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Alternative Fuel Transit Buses

Interim Results from the
National Renewable Energy Laboratory
Vehicle Evaluation Program

First Report • May 1995



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**Interim Results from the
National Renewable Energy Laboratory (NREL)
Vehicle Evaluation Program**

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Office of Transportation Technologies
Office of Energy Efficiency and Renewable Energy**

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Contents

Introduction	1
Overview	1
Buses in the Program	1
Data Collected	3
Reliability	4
Liquefied Natural Gas	4
Compressed Natural Gas	5
Ethanol	5
Methanol	5
Biodiesel	5
Fuel Economy	6
Liquefied Natural Gas	7
Compressed Natural Gas	7
Alcohols	8
Biodiesel	8
Costs	8
Operating Costs	9
Fuel Costs	9
Maintenance Costs	9
Liquefied Natural Gas	10
Compressed Natural Gas	10
Ethanol	11
Methanol	11
Biodiesel	12
Cost per Mile Traveled	12
Capital Costs	12
Additional Bus Acquisition Costs	12
Facilities Costs	13
Emissions	15
Compressed Natural Gas	16
Alcohols	18
Biodiesel	19
Other Considerations	19
Future Plans	20
Numbers, Numbers, Numbers!	20

Alternative Fuel Transit Buses

Introduction

Overview

Recognizing the need to address the impacts of U.S. fuel consumption on national security, the economy, and the environment, Congress established a goal of reducing the nation's dependence on gasoline and diesel fuel. To ensure that this goal is met, Congress enacted the Alternative Motor Fuels Act (AMFA) of 1988. AMFA requires the U.S. Department of Energy (DOE) to collect data on alternative fuel vehicles—including transit buses—to evaluate their performance and cost. DOE designated the National Renewable Energy Laboratory (NREL) as the program manager for the data collection and vehicle evaluation program. NREL makes data on alternative fuel vehicles available to the public through the Alternative Fuels Data Center (AFDC). Staffers of the National Alternative Fuels Hotline (1-800-423-1DOE) can tell you how to connect to the AFDC and can retrieve information from the data center for you.

The transit bus program is designed to provide a comprehensive study of the alternative fuels currently used by the transit bus industry. The study focuses on the reliability, fuel economy, operating costs, and emissions of vehicles running on the various fuels and alternative fuel engines.

Buses in the Program

To obtain the detailed information needed for the study, we selected

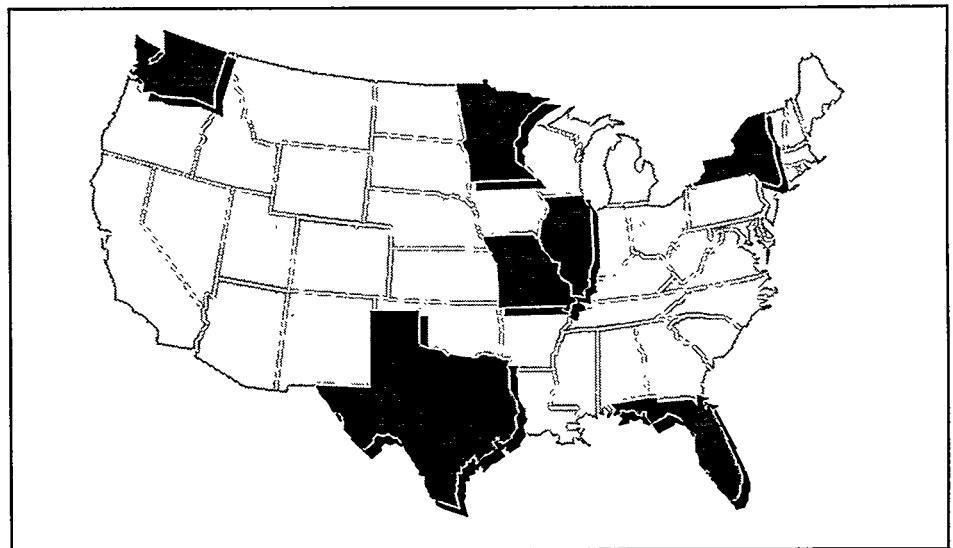
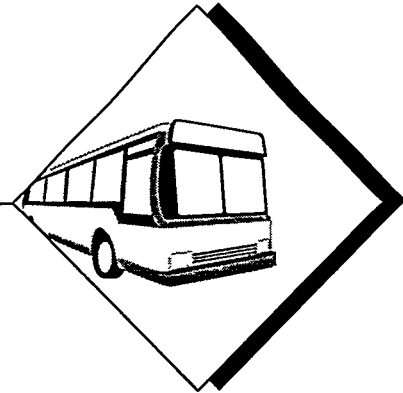


Figure 1. The program tests alternative fuel buses in seven municipalities across the nation.

transit agencies that met the following criteria:

- The transit agency had to have test buses that represented the most current technology available at the time.
- The transit agency had to have control buses that were identical to the alternative fuel buses, except for the fuel system they use.
- The transit agency personnel had to agree to supply detailed data on the vehicles for several years.

Using these criteria, we chose to test buses in seven metropolitan areas: Houston, Texas; Miami, Florida;

Alternative Fuel Transit Buses

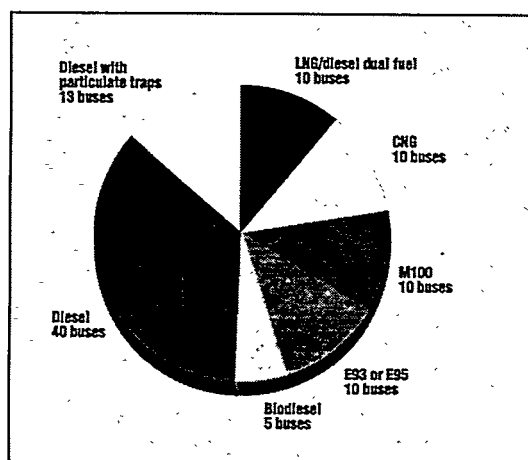


Figure 2. The number of test buses of each fuel type

Figure 3. The University of West Virginia uses its transportable chassis dynamometer to conduct emissions tests at each of the sites.



Minneapolis/St. Paul, Minnesota; New York, New York; Peoria, Illinois; St. Louis, Missouri; and Tacoma, Washington (see Figure 1). We are currently studying five alternative fuels—compressed natural gas (CNG), liquefied natural gas (LNG), 100% methanol (M100), 95% and 93% ethanol (E95 and E93), and a mixture of 80% conventional diesel and 20%

biodiesel (BD20). Each of the alternative fuels being tested in the program is described in the sidebar on page 4. Note that BD20 is not currently considered an alternative fuel under the Energy Policy Act of 1992. Figure 2 shows the number of test

buses of each fuel type. A program target was to test ten buses of each alternative fuel with ten controls, split between two sites. For example, there are 10 Cummins L10 CNG engines in the program, with 10 matching controls, split equally between Miami and Tacoma. Table 1 summarizes the transit buses in the program.

The alternative fuel buses in this program use the most common alternative fuel engines available from the heavy-duty engine manufacturers. In their diesel configuration, these engines are also the most common engines used by the transit bus industry. The engines are:

- Detroit Diesel 6V92TA methanol engine
- Detroit Diesel 6V92TA ethanol engine
- Detroit Diesel 6V92TA pilot ignition natural gas (PING) engine
- Cummins L10 natural gas engine.

The biodiesel buses use BD20 fuel in an unaltered Detroit Diesel Corporation 6V92TA engine. Each of the engines in the program has a horsepower rating of between 240 and 300. Buses in the program are 35-foot and 40-foot models manufactured by Stewart & Stevenson, Flxible, Gillig, TMC, and BIA.

Detroit Diesel Corporation recently introduced a CNG version of its Series 50 diesel engine. We plan to add Series 50 CNG engines to the program in the near future.

