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Clean Air Program

METHANOL STATUS REPORT

U.S. Department of Transportation

Urban Mass Transportation Administration

Office of Technical Assistance and Safety

Prepared by:
Battelle

March 1990

Technical Assistance—an UMTA Program

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TECHNICAL REPORT

on

METHANOL BUS DEMONSTRATION PROGRAM
DATA ANALYSIS REPORT

to

OFFICE OF TECHNICAL ASSISTANCE & SAFETY
URBAN MASS TRANSPORTATION ADMINISTRATION

MARCH, 1990

by

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This report was prepared in support of the UMTA Clean Air Program. This program includes demonstration fleets of methanol-fueled transit buses in the cities of Seattle, New York, Los Angeles, and Denver. An objective of the program is to provide information on safety, reliability, maintainability, costs and public health impacts of methanol fuel use.

This report covers the period from the introduction of methanol buses into revenue service in Seattle in September of 1987 through February of 1990. Data are presented and analyzed for mileage, fuel consumption, oil consumption, maintenance actions and safety/health/accident occurrences for the methanol buses and for diesel control buses operating on the same routes. Data are also presented for methanol buses in Jacksonville, Florida; Riverside, California; and San Rafael, California.

17. Document Analysis a. Descriptors

Buses (vehicles)	Safety	Cost
Fuels	Fuel Consumption	
Methyl Alcohol	Maintenance	

b. Identifiers/Open-Ended Terms

Transit Vehicle	Maintenance Cost
Methanol	

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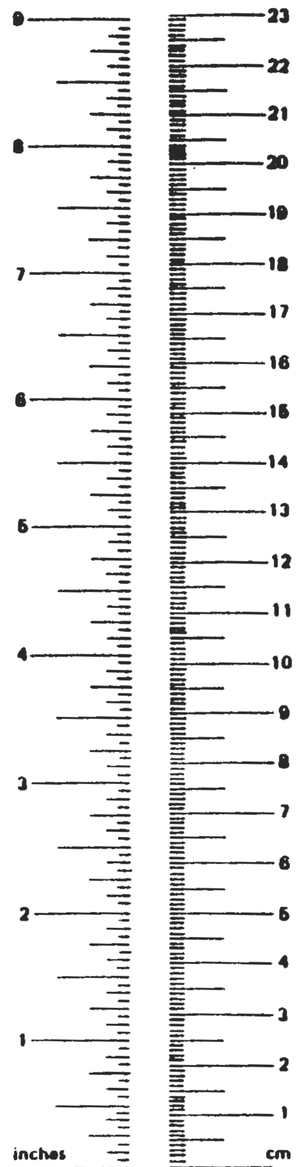
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

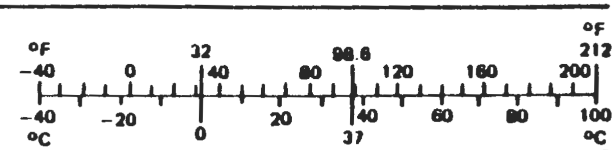
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

The methanol demonstration started in Seattle in September of 1987, in New York in May of 1988, in Denver in May of 1989, and in Los Angeles in August of 1989. This third report of the Methanol Bus Program covers the data collected during the period from the beginning of these demonstrations through February of 1990. In addition to the four properties participating in the UMTA program, data have been received from three other properties, which are currently operating methanol buses: Riverside Transit Agency, Golden Gate Transit, and Jacksonville Transportation Authority. These data are also presented in this report.

The data base was derived from almost two million miles of revenue operation of methanol demonstration buses. The methanol buses have shown great improvements from the first troublesome prototype at Golden Gate to the recent experience at Seattle where methanol buses are providing revenue service miles similar to diesels. For the first 33 months of operation, the methanol buses were roughly 18 percent less fuel efficient, on an energy equivalence basis, than the diesel control buses. The methanol buses required more frequent maintenance actions and more maintenance labor hours per mile than the diesel control buses. Two engine problems have emerged as standout issues. The first is short glowplug life, which appears to have been solved by recent changes to the glowplug controller. The second, plugging of fuel injectors, remains to be solved by DDC (though the M.A.N. methanol buses in the demonstration program have never had this problem). It must be noted that results to date are preliminary and that the methanol engines are prototype designs which are not yet in production.

No significant safety, health, or accident issues arose relating to the use of methanol in transit operations during the 33 month report period. Methanol fuel fires have occurred in some buses but have not injured anyone or caused major damage to the buses. Methanol vapor level measurements were made at Seattle Metro at a fueling station and in a maintenance shop, and in a maintenance shop in Denver. They showed compliance with all pertinent OSHA regulations and other recommended human exposure limits.

METHANOL BUS PROGRAM
DATA ANALYSIS REPORT

1.0 INTRODUCTION

The transit industry is considering methanol fuel as an alternative to diesel fuel for powering heavy-duty transit buses. The interest in neat methanol as a fuel arises from the need to meet federal Environmental Protection Agency (EPA) 1991 transit bus emission standards and from concerns of possible future shortages and increased cost of diesel fuel. This report is the third data analysis report of the demonstration designed to evaluate the effects of methanol fuel use on transit operations.

1.1 Background

The Urban Mass Transportation Administration (UMTA) of the U.S. Department of Transportation (DOT) has established a Methanol Bus Demonstration Program to develop information on a number of concerns that arise with the introduction of the new fuel. Data are being collected and analyzed from several different demonstration sites to provide transit and government officials with the information necessary to evaluate the effects of methanol fuel use on transit operations. UMTA's intent is to develop a data base of the impacts on transit operations of changing from diesel fuel to methanol fuel for heavy-duty transit buses.

UMTA's principal role is to provide funds for assisting grantee participation in the program and to collect, analyze and disseminate information to the transit industry on the use of methanol fuel in transit operations.

1.2 Key Concerns

The key concerns for methanol fuel use are reliability, maintainability, costs, safety, and public health. Federal governmental organizations other than UMTA will be taking active roles in the overall program, including the analysis of emissions and environmental data to add to the data base information on the safety and public health issues. These organizations are the EPA, the National Institute for Occupational Safety and Health (NIOSH) of the Department of Health and Human Services, and the Argonne National Laboratory of the U.S. Department of Energy.

Battelle Columbus Division (Battelle) is the technical support contractor for UMTA, responsible for the analysis of data collected during the program. Battelle manages the data collection activities of the program through interfaces with all of the transit agencies involved in the program. Battelle is responsible for the assembly of program data collected by the transit agencies, the analysis of the data, the publication of reports, and the dissemination of information to the transit industry.

1.3 Demonstration Sites

The methanol bus demonstration program involves a total of 59 methanol fueled buses operating under a variety of operational and environmental conditions. The demonstrations includes both hot and cold climates, high and low altitudes, and various types of service operations (commuter, arterial, and central business district). A listing of transit agencies that are participating in the program is given in Table 1.

Although the experiences of all transit agencies listed in Table 1 are important and are included in these reports, Battelle regularly collects and analyzes data from only the four agencies with the largest number of methanol buses. These agencies are Seattle Metro, Triboro Coach Corporation, Southern California Rapid Transit District, and Denver Regional Transportation District.

1.4 Experimental Design

The experimental design provides a side-by-side comparison of equal numbers of methanol and diesel control buses. This permits the transit manager to make "real-world" informed decisions on a comparative basis.

Data are collected and analyzed from each transit agency separately, but included in the same reports. No comparative analysis of the data between the demonstration sites is planned.

TABLE 1. LISTING OF METHANOL DEMONSTRATIONS WITH STANDARD SIZE BUSES

	Transit Agency	Demonstration Status	Number of Buses	Manufacturer	Bus Engine	Date of Delivery	Date of Revenue Service
(1)	Golden Gate Transit	Revenue Operations	1 1	GMC MAN	6V92TA D2566FMUH	Aug 1983 Jul 1984	Sep 1984 Jul 1984
(2)	Florida Department of Transportation	Terminated October 1988	3	GMC (Blitz Remanufacturer)	6V71NA	May 1986	Jun 1986 Oct 1988
(3)	Seattle Metro	Revenue Operations	10	MAN	M22566MLUH 1987	First Qtr 1987	Jun 1987
(4)	Riverside Transit Agency	Revenue Operations	3	GMC (Retrofit)	6V92TA	Oct 1987	Nov 1987
(5)	Triboro Coach Corp.	Revenue Operations	6	GMC	6V92TA	Dec 1987	Apr 1988
(6)	Southern California Rapid Transit District	Revenue Operations	30	TMC	6V92TA	May 1989 Jan 1990	Jun 1989
(7)	Denver Regional Transportation District	Revenue Operations	5	TMC	6V92TA	Mar and May 1989	Jun 1989

2.0 PURPOSE AND ORGANIZATION

This report contains data collected from the participating transit agencies and analyzed by Battelle. It includes all available data for the 33 month period from September, 1987 through February, 1990. This report includes all the data contained in the two previous data analysis reports.

2.1 What This Report Addresses

Three of the key concerns are reliability, maintainability, and cost. Data from unscheduled maintenance are used to characterize the reliability and maintainability of the methanol and diesel fleets. The frequency, duration, and type of unscheduled maintenance are indicators of reliability. An analysis of unscheduled maintenance, especially from the standpoint of repair duration, presents a picture of the degree of maintainability of each type of bus. Comparative consumables cost information is obtained from analyses of fuel and oil consumption data.

The report also contains information concerning safety and public health. One of these concerns was addressed by investigations of the methanol vapor levels in maintenance and servicing work areas. The results of these investigations at Seattle Metro and at Denver RTD are documented in separate reports[1,2,3]. Safety concerns are addressed by an analysis of incident reports concerning any of the buses in both the methanol demonstration and diesel control fleets.

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[1] Murphy, M. and Turanski, A., "Data Collection on Methanol Vapor Exposure", UMTA, Office of Bus and Paratransit Systems, November, 1987.

[2] Murphy, M. and Krenelka, T., "Methanol Vapor Measurements in a Vehicle Maintenance Pit at Seattle Metro Ryerson Base", UMTA, Office of Technical Assistance and Safety, October, 1988.

[3] Murphy, M.J. and Krenelka, T., "Methanol Vapor Exposure Measurement at Denver RTD", UMTA, Office of Engineering Evaluation, October, 1989.

2.2 Report Organization

Information from each transit agency is reported in separate sections of this report. The section for each demonstration site includes Operations and Maintenance Data Analysis, Safety and Health Data Analysis, and Incident Data Analysis. The scope of information is similar for each of the reporting agencies; however, the level of detail varies with each agency according to the level of detail provided in the data they report.

3.0 OPERATIONS AND MAINTENANCE DATA ANALYSIS

Analyses of consumables usage, unscheduled maintenance, and special tests performed on methanol and diesel control buses are presented in this section. Brief climatological and geographical descriptions of the demonstration site city are also given as the introduction to each section.

Descriptions of routes served are part of this section as well. This information is important to assure similar usage of the demonstration and control buses for equitable comparisons.

3.1 Analysis Approach

The data provided by transit operators are analyzed on a monthly basis. Key data include miles traveled, amounts of fuel and oil consumed, number of engine and fuel system repairs, and number of in-service breakdowns (roadcalls). Some transit operators are able to provide additional details about maintenance actions, such as descriptions of the source of a repair action, costs, or explanation of the mechanical failure. Table 2 shows the formulae used to analyze the data on fuel and oil use, and Table 3 shows the formulae used to analyze the unscheduled maintenance data. Results are rounded for presentation throughout this report. When insufficient data are available for a calculation, "N/A" is entered in the table of results.

3.2 Safety, Health and Accident Data Analysis

This section of the report addresses any safety or health incident occurring at the demonstration site that meets two criteria: a) the incident is reported to Battelle by the transit agency, and b) the incident is related to the safety or health of people interacting with either the methanol demonstration or the diesel control buses. Information on the probable cause, extent of injury or damages, and corrective actions taken are reported.

