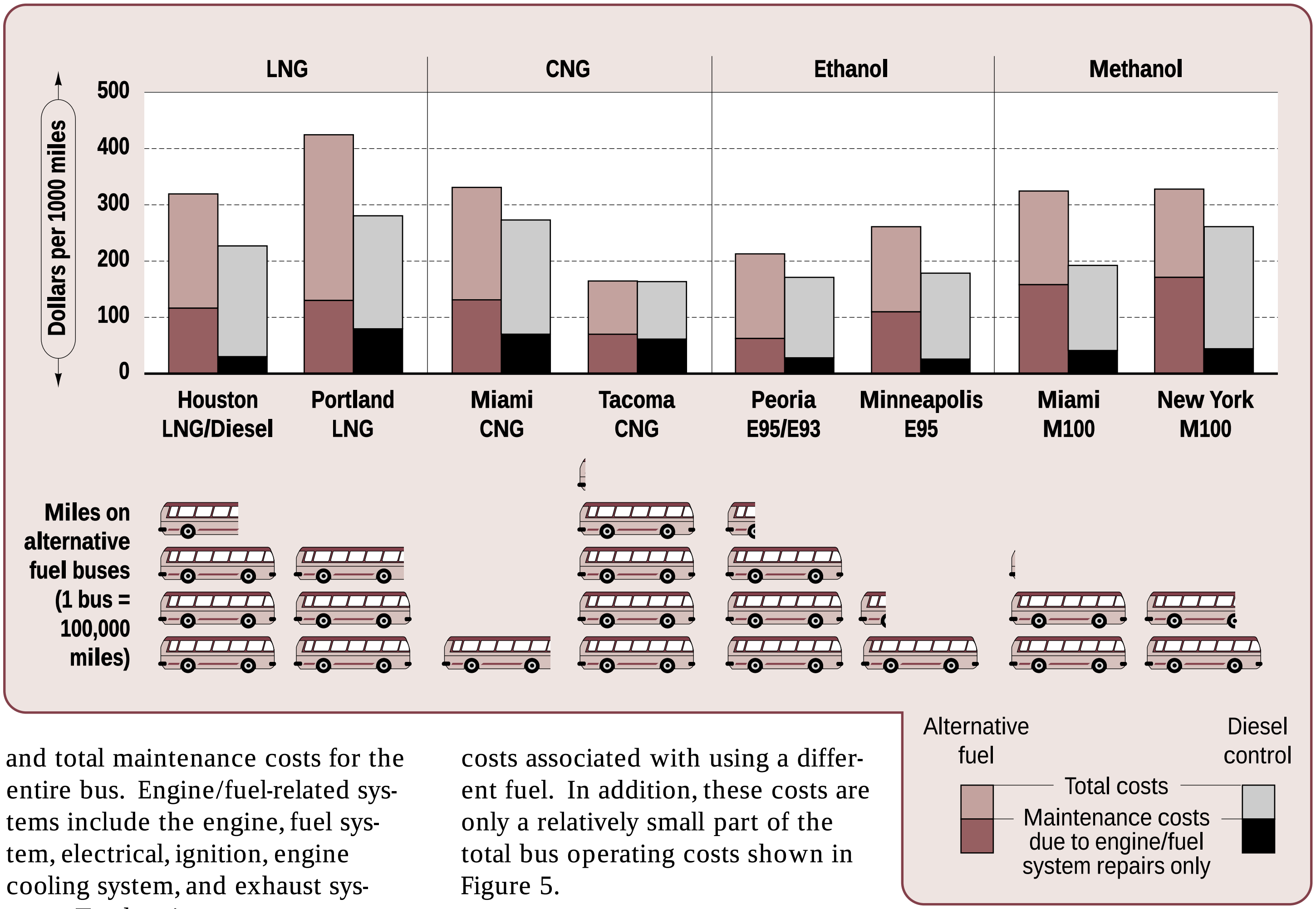

FIGURE 7. Maintenance costs for the buses in the program

and total maintenance costs for the entire bus. Engine/fuel-related systems include the engine, fuel system, electrical, ignition, engine cooling system, and exhaust systems. Total maintenance costs include work on all vehicle systems, including, for example, the engine and fuel system, body hardware, air conditioning and heater systems, suspension, and door systems.

We must keep the costs related to the engine/fuel system on the alternative fuel buses in perspective. For example, in some cases, costs related to these systems on the alternative fuel buses are significantly higher than on the diesel buses. However, these increases often are not driving factors when you consider the total bus maintenance costs. In other words, repairs to systems totally unrelated to alternative fuel use, such as the air conditioning system, often outweigh costs associated with using a different fuel. In addition, these costs are only a relatively small part of the total bus operating costs shown in Figure 5.

The maintenance cost data presented do not include warranty work performed on the buses because the agencies do not bear the cost of this work (except for the in-house labor costs for warranty repairs—these are generally paid by the transit agencies and are included in the maintenance costs presented in this report). Maintenance costs for the biodiesel buses are not shown because of insufficient data.

Comparisons of maintenance data between agencies should not be made because each agency has a different system for maintaining its buses. Alternative fuel buses should only be compared with diesel control buses at the same site.

Liquefied Natural Gas—Houston DDC Dual-Fuel Engines

Maintenance costs for the engine/fuel-related systems on the LNG buses have been more than three times those of the diesel buses. Significant problems occurred with the engine gas injectors. It is believed that contaminants in the fuel, possibly in combination with other problems, caused the injectors to stick open. The engine manufacturer has worked on the problem under warranty, but internal labor costs at Houston Metro were still significant. Fuel system leaks and "false alarms" by the leak detection system have also been a source of cost in the LNG buses.

Liquefied Natural Gas—Portland Dedicated Engines

Maintenance costs for the engine/fuel-related systems on the LNG buses were approximately 50% higher than those for the diesel control buses. Higher costs are largely attributable to fuel leaks (or apparent fuel leaks) that caused the sensors to signal a leak, and to replacing cryogenic pumps and related hardware. In all, 11 cryogenic pumps and 8 hydraulic driver pumps were replaced on the buses during the program. The cryogenic pumps are very expensive, costing about $1,500 for a remanufactured one, or $6,000 for a new one. The parts cost for these pumps was covered under warranty, but a significant amount of the labor to diagnose and replace them was not. Other LNG designs that do not require a fuel pump are now on the market. Other things being equal, these designs should be more reliable.

Compressed Natural Gas

In Tacoma, the engine-related maintenance costs for CNG buses were within 16% of the diesel controls. No major problems or trouble areas were encountered on the CNG buses. Most of the cost difference is attributable to the extra tune-ups required for the spark-ignited CNG engines—spark plugs, plug wires, and other tune-up costs.

In Miami, the engine-related maintenance cost for buses running on CNG was about double that for diesel buses. The Miami buses, however, were only used in "tripper" service and have accumulated only 95,000 miles on CNG, versus more than 400,000 miles for the Tacoma buses that were used in full service against their diesel counterparts. The engines are also one model year newer at Tacoma. We therefore place significantly more weight on the Tacoma data.

Ethanol

The ethanol-powered buses in Peoria had engine/fuel system-related maintenance costs about 75% higher than those of the diesel buses. The cost of maintaining the fuel system contributed most to the overall maintenance cost, and was due primarily to the cost of ethanol fuel filters. The primary and secondary fuel filters together cost nearly $105 for ethanol compared to about $6 for diesel. The higher cost, coupled with a higher replacement rate—caused by material incompatibility problems in the fuel station—results in significantly higher overall fuel system costs. The material incompatibility has since been rectified. Electrical system maintenance costs were also higher for the ethanol buses because of the