Table 1. Summary of Buses in the Program

City (Agency)	Engine	Alternative Fuel/Technology							Total	Bus Description
		M100	E93/ E95	LNG PING*	CNG SI**	BD20	Diesel w/trap***	Diesel Control		
Houston, TX (Houston Metro)	Detroit Diesel 6V92			10				5	15	40 ft Stewart & Stevenson
Miami, FL (Metro-Dade)	Detroit Diesel 6V92	5						5	10	40 ft Flexible
Miami, FL (Metro-Dade)	Cummins L10				5		5	10	20	40 ft Flexible
Minneapolis/St. Paul, MN (MCTO)	Detroit Diesel 6V92		5				5	5	15	40 ft Gillig
Peoria, IL (GP Transit)	Detroit Diesel 6V92		5				3		8	35 ft TMC
Tacoma, WA (Pierce Transit)	Cummins L10				5			5	10	40 ft BIA
New York, NY (New York City Dept. of Trans./ Triboro)	Detroit Diesel 6V92	5							5	40 ft TMC
	Detroit Diesel Series 50							5	5	40 ft TMC
St. Louis (Bi-State)	Detroit Diesel 6V92					5		5	10	40 ft Flexible
Total		10	10	10	10	5	13	40	98	

* Pilot ignition natural gas

** Spark ignited

*** Particulate trap

M100 = 100 percent methanol

E93 = 93 percent ethanol

E95 = 95 percent ethanol

LNG = Liquefied natural gas

CNG = Compressed natural gas

BD20 = 20% biodiesel and 80% diesel blend

Data Collected

Data are collected in four categories:

Bus and Route Descriptions—detailed descriptions of each vehicle in the program as well as a general description of the bus routes.

Bus Operating Data—descriptions and costs of all repair and maintenance work done on the buses. All fuel and oil put in the buses is recorded. We also record any safety incidents or safety-related information.

Emissions Data—from emissions tests conducted by West Virginia University (WVU) personnel, who visit each site and test emissions on the buses using WVU's transportable chassis dynamometer (shown in Figure 3).

Capital Costs—descriptions of the alternative fuel facilities, and facility cost at each site. We also record the incremental cost of the alternative fuel buses.

A subcontractor collects the daily operational data from the transit

Alternative Fuel Transit Buses

The Alternative Fuels Being Tested

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

Ethanol. Ethanol is 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. Biodiesel fuel can be derived from any plant- or animal-derived oil product. The biodiesel blend used in the test buses, called BD20, was 20% biodiesel from soybeans and 80% diesel fuel. (Note: BD20 is not currently considered an alternative fuel under the Energy Policy Act of 1992).

Natural Gas. Natural gas is composed primarily of methane. It can be stored on the vehicle as a compressed gas or as a cryogenic liquid. The program includes vehicles that employ both types of storage.

agencies, converts the information into a standard form for submission to the data center, and analyzes the results. AFDC personnel then make the data available to the public through a series of data base queries and descriptions designed to present the information in a concise and logical format. Reports are also available over the Internet using Worldwide Web browsers such as Mosaic and Netscape. The internet address for the AFDC is:

<http://www.afdc.nrel.gov:70/>

Our goal is to collect 18 months of data on each test bus. Currently, we have approximately 18 months of data for only three of the seven sites. This report summarizes the interim results from the project to date. A more detailed interim report of the program will be available at a later date from the National Alternative Fuels Hotline.

In the sections that follow, we address the performance and reliability, fuel economy, costs, and emissions of the buses in the program. Other considerations for transit agencies are also covered. The final sections of the report outline the future plans for the program, including potential new sites with alternative fuel transit buses, and summarize the interim results.

Reliability

One measure of reliability in a bus is the average number of miles a bus travels between road calls. When the driver cannot complete a route because of a problem with the bus and calls for a replacement bus, a road call is recorded. Road calls encompass all types of events from engine failure to simply running out of fuel. Figure 4 shows the miles between road calls for the buses in the test program. The sections that follow provide a discussion of reliability by fuel type.

Liquefied Natural Gas

As seen in Figure 4, the dual-fuel buses in Houston running on LNG and diesel are experiencing considerably more road calls than the diesel controls—about 1,800 miles between road calls for LNG versus 3,300 miles between road calls for diesel. These road calls are due mainly to two problems: the buses ran out of fuel (63 out of 213 total road calls), or the monitoring system detected a fuel leak and shut down the bus (44 out of 213). If a fuel problem develops with the LNG, the dual-fuel engines will switch to diesel as a backup. Because the dual-fuel buses have very small diesel

Alternative Fuel Transit Buses

fuel tanks, the bus runs out of diesel in a short time; the diesel fuel tank alone is not adequate to run the bus independently for long distances. The dual-fuel buses experienced more than six times the rate of road calls for "out of fuel" as did the diesel controls.

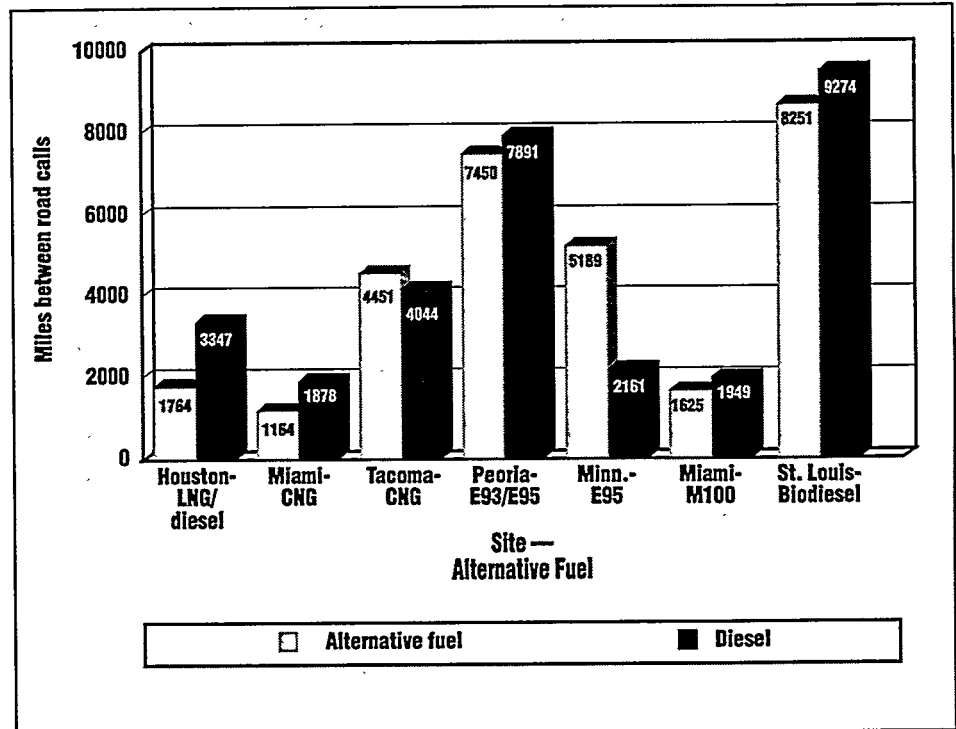
In the future, we will add an additional site for buses running on LNG. The additional buses will have different engines—Cummins L10G burning LNG exclusively.

Compressed Natural Gas

Buses running on CNG traveled about 38% fewer miles between road calls than their diesel controls in Miami (despite the fact that the diesel buses are older, with higher mileage), but traveled about 10% more miles between road calls in Tacoma. The total mileage accumulated on the Miami CNG buses is quite limited because the CNG buses are only being used an average of 1,000 miles per month.