TABLE 2. MONTHLY CONSUMABLES DATA FORMULAE

Performance Measure	Formula
(1) Average Bus Mileage	Total Number of Fleet Miles / Total Number of Fleet Buses in Service
(2) Average Miles Per Gallon (Fuel)	Total Number of Fleet Miles / Total Number of Fleet Gallons of Fuel Consumed
(3) Average Miles Per Energy Equivalent*	Methanol Average Miles Per Gallon x 2.28
(4) Percent Less Miles Per Energy Equivalent for Methanol	(Diesel MPG - Methanol MPEQ) x 100% / Diesel MPG
(5) MPG Ratio	Diesel MPG / Methanol MPG
(6) Cost Per Mile, Fuel, Average Bus	Cost Per Gallon Fuel / Average Fleet Miles Per Gallon (Fuel)
(7) Average Miles Per Quart (Oil)	Total Number of Fleet Miles / Total Number of Fleet Quarts of Oil Added
(8) Cost Per 1000 Miles, Oil, Average Bus	Cost Per Quart of Oil x 1,000 / Average Fleet Miles Per Quart (Oil)

* Definition of Energy Equivalent: Miles-per-gallon data achieved by the methanol buses are multiplied by 2.28 so that the fuel economy can be compared on an equivalent energy basis. This formulation stems from the fact that a gallon of methanol has about one-half the energy content of a gallon of diesel fuel, based on lower heating values. See Appendix C for full discussion.

TABLE 3. UNSCHEDULED MAINTENANCE DATA FORMULAE

Performance Measure	Formula
(1) Average Number of UWO's* Per 1,000 Mile	Total Number of UWO'S x 1,000 / Total Fleet Miles
(2) Average Labor Hours Per UWO	Total Number of UWO Labor Hours / Total Number of UWO's
(3) UWO Labor Hours Per 1,000 Mile	Total Number of UWO Labor Hours x 1,000 / Total Fleet Miles
(4) Average Mileage Between all UWO's	Total Number of Fleet Miles / Total Number of UWO's
(5) Average Mileage Between Each UWO Type	Same as (4) above, but specific to each UWO type
(6) Average Mileage Between Each Repair System UWO Type	Same as (4) above, but specific to all repairs coded engine, fuel system, etc.

* Note: UWO refers to all unscheduled work orders for maintenance.

3.3 Status of DDC Methanol Bus Engine

Developmental versions of the DDC methanol fueled 6V-92TA-M engine are used in all of the methanol demonstration buses except the Seattle Metro M.A.N.'s and the Jacksonville 6V-72 methanol conversions. The 6V-92TA-M is a 6 cylinder, two stroke, vee-type engine with both a turbo charger and a blower. The methanol 6V-92 has undergone significant improvement during the course of these methanol demonstrations, and has had several configurations in service. DDC has refined the engine to improve performance, reduce emissions, improve reliability, and increase efficiency.

Early versions of the 6V-92TA-M engine had very limited glowplug life. Recent data indicate that DDC has solved the problem by using a redesigned glowplug controller with other engine design changes. The new controller is a solid state unit which uses pulse-width modulation to greatly reduce glowplug stress while maintaining proper ignition. In addition, the compression ratio has been raised from 19:1 to 23:1. This reduces the need for glowplugs, although glowplugs are still required for some operating conditions. The higher compression ratio also increases fuel economy and decreases emissions. The peak cylinder pressure in the 23:1 methanol 6V-92TA-M is actually lower than the 19:1 diesel fueled 6V-92TA. Because of methanol's lower energy content, more than twice as much methanol as diesel fuel must be injected in each stroke. This spreads the fuel injection period for methanol over a greater time period. When combined with the good combustion characteristics of methanol, the result is much lower peak pressure and mechanical stress on the methanol engine.

DDC has implemented a half-engine idle on some of the latest methanol engines as a test. These engines idle on only three cylinders to reduce emissions. No decision has yet been made as to whether the production methanol engines will use the half-engine idle. Improvements have also been made to the details of liner port height, exhaust cam profiles, turbocharger matching, and blower bypass implementation. Secondary fuel filters effective to one micron have also been added.

DDC is still working on one major outstanding problem - injector reliability. All prototype methanol 6V-92TA-M configurations so far have suffered from injector plugging and (to a lesser extent) scoring and seizing. Deposits are building up in just a few thousand miles which require injector replacement. The problem is under study by DDC, and they feel they are approaching a solution.

The source of the deposits is now known to be lube oil additives. DDC has laboratory tests which indicate that when methanol comes in contact with lube oil, the lube oil additives will migrate out of the oil into the methanol by extraction, leaving an insoluble precipitate. The oil additives are transferred to the methanol in the fuel injector body. They eventually travel with the fuel to the injector tip and are deposited. The deposits quickly plug the injector tip.

DDC is approaching the problem by searching for a combination of oil additives and fuel additives that will eliminate the problem.

They have used fuel additives with common lube oil in their laboratories and report complete elimination of scoring, seizing, and plugging. DDC feels that tip plugging has been eliminated completely with these better combinations of fuel and oil additives.

The methanol fuel additive has been developed by the Lubrizol company and DDC. It is expected to be used at a 0.06 percent concentration, and to have a very low cost impact on the fuel price. The additive is primarily detergents, and is similar to the additives used in gasoline.

DDC has designed a high strength 9-hole injector tip which significantly improves emissions over the current 8-hole tip. Early versions of the methanol 6V-92TA-M had 12-hole low-sac injectors which broke due to needle impact. The new 9-hole injector tip has been redesigned to be strong enough to withstand these forces.

DDC reports that the latest methanol 6V-92TA-M engine will comfortably meet the 1991 bus emissions without any exhaust aftertreatment by catalytic converter. DDC plans to offer various catalytic converters as options for customers who wish to exceed federal emissions standards.

According to DDC, the methanol 6V-92TA-M will be offered for sale in 1991. The exact date of availability and numbers of engines offered will depend on the speed of their progress with improving methanol injector life.

No emissions data have been published which accurately reflect the emissions levels of the latest methanol 6V-92TA-M engines. Existing emissions data which have been published are either results for early engine prototypes or have shortcomings in the test procedures. Complete and accurate emissions data for the production methanol 6V-92TA-M should be available in 1990.

3.4 Summary of Methanol Safety

The experience to date includes 33 months and almost 2 million miles of revenue service by methanol buses. During this time, there have been no reported injuries, illnesses, or worker's compensation claims related to the use of methanol. There have, however, been three small engine fires in methanol buses.

Two of these fires occurred at Jacksonville, and were exhaust fires. The Jacksonville buses used DDC 6V-71 engines. In both cases, a glowplug failure is reported to have caused unburned methanol to be dumped into the exhaust system, where it ignited. The methanol fires were contained inside the exhaust system in both cases, although the extreme heat of the exhaust system caused damage to nearby structure.

The third methanol fire occurred in Seattle in a M.A.N. bus with a M.A.N. 4-cycle spark ignition engine. The fire was reported to be caused by a faulty fuel line fitting that leaked methanol onto hot engine parts. Damage was minor, consisting of burned wires and hoses. This safety incident is the only one reported by Seattle Metro in 33 months and 1,021,000 miles of methanol bus operation.

Triboro has reported no safety incidents in 24 months and 393,000 miles of methanol bus operation.

Denver RTD and SCRTD have not reported any safety incidents. Denver has been operating for 10 months and 145,700 miles, and SCRTD has been operating for 10 months and 304,000 miles.

3.5 Seattle Metro

3.5.1 Demonstration Site Introduction

Seattle is the largest city in the state of Washington, situated on a neck of land between Elliott Bay (saltwater Puget Sound) and Lake Washington (freshwater). It is 125 nautical miles from the Pacific Ocean and 110 miles south of the Canadian border. The 1988 adjusted population census shows a population of 488,474 within the city limits of about 83 square miles for a population density of 5,879 per square mile. The larger Seattle metropolitan area contains about 1,606,800 people. The core city is situated on a series of hills, some reaching from sea level to 500 feet in elevation.

Average annual precipitation is 33.44 inches, with about 80 percent of this falling between October and April. The average maximum daily temperature in July is 75°F, and the average January minimum is 36°F. Frequent overcast days (50 percent sunshine) give the city its reputation of being rainy. Average snowfall is less than 9 inches per year.

3.5.2 Bus Specifications

As listed in Table 1, the Seattle Metro demonstration involves ten M.A.N. methanol buses and a control fleet of ten M.A.N. diesel buses. All are using M.A.N. 4 stroke 2566 type diesel engines. Much larger fuel tanks made of stainless steel are used in the methanol buses, as are stainless steel fuel lines. The methanol engines have higher volume fuel injectors, and are fitted with spark plugs.

The methanol buses are similar to the diesel buses, except for modifications to the engine, fuel system, and some associated components. The demonstration buses began revenue operation in September of 1987. At the beginning of the demonstration period, the average methanol bus had already accumulated about 6,200 miles while the average diesel control bus had already accumulated about 44,800 miles. The description of the methanol bus are given in Appendix A, Table A1. The description of the diesel bus are given in Appendix A, Table A2.

During April of 1989, after 19 months of revenue service, the methanol engines were extensively modified. This engine rebuild included the following items:

1. Crankshaft Bearings. Crankshaft bearings using a new material were installed.
2. Pistons. New pistons with a hard anodized surface and a larger radius at the firing bowl edge were installed.
3. Liners. All cylinder liners were replaced without modifications.
4. Cylinder Heads. New cylinder heads with modified valves and valve seats were installed.
5. Injectors. New injectors with modified pressure springs and spring seats and raised operating pressure (230 + 10 bar) were installed.
6. Injector Pump. New delivery valves were installed.

These modifications were accomplished after M.A.N. examined a methanol engine which was sent to them in Germany. This engine (as well as others) was found to have cracked pistons. It should be noted that cracked pistons are not unique to the methanol engines; diesel M.A.N. engines of similar design have also shown cracked pistons.

M.A.N. reported the following findings upon examination of the methanol engine:

1. Injection Pump
   - Small areas of flaking nickel plating in suction area presumably due to poor surface preparation.
   - A worn delivery valve for one cylinder.
2. Injectors
   - The pressure setting of the injectors had dropped from 185 bar to 90-135 bar due to wear on pressure springs and their seats.

3. Cylinder Heads
   - Valves and valve seats unusually worn.
4. Pistons
   - All six pistons cracked on injector side.
5. Piston Rings, Cylinder Liners, Rod Bearings:
   - No unusual wear
6. Crankshaft Bearings
   - Some wear and unusual deposits found on all main bearings.

The engine rebuild of April, 1989 was performed on all ten methanol engines to correct these problems.

3.5.3 Bus Routing

The 18 routes that are served by buses from Seattle Metro's demonstration fleet all have some portion operating in the downtown Seattle business district. All routes operate over a hilly terrain with two routes having rather steep grades of 18 to 20 percent. One route (No. 370) has a significant amount of freeway operation. The routes are listed and described in detail in Appendix B, Table B1. Each route is served by both methanol and diesel control buses.

3.5.4 Consumables

This subsection is a comparison of the fuel and make-up oil consumption characteristics of the methanol demonstration bus fleet and the diesel control bus fleet at Seattle Metro. These characteristics include miles operated, consumables used, and consumable costs. All data were sent to Battelle by Seattle Metro on a monthly basis. The data consist of miles traveled and consumption of fuel and make-up oil for both methanol and diesel buses during each of the months from September of 1987 through February of 1990.