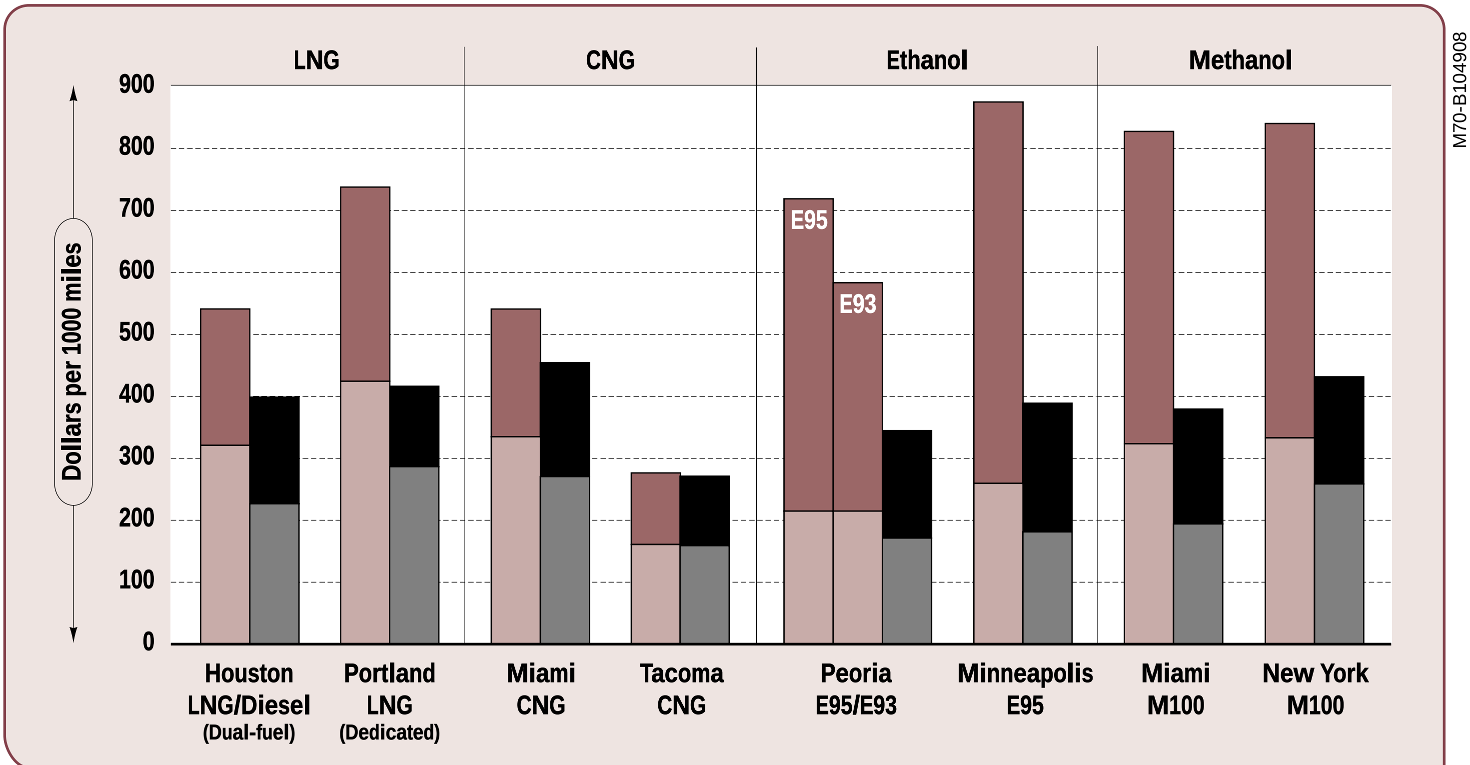

FIGURE 8. Total fuel and maintenance costs per mile traveled

higher replacement rate of starters, batteries, and glow plugs.

Minneapolis experienced similar issues, with engine/fuel system-related costs almost four times higher than those for the diesel buses.

Methanol

Miami and New York methanol buses experienced issues similar to the ethanol buses. At both Miami and New York, engine/fuel system-related costs were almost four times as high on the methanol buses as on the diesel control buses. The largest cost increases occurred in the fuel system and electrical area, with fuel filter and electrical problems similar to the ethanol buses.

Biodiesel

As a result of the problems with the inadequate mixing of the biodiesel and diesel discussed earlier, we decided there were insufficient data after the fuel "clean point" (when we knew the fuel had been properly mixed) to analyze maintenance costs. At least one issue did arise that is worth mentioning. Some of the older buses had elastomer materials in the fuel pumps (a seal around the shaft) that were incompatible with the biodiesel blend. Later in the program these were changed to a synthetic material (Viton®) that is compatible with biodiesel. Newer fuel pumps sold by the manufacturer come equipped with the synthetic seal.

Cost per Mile Traveled

Figure 8 shows the total fuel and maintenance costs per mile traveled. In all cases the oil cost was insignificant compared to the fuel and maintenance costs. The fuel cost per mile was calculated using the average in-use fuel economy and the actual fuel cost paid by the transit agencies. The fuel and maintenance cost per mile for test buses running on CNG has been about the same as those for buses running on diesel fuel. However, the analogous costs for all buses that use alcohol fuel have been up to twice as high as the costs for buses using diesel. The costs for LNG buses have been 35% to 80% higher than their diesel counterparts.

This figure shows clearly that maintenance costs are the smaller part of the cost equation, and that fuel costs are the determining factor for costs directly related to operating the bus (excluding driver labor costs).

Capital Costs

Adding alternative fuel buses to a fleet requires not only the acquisition of alternative fuel buses, but in most cases also requires changes in the refueling, maintenance, and storage facilities at the site.

Table 2. Incremental Capital Costs of 40-Foot Buses by Fuel Type (1994 $).
(The base price for a diesel bus is $215,000.)

Fuel Type	Incremental Cost
Diesel	Base
LNG	$55,000
CNG	$50,000
Ethanol	$20,000
Methanol	$20,000
Biodiesel	$0
Propane	$40,000

Source: Battelle

Additional Bus Acquisition Costs

At this time, buses that run on alternative fuels are more expensive to purchase than those that run on diesel. Higher engine costs, driven by low production volumes, add about $15,000 to $30,000 to the price of the bus. As volumes increase, the cost of alternative fuel engines should approach that of their diesel counterparts. Some knowledgeable people believe that they will be equal to diesel in the not-too-distant future.

Biodiesel buses are the exception. Because the buses that ran on BD-20 in this program use conventional diesel engines, there was no additional acquisition cost. (However, biodiesel has not yet been approved by most engine manufacturers as a diesel substitute. Because the use of biodiesel may affect engine warranty claims, a transit agency should check with the engine manufacturer before using the fuel.)

The fuel tanks of alternative fuel buses are also generally more expensive than diesel fuel tanks. These additional costs can run from $5,000 for a bus that operates on E95 to about $20,000 for one that operates on CNG. Again, fuel tanks represent no additional expense for buses running on biodiesel. Table 2 presents estimated incremental costs (over and above a diesel-fueled bus) for new alternative fuel 40-foot transit buses. The incremental costs for an LPG-fueled bus have been included because we will study LPG buses as they become available. These prices are only for comparison purposes; actual bus prices will vary with each transit property because of variations in

Table 3. Maintenance and Storage Facility Modifications for Alternative Fuel Transit Bus Fleets

Fuel	Ventilation	Electrical	Heating	Other	Comments
Natural gas (CNG and LNG)	At ceiling highest points	No overhead sparking contacts	No open flame heaters overhead	—	Requires sensors for combustible fuel detection
Ethanol	No change[1]	Unclassified electrical 18 inches above finished floor, no change[1]	No change[1]	Requires cistern for drain to trap fuel leakage	No ignition sources in floor area (18 inches and lower)
Methanol	No change	Unclassified electrical 18 inches above finished floor, no change[1]	No change[1]	Requires cistern for drain to trap fuel leakage	No ignition sources in floor area (18 inches and lower)
Biodiesel blend	No change	No change	No change	—	—
Propane (LPG)	Forced ventilation within 18 inches of floor	Unclassified electrical 18 inches above finished floor, no change[1]	No change[1]	—	No ignition sources in floor area (18 inches and lower). See also Note below.

[1] If facility is certified for gasoline fuel.

Source: Battelle

Note: Additional considerations for propane facilities: Propane fuel tanks should never be overfilled, because thermal expansion of the fuel can actuate the tank relief valve. However, both facility codes and design practices often make some allowance for this contingency. Thus, the installation of propane gas detection systems in areas where propane-fueled vehicles are parked or maintained may be required by local authorities or considered to be good practice by facility design engineers. Increased ventilation to handle possible propane releases may also be included in the facility design. Often, the operation of such increased ventilation is tied to the gas detection system.

vehicle specifications and the size of the order.

We obtained these cost estimates from transit agency bus bids and in conversations with bus manufacturers. They reflect market prices after a few years of alternative fuel bus production, with relatively low production volumes. As volumes increase, prices should decrease.