Ethanol

Both the ethanol buses and the diesel control buses with particulate traps operating in Peoria ran relatively long distances between road calls—about 7,500 and 7,900 miles, respectively. In Minneapolis/St. Paul, the E95 buses traveled an average of 5,200 miles between road calls, versus 2,200 miles for the diesel control buses. However, the E95 buses are not used as heavily as the diesel buses—1,300 versus 3,800 miles per bus each month.



Methanol

The Miami buses operating on M100 traveled fewer miles between road calls than their diesel counterparts—about 1600 miles versus 1900 miles for the diesel control vehicles. This difference is primarily due to fuel system problems that resulted in engine stalls in the methanol buses. Many of the engine stalls were caused by clogged fuel filters, which may indicate a problem with fuel supply, not with the engine (fuel filter clogging has also been a problem with the ethanol buses). We recently added a second site—New York City (Triboro)—to test more buses running on M100 and see if similar problems are encountered.

Biodiesel

The biodiesel and diesel buses in St. Louis traveled relatively long distances between road calls: about 8,300 miles for the biodiesel buses and 9,300 for the diesel buses.

Figure 4. Average miles traveled between road calls at each site

Alternative Fuel Transit Buses

Fuel Economy

Fuel economy and fuel costs are very important to transit agencies because the fuel cost represents a large portion of the operating cost of a transit bus. Excluding driver labor costs, the fuel cost is approximately half of the operating cost of a diesel bus, and more than half for some alternative fuel buses. The average monthly in-use fuel economy was calculated from the fuel added and odometer reading each time the bus refueled. The fuel economy often varied from month to month.

Miles to go Before We're Done

The goal of the program is to gather sufficient data on ten buses for each fuel type, with five buses at one site and five at another. At this time, the program is approximately half complete. Some sites have reported a substantial amount of data; others have just started to report data. Differences often emerge between sites as a result of different experience with the buses, different operating conditions, and different reporting procedures. Care should be taken in drawing conclusions from the program at this time. The amount of data included in the analysis for the final report will approximately double—an increase that should substantially enhance the validity of all results and findings.

Total Mileage of the Test Buses

Site	Alternative Fuel	Months of Data	Total Mileage on Alternative Fuel Buses
Houston, TX	LNG	17	376,000
Tacoma, WA	CNG	14	294,000
Miami, FL	CNG	17	87,000
Peoria, IL	E93*	23	389,000
Minneapolis/ St. Paul, MN	E95	9	57,000
Miami, FL	M100	17	193,000
New York, NY	M100	0	0
St. Louis, MO	BD20	9	165,000

* Fleet started on E95 and then switched to E93

Figure 5 shows the range of monthly average fuel economy for the alternative fuel and diesel buses at each site. The fuel economy is expressed as miles per diesel equivalent gallon. A diesel equivalent gallon is the quantity of alternative fuel that has the same energy content as one gallon of diesel fuel. Expressing the fuel economy in miles per diesel equivalent gallon allows for a direct comparison of the relative energy efficiency of the various alternative fuel engine technologies.

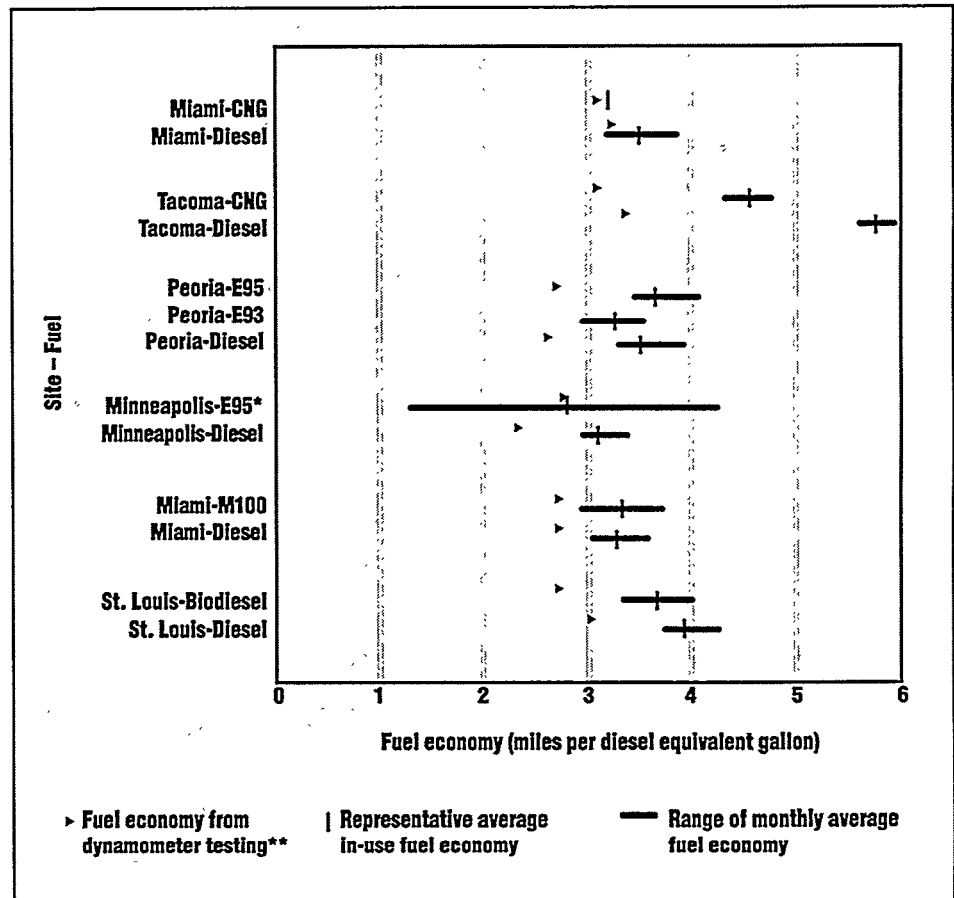
The spread in the fuel economy data is different for each site. This variability may result from differences in driving cycles from bus to bus and from site to site.

Periodically, the test buses were removed from service and emissions tested using a chassis dynamometer. During these tests, the fuel economy of the buses was also measured. These dynamometer results (which were all obtained using the Central Business District driving cycle) are shown as triangular points in Figure 5. The fuel economy measured using the dynamometer was relatively consistent throughout each test fleet. This indicates that the variations in the in-use fuel economy results are probably due to driving cycles. Because the dynamometer results are consistently below the average in-use results, the Central Business District driving cycle may not be representative of the actual driving cycles of the test buses. The sections that follow summarize fuel economy by fuel type.

Liquefied Natural Gas

The Houston buses use DDC 6V92 PING engines, which operate on a compression-ignition cycle using diesel fuel as the “pilot ignition” source to ignite the natural gas. The average fuel economy for these buses (not shown in Figure 5) was calculated by summing 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 gallons) was approximately 14% 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 majority is most likely attributable to engine operating problems (see maintenance section), differences in driving cycles, or LNG measurement inaccuracies. When the dual-fuel buses were operating in their “backup” mode of diesel only, the fuel economy was within 4% of that of the control buses.

Since the beginning of the program, the PING engines used in Houston have been removed from the market in favor of a new engine design—the DDC Series 50G. Houston has plans to use the Series 50G engine in some buses running on LNG. We are in the process of adding a second site with LNG buses to the program. The additional buses will run on spark-ignited throttled engines rather than PING engines.



Compressed Natural Gas

The CNG engines operating in Miami and Tacoma are spark-ignited throttled engines; the diesel engines are unthrottled compression-ignition engines. When a diesel compression-ignition engine is redesigned into a spark-ignition engine running on natural gas (as is the case with all the CNG 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, the CNG engines have a

Figure 5. Fuel economy of the test buses***

* During cold weather the ethanol buses in Minneapolis are left idling overnight to assure smooth operation in the morning. This leads to the wide range of fuel economies shown in the figure. The average warm weather fuel economy of these buses is about 3.5 miles per diesel equivalent gallon. The average warm weather fuel economy of the diesel control buses is about 3.2 miles per gallon.