3.5.4.1 Fuel Usage Comparisons. As seen in Table 4, the diesel control fleet has accumulated about 5 percent more mileage to date than the methanol demonstration fleet (1,070,198 miles versus 1,021,845 miles, respectively). The diesel fleet used substantially less fuel (254,000 gallons

TABLE 4. FUEL USAGE TOTALS AND AVERAGES FOR SEATTLE METRO FOR THE PERIOD SEPTEMBER 87 THROUGH FEBRUARY 90

1.	Total Fleet Mileage (Miles)	(M) (D)	1,021,845 1,070,198
2.	Total Fleet Fuel Usage (Gal)	(M) (D)	677,080 254,280
3.	Average Bus Mileage (Miles)	(M) (D)	102,185 107,020
4.	Average Miles Per Gallon (MPG)	(M) (D)	1.51 4.21
5.	Average Miles Per Energy Equivalent (MPEQ)	(M)	3.44
6.	% Less Miles Per Energy Equivalent for Methanol than for Diesel	(M)	18.3 %
7.	Average MPG Ratio (D/M)		2.79
8.	Average Fuel Cost Per Gallon ($)	(M) (D)	$ 0.636 $ 0.511
9.	Average Fuel Cost Per Mile ($/Mile)	(M) (D)	$ 0.42 $ 0.12
10.	Total Fleet Fuel Cost ($)	(M) (D)	$ 431,656 $ 129,860
11.	Total Fleet Make-Up Oil Consumption (Qt)	(M) (D)	1,583 2,790
12.	Average Fleet Miles Per Quart	(M) (D)	645 384

(D) - Diesel fueled control buses
(M) - Methanol fueled test buses

versus 688,000 gallons), and had a lower average fuel cost per mile ($0.12 versus $0.43) than the methanol fleet.

Figure 1 shows the fuel economy (on an energy equivalent basis) of the methanol and diesel fleets and demonstrates remarkable parallelism between the diesel and methanol fuel economy. Fuel economy has generally risen and fallen for both methanol and diesel throughout the demonstration. Fuel economy is defined as the miles per gallon of fuel obtained by a methanol or diesel bus in revenue service. Since a gallon of diesel fuel contains roughly twice the energy of a gallon of methanol fuel, the data for miles per gallon of fuel reported for the methanol fleet are converted to an energy equivalent basis by multiplying the methanol fuel economy data by a constant (2.28). This constant is the ratio of the volumetric low heat values. A complete discussion of the relative energy content of the two fuels and the reasons for choosing the 2.28 ratio are contained in Appendix C. This treatment allows an equitable comparison of the energy consumption data between the two fleets. Therefore, fuel economy is shown with miles per gallon (for the diesel fleet) and miles per energy equivalent gallon (for the methanol fleet) on the same scale in Figure 1. Figure 2 shows the actual ratio of diesel MPG to methanol MPG along with the theoretical minimum ratio of 2.28 based on fuel heating values. Complete fuel usage data for the demonstration fleet are presented in Table 5.

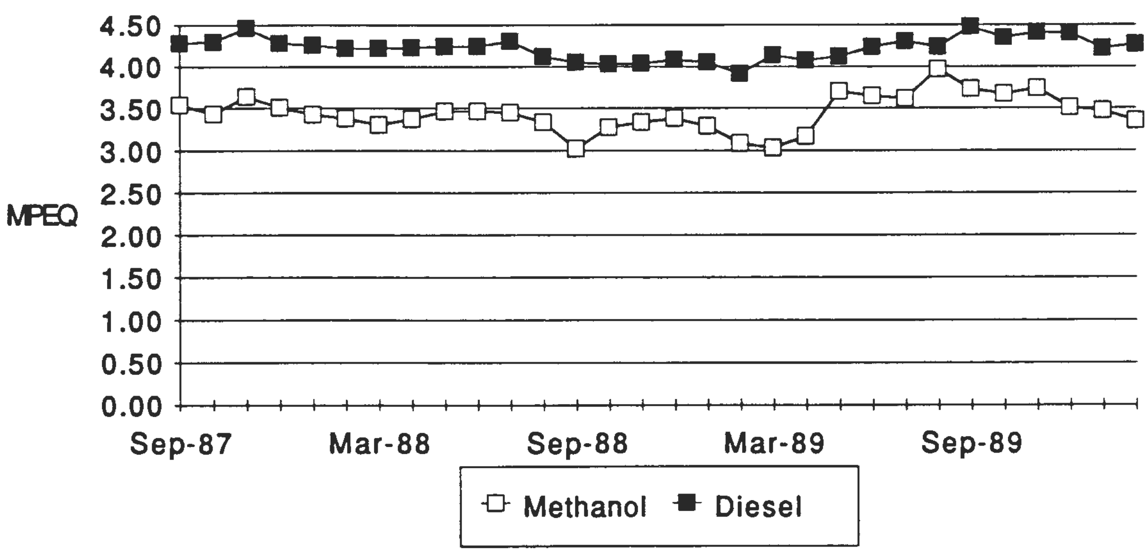

FIGURE 1. FUEL ECONOMY COMPARISON FOR SEATTLE METRO

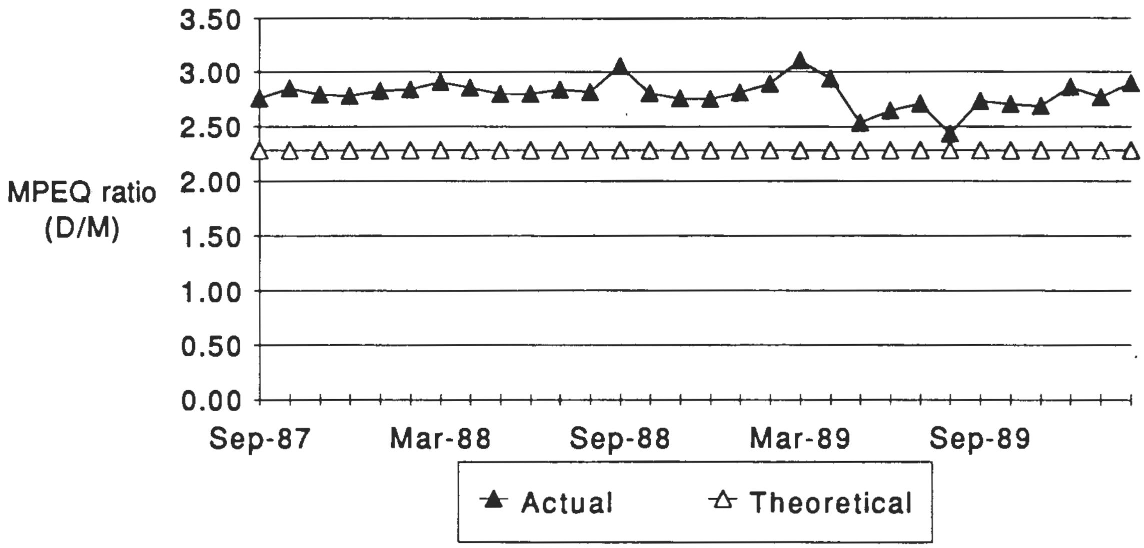

FIGURE 2. FUEL ECONOMY RATIO FOR SEATTLE METRO
(DIESEL MPG/METHANOL MPEQ)

Figure 3 shows the equivalent cost of fuel each month for both diesel and methanol. The actual cost for a gallon of methanol has been multiplied by 2.28 in this chart also.

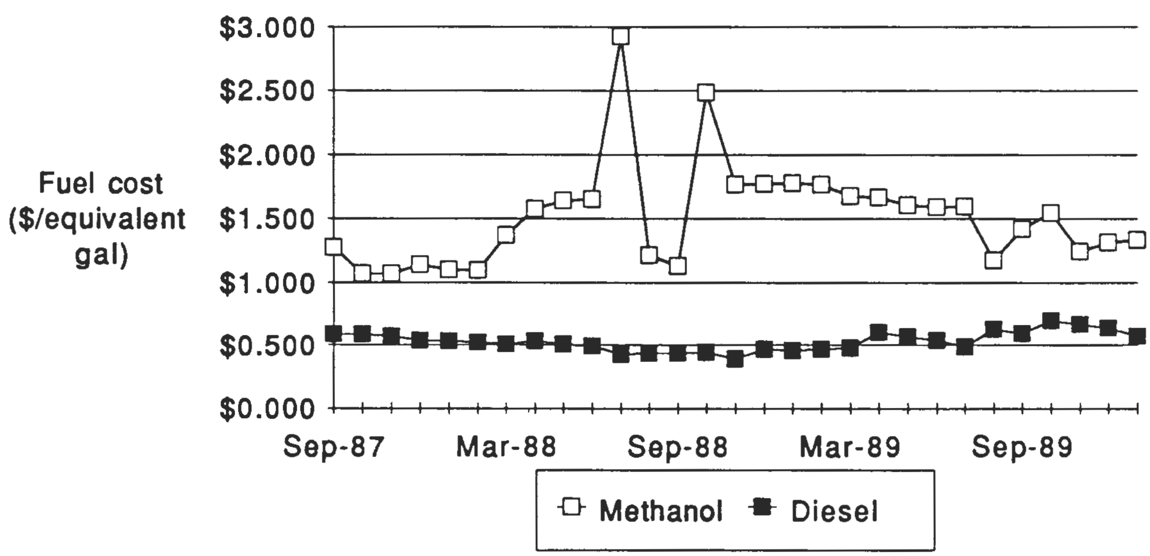

FIGURE 3. EQUIVALENT FUEL PRICES AT SEATTLE METRO

TABLE 5. FUEL CONSUMPTION FOR SEATTLE METRO

		Sep-87	Oct-87	Nov-87	Dec-87	Jan-88	Feb-88
1. Total Fleet Miles	(M)	23,928	26,901	31,935	40,086	41,488	40,562
	(D)	30,318	30,746	29,071	29,211	27,851	31,087
2. Total Fleet Fuel Usage	(M)	15,415	17,858	19,997	26,044	27,574	27,321
(in Gallons)	(D)	7,087	7,163	6,521	6,831	6,550	7,376
3. Average Fleet Miles	(M)	1.55	1.51	1.60	1.54	1.50	1.48
Per Gallon	(D)	4.28	4.29	4.46	4.28	4.25	4.21
4. Average Fleet Miles Per Energy Equivalent	(M)	3.54	3.43	3.64	3.51	3.43	3.38
5. Percent Less Miles Per Energy Equivalent	(M)	17.3%	20.0%	18.3%	17.9%	19.3%	19.7%
6. Average MPG Ratio (D/M)		2.76	2.85	2.79	2.78	2.83	2.84
7. Fuel Cost Per Gallon	(M)	$ 0.560	$ 0.470	$ 0.470	$ 0.500	$ 0.483	$ 0.480
	(D)	$ 0.588	$ 0.586	$ 0.572	$ 0.538	$ 0.534	$ 0.521
8. Fuel Cost Per Mile,	(M)	$ 0.36	$ 0.31	$ 0.29	$ 0.32	$ 0.32	$ 0.32
Average Bus	(D)	$ 0.14	$ 0.14	$ 0.13	$ 0.13	$ 0.13	$ 0.12
9. Fuel Cost for Total	(M)	$ 8,632	$ 8,393	$ 9,399	$13,022	$13,318	$13,114
Fleet Miles	(D)	$ 4,167	$ 4,198	$ 3,730	$ 3,675	$ 3,498	$ 3,843
10. Make-Up Oil Usage	(M)	4.00	7.70	13.00	50.10	44.00	48.00
(Quarts)	(D)	94.60	61.50	64.20	76.60	80.80	84.40
11. Average Fleet Miles	(M)	5,982	3,494	2,457	800	943	845
Per Quart	(D)	320	500	453	381	345	368

TABLE 5. FUEL CONSUMPTION FOR SEATTLE METRO (CONTINUED)