Facilities Costs

Transit buses are stored and refueled centrally in facilities owned and operated by transit agencies. As a result, the capital and operating costs for any changes made to a facility to accommodate alternative fuel buses are important to consider when calculating the overall cost of operating with alternative fuels.

The capital and operating costs for new facilities or modifying facilities vary considerably, even for one type of alternative fuel. Necessary changes can include installing new refueling equipment or installing monitoring and ventilation equipment in maintenance and storage facilities.

Table 3 lists the typical modifications needed for transit bus maintenance and storage facilities for each type of alternative fuel. For alcohol fuels and propane, ventilation and electrical designs for gasoline facilities are often acceptable to the fire marshal or other local officials. However, both CNG and LNG require modifications to bus maintenance facilities and indoor storage areas. In all cases, you should

Table 4. Refueling Facilities for a Fleet of 80 to 160 Alternative Fuel Buses

Alternative Fuel	Inventory Storage Options	Range of Incremental Capital Cost	Operating Cost	Comments
Diesel[1] (Baseline)	Underground tank	Baseline	Low	Tank insurance would be needed.[2]
LNG	Above-ground tank	$750,000 to $900,000	Low	
CNG (fast-fill)	Small high pressure accumulator tank & buffer	$750,000 to $1,500,000	Low to Medium	Compressors would require noise suppression.
CNG (slow-fill)	No storage needed	$600,000 to $900,000	Low	Noise suppression measures required for night operation.
Ethanol[1]	Underground tank	$50,000 to $100,000	Low	Tank insurance would be needed.[2]
Methanol[1] (M100 or M95)	Underground tank	$50,000 to $100,000	Low	Tank insurance would be needed.[2]
Biodiesel blend[1]	Underground tank	$0	Low	Tank insurance would be needed.[2]
Propane	Above-ground tank	$100,000 to $150,000	Low	Fire suppression system required.

[1] Mobile fueling could be used, which eliminates capital costs, inventory costs, insurance costs, and is generally allowed by current codes/regulations.

[2] Tank insurance is insurance that covers fuel spills from the tank.

Table 5. Incremental Facility Costs for a Fleet of 160 Alternative Fuel Buses (in millions of 1994 $)

	LNG	CNG	Alcohols[1]	Biodiesel	Propane
Fueling Facility	$0.90	$1.50	$0.10	N/C	$0.15
Maintenance Facility	$1.17	$1.08	N/C	N/C	N/C[2]
Bus Storage Facility	$1.44	$1.17	N/C	N/C	N/C[2]
Total	$3.51	$3.75	$0.10	N/C	$0.15

N/C = No change if facility is certified for gasoline

Source: Battelle

[1] Methanol and ethanol

[2] See Note to Table 3.

check with local authorities for requirements in your area.

The costs of maintaining and modifying storage and refueling facilities also depend on the size of the agency, as well as on state and local building codes. Table 4 lists the types of refueling facilities required for each alternative fuel, and shows estimates of the cost range for a refueling facility capable of refueling 80 to 160 alternative fuel buses.

For each alternative fuel, we also estimated the total costs of the necessary modifications to the fueling and maintenance facilities for a bus fleet of 160 alternative fuel buses. We estimated the costs of upgrading the building, mechanical systems, and electrical systems, and of acquiring new equipment. Estimates included contractor overhead and profit (assumed to be 17%), and contingency (assumed to be 25%). We assumed the facilities were converted in three phases to allow normal operations to continue and to serve a mix of diesel, gasoline, and alternative fuel vehicles. Table 5 shows the cost estimates for converting a 160-bus facility with 84,850 square feet of indoor storage, 19,250 square feet for the maintenance area, and a 9,120-square-foot fueling area.

At this time, CNG and LNG facilities have the highest capital costs.

Each alternative fuel facility must be custom designed to meet the specific needs of the transit agency. The cost of the facility can vary significantly. The cost estimates presented above should be viewed as representative for typical facilities. You should consult architectural and engineering firms experienced in alternative fuels for cost estimates for your particular site.

Emissions

WVU conducted emissions testing on the buses with its transportable chassis dynamometer, which was transported to each transit agency in the program. In performing the chassis dynamometer emissions tests, buses were driven according to the CBD driving cycle, which was designed to simulate the speeds, loads, and conditions experienced by buses during a typical route through a city's central business district. Buses were tested with the fuel in the bus at the time. Most of the buses were tested in two consecutive years—1994 and 1995.

Compressed Natural Gas

The results of chassis dynamometer emissions tests on CNG and diesel buses powered by Cummins L10 engines are summarized in Table 6 and shown in Figure 9. The five CNG buses tested in Miami and five 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 U.S. Environmental Protection Agency (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 L10-260G) have been certified by CARB. Five buses with the newer engines were tested in Tacoma, and five were tested in New York City.

There is a substantial amount of scatter in the data, but we can draw several general conclusions. The most obvious result is that the PM emissions levels are reduced to nearly zero with CNG. Figure 9 shows that all CNG buses tested (including vehicles with mileage greater than 150,000 miles) had PM levels an order of magnitude lower than the diesel buses.

It is important to note that the Cummins diesel engines tested thus far were 1992 model year or older. Since 1992, the EPA heavy-duty engine emissions certification standard (measured in grams [g] per brake horsepower hour [bhp-hr]) for PM in urban buses has been reduced by a factor of five (from 0.25 to 0.05 g/bhp-hr). Likewise, substantial improvements have been made in PM emissions from diesel engines. Although a direct correlation between dynamometer certification emissions and in-use chassis dynamometer emissions does not exist, recent engine certification data from the latest CNG and diesel engines suggest that the gap between CNG and diesel PM has been narrowed considerably.

Figure 9 also shows that buses equipped with the newer CARB-certified CNG Cummins L10-260G engines exhibited lower carbon monoxide (CO) and oxides of nitrogen (NO_x) emissions than either the original CNG demonstration or the diesel control buses. The L10-260G tests were performed at 20,000 miles or less. The total hydrocarbon (HC) emissions levels from the CNG buses are higher

Table 6. Average Chassis Dynamometer Emissions Results for CNG (g/mi) - *Cummins L10 Engines*

City	Engine Model*	Test Fuel	Number of Buses	Number of Tests	Odometer Minimum	Odometer Maximum	PM	NO_X	HC	CO
Miami	L10-240G	CNG	5	7	8,000	52,000	0.01	29	20.6	15.8
Tacoma	L10-240G	CNG	5	10	97,000	170,000	0.01	30.4	9.3	21.8
New York	L10-260G	CNG	5	10	3,000	20,000	0.03	12	16.1	1.6
Tacoma	L10-260G	CNG	5	5	10,000**	10,000**	0.02	11.2	15.5	0.7
Miami	L10	Diesel	6	7	153,000	250,000	1.99	22.0	1.9	23.5
Tacoma	L10	Diesel	5	9	144,000	220,000	1.74	24.6	2.4	11.2

* L10-240G is a non-emissions-certified demonstration engine. L10-260G is the CARB-certified version.
** Estimated odometer reading at the time

than those from the diesel buses. However, HC emissions from CNG vehicles are typically composed of more than 95% methane. EPA and CARB regulations are written in terms of non-methane hydrocarbons (NMHC) because methane is considered to be nonreactive 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 those from the diesel buses.

To investigate the causes of high emissions observed on some buses, we diagnosed, repaired, and retested three of the L10-240G buses in Tacoma with higher-than-expected CO emissions. The repairs included replacing air:fuel mixing valve components and adjusting the air:fuel ratio. All three buses showed reductions in CO that averaged approximately 93% (an average of 30 g/mi before repairs to 2 g/mi after repairs). A complete description of this work will be available in a separate short report published by NREL. Call our hotline or check our web site for a copy. *(Our web address and hotline phone number are given at the front of this report.)*

Cummins has recently begun to produce even newer versions of the Cummins L10 CNG engines—the L10-280G and L10-300G. These engines use closed-loop feedback control to provide much better control of the air:fuel ratio, which should make emissions much more consistent from bus to bus and from test to test. We are now looking for sites that have these buses for future testing.