** The triangular points represent the fuel economy from chassis dynamometer testing using the standard Central Business District driving cycle.

*** The LNG fuel economy is not shown because the data are insufficient to calculate the range of monthly in-use fuel economy.

Alternative Fuel Transit Buses

lower compression ratio than their diesel counterparts: 10.5 to 1 for the CNG engines versus 16.3 to 1 for the diesel engines, which also tends to lower efficiency.

An added disadvantage for the CNG buses is their weight—they weigh about 3,900 pounds more than their diesel counterparts. This weight penalty results largely from the weight of the CNG tanks, and increases the curb weight of a bus by about a 14% (the diesel control buses have a curb weight of approximately 27,000 pounds). These three factors led us to expect that energy efficiency might be significantly reduced. A difference in the fuel economy of the CNG and diesel buses was observed both in the average results and the dynamometer results. The fuel economy of the CNG buses was about 10 to 20% lower than that of their diesel counterparts.

Alcohols

The alcohol buses also suffer from weight penalties. The alcohol option results in a weight penalty of between 1,000 and 1,500 pounds, depending on the fuel tank capacity. In addition, the alcohol buses at the Miami site have an additional weight penalty of 1,200 pounds, which is partially due to options and specifications unrelated to the alcohol fuel engine. We expected this extra weight to reduce the fuel economy of the alcohol buses.

In addition, the alcohol buses have very high compression ratios (more than 20 to 1), which was expected to lower fuel economy because of higher friction losses (such as piston

side loading). The results to date, however, indicate that the alcohol fuel buses at all the sites are performing very well, delivering fuel economy comparable to that of the diesel control buses on an equivalent energy basis. (Note that the diesel control buses at Peoria are equipped with particulate traps, which are known to lower fuel economy slightly.)

Biodiesel

The St. Louis biodiesel buses exhibited approximately 6% lower average fuel economy than the diesel control buses. Dynamometer data also showed a similar drop in fuel economy. Because the fuel economies quoted are already based on diesel equivalent gallons to eliminate any differences in fuel energy content, we did not expect this drop. We are currently investigating the cause of this drop.

In summary, the fuel economy results are in line with expectations from the various engine technologies, with the possible exceptions of the LNG dual-fuel engine, and the biodiesel buses, where the reason for the lowered fuel economy is not readily apparent.

Costs

The cost of operating alternative fuel buses versus their diesel controls can be broken down into operating and capital costs. These categories can, in turn, be broken down further. Operating costs consist of fuel, oil, maintenance, and repair costs. Capital costs consist of the additional costs of the alternative fuel bus and

Alternative Fuel Transit Buses

the costs of modifying the facilities for alternative fuel use.

Operating Costs

Fuel Costs

In September 1994, the price paid for a gallon of diesel fuel by the transit agencies varied from about \$0.47 to \$0.67. The price paid per diesel equivalent gallon varied considerably for some of the alternative fuels. The price paid for CNG was the lowest, at \$0.55 to \$0.69 per diesel equivalent gallon (this price excludes the cost of the electricity needed to compress the fuel — we are currently calculating this cost and will present it in future reports). Methanol prices have been volatile in recent years. At \$2.29 per diesel equivalent gallon, M100 was the most costly of the alternative fuels in the test program. The price paid for E95 was about \$1.80 per diesel equivalent gallon. Early in 1994 the Peoria Transit Agency switched from using E95 to E93 to take advantage of a \$0.43 per gallon “blenders credit,” which lowered their fuel cost to \$1.21 per diesel equivalent gallon. The BD20 used in Missouri cost \$1.00 per diesel equivalent gallon. In Houston, the cost of LNG has been \$0.80 per diesel equivalent gallon.

In general, alternative fuel prices have varied more 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 volatile recently. As their use increases, the price volatility of alternative fuels should moderate.

Table 2. Maintenance Costs for the Buses

		Houston LNG	Miami CNG	Tacoma CNG	Peoria E95/E93	Minn E95	Miami M100	St. Louis BD20
Number of Buses	AF	10	5	5	5	5	5	5
	DC	5	5	5	3	5	5	5
Mileage in Program	AF	375,694	87,329	293,753	388,654	57,245	193,357	165,017
	DC	431,797	311,813	537,884	225,377	170,731	368,408	204,036
Engine/fuel system related maintenance costs* per 1,000 miles	AF	\$92	\$101	\$51	\$45	\$94	\$115	\$57
	DC	\$38	\$63	\$54	\$25	\$31	\$77	\$41
Total bus maint. costs per 1,000 miles	AF	\$247	\$243	\$124	\$150	\$207	\$229	N/A
	DC	\$198	\$312	\$136	\$120	\$176	\$256	N/A

* Includes maintenance in the engine, fuel system, exhaust, cooling, air intake, ignition, cranking, charging, and general electrical areas. Excludes all other areas of the bus.

AF = Alternative Fuel

DC = Diesel Control

N/A = Not Available

Maintenance Costs

We are tracking maintenance costs on all the buses. We receive copies of all the work orders and parts replaced on the entire bus from the transit agency. The work performed and parts replaced are coded by type of work (scheduled maintenance, unscheduled maintenance, road calls, and configuration changes to the buses), as well as by vehicle subsystem such as engine, fuel, exhaust, and suspension. Labor hours are also recorded and a standard labor rate of \$15 per hour is used to calculate the labor costs for each of the transit agencies. Maintenance cost data in this report 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 cost for warranty repairs—these costs are generally paid by the transit agencies and are

Alternative Fuel Transit Buses

included in the maintenance costs presented in this report).

Table 2 shows the maintenance costs for the buses in the program. The maintenance costs have been totaled in two different ways. First, we calculated the engine/fuel system related costs. This includes the maintenance costs for the engine, fuel system, exhaust, cooling, air intake, ignition, cranking, charging and general electrical system, because these areas are most likely to be affected by the alternative fuel. We also calculated the total maintenance costs for the entire bus. An alternative fuel bus will sometimes have higher engine/fuel system related maintenance costs but these are often overshadowed by costs for repairs on other parts of the bus, such as the air conditioning and heating system.

A few words of caution are necessary in using the data. Some of the fleets have many miles on the buses; others do not. As more miles are logged by the test vehicles, a better average maintenance profile emerges from the data. Also, comparisons of maintenance data from different agencies should not be made because each agency has a different system for recording and submitting data. Alternative fuel buses should only be compared with their diesel control buses at the same site. The sections that follow summarize maintenance costs by fuel type.

Liquefied Natural Gas—Total bus maintenance costs for the Houston dual-fuel buses (which run on LNG and diesel) have been about 25% higher than for the control buses.

Engine/fuel system related costs were about \$92 per 1,000 miles for the dual-fuel buses and about \$38 per 1,000 miles for the diesel control buses. The higher costs of the dual-fuel buses are largely attributable to a few problem areas in the engine and fuel system. Significant problems occurred with the dual-fuel engine gas injectors. It is believed that dirt in the fuel injectors, possibly combined with other problems, caused the injectors to stick open. The engine manufacturer worked on the problem under warranty, but internal labor costs at Houston Metro were still significant. In addition, fuel system leaks have also been a source of cost in the LNG buses.

Compressed Natural Gas—In Tacoma, the total bus maintenance costs for CNG buses were approximately 9% lower than the diesel controls. Costs in the engine/fuel system related areas were 6% lower.

In Miami, the total maintenance costs for buses running on CNG was about 22% lower than the maintenance cost for diesel buses. The Miami CNG buses, however, have accumulated only 87,000 miles, whereas the diesel buses are one model year older and have accumulated more than 300,000 miles. Also, when the Miami diesel buses started in the program, they had already accumulated a significant number of miles. The data, therefore, reflect maintenance done during different periods in the buses' lives. We have requested back data on the diesel buses in Miami, and when we receive this information, we will re-do the analysis with comparable

mileage and periods in the buses' lives. Even though the total maintenance costs for the buses were lower for CNG than diesel, the engine/fuel system related costs were higher: about \$101 per 1,000 miles versus \$63 per 1,000 miles for the diesel buses.