		Mar-88	Apr-88	May-88	Jun-88	Jul-88	Aug-88
1. Total Fleet Miles	(M)	38,400	36,063	31,477	31,477	36,155	34,587
	(D)	35,253	40,703	38,839	38,839	39,528	34,864
2. Total Fleet Fuel Usage (in Gallons)	(M)	26,507	24,377	20,723	20,723	23,871	23,618
	(D)	8,363	9,629	9,152	9,152	9,188	8,461
3. Average Fleet Miles Per Gallon	(M)	1.45	1.48	1.52	1.52	1.51	1.46
	(D)	4.22	4.23	4.24	4.24	4.30	4.12
4. Average Fleet Miles Per Energy Equivalent	(M)	3.30	3.37	3.46	3.46	3.45	3.34
5. Percent Less Miles Per Energy Equivalent	(M)	21.6%	20.2%	18.4%	18.4%	19.7%	19.0%
6. Average MPG Ratio (D/M)		2.91	2.86	2.79	2.79	2.84	2.81
7. Fuel Cost Per Gallon	(M)	$ 0.602	$ 0.693	$ 0.721	$ 0.725	$ 1.284	$ 0.533
	(D)	$ 0.508	$ 0.534	$ 0.507	$ 0.492	$ 0.428	$ 0.437
8. Fuel Cost Per Mile, Average Bus	(M)	$ 0.42	$ 0.47	$ 0.47	$ 0.48	$ 0.85	$ 0.36
	(D)	$ 0.12	$ 0.13	$ 0.12	$ 0.12	$ 0.10	$ 0.11
9. Fuel Cost for Total Fleet Miles	(M)	$15,957	$16,893	$14,941	$15,024	$30,651	$12,588
	(D)	$ 4,248	$ 5,142	$ 4,640	$ 4,503	$ 3,932	$ 3,698
10. Make-Up Oil Usage (Quarts)	(M)	51.00	45.00	47.50	25.00	54.00	26.60
	(D)	89.80	104.00	95.90	72.40	74.80	57.40
11. Average Fleet Miles Per Quart	(M)	753	801	663	1,259	670	1,300
	(D)	393	391	405	536	528	607

TABLE 5. FUEL CONSUMPTION FOR SEATTLE METRO (CONTINUED)

		Sep-88	Oct-88	Nov-88	Dec-88	Jan-89	Feb-89
1. Total Fleet Miles	(M) (D)	31,605 33,970	28,657 36,095	26,755 36,813	39,067 40,312	33,744 37,695	33,048 32,837
2. Total Fleet Fuel Usage (in Gallons)	(M) (D)	23,809 8,381	19,938 8,968	18,294 9,131	26,354 9,878	23,396 9,309	24,415 8,396
3. Average Fleet Miles Per Gallon	(M) (D)	1.33 4.05	1.44 4.02	1.46 4.03	1.48 4.08	1.44 4.05	1.35 3.91
4. Average Fleet Miles Per Energy Equivalent	(M)	3.03	3.28	3.33	3.38	3.29	3.09
5. Percent Less Miles Per Energy Equivalent	(M)	25.3%	18.6%	17.3%	17.2%	18.8%	21.1%
6. Average MPG Ratio (D/M)		3.05	2.80	2.76	2.75	2.81	2.89
7. Fuel Cost Per Gallon	(M) (D)	$ 0.495 $ 0.436	$ 1.090 $ 0.444	$ 0.776 $ 0.393	$ 0.778 $ 0.469	$ 0.780 $ 0.454	$ 0.775 $ 0.465
8. Fuel Cost Per Mile, Average Bus	(M) (D)	$ 0.37 $ 0.11	$ 0.76 $ 0.11	$ 0.53 $ 0.10	$ 0.52 $ 0.11	$ 0.54 $ 0.11	$ 0.57 $ 0.12
9. Fuel Cost for Total Fleet Miles	(M) (D)	$11,785 $ 3,654	$21,733 $ 3,982	$14,196 $ 3,589	$20,504 $ 4,633	$18,239 $ 4,226	$18,917 $ 3,904
10. Make-Up Oil Usage (Quarts)	(M) (D)	25.30 76.80	52.00 107.00	75.00 80.50	70.00 108.50	75.00 97.90	52.00 63.10
11. Average Fleet Miles Per Quart	(M) (D)	1,249 442	551 337	357 457	558 372	450 385	636 520

TABLE 5. FUEL CONSUMPTION FOR SEATTLE METRO (CONTINUED)

		Mar-89	Apr-89	May-89	Jun-89	Jul-89	Aug-89
1. Total Fleet Miles	(M)	26,231	22,989	38,878	35,556	30,173	30,548
	(D)	40,596	36,453	36,247	34,998	37,257	35,501
2. Total Fleet Fuel Usage (in Gallons)	(M)	19,726	16,553	23,927	22,203	19,017	17,558
	(D)	9,822	8,943	8,804	8,266	8,663.5	8,387
3. Average Fleet Miles Per Gallon	(M)	1.33	1.39	1.62	1.60	1.59	1.74
	(D)	4.13	4.08	4.12	4.23	4.30	4.23
4. Average Fleet Miles Per Energy Equivalent	(M)	3.03	3.17	3.70	3.65	3.62	3.97
5. Percent Less Miles Per Energy Equivalent	(M)	26.6%	22.3%	10.0%	13.8%	15.9%	6.3%
6. Average MPG Ratio (D/M)		3.11	2.94	2.53	2.64	2.71	2.43
7. Fuel Cost Per Gallon	(M)	$ 0.735	$ 0.732	$ 0.706	$ 0.698	$ 0.700	$ 0.515
	(D)	$ 0.475	$ 0.601	$ 0.568	$ 0.535	$ 0.489	$ 0.628
8. Fuel Cost Per Mile, Average Bus	(M)	$ 0.55	$ 0.53	$ 0.43	$ 0.44	$ 0.44	$ 0.30
	(D)	$ 0.11	$ 0.15	$ 0.14	$ 0.13	$ 0.11	$ 0.15
9. Fuel Cost for Total Fleet Miles	(M)	$14,502	$12,112	$16,885	$15,500	$13,320	$ 9,042
	(D)	$ 4,665	$ 5,375	$ 5,001	$ 4,423	$ 4,236	$ 5,267
10. Make-Up Oil Usage (Quarts)	(M)	31.00	30.00	63.40	14.00	9.00	15.00
	(D)	68.70	72.00	63.80	35.90	41.00	44.70
11. Average Fleet Miles Per Quart	(M)	846	766	613	2,540	3,353	2,037
	(D)	591	506	568	975	909	794

TABLE 5. FUEL CONSUMPTION FOR SEATTLE METRO (CONTINUED)

		Sep-89	Oct-89	Nov-89	Dec-89	Jan-90	Feb-90
1. Total Fleet Miles	(M)	31,590	42,280	41,003	38,473	38,940	39,249
	(D)	38,491	39,346	36,100	39,688	35,988	35,501
2. Total Fleet Fuel Usage (in Gallons)	(M)	19,030.5	26,283.3	25,028.4	25,009.4	25,541.1	26,693.0
	(D)	8,716.1	9,059.4	8,197.6	9,018.1	8,538.6	8,329.2
3. Average Fleet Miles Per Gallon	(M)	1.66	1.61	1.64	1.54	1.52	1.47
	(D)	4.42	4.34	4.40	4.40	4.21	4.26
4. Average Fleet Miles Per Energy Equivalent	(M)	3.78	3.67	3.74	3.51	3.48	3.35
5. Percent Less Miles Per Energy Equivalent	(M)	14.3%	15.6%	15.2%	20.3%	17.5%	21.3%
6. Average MPG Ratio (D/M)		2.66	2.70	2.69	2.86	2.76	2.90
7. Fuel Cost Per Gallon	(M)	$ 0.623	$ 0.679	$ 0.547	$ 0.578	$ 0.586	N/A
	(D)	$ 0.593	$ 0.699	$ 0.670	$ 0.640	$ 0.570	N/A
8. Fuel Cost Per Mile, Average Bus	(M)	$ 0.38	$ 0.42	$ 0.33	$ 0.38	$ 0.38	N/A
	(D)	$ 0.13	$ 0.16	$ 0.15	$ 0.15	$ 0.14	N/A
9. Fuel Cost for Total Fleet Miles	(M)	$11,856	$17,846	$13,691	$14,455	$14,967	N/A
	(D)	$ 5,169	$ 6,333	$ 5,492	5,772	$ 4,867	N/A
10. Make-Up Oil Usage (Quarts)	(M)	0.10	72.00	259.10	182.00	36.30	106.00
	(D)	49.50	58.60	229.00	315.20	61.30	260.50
11. Average Fleet Miles Per Quart	(M)	315,900	587	158	211	1,073	370
	(D)	778	671	158	126	587	136

3.5.4.2 Engine Make-Up Oil Consumption. Engine make-up oil is defined as that oil added at the time of routine servicing of the coach to bring the engine oil volume up to the full mark on the engine dipstick. Make-up oil does not include oil used during an oil change.

The oil consumption data reported by Seattle Metro is shown in Tables 4 and 5 and in Figure 4. Figure 4 shows that the methanol oil consumption has varied greatly, while the diesel oil consumption was more constant. During late 1987, mid 1988, and mid 1989, the methanol buses show much lower oil consumption. This may be due to the fact that oil consumption is recorded automatically for the diesels by a computerized oil dispensing system, and the methanol oil is dispensed and recorded manually. During the three periods of usually low methanol bus oil consumption (i.e., high miles per quart), oil may have been added to the methanol buses and not properly recorded. During the three periods when the methanol oil consumption was higher (i.e., lower miles per quart) the methanol oil consumption was still substantially below the diesel control buses. It should also be noted that the two fleets are using different motor oils. The methanol buses are using a premium grade, low-ash content oil developed for use in methanol engines.

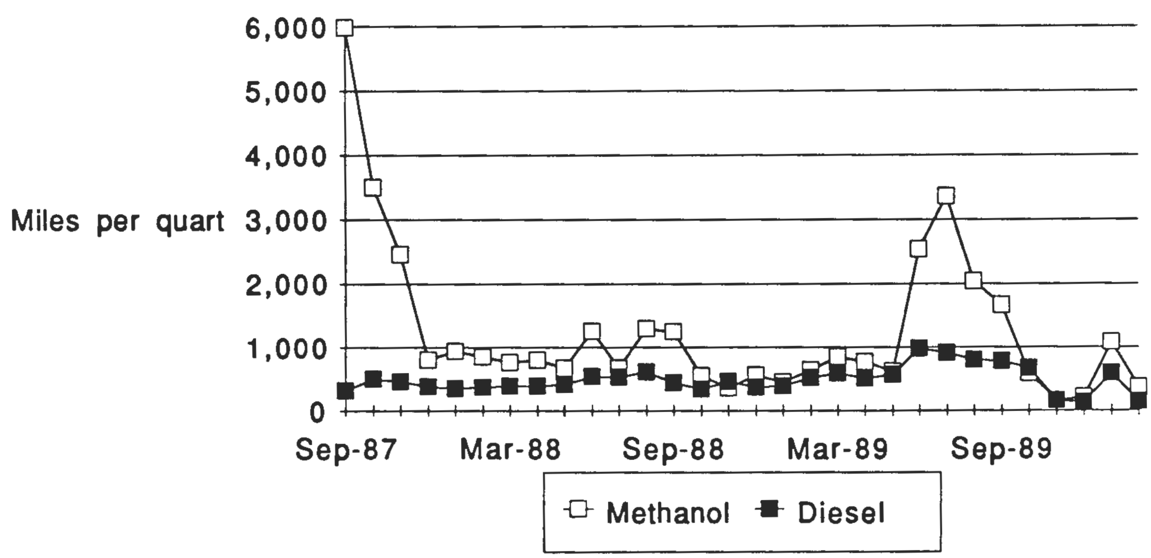

FIGURE 4. MILES PER QUART OF MAKE-UP OIL FOR SEATTLE METRO

3.5.5 Scheduled Maintenance

The preventative maintenance (PM) policies at Seattle Metro require additional PM for the methanol buses. While both the methanol and diesel buses receive all PM scheduled for normal diesel buses, the methanol buses have additional special PM requirements for spark plugs, fuel injector lines, and catalytic converters.

A major additional expense for the M.A.N. methanol engines is spark plug replacement. The methanol engines are fitted with spark plugs to assist ignition, and PM policy at Seattle Metro requires a plug change every 6,000 miles. The plugs cost $125 each, and there are six per engine. Although the PM reduces in-service plug failures to an insignificant level, it adds a cost of 12½¢ per mile for spark plugs.

The bus manufacturer (M.A.N.) has recently required the methanol fuel injector lines to be changed every 30,000 miles and the methanol catalytic converters to be changed at 2 years or 75,000 miles (whichever comes first).