Alcohol

The results of chassis dynamometer emissions testing on ethanol and methanol buses powered by DDC 6V92TA engines are summarized in Table 7 and illustrated in Figure 10. In 1994 and 1995, 10 buses in Peoria and Minneapolis were tested on ethanol, and 10 were tested on methanol in Miami and New York. Additionally, 17 diesel control buses

FIGURE 9. Chassis dynamometer emissions from buses with Cummins L-10 engines

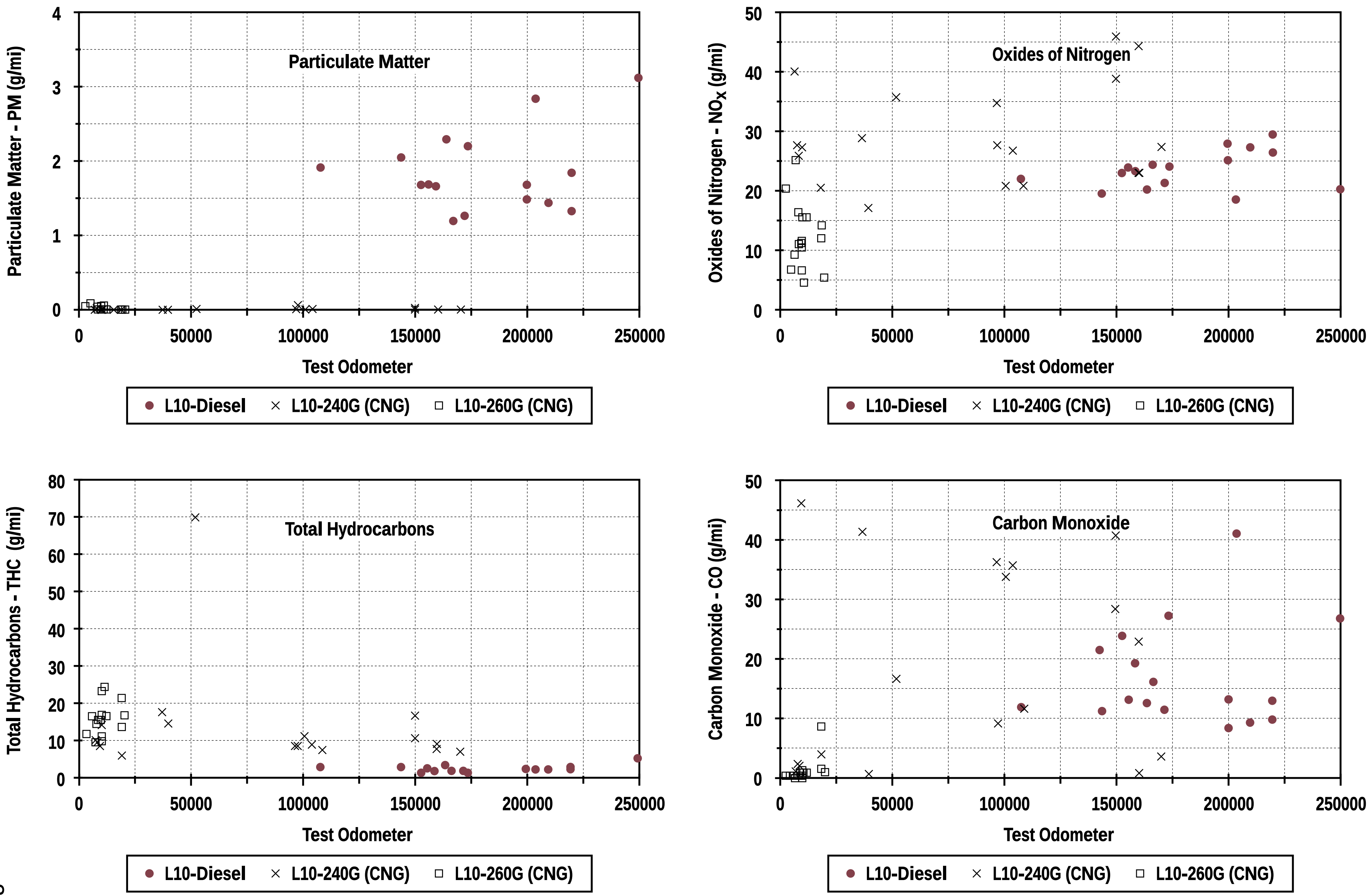

Table 7. Average Chassis Dynamometer Emissions Results for Alcohol (g/mi) - *DDC 6V92 Engines*

City	Test Fuel	Particulate Trap (Diesels only)	Number of Buses	Number of Tests	Odometer Minimum	Odometer Maximum	PM	NO_X	HC	CO
Peoria	Ethanol		5	8	60,000	104,000	0.63	13.4	8.9	37.1
Minneapolis/ St. Paul	Ethanol		5	8	28,000	43,000	0.49	22.0	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	6.8	2.1	8.4
Peoria	Diesel	No	3	6	89,000	108,000	0.72	25.3	2.7	7.5
	Diesel	Yes	3	3	58,000	69,000	0.44	–	–	–
Minneapolis/ St. Paul	Diesel	No	5	9	107,000	151,000	1.05	25.3	3.4	9.5
	Diesel	No	5	10	43,000	69,000	0.81	26.4	2.1	6.7
	Diesel	Yes	5	5	26,000	41,000	0.34	–	–	–
Miami	Diesel	No	4	6	181,00	256,000	2.53	26.7	2.1	16.0

were tested in Peoria, Minneapolis, 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 10 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 odometer readings, but is not intended to represent how emissions from a single bus deteriorate over time. Table 7 indicates the range of odometer readings for which buses were tested at a given site during the 2-year period.

Results from the alcohol buses vary considerably from site to site and from bus to bus. In general, the buses tested on ethanol and methanol appear to emit PM levels similar to diesel buses equipped with particulate traps, and significantly less PM than diesel buses without traps. Although the particulate traps effectively reduced PM levels from diesel vehicles, they were removed because of maintenance and durability problems. However, recent diesel engine emissions certification data show that PM levels from diesel engines have been reduced substantially in order to meet tougher EPA PM standards. Most ethanol- and all methanol-powered buses emitted lower NO_X levels, and had significantly higher amounts of HC and CO, than the diesel controls. However, newer methanol buses with DDC 6V92TA engines (with odometer readings between 6,700 and 42,000) tested in New York City had consistently lower CO and HC emissions than the older alcohol-fueled buses. The emissions levels from the newer methanol engines were similar to the diesel control levels.