Tacoma has accumulated many more miles on its CNG buses than Miami: 294,000 versus 87,000. Therefore, greater emphasis should be placed on the Tacoma data than the Miami data.

Ethanol—The ethanol buses in Peoria exhibited total bus maintenance costs about 25% higher than their diesel counterparts.

Engine/fuel system related costs for the ethanol buses were about \$45 per 1,000 miles versus \$25 per 1,000 miles for the diesel buses. The additional cost of maintaining the fuel system was the highest contributor to the overall maintenance cost increase. The high fuel system maintenance cost resulted primarily from the cost of ethanol fuel filters. The primary and secondary fuel filters together cost nearly \$105 for ethanol, compared to about \$6 for diesel. This cost differential probably results from the need to use ethanol-compatible materials and the limited demand for ethanol filters. The frequent replacement of fuel filters on the ethanol buses is a potential indicator of fuel quality problems. This was in fact the case, and Peoria recently replaced its refueling hose (which was found to be incompatible with ethanol) to make the system fully ethanol compatible.

Electrical system maintenance costs were also higher for the ethanol buses because two starters, several batteries, and nine glow plugs had to be replaced.

Total maintenance costs on the Minneapolis/St. Paul ethanol buses were about 18% higher than those for the diesel control buses. Engine/fuel system related costs were significantly higher for the ethanol buses—about \$94 per 1,000 miles versus \$31 per 1,000 miles for the diesel controls. As in Peoria, the higher maintenance cost was primarily in the fuel system area and attributable largely to the cost of the ethanol fuel filters. Again, fuel filter fouling may result from poor fuel quality caused by ethanol-incompatible materials in the fuel delivery system.

Methanol—The Miami buses running on methanol have had lower total bus maintenance costs than their diesel control buses (about 10% lower), but the costs related to the engine fuel system have been about 50% higher. Many of the buses' fuel filters had to be replaced, and methanol fuel filters cost Miami about \$72 per set versus \$6 per set for diesel. As with the Miami CNG buses, that the diesel control buses are older and have accumulated more mileage on them than the M100 buses. We have requested back data on these buses from the Miami transit agency. Adding New York as a second methanol site will aid in the cost analysis of methanol buses.

Alternative Fuel Transit Buses

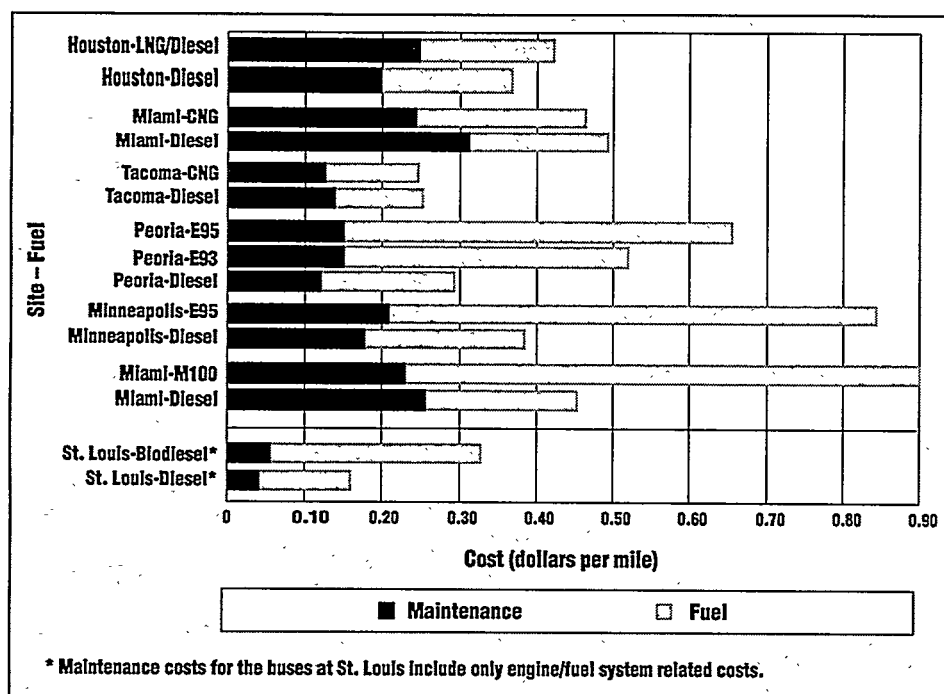


Figure 6. Average maintenance and fuel cost per mile traveled

Biodiesel—In St. Louis, we collected only maintenance data for the engine-and fuel-related systems, because the test fleet consisted of older buses that had been retrofit with re-built engines for the program. The engine/fuel system related maintenance costs for the biodiesel buses operating in St. Louis were about \$16 per 1,000 miles higher than those for their diesel counterparts. Much of this cost difference arises from having to replace several injectors on the biodiesel buses just as this report was going to press. We are investigating the cause of the replacements. Only 165,000 miles have accumulated on these buses so far. We plan to add a second biodiesel site in the near future.

Cost per Mile Traveled

Figure 6 shows the average fuel and maintenance costs per mile traveled. In all cases, the oil cost was insignificant compared to the fuel and maintenance costs. We calculated the fuel

cost per mile using the representative average in-use fuel economy and the actual fuel cost paid by the transit agencies. Neglecting the cost of compressing the natural gas, 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 fuel and maintenance costs for all of the buses using alcohol fuel and buses using BD20 have been about twice as high as the costs for buses using diesel. The costs for LNG/diesel buses have been about 14% higher than for their diesel counterparts.

Capital Costs

Adding alternative fuel buses to a fleet requires not only that the buses be acquired, but also that changes be made to the refueling, maintenance and storage facilities at the site (in most cases). The capital costs presented in this section are based on data collected from the transit agencies as well as studies of representative costs nationwide.

Additional Bus Acquisition Costs

At this time, buses running on alternative fuels are more expensive than those running on diesel. Higher engine costs represent a significant portion of this increased expense. Because these engines are early production engines, the manufacturers have been charging about \$15,000 to \$30,000 more for an alternative fuel engine than for a diesel engine. We expect that, as their production volume increases, the cost of alternative fuel engines will begin to approach that of their diesel counterparts.

There is, however, insufficient information to indicate if they will equal the cost of diesel engines some time in the future.

Biodiesel buses are the exception to the rule. Because the buses running on BD20 in this program use conventional diesel engines, there is no additional acquisition cost. (It should be noted, however, that currently biodiesel is not 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 operating on E95 to around \$20,000 for one operating on CNG. Again, fuel tanks represent no additional expense for buses running on biodiesel.

Table 3 presents estimated incremental costs (over and above a diesel-fueled bus) for new alternative fuel 40-foot transit buses. The incremental costs for a propane-fueled bus have been included because we will add a propane site to the program in the near future. These prices are only for comparison purposes; actual bus prices will vary with each transit property because of variations in vehicle specifications and the size of the order.

The current cost estimates reflect market prices after a few years of alternative fuel bus production experience. The technology is not yet

Table 3. 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

mature. Before products reach the mature stage, prices are usually higher because of production start-up problems and unknown warranty exposure. Manufacturers charge a premium for early production models of alternative fuel bus engines, but that premium should decrease over time. We obtained these cost estimates from transit agency bus bids and in conversations with bus manufacturers.

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 modifications to existing facilities vary considerably, even for one type

Alternative Fuel Transit Buses

Table 4. 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*	Unclassified electrical 18 inches above finished floor, no change*	No change*	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*	No change*	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*	No change*	—	No ignition sources in floor area (18 inches and lower). See also Note 1 below.