These additional PM actions appear to be sufficient to keep the methanol buses in service, because the total mileages accumulated on the methanol and diesel control bus fleets are very nearly the same. However, the cost of this extra PM is substantial. Figure 5 shows the total mileage accumulations for the diesel and methanol fleets at Seattle. It shows that the methanol fleet has been able to provide nearly as much revenue service as the diesel control fleet.

3.5.6 Unscheduled Maintenance

Unscheduled maintenance is composed of all maintenance activity associated with work orders of three types: 1) the operator request (OR) type which is a repair due to driver write-up, 2) the shop request (SR) type due to a mechanic's write-up, and 3) the road call (RC) type of repair due to an interruption in revenue service.

These data are presented in Table 6, a summary of all unscheduled maintenance work orders. Table 7 shows these data by month.

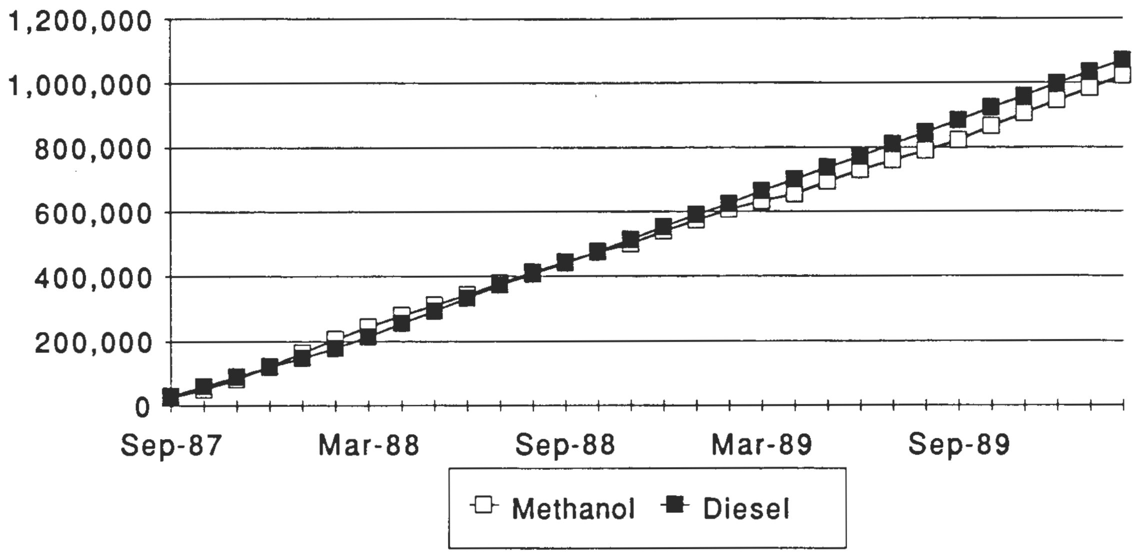

FIGURE 5. TOTAL MILEAGE ACCUMULATIONS FOR METHANOL AND DIESEL CONTROL FLEETS AT SEATTLE METRO

TABLE 6. TOTALS AND AVERAGES OF UNSCHEDULED MAINTENANCE FOR SEATTLE METRO FOR THE PERIOD SEPT 87 THROUGH FEB 90

1. Total Fleet Miles	(M)	1,021,845
	(D)	1,070,198
2. Total No. of Work Orders	(M)	1,826
	(D)	1,426
3. Total No. of Work Order Labor Hours	(M)	3,816.2
	(D)	2,330.8
4. Average No. of Work Orders Per 1,000 Mile	(M)	1.79
	(D)	1.33
5. Average Labor Hours Per Work Order	(M)	2.09
	(D)	1.63
6. Average Labor Hours Per 1,000 Mile	(M)	3.73
	(D)	2.18
7. Average Miles Between Work Order	(M)	560
	(D)	750

TABLE 7. UNSCHEDULED MAINTENANCE AT SEATTLE METRO

		Sep-87	Oct-87	Nov-87	Dec-87	Jan-88	Feb-88	Mar-88	Apr-88
1. Total Fleet Miles	(M)	23,928	26,901	31,935	40,086	41,488	40,562	38,400	36,063
	(D)	30,318	30,746	29,071	29,211	27,851	31,087	35,253	40,703
2. Number of Work Orders	(M)	36	57	51	67	61	69	75	61
	(D)	41	51	41	52	30	30	39	45
3. Number of Work Order Labor Hours	(M)	39.5	83.3	88.6	118.95	166.6	123.1	139.3	111.6
	(D)	46.65	51.5	68.1	103.3	38.3	55.7	56.2	68.9
4. Average Number of Work Order Per 1,000 Miles	(M)	1.50	2.12	1.60	1.67	1.47	1.70	1.95	1.69
	(D)	1.35	1.66	1.41	1.78	1.08	0.97	1.11	1.11
5. Average Labor Hours Per Work Order	(M)	1.10	1.46	1.74	1.78	2.73	1.78	1.86	1.83
	(D)	1.14	1.01	1.66	1.99	1.28	1.86	1.44	1.53
6. Average Number of Labor Hours Per 1,000 Miles	(M)	1.65	3.10	2.77	2.97	4.02	3.03	3.63	3.09
	(D)	1.54	1.68	2.34	3.54	1.38	1.79	1.59	1.69
7. Average Miles Between Work Orders	(M)	665	472	626	598	680	588	512	591
	(D)	739	603	709	562	928	1,036	904	905
8. Number of Roadcalls	(M)	5	6	6	22	13	15	18	20
	(D)	11	11	9	9	8	13	9	15

TABLE 7. UNSCHEDULED MAINTENANCE AT SEATTLE METRO (CONTINUED)

		May-88	Jun-88	Jul-88	Aug-88	Sep-88	Oct-88	Nov-88	Dec-88
1. Total Fleet Miles	(M) (D)	31,477 38,839	31,477 38,839	36,155 39,528	34,587 34,864	31,605 33,970	28,657 36,095	26,755 36,813	39,067 40,312
2. Number of Work Orders	(M) (D)	79 42	50 62	50 37	64 39	62 40	61 31	46 34	56 53
3. Number of Work Order Labor Hours	(M) (D)	131.2 70.9	105.5 76.7	99.35 61.25	168.25 57.15	162.2 50.7	161.7 49.65	103.6 152.5	149.65 91.5
4. Average Number of Work Order Per 1,000 Miles	(M) (D)	2.51 1.08	1.59 1.60	1.38 0.94	1.85 1.12	1.96 1.18	2.13 0.86	1.72 0.92	1.43 1.31
5. Average Labor Hours Per Work Order	(M) (D)	1.66 1.69	2.11 1.24	1.99 1.66	2.63 1.47	2.62 1.27	2.65 1.60	2.25 4.49	2.67 1.73
6. Average Number of Labor Hours Per 1,000 Miles	(M) (D)	4.17 1.83	3.35 1.97	2.75 1.55	4.86 1.64	5.13 1.49	5.64 1.38	3.87 4.14	3.83 2.27
7. Average Miles Between Work Orders	(M) (D)	398 925	630 626	723 1,068	540 894	510 849	470 1,164	582 1,083	698 761
8. Number of Roadcalls	(M) (D)	26 13	18 14	16 10	22 9	14 12	23 9	18 8	15 12

TABLE 7. UNSCHEDULED MAINTENANCE AT SEATTLE METRO (CONTINUED)

		Jan-89	Feb-89	Mar-89	Apr-89	May-89	Jun-89	Jul-89	Aug-89
1. Total Fleet Miles	(M)	33,744	33,048	26,231	22,989	38,878	35,556	30,173	30,548
	(D)	37,695	32,837	40,596	36,453	36,247	34,998	37,257	35,501
2. Number of Work Orders	(M)	80	65	61	93	53	48	54	52
	(D)	65	60	61	57	45	50	48	61
3. Number of Work Order Labor Hours	(M)	128.45	112.95	145.6	83.8	222.5	127.25	104.65	132.4
	(D)	120.5	97	105.7	37.5	80.8	90.75	102.15	97.6
4. Average Number of Work Order Per 1,000 Miles	(M)	2.37	1.97	2.33	4.05	1.36	1.35	1.79	1.70
	(D)	1.72	1.83	1.50	1.56	1.24	1.43	1.29	1.72
5. Average Labor Hours Per Work Order	(M)	1.61	1.74	2.39	0.90	4.20	2.65	1.94	2.55
	(D)	1.85	1.62	1.73	0.66	1.80	1.82	2.13	1.60
6. Average Number of Labor Hours Per 1,000 Miles	(M)	3.81	3.42	5.55	3.65	5.72	3.58	3.47	4.33
	(D)	3.20	2.95	2.60	1.03	2.23	2.59	2.74	2.75
7. Average Miles Between Work Orders	(M)	422	508	430	247	734	741	559	587
	(D)	580	547	666	640	805	700	776	582
8. Number of Roadcalls	(M)	15	17	20	28	19	12	16	14
	(D)	17	13	20	15	8	12	11	15

TABLE 7. UNSCHEDULED MAINTENANCE AT SEATTLE METRO (CONTINUED)

		Sep-89	Oct-89	Nov-89	Dec-89	Jan-90	Feb-90
1. Total Fleet Miles	(M)	31,590	42,280	41,003	38,473	38,940	39,249
	(D)	38,491	39,346	36,100	39,688	35,988	35,501
2. Number of Work Orders	(M)	53	62	77	56	75	52
	(D)	54	54	60	44	46	54
3. Number of Work Order Labor Hours	(M)	142.8	118.6	122.20	121.45	184.20	117.25
	(D)	88.7	76.35	96.95	76.80	79.25	81.90
4. Average Number of Work Order Per 1,000 Miles	(M)	1.68	1.47	1.88	1.46	1.93	1.32
	(D)	1.40	1.37	1.66	1.11	1.28	1.52
5. Average Labor Hours Per Work Order	(M)	2.69	1.91	1.59	2.17	2.46	2.25
	(D)	1.64	1.41	1.62	1.75	1.72	1.52
6. Average Number of Labor Hours Per 1,000 Miles	(M)	4.52	2.81	2.98	3.16	4.73	2.99
	(D)	2.30	1.94	2.69	1.94	2.20	2.31
7. Average Miles Between Work Orders	(M)	596	682	533	687	519	755
	(D)	713	729	602	902	782	657
8. Number of Roadcalls	(M)	7	20	23	18	19	17
	(D)	13	17	24	12	13	9

The methanol fleet has experienced more work orders than the diesel fleet, accumulating 1,826 work orders for the 30 month time period as compared to 1,426 for the diesel fleet.