Figure 10. Chassis dynamometer emissions from buses with DDC 6V92 engines

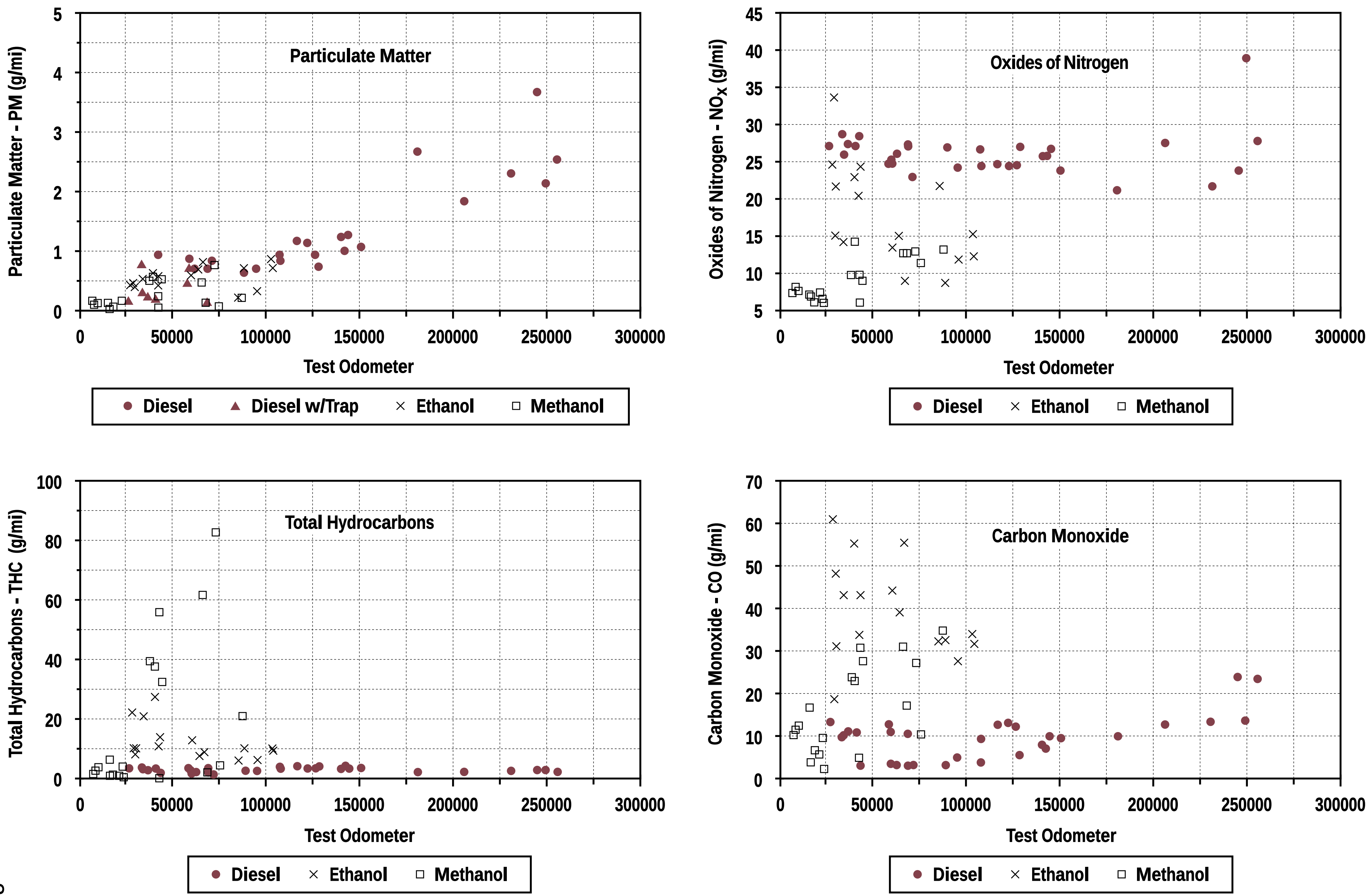

Table 8. Average Chassis Dynamometer Emissions Results for 20% Biodiesel Blend (g/mi) - *DDC 6V92 Engines*

City	Test Fuel	Number of Buses	Number of Tests	Odometer		PM	NO_X	HC	CO
				Minimum	Maximum				
St. Louis	BD-20	4*	4	n/a	238,702	0.89	54.5	2.2	9.6
St. Louis	Diesel	4*	4	n/a	238,702	0.85	52.4	2.6	9.6

* Note: The same four buses were tested on both fuels.

The EPA engine certification data from the methanol DDC 6V92TA (ethanol has not been certified) have shown emissions reductions in all four components (HC, CO, NO_X, and PM) versus the diesel 6V92TA. To investigate the reason for the relatively high emissions on some engines, two buses in Peoria that showed high CO and HC emissions were diagnosed, repaired, and retested. Several repairs, which included adjusting blower bypass valve settings and replacing fuel injectors or catalytic converters, were performed.

Tests on both buses performed before and after the catalytic converters were replaced showed CO reductions of approximately 85% (approximately 40 g/mi to 6 g/mi) and HC reductions of approximately 67% (approximately 11 g/mi to 4 g/mi). A complete description of this work will be available in a separate short report published by NREL. Call our hotline or check our web site for a copy. *(Our web address and hotline phone numbers are given at the front of this report.)*

Biodiesel

Tests were run on buses using both BD-20 and straight diesel back-to-back. The results are shown in Table 8. With the limited number of buses run (four), and the relative scatter in the data, we were unable to draw any conclusions. BD-20 is generally believed to have a relatively small effect on exhaust emissions. This type of change is probably best evaluated on an engine dynamometer where it is possible to have much better control of the test variables and measure smaller changes in emissions levels.

Emissions Summary

The CNG and alcohol buses appear to be particularly well suited to reducing PM and NO_X emissions. This feature is quite important, as the federal emissions standards for PM and NO_X are becoming more stringent. Diesel technology has been developed to meet these more stringent PM standards, thereby narrowing the gap between alternative fuels and diesel. However, virtually all current engine certification data still show CNG with an advantage.

Results from chassis dynamometer emissions testing have also shown high variability in some emissions levels from these early generation CNG and alcohol engines compared to the diesel control engines (which have decades rather than only a few years of development).

Both the engine certification and the chassis dynamometer testing have shown that CNG and alcohol engines have the potential to substantially reduce emissions levels, but emissions are also highly dependent on the engine technology and the condition of the vehicle. Testing showed that some engines in the program exhibited high HC and CO emissions. In cooperation with the engine manufacturers, we discovered that many of these buses were either improperly tuned or had problems with fuel injectors, catalytic converters, mixing valves, and other engine components. Correcting these problems resulted in dramatic reductions in emissions, and shows the importance of proper maintenance in achieving low emissions, as well as the need for technology that is more robust in maintaining optimum air:fuel ratio.

NREL and WVU have attempted to select the latest technologies available; however, many vehicles tested during the past several years represent early versions of alternative fuel engines. Technology is changing rapidly in this industry, and more advanced designs appear almost yearly. Newer CNG engine designs that feature closed-loop feedback control should provide much better control of the air:fuel ratio, and hence more consistent emissions. However, diesel engines also continue to improve and provide tough competition for alternative fuels. As these newer designs become available for testing, we will test and report on them.

Other Considerations

All alternative fuels, except biodiesel, add to the curb weight of the bus. Table 9 shows the approximate increase in curb weight of a 40-foot bus as a result of the alternative fuel option.

Because of tank weight, CNG has the greatest weight penalty. The lower number in Table 9 represents the weight penalty with the latest design composite tanks.

Most municipal, state, and federal highways have axle loading limits to prevent excessive damage to the roadways. As a result, adding the CNG option often substantially reduces maximum passenger loading. If enforced, this will restrict the utility of the bus.

Table 9. Approximate Increase in Curb Weight for a 40-ft Transit Bus (diesel curb weight of approximately 27,000 lbs)

Alternative Fuel Option	Approximate Increase in Curb Weight (lbs)
LNG	860
CNG	2,500–3,900
E95/M100	1,000–1,500
Biodiesel	0

The other alternative fuels have substantially lower weight penalties. Biodiesel has none.

Lessons Learned

During the course of this program we learned numerous lessons that do not appear in the numbers above. We have listed key ones here:

- For alternative fuel buses to deliver the maximum benefit to the environment, proper maintenance is very important, perhaps even more so than for diesels because of the relative immaturity of the technology.
- If you use a biodiesel blend, don't splash blend on site. Require that your contractor deliver a properly pre-mixed batch of fuel. You should also check with the engine and fuel system supplier(s) to make sure that all materials used in the system are biodiesel-blend compatible.
- The one item that seems to have separated the truly successful sites from the others is the commitment to the alternative fuel—from the top of the organization down. The successful sites' attitude is "if you are going to do it, do it right." Everyone has to be committed to the project, resources have to be allocated to train people up front, and fuel must be on site or very readily accessible. We have a separate case study that covers the success of Pierce Transit in accomplishing just that. Call our hotline at (800) 423-1DOE and ask for a copy.

Future Plans

The program is now complete except for a few open items we would like to address:

- Earlier versions of CNG engines with open-loop control have had inconsistent emissions in some areas. We plan to evaluate the latest closed-loop feedback engines as they become available. Ideally, we are looking for a fleet that has buses with CNG feedback engines with otherwise identical diesel buses for comparison. If you have these types of alternative fuel and control buses, and would like to participate in this program, please call us at (303) 275-4482.
- We plan to evaluate LPG, which has the potential for relatively low up-front costs and low operating costs, as it becomes available.
- We may look at one more LNG site to investigate its operating costs and reliability on a system that has no cryogenic pump. If you have these types of alternative fuel and control buses, and would like to participate in this program, please call us at (303) 275-4482.