*If facility is certified for gasoline fuel.

Note 1: 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.

Source: Battelle

of alternative fuel. Necessary changes can include installing new refueling equipment or installing monitoring and ventilation equipment in maintenance and storage facilities.

Table 4 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 existing bus maintenance facilities and indoor storage areas. In all cases, check with local authorities for requirements in your area.

The costs of the maintenance and storage facility modifications and refueling facilities also depend on the size of the agency, as well as on state and local building codes. Table 5 lists the types of refueling facilities required for each alternative fuel. The table also shows estimates of the cost range for a refueling facility capable of refueling a 80 to 160 alternative fuel bus fleet.

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. The cost of the changes to the building, mechanical systems, and electrical systems, as well as the cost of acquiring new equipment, was taken into consideration in the analysis. The estimates were done on the basis of square footage of fueling and maintenance facilities. Cost estimates include contractor overhead and profit (assumed to be 17%) and contingency (assumed to be 25%). We assumed that the facilities were converted in three phases to allow normal operations to continue and to

Alternative Fuel Transit Buses

serve a mix of diesel, gasoline, and alternative fuel vehicles. Table 6 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 figures for typical facilities. Consult Architect and Engineering firms experienced in alternative fuels for cost estimates for your particular site.

Emissions

With funding from DOE, West Virginia University's Department of Mechanical and Aerospace Engineering designed and constructed a transportable chassis dynamometer to test emissions levels from heavy-duty vehicles. The portability of this chassis dynamometer allows a large number of on-site emissions tests to be performed 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 downtime.

The university has available a detailed description of the test procedures and the facility design.

Table 5. 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* (Baseline)	Underground Tank	Baseline	Low	Tank insurance would be needed.**
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*	Underground Tank	\$50,000 to \$100,000	Low	Tank insurance would be needed.**
Methanol* (M100 or M95)	Underground Tank	\$50,000 to \$100,000	Low	Tank insurance would be needed.**
Biodiesel Blend*	Underground Tank	\$0	Low	Tank insurance would be needed.**
Propane	Above-ground Tank	\$100,000 to \$150,000	Low	Fire suppression system required.

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

** Tank insurance is insurance that covers fuel spills from the tank.

Table 6. Incremental Facility Costs for a Fleet of 160 Alternative Fuel Buses

(In millions of 1994 \$)

	LNG	CNG	Alcohols*	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**
Bus Storage Facility	\$1.44	\$1.17	N/C	N/C	N/C**
Total	\$3.51	\$3.75	\$0.10	N/C	\$0.15

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

* Methanol and ethanol

**See Note 1 of Table 4.

Source: Battelle

Alternative Fuel Transit Buses

Typically, the transportable chassis dynamometer is set up on the grounds of the test fleet or local transit agency and the selected heavy-duty trucks or 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 the test program, WVU personnel used the standard Central Business District (CBD) 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 from WVU's testing show very high variability in emissions levels from the alternative fuel vehicles. Comparing emissions levels between heavy-duty vehicle technologies is a complex and evolving matter. Both engine certification and chassis dynamometer tests have shown that alternative fuels have a potential for substantially reducing emissions levels, but emissions are also highly dependent on the level of 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 fuel engines that were put on the road as part of a demonstration, or to assist in the development of the technology. Each manufacturer has updated its designs based on results from these demonstrations. Test results from the most recent offerings of both CNG and alcohol fueled engines suggest that

emissions can be reduced significantly.

In early testing, some of the alternative fuel buses exhibited high levels of hydrocarbon (HC) and carbon monoxide (CO) emissions. In cooperation with the engine manufacturers, WVU discovered that many of these vehicles were either improperly tuned, or had problems with injectors, catalytic converters, or mixing valves. Recently, dramatic reductions in HC and CO emissions were achieved on a CNG bus in Miami after the catalytic converter and mixing valve were replaced.

WVU's emission testing has brought to light two very important points. First, by participating in demonstration programs, the transit agencies have played an important role in developing technologies that will help improve air quality. Second, alternative fuels play an important role in emissions reduction, but engine technology development and proper vehicle maintenance are also crucial factors.

A summary of the results from emissions tests performed in 1994 on 15 CNG, 10 methanol, 8 ethanol, 5 biodiesel, along with diesel control buses for each fuel type, is provided below.

Compressed Natural Gas

Most of the CNG buses tested so far have been early versions of the Cummins L10 engine that were not certified by the Environmental Protection Agency. Cummins has since made several improvements to enhance the performance of its engines, and to reduce their emis-

sions levels. The California Air Resources Board has certified the later versions of this engine. Several L10 engines in New York City buses were upgraded to the certified configuration and tested late in 1994.

Figure 7 shows frequency distributions of the results from the CNG and diesel control buses tested by WVU. The height of the bar on the distribution diagram indicates the number of tests for which the emissions results were within the range of values shown on the x-axis. This figure shows that the particulate matter (PM) emission levels from the CNG vehicles were much lower than any of the diesel control vehicles. The CNG vehicles tested exhibited similar oxides of nitrogen (NO_x) levels to diesel controls. A significant number of vehicles tested on CNG exhibit lower CO emissions than do the diesel buses, but there were also a significant number of CNG buses with high CO levels. All of the buses exhibiting high CO levels were early uncertified versions of the L10 engine. All 6 buses with upgraded L10 engines had CO levels less than 1 gram per mile. Finally, the CNG buses tended to have higher total HC emission levels. The higher hydrocarbon emissions results are most likely due to methane emissions, which were not measured separately at the time of the tests. Because methane is considered to be non-reactive in forming ozone in the atmosphere, the Environmental Protection Agency has written the new regulations in terms of non-methane hydrocarbons. WVU plans