On a mileage basis, the methanol buses averaged 560 miles between work orders while the diesel control buses averaged 750 miles between work orders. Figure 6 shows the average miles between work orders at Seattle. Not only did the methanol buses require a greater number of repairs and more frequent repairs, they took an average of 25 percent more time to repair (1.79 hours per work order, compared to 1.33 hours per work order). These facts combine to produce requirements for labor due to unscheduled maintenance at a rate of 3.07 hours per 1,000 miles for the methanol buses and 1.84 hours per 1,000 miles for the diesel control buses. Figure 7 shows the unscheduled labor per 1,000 miles. The methanol buses required approximately 60 percent more unscheduled maintenance labor than the diesel control buses. Although no detailed data for parts costs were submitted to Battelle by Seattle Metro, some figures are available. Mr. Jim Boon, Supervisor of Vehicle Maintenance

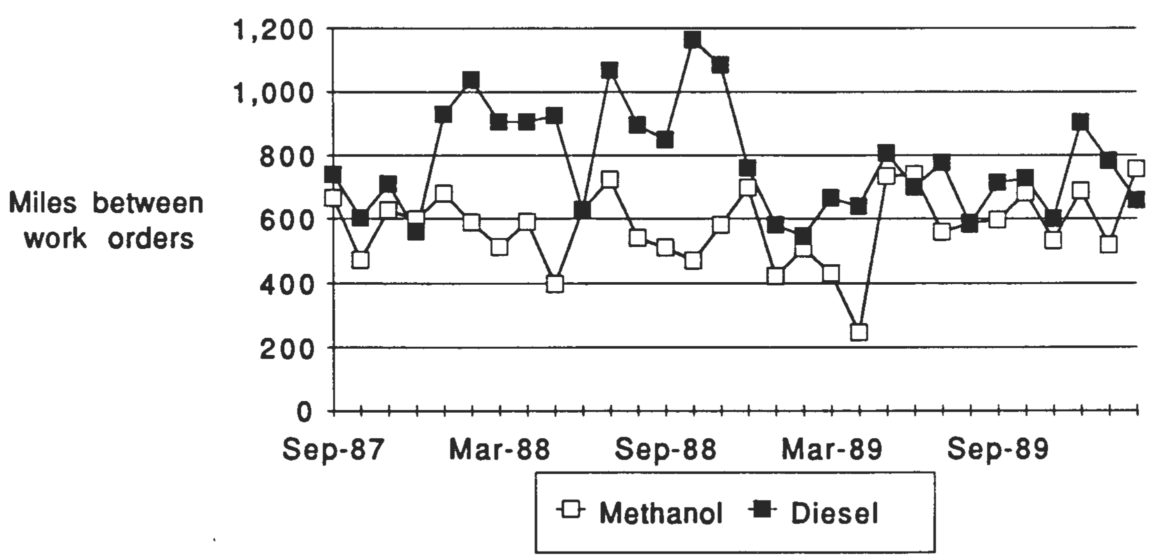

FIGURE 6. AVERAGE MILES BETWEEN WORK ORDERS AT SEATTLE METRO

for Seattle Metro, reported in a paper presented to APTA[4] that the average parts cost for the methanol buses during 1988 was 0.1223 cents per mile, while the average for the entire Metro diesel bus fleet during the same period was 0.0460 cents per mile. This is a methanol-to-diesel parts cost per mile ratio of 2.66:1.

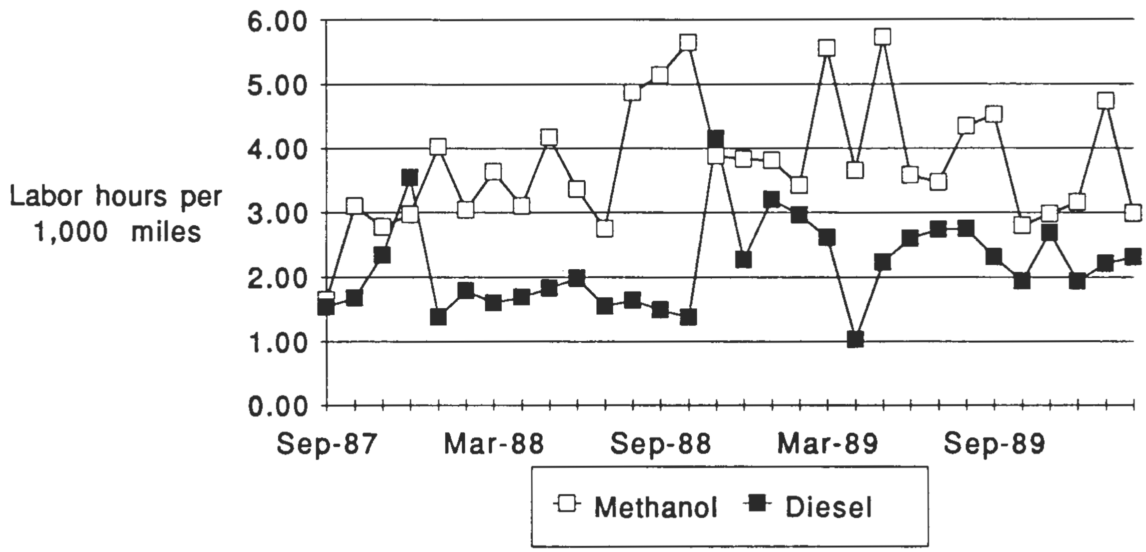

FIGURE 7. AVERAGE LABOR HOURS PER 1,000 MILES FOR UNSCHEDULED MAINTENANCE AT SEATTLE METRO

Assuming that miles between unscheduled work orders is an indicator of reliability, the prototype M.A.N. methanol buses are less reliable than the production diesel control buses. However, the methanol buses are accumulating nearly the same average annual mileage as the diesel control buses. This indicates that the methanol buses are capable of providing the same service as diesel buses if the methanol buses are allowed to incur significantly higher costs for repair.

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4 Methanol-Seattle Metro 1988 Operating Experience, prepared for and presented at APTA Eastern Alternative Fuels Workshop, May 24, 1989, by Jim Boon, Metro Transit, Seattle, Washington.

Assuming that mean time to repair (expressed as average labor hours per work order) is an indicator of maintainability, then the prototype methanol buses are significantly less maintainable than the diesel control buses. It should be noted that the maintenance mechanics have long experience with diesel engines, but are new to methanol engines. This may be a contributing factor to the difference.

No single type of in-service failure stands out clearly for the M.A.N. methanol buses. For preventative maintenance, spark plug life stands out as a major maintenance cost; improvements in this area would substantially reduce the cost of operating these buses.

It is interesting to note that the M.A.N. methanol engines at Seattle Metro do not suffer from the chronic fuel injector clogging which is evident at the other demonstration sites using the DDC 6V-92TAM methanol engines. Because the DDC engines have experienced severe injector reliability problems, the data for the Seattle M.A.N.s were specially searched to tally injector repairs. In the 30 months of the demonstration, the methanol buses have had 8 repair actions for injectors, while the diesels have had none. Detailed descriptions of these injector problems are not available. Of the eight actions, five are marked "replace injector(s)", one is marked "secure injector(s)", and two are marked "retrofit injector(s)". The M.A.N.s have therefore had seven incidents of injector failures in the methanol buses. Given that the data cover 30 months and 1,021,845 miles of methanol bus operation, the M.A.N. methanol injectors seem to be highly reliable. This is an average of approximately 146,000 miles between methanol injector failures.

3.5.7 Special Tests

The Seattle Metro demonstration fleet has been subjected to special tests in addition to the observation of revenue service. These tests cover the subjects of vehicle performance, methanol vapor levels in the work environment, and attitudes of personnel directly impacted by the use of methanol buses such as the riding public, drivers, and various bus servicing and maintenance workers.

3.5.7.1 Proving Ground Comparison Tests for Driveability, Acceleration, and Noise. Reliability, maintainability, and cost considerations are addressed in this report by analysis of revenue service data such as scheduled and unscheduled maintenance and fuel consumption data in other sections of this report. However, the vehicular characteristics of driveability, acceleration, and noise are best evaluated by conducting controlled proving ground tests. Special tests have been conducted to evaluate these three characteristics under carefully controlled conditions.

Three methanol and three diesel control buses from the demonstration fleet were used for these tests. The tests were conducted at the PACCAR Technical Center proving grounds near Mount Vernon, Washington. The testing was conducted twice; once in January 1988, and again in August 1988. This allowed comparison of cold and warm weather performance. The testing revealed no important differences between the methanol and diesel buses in noise, gradeability, or acceleration. Driveability of the methanol buses was less than the diesel due to hard starting and stumble. A complete account of these tests is contained in the report submitted to UMTA by Battelle[5].

3.5.7.2 Methanol Vapor Level Measurements. The purpose of this particular special test was to perform measurements of methanol vapor levels under realistic transit operating conditions at Seattle Metro maintenance facilities. The measurements were intended to determine the methanol vapor concentrations associated with normal fueling, maintenance, and operation of the methanol buses. No measurements were made that might be associated with large spills or accidents, although small amounts of methanol were spilled to simulate leakage during maintenance activities. A report on the methods and

[5] Francis, G.A. and King, R.D., "Proving Ground Comparison of M.A.N. Methanol and Diesel Buses", UMTA-IT-06-0322-88-4, October, 1988.

results of the particular measurements taken at Seattle Metro is available[6,7]. Some important conclusions drawn from the analysis of these data follow:

- The amounts of methanol vapor associated with normal fueling and maintenance operations are small enough that all pertinent OSHA regulations and other recommended human exposure limits are satisfied.

- Some short duration, but high concentration level "spikes" of methanol vapor show that while there is no cause for concern from current handling practices, this fuel, like gasoline, demands respect--careless use could cause exposure limits to be exceeded.

- Under normal operating conditions, and with no leaks in the methanol fuel supply system, no measurable methanol vapors were detected in the passenger compartment of the bus.

Note that these conclusions are not general. They are site specific and relate only to observed operations at the Seattle Metro demonstration site. Methanol level measurements are planned to be conducted at least once during the program's duration at each of the other demonstration sites.

<u>3.5.7.3 Driver Surveys</u>. Questionnaires seeking drivers' opinions on the performance of the methanol buses versus the diesel buses were given to approximately 300 drivers at Seattle Metro's Ryerson Base after the first 10 months of revenue operation. A copy of this questionnaire is contained in Appendix D. Of this population, 103 responses to the survey were received, equating to a sample of 34.3 percent of the survey population. Of the 103 responses, 73 drivers had driven the methanol buses more than 10 times and had

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6 Murphy, M., "Data Collection on Methanol Vapor Exposure", UMTA, Office of Bus and Paratransit Systems, November, 1987.

7 Murphy, M. and Krenelka, T., "Methanol Vapor Measurements in a Vehicle Maintenance Pit at Seattle Metro Ryerson Base", UMTA, Office of Technical Assistance and Safety, October, 1988.

more than 1 year's experience in operating coaches in transit service. These 73 drivers represent 70.9 percent of the total responses to the survey with this kind of methanol bus operation experience. Some questionnaires were returned with answers omitted for unknown reasons. In all cases, the total number of responses to a given question was counted and used as the 100 percent number for comparison.

The responses to two of the questions in the survey are as follows:

A. Overall, do you prefer to drive the methanol bus instead of the diesel bus?
   - 53.8% said Yes
   - 23.1% said No (opposite is true)
   - 23.1% said The Same

B. Do you write up the methanol bus for repairs more often than the diesel bus?
   - 4.7% said Yes
   - 45.9% said No (opposite is true)
   - 49.4% said The Same
   - There were four no-responses to this question.

A majority of the drivers responding to the survey prefer to drive the methanol bus over the diesel bus. Very few drivers believed that they wrote up the methanol buses more often, while nearly half believed that they wrote up the diesel buses more often. This perception by the drivers is in direct conflict with the repair records at Seattle Metro, which show the methanol buses are written up much more often than the diesels. Table 8 shows that over the 10 month survey period, the methanol buses only averaged 576 miles between work orders while the diesel buses averaged 761 miles between work orders. The driver survey appears to indicate that this 1.3 to 1 increase in write-ups is not perceptible to the drivers. In fact, they believe the opposite is true when they perceive a difference.

TABLE 8. FUEL USAGE TOTALS AND AVERAGES FOR TRIBORO FOR THE PERIOD MAY 1988 THROUGH OCTOBER 1989

1. Total Fleet Mileage	(M) (D)	320,615 389,022
2. Total Fleet Fuel Usage (in Gallons)	(M) (D)	283,406 125,707
3. Average Bus Mileage	(M) (D)	53,436 64,837
4. Average Bus MPG	(M) (D)	1.1 3.1
5. Average Methanol Miles Per Energy Equivalent	(M)	2.6
6. Percent Less MPEQ for Methanol than Diesel	(M)	16.7%
7. Average MPG Ratio (D/M)		2.74
8. Average Fleet Miles Per Qt of Make-Up Oil (mi/qt)	(M) (D)	365 560

3.5.8 Safety, Health, and Accident Reports

On September 30, 1987, one of the diesel control buses (coach #3138) was involved in a collision with a delivery van. The front of the bus struck the left side of the van. The bus remained upright while the van overturned onto its side. The van driver and five of the bus passengers were injured. There were no fatalities. The bus was placed out-of-service for front end repair for the entire month of October, 1987.

On October 1, 1989, a methanol bus experienced a methanol fuel fire while in passenger service. No people were injured and the bus sustained only minor damage.

The driver noticed smoke coming from the rear of the bus, followed quickly by the engine fire warning buzzer. The driver stopped the bus, opened all doors, and then went outside to verify the fire. Upon finding a fire in the engine compartment, the driver immediately evacuated all passengers. The driver then used the fire extinguisher to suppress the fire; the fire department arrived and completed extinguishing the fire.