Summary and Conclusions

Transit buses represent one of the best potential applications for alternative fuels, which have already made significant inroads into the transit bus market. The alternative fuel engines in this program have only a few years of product development—versus decades for the diesel engine—but the results show they are competing very well with diesels in many areas:

- In reliability, one site—Tacoma—is equal to diesel. Most other sites show some reliability penalty, but in many cases the causes are either relatively minor (the bus runs out of fuel because the driver is unfamiliar with the vehicle), or appear solvable (fuel filter plugging at the alcohol sites).
- Operating costs of the buses are driven by the fuel cost. In other words, fuel cost differences versus diesel far outweigh any differences in maintenance costs between the alternative fuel and diesel bus. Operating costs are lowest for the CNG buses and highest for the alcohol and biodiesel buses.
- Capital costs are inverse to the operating costs—they are highest for CNG/LNG buses, and lowest for the alcohol and biodiesel buses. At the present time, no fuel combines a low operating cost with a low up-front capital cost.
- Natural gas and alcohol buses have the potential to significantly lower PM and NO_x emissions. With natural gas, PM emissions are virtually eliminated.

Newer, significantly more advanced alternative fuel engines than were used in this program have already been introduced, and they promise even better performance.

Numbers, Numbers, Numbers

The following tables summarize the key results of the transit bus program.

Table 10. Summary of Program Results

	Fleet	Houston LNG	Portland LNG	Miami CNG	Tacoma CNG	Peoria		Mpls/St. Paul E95	Miami M100	New York M100	St. Louis BD-20
						E95	E93				
Number of buses	AF DC	10 5	8 5	5 5	5 5	5 3		5 5	5 5	5 5	5 5
Mileage in program	AF DC	367,174 278,409	297,065 349,930	93,570 327,491	407,778 451,337	324,668 173,609		120,941 344,472	203,206 376,070	181,134 217,355	102,307 105,761
Engine/fuel system-related road calls per 1,000 miles	AF DC	0.39 0.06	0.22 0.15	0.52 0.13	0.11 0.11	0.12 0.07		0.16 0.14	0.32 0.26	0.17 0.07	N/A N/A
Total road calls per 1,000 miles	AF DC	0.57 0.26	0.58 0.23	0.87 0.54	0.21 0.21	0.19 0.17		0.18 0.29	0.61 0.52	0.26 0.15	N/A N/A
Representative MPG (per diesel #2 equivalent gallon)	AF DC	3.1 3.5	3.0 4.2	3.4 3.5	4.5 5.8	3.6 3.6	3.3 3.4	2.9 3.1	3.4 3.5	2.6 3.0	4.0 4.0
MPG ratio (AF/DC)		0.87	0.70	0.97	0.77	1.02	0.96	0.94	0.99	0.87	1.01
Fuel cost per 1,000 miles (per diesel #2 equivalent gallon)	AF DC	$218 $172	$313 $130	$206 $184	$116 $112	$504 $173	$369	$616 $208	$504 $185	$507 $173	$329 $142
Engine oil consumption cost per 1,000 miles	AF DC	$1 $2	$9 $2	$2 $2	$3 $2	$5 $2		$4 $1	$3 $3	$5 $1	$2 $1
Engine/fuel system-related maintenance cost per 1,000 miles	AF DC	$115 $33	$133 $88	$134 $69	$64 $56	$56 $32		$108 $29	$154 $42	$170 $46	N/A N/A
Total bus maintenance cost per 1,000 miles	AF DC	$321 $227	$424 $287	$335 $270	$161 $159	$215 $171		$259 $181	$324 $194	$333 $259	N/A N/A
Total bus operating cost per 1,000 miles	AF DC	$540 $400	$746 $419	$542 $456	$279 $273	$713 $303	$584 $423	$879 $390	$831 $382	$845 $433	N/A N/A

AF = Alternative Fuel, DC = Diesel Control

N/A = insufficient data

1. The engine/fuel system-related areas are: general electrical, charging, cranking, ignition, air intake, cooling, exhaust, fuel, and engine. The rest of the maintenance costs in the total bus maintenance cost are an average of $169 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.
2. 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.
3. For Houston, the fuel cost does not include a fuel loss due to storage over time and during transfer, which could be as significant as 25%. These are dual-fuel buses that were using 50%–70% diesel fuel during the period used to calculate fuel economy and cost.
4. At Portland, the LNG is purchased from the local utility. Therefore, the purchase price includes the fuel cost, maintenance labor, and parts for the station, as well as capital costs for the station. Also, of the truck and bus operators in the United States using LNG, Portland pays the highest price for LNG.

Table 11. Summary of Emissions Results

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

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
									PM	NO_X	HC	CO
MDTA-9201	FLX	Cummins	L-10 240G	1991	1/26/94	10000	CNG		0.00	27.4	14.3	46.1
MDTA-9202	FLX	Cummins	L-10 240G	1991	1/28/94	9018	CNG		0.00	25.9	8.3	2.1
MDTA-9202	FLX	Cummins	L-10 240G	1991	2/18/95	39670	CNG		0.00	17.1	14.5	0.6
MDTA-9203	FLX	Cummins	L-10 240G	1991	1/26/94	7004	CNG		0.00	40.1	10.0	1.0
MDTA-9204	FLX	Cummins	L-10 240G	1991	1/27/94	36973	CNG		0.00	29.0	17.5	41.4
MDTA-9204	FLX	Cummins	L-10 240G	1991	2/20/95	52182	CNG		0.02	35.7	70.2	16.8
MDTA-9205	FLX	Cummins	L-10 240G	1991	2/3/94	7944	CNG		0.02	27.8	9.3	2.4
							Count		7	7	7	7
							Average		0.01	29.0	20.6	15.8
							Max		0.02	40.1	70.2	46.1
							Min		0.00	17.1	8.3	0.6

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

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
									PM	NO_X	HC	CO
PT-478	BIA	Cummins	L-10 240G	1992	8/12/94	104000	CNG		0.01	26.8	9.2	35.8
PT-478	BIA	Cummins	L-10 240G	1992	7/4/95	160000	CNG		0.00	44.3	8.8	22.8
PT-479	BIA	Cummins	L-10 240G	1992	8/5/94	109010	CNG			21.0	7.4	11.5
PT-479	BIA	Cummins	L-10 240G	1992	7/5/95	170000	CNG		0.00	27.3	7.0	3.6
PT-480	BIA	Cummins	L-10 240G	1992	8/9/94	96730	CNG		0.02	34.7	8.6	36.4
PT-480	BIA	Cummins	L-10 240G	1992	7/6/95	150000	CNG		0.03	46.1	10.5	40.7
PT-481	BIA	Cummins	L-10 240G	1992	8/11/94	100800	CNG		0.00	20.9	11.2	33.7
PT-481	BIA	Cummins	L-10 240G	1992	7/7/95	150000	CNG		0.00	38.8	16.9	28.3
PT-482	BIA	Cummins	L-10 240G	1992	8/15/94	108654	CNG		0.00	20.6	6.0	4.0
PT-482	BIA	Cummins	L-10 240G	1992	7/8/95	160000	CNG		0.00	23.2	7.7	0.8
							Count		9	10	10	10
							Average		0.01	30.4	9.3	21.8
							Max		0.03	46.1	16.9	40.7
							Min		0.00	20.6	6.0	0.8

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

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
									PM	NO_X	HC	CO
CBC-4903	TMC	Cummins	L-10 260G	1993	12/9/94	8517	CNG		0.04	20.9	14.9	0.6
CBC-4903	TMC	Cummins	L-10 260G	1993	7/25/95	18872	CNG		0.01	12.0	21.4	1.5
CBC-4904	TMC	Cummins	L-10 260G	1993	11/20/94	6764	CNG		0.04	9.2	9.5	0.4
CBC-4904	TMC	Cummins	L-10 260G	1993	7/25/95	18666	CNG		0.01	14.2	13.7	8.7
CBC-4907	TMC	Cummins	L-10 260G	1993	11/29/94	9048	CNG		0.01	11.1	15.5	0.8
CBC-4907	TMC	Cummins	L-10 260G	1993	7/26/95	20091	CNG		0.00	5.4	16.7	0.8
TBCC-2051	TMC	Cummins	L-10 260G	1993	11/17/94	5223	CNG		0.05	6.9	16.7	0.6
TBCC-2051	TMC	Cummins	L-10 260G	1993	6/24/95	10871	CNG		0.05	4.6	24.1	0.8
TBCC-2054	TMC	Cummins	L-10 260G	1993	11/19/94	2774	CNG		0.03	20.4	11.7	0.5
TBCC-2054	TMC	Cummins	L-10 260G	1993	6/23/95	11993	CNG		0.02	15.5	16.5	0.9
							Count		10	10	10	10
							Average		0.03	12.0	16.1	1.6
							Max		0.05	20.9	24.1	8.7
							Min		0.00	4.6	9.5	0.4