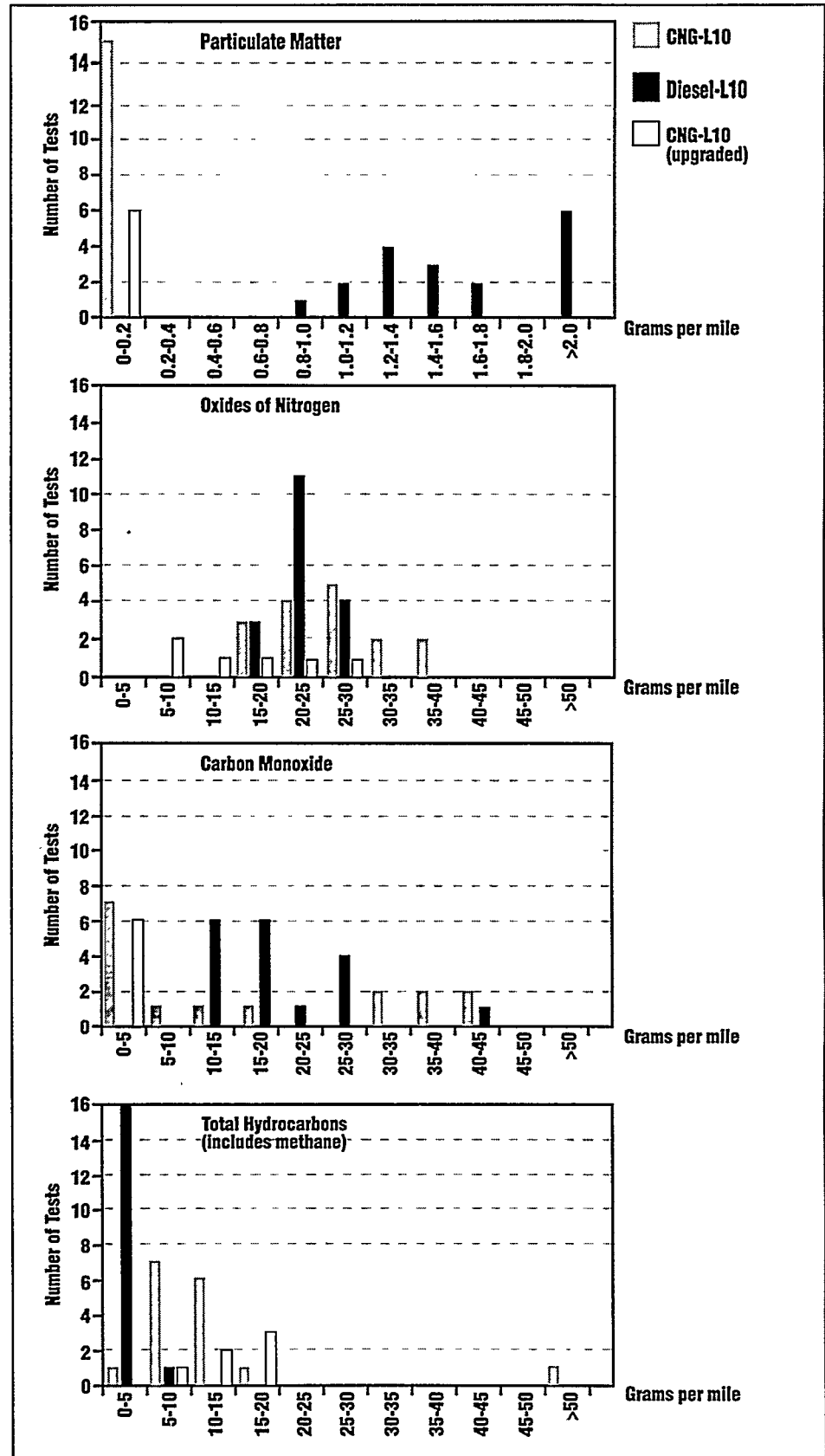


Figure 7. Frequency distribution of emissions from CNG and diesel buses

Alternative Fuel Transit Buses

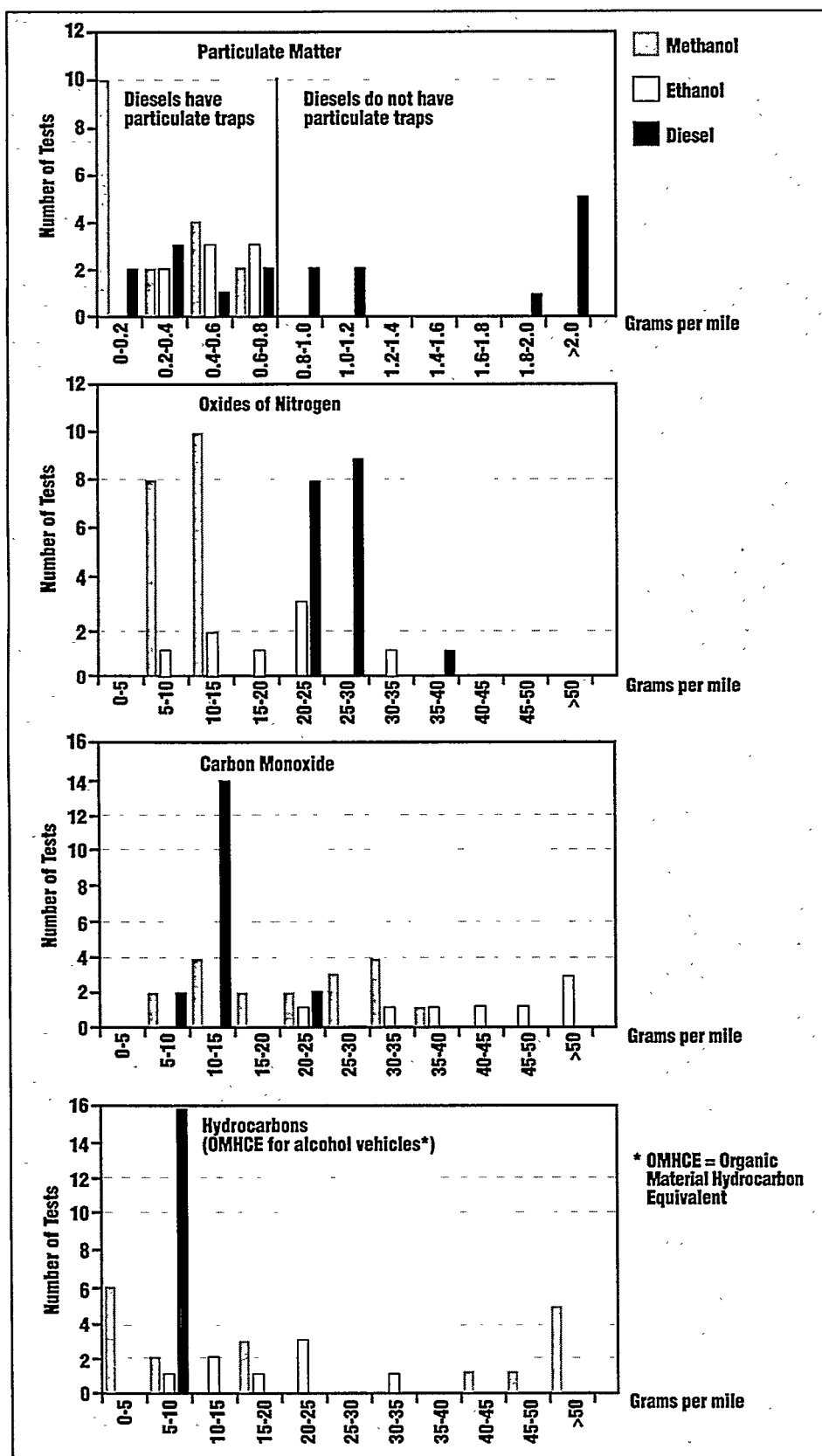


Figure 8. Frequency distribution of emissions from alcohol and diesel buses

to incorporate methane analyzers in future testing.

Alcohols

The results of chassis dynamometer emissions tests on ethanol and methanol buses powered by DDC 6V92TA engines are shown in Figure 8. The results from the alcohol buses are quite variable from site to site and bus to bus. Nonetheless, we can make some general observations. 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. Both ethanol and methanol buses emitted significantly lower levels of NO_x than did the diesel controls. The ethanol and methanol buses emitted significantly higher amounts of HC and CO. Note, however, that the HC data for the alcohol fueled buses are reported as organic material hydrocarbon equivalent, which includes a fraction of the unburned alcohol and aldehydes measured. Several newer methanol buses with DDC 6V92TA engines were tested in New York City late in 1994. These buses exhibited lower CO and HC levels than either the diesel or the older alcohol fueled buses.

Engine certification data from the DDC 6V92TA has shown emissions reductions in all four components (HC, CO, NO_x , and PM). We are investigating possible causes (including catalytic converters) for the increased HC and CO emissions levels from the test buses. Detroit Diesel Corporation has made recent

improvements to the fuel injectors, which also may help to improve emissions levels.

Biodiesel

Figure 9 shows the results from the first round of chassis dynamometer tests on five DDC 6V92TA-powered buses run on biodiesel and five run on conventional diesel. The fuel used in the biodiesel buses was a mix of 20% soy biodiesel and 80% conventional diesel fuel. In the initial round of tests, the buses using the biodiesel fuel showed average reductions in CO, total HC, and NO_x emissions compared to the diesel buses, but the results were mixed from vehicle to vehicle. The differences seen so far are not statistically significant. The average particulate matter emissions seen in this testing was about the same for both diesel and biodiesel buses. Further testing will be conducted, and we will add a second biodiesel site to the program to determine the impact of biodiesel on emissions.

Other Considerations

All of the alternative fuels except biodiesel add to the curb weight of the bus. Table 7 shows the approximate increase in curb weight of a 40-foot bus as a result of the alternative fuel option.