Subsequent investigation revealed that a fuel injector line had leaked. The methanol ran down to the exhaust manifold and ignited there. Evidence indicates that when the fuel line was replaced, a connection leaked. Pipe thread sealer was used to stop the leak. This compound eventually failed, and the leak resumed at substantial volume. Damage was limited to burned rubber hoses and electrical wiring near the fire and was considered minor.

As a corrective action, all methanol bus mechanics at Metro were informed that pipe thread compound is dissolved by methanol, and that its use on methanol fuel systems is now prohibited.

3.6 Triboro Coach Corporation

3.6.1 Demonstration Site Introduction

The Triboro demonstration buses are operating in Queens, New York. Located on Long Island, Queens has shoreline on both Long Island Sound and the Atlantic Ocean. The borough of Queens has a population of nearly 2 million residents in its 109 square miles, of which 50 percent ride public transportation to work.

The terrain is relatively flat and low, with annual precipitation of approximately 40 inches. The average August maximum daily temperature is 86°F, while the average February maximum daily temperature is 33°F.

3.6.2 Bus Specifications

Triboro is operating six methanol and six diesel buses in the demonstration. The demonstration buses began revenue operation in May of 1988. All 12 buses are G.M.C. model T80206 buses with Detroit Diesel 6V-92TA engines. The buses are similar, except for details of the engine and fuel system which were modified to accommodate methanol. The methanol buses are fitted with much larger fuel tanks made of stainless steel, and with methanol compatible stainless steel and synthetic fuel lines. Extra fuel filters, effective to 1 micron, are used. The complete specifications for the Triboro diesel and methanol buses are contained in Appendix A, Tables A3 and A4.

The engine uses the basic DDC 6V-92TA hardware. Higher volume fuel injectors are used, and many small details of the engine such as the exhaust cam profile, turbocharger matching, liner port height, and blower bypass implementation have been changed to optimize the engine for methanol. A major change is increasing the compression ratio from 19:1 to 23:1 by using a different crankshaft. The higher compression engine retains all the same bearings, connecting rods, and pistons of the lower compression ratio diesel engine because of methanol's favorable combustion properties (see "Status of DDC Methanol Bus Engine" for full details). The methanol engines use the

DDECII electronic engine control system, and the software look-up tables for the methanol engine are substantially different than for the diesels. The software is used to implement a half-engine idle by shutting down the injectors for three cylinders.

It should be noted that the methanol buses have been modified several times during the course of this demonstration. Changes have been as minor as switching glowplug styles and as major as changing the compression ratios. The modifications are being performed by the engine manufacturer, DDC, as a normal part of prototype engine development. These continuing engine modifications make it difficult to compare data over long periods of time.

In December 1988, after seven months of revenue service, the Triboro methanol bus engines were extensively upgraded with six distinct changes. These changes are:

1. Installation of a new glowplug controller. The new controller uses pulse-width modulation for the glowplugs, is a fully solid-state device, and accepts 24 volt supply power. This change is intended to improve glowplug life and performance.

2. Installation of new Electronic Control Module (ECM) and change of mounting location for glowplug controller. This is intended to provide easier access to these components and to improve cooling for them.

3. Change liner height from 0.75 inch to 0.65 inch, install new profile exhaust cam, and improve turbo match. These changes are intended to improve combustion and fuel economy and reduce exhaust emissions.

4. Install secondary fuel filter with finer filtration. This is intended to reduce fuel injector failures due to seizing and scoring.

5. Increase compression ratio from 19:1 to 23:1. This is intended to improve ignition, combustion, and fuel economy; reduce exhaust emissions; and improve glowplug life through reduced use. Only three of the methanol buses have had this accomplished to date.

6. Change to 3-cylinder idle scheme. This half-engine idle is intended to improve emissions.

3.6.3 Bus Routing

The Triboro buses are presently running on six routes. Each route has both a diesel and a methanol bus in service on it. The routes range from 4.4 to 8 miles in length, with no significant amounts of freeway operation. The routes are listed in Table B2 in Appendix B.

3.6.4 Consumables

The methanol buses were placed in revenue service over a period of two months during April and May of 1988; the diesel control buses were put in revenue service in May of 1988. Data for consumables are available for the 18 months between the start of service through October of 1989.

3.6.4.1 Fuel Usage Comparisons. The Triboro Coach Corp. has arranged to purchase methanol fuel at a highly subsidized price for this demonstration. The methanol supplier agreed to provide a fixed amount (500,000 gallons) of fuel at diesel fuel price. The methanol was priced at Triboro's weighted average diesel fuel price per gallon, divided by an energy equivalence factor of 2.2. This results in Triboro enjoying a subsidized methanol fuel price which does not relate to the actual market price of methanol. For this reason, the fuel cost of the methanol is not presented in the analysis of Triboro's consumables.

As shown in Table 8, the diesel control fleet has accumulated 22 percent more mileage to date. When the fuel usage is put on an energy-equivalent basis, the methanol buses still display almost 17 percent more fuel consumption than the diesels. Figure 8 shows the equivalent fuel economy for the methanol and diesel buses. The data show a general parallelism, with the diesel and methanol fuel economy rising and falling together. Figure 9 shows the ratio of diesel MPG to methanol MPG. Table 9 shows the complete consumables data for Triboro.

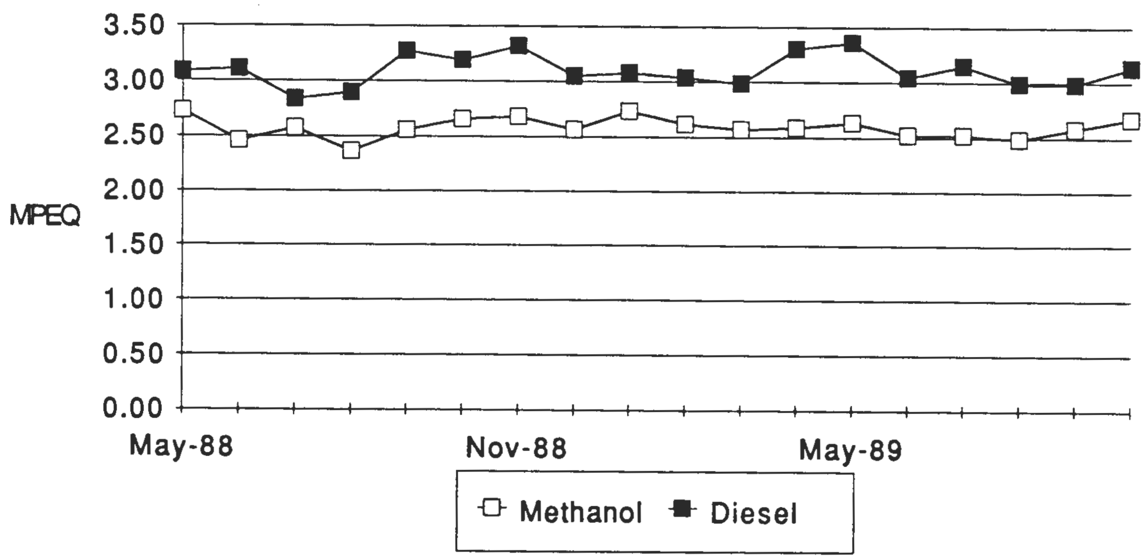

FIGURE 8. EQUIVALENT FUEL ECONOMY AT NEW YORK TRIBORO

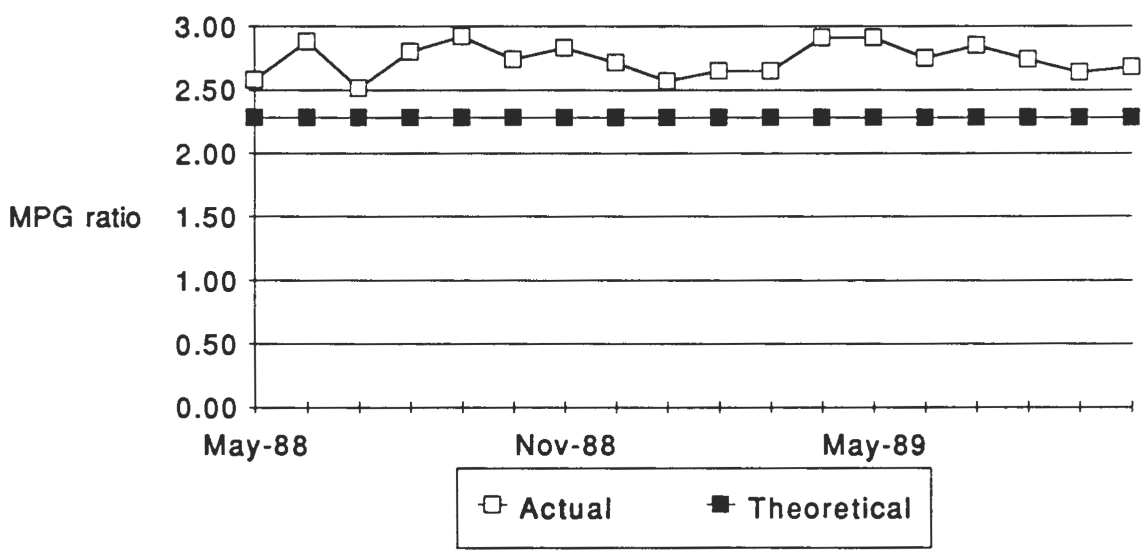

FIGURE 9. FUEL ECONOMY RATIO (DIESEL MPG/METHANOL MPG) AT NEW YORK TRIBORO

TABLE 9. FUEL CONSUMPTION FOR TRIBORO

		May-88	Jun-88	Jul-88	Aug-88	Sep-88	Oct-88	Nov-88
1. Total Fleet Miles	(M) (D)	17,441 14,582	20,970 23,011	16,486 24,642	19,392 25,297	16,774 22,314	19,654 22,272	20,053 22,024
2. Total Fleet Fuel Usage (in Gallons)	(M) (D)	14,584 4,731	19,456 7,408	14,591 8,677	18,723 8,726	14,960 6,816	16,862 6,978	17,077 6,633
3. Average Fleet Miles Per Gallon	(M) (D)	1.20 3.08	1.08 3.11	1.13 2.84	1.04 2.90	1.12 3.27	1.17 3.19	1.17 3.32
4. Average Fleet Miles Per Energy Equivalent		2.73	2.46	2.58	2.36	2.56	2.66	2.68
5. Percent Less Miles Per Energy Equivalent for Methanol		11.5%	20.9%	9.3%	18.5%	21.9%	16.7%	19.4%
6. Average MPG Ratio (D/M)		2.58	2.88	2.51	2.80	2.92	2.74	2.83
7. Total Fleet Oil Consumption (qts)	(M) (D)	34.1 10.0	32.0 40.0	20.0 24.0	32.0 26.0	51.9 34.0	55.1 48.9	28.0 37.0
8. Average Miles per Quart	(M) (D)	512 1,458	655 575	824 1,027	606 973	323 656	357 455	716 595

TABLE 9. FUEL CONSUMPTION FOR TRIBORO (CONTINUED)

		Dec-88	Jan-89	Feb-89	Mar-89	Apr-89	May-89	Jun-89
1. Total Fleet Miles	(M)	20,358	20,097	13,866	20,254	15,522	15,183	18,959
	(D)	21,356	22,673	20,750	20,579	22,045	23,479	20,662
2. Total Fleet Fuel Usage (in Gallons)	(M)	18,133	16,770	12,095	18,000	13,696	13,152	17,144
	(D)	7,004	7,368	6,833	6,900	6,680	6,984	6,793
3. Average Fleet Miles Per Gallon	(M)	1.12	1.20	1.15	1.13	1.13	1.15	1.11
	(D)	3.05	3.08	3.04	2.98	3.30	3.36	3.04
4. Average Fleet Miles Per Energy Equivalent		2.56	2.73	2.61	2.57	2.58	2.63	2.52
5. Percent Less Miles Per Energy Equivalent for Methanol		16.0%	11.2%	13.9%	14.0%	21.7%	21.7%	17.1%
6. Average MPG Ratio (D/M)		2.72	2.57	2.65	2.65	2.91	2.91	2.75
7. Total Fleet Oil Consumption (qts)	(M)	54.0	62.0	55.9	113.2	40	31	38
	(D)	30.0	24.0	32.0	52.0	36	10	38
8. Average Miles per Quart	(M)	377	324	248	179	388.1	489.8	498.9
	(D)	712	945	648	396	612.4	2,347.9	543.7