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

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom*	Test Fuel	Emissions Test Results (g/mi)			
								PM	NO_x	HC	CO
PT-803	BIA	Cummins	L-10 260G	1994	7/10/95	10000	CNG	0.03	11.6	9.7	0.7
PT-804	BIA	Cummins	L-10 260G	1994	7/12/95	10000	CNG	0.01	6.6	16.1	0.4
PT-806	BIA	Cummins	L-10 260G	1994	7/10/95	10000	CNG	0.03	15.6	17.2	0.6
PT-807	BIA	Cummins	L-10 260G	1994	7/14/95	10000	CNG	0.00	11.6	23.3	0.9
PT-811	BIA	Cummins	L-10 260G	1994	7/13/95	10000	CNG	0.01	10.6	11.1	1.1
							Count	5	5	5	5
							Average	0.02	11.2	15.5	0.7
							Max	0.03	15.6	23.3	1.1
							Min	0.00	6.6	9.7	0.4

* Estimated odometer reading at time of test

Diesel Buses - Cummins L10 - Miami, FL

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)			
								PM	NO_x	HC	CO
MDTA-9001	FLX	Cummins	L-10	1990	2/7/94	204000	D2	2.83	18.4	2.1	40.9
MDTA-9001	FLX	Cummins	L-10	1990	2/24/95	250000	D1	3.10	20.2	4.9	26.6
MDTA-9003	FLX	Cummins	L-10	1990	2/7/94	153000	D2	1.68	22.9	1.0	23.8
MDTA-9004	FLX	Cummins	L-10	1990	2/8/94	174000	D2	2.19	24.0	1.0	27.1
MDTA-9081	FLX	Cummins	L-10	1990	2/8/94	167000	D2	1.20	24.3	1.5	16.0
MDTA-9082	FLX	Cummins	L-10	1990	2/9/94	172000	D2	1.26	21.2	1.5	11.3
MDTA-9083	FLX	Cummins	L-10	1990	2/9/94	159000	D2	1.66	23.2	1.6	19.0
							Count	7	7	7	7
							Average	1.99	22.0	1.9	23.5
							Max	3.10	24.3	4.9	40.9
							Min	1.20	18.4	1.0	11.3

Diesel Buses - Cummins L10 - Tacoma, WA

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)			
								PM	NO_x	HC	CO
PT-464	BIA	Cummins	L-10	1991	7/3/95	200000	D2	1.48	27.9	1.9	13.1
PT-465	BIA	Cummins	L-10	1991	8/18/94	164006	D2	2.29	20.0	3.2	12.5
PT-465	BIA	Cummins	L-10	1991	7/15/95	220000	D2	1.83	26.3	2.6	9.5
PT-466	BIA	Cummins	L-10	1991	8/19/94	107943	D2	1.91	21.9	2.6	11.7
PT-466	BIA	Cummins	L-10	1991	7/17/95	210000	D2	1.44	27.2	2.1	9.2
PT-467	BIA	Cummins	L-10	1991	8/20/94	155815	D2	1.68	23.8	2.3	13.0
PT-467	BIA	Cummins	L-10	1991	7/18/95	220000	D2	1.32	29.3	1.9	12.8
PT-468	BIA	Cummins	L-10	1991	8/22/94	144051	D2	2.05	19.5	2.5	11.1
PT-468	BIA	Cummins	L-10	1991	7/20/95	200000	D2	1.67	25.1	2.2	8.1
							Count	9	9	9	9
							Average	1.74	24.6	2.4	11.2
							Max	2.29	29.3	3.2	13.1
							Min	1.32	19.5	1.9	8.1

Ethanol Buses - Peoria, IL

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
									PM	NO_x	HC	CO
GPT-1504E	TMC	DDC	6V-92TA	1992	4/19/94	59925	E93		0.61	13.4	12.7	44.1
GPT-1504E	TMC	DDC	6V-92TA	1992	4/18/95	94999	E93		0.33	11.9	6.1	27.6
GPT-1506E	TMC	DDC	6V-92TA	1992	4/25/94	66567	E93		0.82	8.9	9.0	55.6
GPT-1506E	TMC	DDC	6V-92TA	1992	4/10/95	103481	E93		0.72	12.2	9.2	31.6
GPT-1507E	TMC	DDC	6V-92TA	1992	4/21/94	63588	E93		0.71	15.0	7.6	39.1
GPT-1507E	TMC	DDC	6V-92TA	1992	4/6/95	102819	E93		0.88	15.2	10.1	33.8
GPT-1508E	TMC	DDC	6V-92TA	1992	4/10/95	88049	E93		0.72	8.7	10.2	32.5
GPT-1516E	TMC	DDC	6V-92TA	1992	4/20/94	84911	E93		0.22	21.6	6.0	32.3
							Count		8	8	8	8
							Average		0.63	13.4	8.9	37.1
							Max		0.88	21.6	12.7	55.6
							Min		0.22	8.7	6.0	27.6

Ethanol Buses - St. Paul, MN

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
									PM	NO_x	HC	CO
MTC-8000	GLG	DDC	6V-92TA	1991	10/5/94	27605	E95		0.44	24.5	22.2	61.3
MTC-8000	GLG	DDC	6V-92TA	1991	5/21/95	39609	E95		0.63	22.8	27.6	55.5
MTC-8001	GLG	DDC	6V-92TA	1991	10/1/94	29694	E95		0.40	21.6	10.2	31.2
MTC-8001	GLG	DDC	6V-92TA	1991	5/22/95	41979	E95		0.45	20.4	10.7	33.8
MTC-8002	GLG	DDC	6V-92TA	1991	5/25/95	33831	E95		0.55	14.2	20.8	43.2
MTC-8003	GLG	DDC	6V-92TA	1991	10/4/94	28722	E95		0.46	33.5	10.2	18.7
MTC-8003	GLG	DDC	6V-92TA	1991	5/25/95	42581	E95		0.59	24.3	13.7	43.2
MTC-8004	GLG	DDC	6V-92TA	1991	10/5/94	29119	E95		0.41	15.0	8.1	48.1
							Count		8	8	8	8
							Average		0.49	22.0	15.4	41.9
							Max		0.63	33.5	27.6	61.3
							Min		0.40	14.2	8.1	18.7

Methanol Buses - Miami, FL

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
									PM	NO_x	HC	CO
MDTA-9211	FLX	DDC	6V-92TA	1992	1/21/94	42283	M100		0.24	9.6	55.9	30.9
MDTA-9211	FLX	DDC	6V-92TA	1992	2/14/95	87000	M100		0.23	13.1	20.9	34.9
MDTA-9212	FLX	DDC	6V-92TA	1992	1/22/94	37745	M100		0.50	9.7	39.3	23.9
MDTA-9212	FLX	DDC	6V-92TA	1992	2/15/95	72364	M100		0.78	13.0	83.2	27.3
MDTA-9213	FLX	DDC	6V-92TA	1992	1/24/94	39500	M100		0.56	14.2	37.5	22.7
MDTA-9213	FLX	DDC	6V-92TA	1992	2/14/95	67697	M100		0.15	12.7	1.9	17.1
MDTA-9214	FLX	DDC	6V-92TA	1992	1/25/94	65450	M100		0.48	12.5	61.8	31.0
MDTA-9215	FLX	DDC	6V-92TA	1992	1/24/94	43800	M100		0.54	8.8	32.2	27.8
MDTA-9215	FLX	DDC	6V-92TA	1992	2/16/95	75000	M100		0.06	11.3	4.5	10.3
							Count		9	9	9	9
							Average		0.39	11.6	37.5	25.1
							Max		0.78	14.2	83.2	34.9
							Min		0.06	8.8	1.9	10.3