CNG has the greatest weight penalty because of the weight of the tanks. As tank technology advances, we expect some decrease in this penalty.

Most municipal, state, and federal highways have restrictions on the axle loading that is allowed, to prevent excessive damage to the

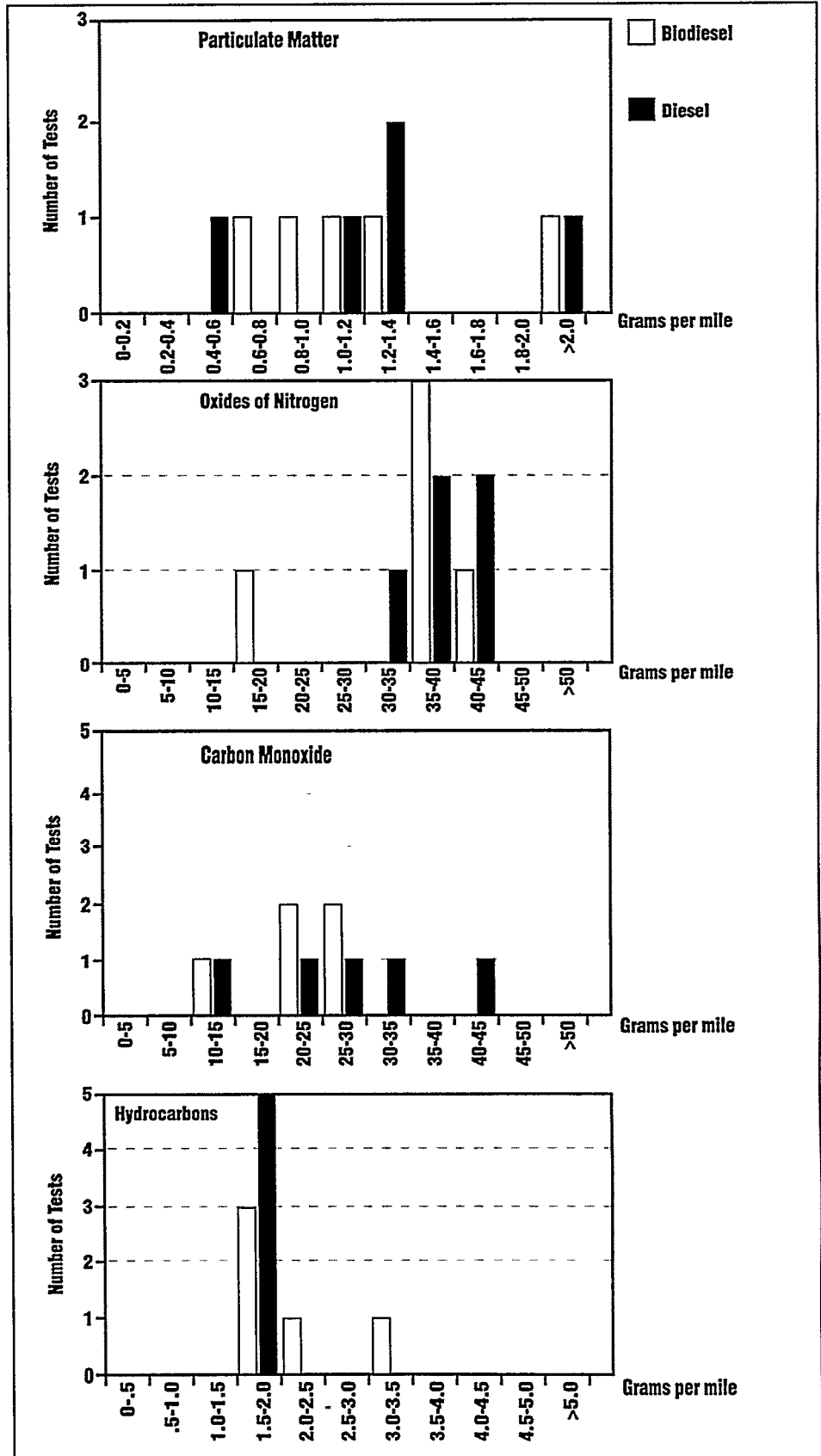


Figure 9. Frequency distribution of emissions from biodiesel and diesel buses

Alternative Fuel Transit Buses

Table 7. Approximate Increase in Curb Weight for a 40-foot Transit Bus

(The curb weight of a diesel bus is approximately 28,000 pounds.)

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

roadway. As a result, the addition of the CNG option often results in a substantial reduction in peak passenger loading, which, if enforced, will restrict the utility of the bus.

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

Future Plans

We will continue taking operations data until approximately 18 months of data have been collected from each site. WVU will also continue

emissions testing on the buses in the program once per year. We plan to have at least two sets of emissions tests done on each bus in the program.

Several new sites will also likely be added to the program in the coming year. Among the sites being considered for the program are:

- Corpus Christi, Texas (DDC Series 50 engines, running on propane)
- Portland, Oregon (Cummins L10 engines, running on LNG)
- San Francisco, California (Engines to be determined, running on biodiesel)
- Denver, Colorado (DDC Series 50 engines, running on CNG and propane).

Numbers, Numbers, Numbers!

Table 8 summarizes the key interim results of the transit bus program.

Alternative Fuel Transit Buses

Table 8. Summary of Program Results

(Preliminary results by site and alternative fuel)

AF = Alternative Fuels DC = Diesel Control

		Houston LNG	Miami CNG	Tacoma CNG	Peoria		Minn. E95	Miami M100	St. Louis BD20*
					E95	E93			
Number of buses	AF	10	5	5	5		5	5	5
	DC	5	5	5	3		5	5	5
Mileage in program	AF	375,694	87,329	293,753	269,966	118,688	57,245	193,357	165,017
	DC	431,797	311,813	537,884	157,866	67,491	170,731	368,408	204,036
Average mileage between road calls	AF	1,764	1,164	4,451	7,450		5,189	1,625	8,251
	DC	3,347	1,878	4,044	7,891		2,161	1,949	9,274
Representative MPG (diesel #2 energy equivalent)	AF	3.05	3.22	4.60	3.63	3.26	2.83	3.42	3.71
	DC	3.56	3.57	5.81	3.55	3.41	3.13	3.26	3.94
MPG ratio (AF/DC)		0.86	0.90	0.79	1.02	0.96	0.90	1.05	0.94
Fuel cost (per D2 equivalent gallon)	AF	\$0.80	\$0.69	\$0.55	\$1.83	\$1.21	\$1.80	\$2.29	\$1.00
	DC	\$0.61	\$0.64	\$0.67	\$0.61	\$0.61	\$0.65	\$0.64	\$0.47
Fuel cost per 1,000 miles**	AF	\$173	\$220	\$121	\$504	\$369	\$635	\$671	\$270
	DC	\$170	\$179	\$115	\$172	\$179	\$207	\$196	\$119
Oil cost per 1,000 miles	AF	\$1.45	\$5.54	\$1.74	\$3.94	\$7.76	\$4.41	\$3.27	\$0.69
	DC	\$1.49	\$2.99	\$1.58	\$1.75	\$2.14	\$1.55	\$2.78	\$1.69
Bus maint, cost per 1,000 miles*	AF	\$247	\$243	\$124	\$150		\$207	\$229	\$57
	DC	\$198	\$312	\$136	\$120		\$176	\$256	\$41
Total bus cost per 1,000 miles	AF	\$421	\$469	\$247	\$658	\$527	\$847	\$940	N/A
	DC	\$370	\$495	\$253	\$294	\$301	\$384	\$455	N/A

* Includes engine/fuel systems only for St. Louis biodiesel

** For LNG, fuel cost per 1,000 miles includes limited use of LNG in the dual-fuel engines. LNG fuel cost calculations do not include cost estimates for venting, which can be significant. CNG fuel cost calculations do not include the cost of compression.

N/A = Not available