Methanol Buses - New York City

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
									PM	NO_x	HC	CO
TBCC-2136	TMC	DDC	6V-92TA	1993	11/12/94	22582	M100		0.16	6.4	4.0	9.6
TBCC-2136	TMC	DDC	6V-92TA	1993	6/19/95	42100	M100		0.05	5.9	0.5	4.8
TBCC-2137	TMC	DDC	6V-92TA	1993	11/16/94	9484	M100		0.15	7.5	3.7	12.5
TBCC-2137	TMC	DDC	6V-92TA	1993	6/19/95	17854	M100		0.07	6.1	1.1	6.6
TBCC-2138	TMC	DDC	6V-92TA	1993	11/14/94	6674	M100		0.16	7.4	1.5	10.4
TBCC-2138	TMC	DDC	6V-92TA	1993	7/11/95	16067	M100		0.04	6.7	0.2	3.8
TBCC-2139	TMC	DDC	6V-92TA	1993	11/15/94	7979	M100		0.11	8.0	2.5	11.5
TBCC-2139	TMC	DDC	6V-92TA	1993	6/21/95	20765	M100			7.3	0.8	5.9
TBCC-2140	TMC	DDC	6V-92TA	1993	11/17/94	15561	M100		0.14	7.1	6.1	16.7
TBCC-2140	TMC	DDC	6V-92TA	1993	6/21/95	23036	M100			6.0	0.5	2.2
							Count		8	10	10	10
							Average		0.11	6.8	2.1	8.4
							Max		0.16	8.0	6.1	16.7
							Min		0.04	5.9	0.2	2.2

Diesel Buses with Particulate Traps (traps removed prior to 1995 test date) - Peoria, IL

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
								PM[1]	PM[2]	NO_x	HC	CO
GPT-1501	TMC	DDC	6V-92TA	1992	4/15/94	68721	D1	0.14		27.0	2.8	10.4
GPT-1501	TMC	DDC	6V-92TA	1992	4/4/95	107954	D1		0.84	24.2	2.8	3.4
GPT-1502	TMC	DDC	6V-92TA	1992	4/15/94	59373	D1	0.70		25.1	2.5	10.7
GPT-1502	TMC	DDC	6V-92TA	1992	4/18/95	95032	D1		0.69	24.0	2.5	4.6
GPT-1503	TMC	DDC	6V-92TA	1992	4/27/94	58287	D1	0.48		24.6	2.8	12.6
GPT-1503	TMC	DDC	6V-92TA	1992	4/19/95	88913	D1		0.64	26.7	2.5	3.0
							Count	3	3	6	6	6
							Average	0.44	0.72	25.3	2.6	7.5
							Max	0.70	0.84	27.0	2.8	12.6
							Min	0.14	0.64	24.0	2.5	3.0

[1] PM results with particulate traps

[2] PM results without particulate traps

Diesel Buses without Particulate Traps - St. Paul, MN

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
									PM	NO_x	HC	CO
MTC-2207	GLG	DDC	6V-92TA	1991	9/13/94	116911	D1		1.16	24.6	3.7	12.5
MTC-2207	GLG	DDC	6V-92TA	1991	5/19/95	142835	D1		1.01	25.6	3.6	6.6
MTC-2208	GLG	DDC	6V-92TA	1991	5/17/95	140678	D1		1.23	25.6	3.2	7.7
MTC-2209	GLG	DDC	6V-92TA	1991	9/15/94	126622	D1		0.94	24.4	3.2	12.2
MTC-2209	GLG	DDC	6V-92TA	1991	5/17/95	144612	D1		1.27	26.4	3.2	9.9
MTC-2210	GLG	DDC	6V-92TA	1991	9/17/94	122545	D1		1.13	24.3	3.2	12.8
MTC-2210	GLG	DDC	6V-92TA	1991	5/16/95	151201	D1		1.06	23.7	3.0	9.2
MTC-2211	GLG	DDC	6V-92TA	1991	9/16/94	107614	D1		0.92	26.5	3.5	9.1
MTC-2211	GLG	DDC	6V-92TA	1991	5/17/95	128418	D1		0.74	26.8	3.6	5.2
							Count		9	9	9	9
							Average		1.05	25.3	3.3	9.5
							Max		1.27	26.8	3.7	12.8
							Min		0.74	23.7	3.0	5.2

Diesel Buses with Particulate Traps (traps removed prior to 1995 test date) - St. Paul, MN

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
								PM[1]	PM[2]	NO_X	HC	CO
MTC-2222	GLG	DDC	6V-92TA	1993	9/23/94	36670	D1	0.23		27.1	2.5	10.8
MTC-2222	GLG	DDC	6V-92TA	1993	5/18/95	62561	D1		0.72	25.9	1.7	2.8
MTC-2223	GLG	DDC	6V-92TA	1993	9/26/94	34101	D1	0.79		25.8	2.7	9.9
MTC-2223	GLG	DDC	6V-92TA	1993	5/19/95	60000	D1		0.87	24.6	1.4	2.9
MTC-2224	GLG	DDC	6V-92TA	1993	9/27/94	40812	D1	0.20		27.0	2.9	10.5
MTC-2224	GLG	DDC	6V-92TA	1993	5/20/95	68890	D1		0.71	27.3	1.6	2.6
MTC-2225	GLG	DDC	6V-92TA	1993	9/28/94	33720	D1	0.31		28.4	2.9	9.2
MTC-2225	GLG	DDC	6V-92TA	1993	5/12/95	71583	D1		0.83	22.8	1.3	2.8
MTC-2226	GLG	DDC	6V-92TA	1993	9/29/94	26370	D1	0.18		26.9	2.8	12.8
MTC-2226	GLG	DDC	6V-92TA	1993	5/15/95	43043	D1		0.92	28.3	1.4	2.5
							Count	5	5	10	10	10
							Average	0.34	0.81	26.4	2.1	6.7
							Max	0.79	0.92	28.4	2.9	12.8
							Min	0.18	0.71	22.8	1.3	2.5

[1] PM results with particulate traps
[2] PM results without particulate traps

Diesel Buses without Particulate Traps - Miami, FL

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
									PM	NO_X	HC	CO
MDTA-9067	FLX	DDC	6V-92TA	1990	1/18/94	181385	D2		2.68	20.7	1.9	9.9
MDTA-9067	FLX	DDC	6V-92TA	1990	2/6/95	231619	D1		2.31	21.7	2.1	13.2
MDTA-9068	FLX	DDC	6V-92TA	1990	1/19/94	206506	D2		1.85	27.5	1.7	12.6
MDTA-9068	FLX	DDC	6V-92TA	1990	2/23/95	256087	D1		2.53	27.6	1.8	23.2
MDTA-9070	FLX	DDC	6V-92TA	1990	2/22/95	250000	D1		2.14	38.9	2.5	13.4
MDTA-9071	FLX	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	26.7	2.1	16.0
							Max		3.66	38.9	2.5	23.8
							Min		1.85	20.7	1.7	9.9

Diesel Buses tested on Biodiesel Blend - St. Louis, MO

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
									PM	NO_X	HC	CO
SL-010BFD	FLX	DDC	6V-92TA	1988	04/24/96	22582	BD20		0.82	57.3	2.2	13.3
SL-003BFD	FLX	DDC	6V-92TA	1988	04/15/96	36457	BD20		0.98	52.5	2.2	5.3
SL-007BFD	FLX	DDC	6V-92TA	1988	04/13/96	238065	BD20		0.76	51.9	2.1	7.2
SL-001BFD	FLX	DDC	6V-92TA	1988	04/12/96	140966	BD20		0.98	56.3	2.3	12.4
							Count		4	4	4	4
							Average		0.89	54.5	2.2	9.6
							Max		0.98	57.3	2.3	13.3
							Min		0.76	51.9	2.1	5.3

Diesel Buses (the same buses were tested on Biodiesel Blend) - St. Louis, MO

Vehicle Number	Bus Make	Engine Make	Engine Model	Engine Year	Test Date	Test Odom	Test Fuel	Emissions Test Results (g/mi)				
									PM	NO_X	HC	CO
SL-010BFD	FLX	DDC	6V-92TA	1988	04/24/96	22592	D2		0.96	58.8	2.4	17.4
SL-003BFD	FLX	DDC	6V-92TA	1988	04/22/96	37224	D2		0.73	51.6	2.6	6.9
SL-007BFD	FLX	DDC	6V-92TA	1988	04/22/96	238702	D2		0.53	53.1	2.7	6.3
SL-001BFD	FLX	DDC	6V-92TA	1988	04/20/96	141193	D2		1.16	46.0	2.9	7.8
							Count		4	4	4	4
							Average		0.85	52.4	2.6	9.6
							Max		1.16	58.8	2.9	17.4
							Min		0.53	46.0	2.4	6.3

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