TABLE 9. FUEL CONSUMPTION FOR TRIBORO (CONTINUED)

		Jul-89	Aug-89	Sep-89	Oct-89
1. Total Fleet Miles	(M) (D)	13,940 22,228	15,488 21,020	16,370 19,770	19,808 20,318
2. Total Fleet Fuel Usage (in Gallons)	(M) (D)	12,608 7,058	14,186 7,025	14,469 6,621	16,900 6,472
3. Average Fleet Miles Per Gallon	(M) (D)	1.11 3.15	1.09 2.99	1.13 2.99	1.17 3.14
4. Average Fleet Miles Per Energy Equivalent		2.52	2.49	2.58	2.67
5. Percent Less Miles Per Energy Equivalent for Methanol		20.0%	16.8%	13.6%	14.9%
6. Average MPG Ratio (D/M)		2.85	2.74	2.64	2.68
7. Total Fleet Oil Consumption (qts)	(M) (D)	16 55	30 68	48 54	42 53
8. Average Miles per Quart	(M) (D)	871.3 404.1	516 309	341 366	472 383

3.6.4.2 Engine Make-Up Oil Consumption. The Triboro diesel buses have experienced significantly lower oil consumption than the methanol buses. In the first 18 months of the demonstration, the diesel control buses averaged 579 miles per quart, while the methanol buses averaged 409 miles per quart. This is approximately 30 percent fewer miles per quart for the methanol buses. Table 9 shows the miles per quart data reported. Figure 10 shows these data plotted.

3.6.5 Unscheduled Maintenance

Triboro has reported only methanol bus unscheduled maintenance which is engine related. Although this allows no comparison between diesel and methanol buses at this site, it does allow evaluation of Triboro's unscheduled methanol bus maintenance. Table 10 shows the totals and averages for unscheduled maintenance at Triboro. Table 11 shows the complete data for unscheduled maintenance at Triboro.

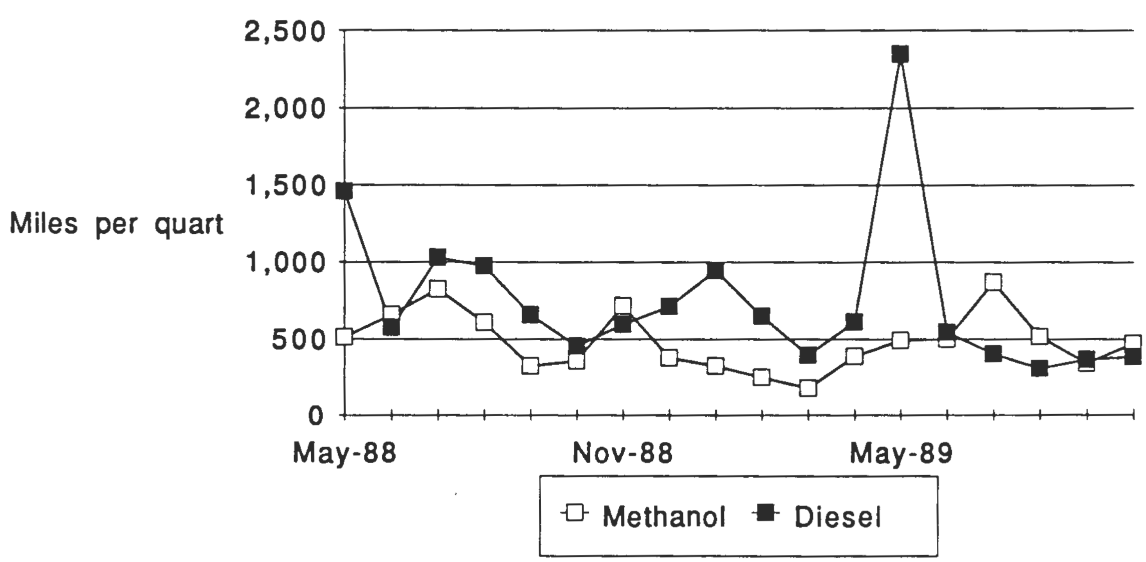

FIGURE 10. MILES PER QUART AT TRIBORO

TABLE 10. TOTALS AND AVERAGES OF UNSCHEDULED MAINTENANCE AT TRIBORO FROM MAY 1988 THROUGH OCTOBER 1989

1.	Total Fleet Miles	(M) (D)	320,615 389,022
2.	Total Number of Roadcalls	(M) (D)	200 50
3.	Average Number of Roadcalls Per 1,000 Miles	(M) (D)	0.62380113 0.12852744
4.	Average Miles Between Roadcalls	(M) (D)	1,603 7,780
5.	Total Glowplug Failures		196
6.	Total Injector Failures		251
7.	Total Bypass Actuator Failures		43
8.	Average Miles Between Glowplug Failures		1,636
9.	Average Miles Between Injector Failures		1,277
10.	Average Miles Between Bypass Actuator Failures		7,456

Figure 11 shows the miles between road calls at Triboro. The data for the methanol and diesel control buses are plotted, along with the fleetwide average for all of Triboro's diesel buses for the first quarter of 1989. The New York City Department of Transportation has reported since the beginning of the demonstration that the six diesel control buses are unusually trouble-free compared to the entire fleet. Figure 10 shows that this is true. Therefore, it may be more reasonable to compare the reliability data for Triboro's methanol and diesel control buses only after late 1988, when the diesel control buses achieved a reliability closer to the fleet average. Figure 10 also shows a slight improvement in methanol bus reliability over the course of the demonstration as DDC improves the engine design.

TABLE 11. TRIBORO MAINTENANCE DATA

		May-88	Jun-88	Jul-88	Aug-88	Sep-88	Oct-88	Nov-88
1. Total Fleet Miles	(M) (D)	17,441 14,582	20,970 23,011	16,486 24,642	19,392 25,297	16,774 22,314	19,654 22,272	20,053 22,024
2. Number Roadcalls	(M) (D)	22 1	17 1	17 2	14 3	8 2	15 4	14 2
3. Average Number of Road-Calls Per 1,000 Miles	(M) (D)	1.26 0.07	0.81 0.04	1.03 0.08	0.72 0.12	0.48 0.09	0.76 0.18	0.70 0.09
4. Average Miles Between Roadcalls	(M) (D)	793 14,582	1,234 23,011	970 12,321	1,385 8,432	2,097 11,157	1,310 5,568	1,432 11,012
5. Glowplug Failures	(M)	23	38	14	26	9	3	7
6. Injector Failures	(M)	0	0	12	3	2	23	20
7. Bypass Actuator Failures	(M)	10	10	12	9	0	0	0

TABLE 11. TRIBORO MAINTENANCE DATA (CONTINUED)

		Dec-88	Jan-89	Feb-89	Mar-89	Apr-89	May-89	Jun-89
1. Total Fleet Miles	(M)	20,358	20,097	13,866	20,254	15,522	15,183	18,959
	(D)	21,356	22,673	20,750	20,579	22,045	23,479	20,662
2. Number of Roadcalls	(M)	5	8	5	8	12	3	7
	(D)	3	6	2	3	4	2	1
3. Average Number of Road-Calls Per 1,000 Miles	(M)	0.25	0.40	0.36	0.39	0.77	0.20	0.37
	(D)	0.14	0.26	0.10	0.15	0.18	0.09	0.05
4. Average Miles Between Roadcalls	(M)	4,072	2,512	2,773	2,532	1,294	5,061	2,708
	(D)	7,119	3,779	10,375	6,860	5,511	11,740	20,662
5. Glowplug Failures	(M)	11	5	5	7	23	0	0
6. Injector Failures	(M)	8	8	7	16	8	4	16
7. Bypass Actuator Failures	(M)	0	0	0	0	2	0	0

TABLE 11. TRIBORO MAINTENANCE DATA (CONTINUED)

		Jul-89	Aug-89	Sep-89	Oct-89
1. Total Fleet Miles	(M)	13,940	15,488	16,370	19,808
	(D)	22,228	21,020	19,770	20,318
2. Number of Roadcalls	(M)	6	13	15	11
	(D)	1	3	4	6
3. Average Number of Road-Calls Per 1,000 Miles	(M)	0.43	0.84	0.92	0.56
	(D)	0.04	0.14	0.20	0.30
4. Average Miles Between Roadcalls	(M)	2,323	1,191	1,091	1,801
	(D)	22,228	7,007	4,943	3,386
5. Glowplug Failures	(M)	7	0	16	2
6. Injector Failures	(M)	23	60	22	19
7. Bypass Actuator Failures	(M)	0	0	0	0

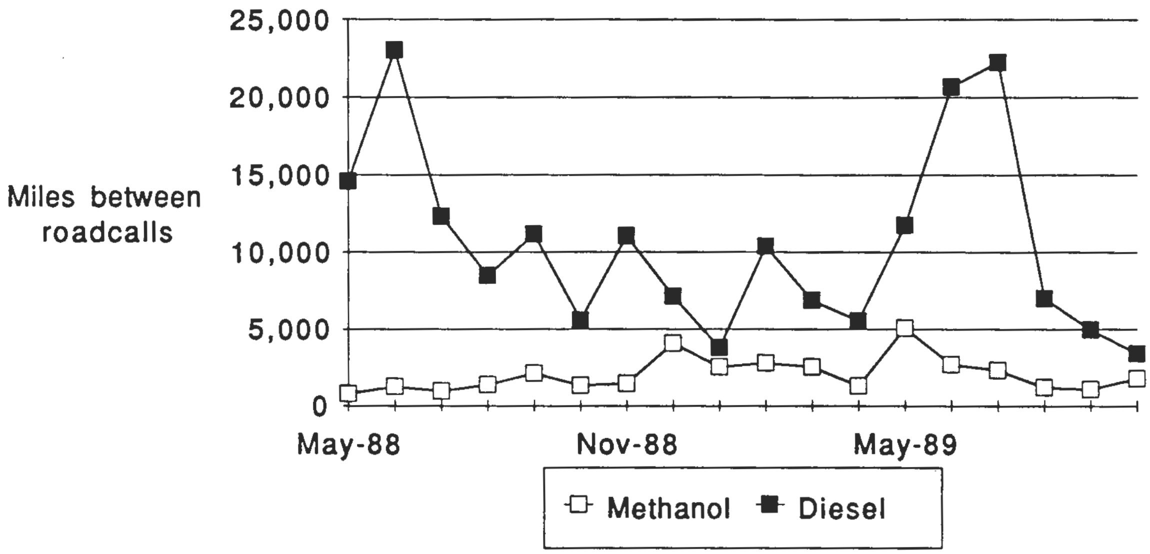

FIGURE 11. MILES BETWEEN ROADCALLS AT NEW YORK TRIBORO

The failure rates for Triboro's methanol buses have been dominated by fuel injectors, glowplugs, and bypass actuators. Early in the demonstration, glowplugs and bypass actuators accounted for the majority of the engine failures. Improvements in these systems by DDC has caused dramatic improvements in the failure rates of these two components. Figure 12 shows the bypass actuator failures, and Figure 13 shows the glowplug failures. Both plots show reductions in failure rates. The data indicate that the bypass actuator problem has been solved, and that the glowplug problem has been significantly reduced.

Figure 14 shows fuel injector failures, and it shows that the injectors are becoming less reliable over time. DDC has been working continuously on the problem, but the data show that efforts to date have not been successful. Triboro's experience is typical of other demonstrations of the DDC 6V-92TAM engine. Injector failure modes are predominately plugging, leaking, and seizing.

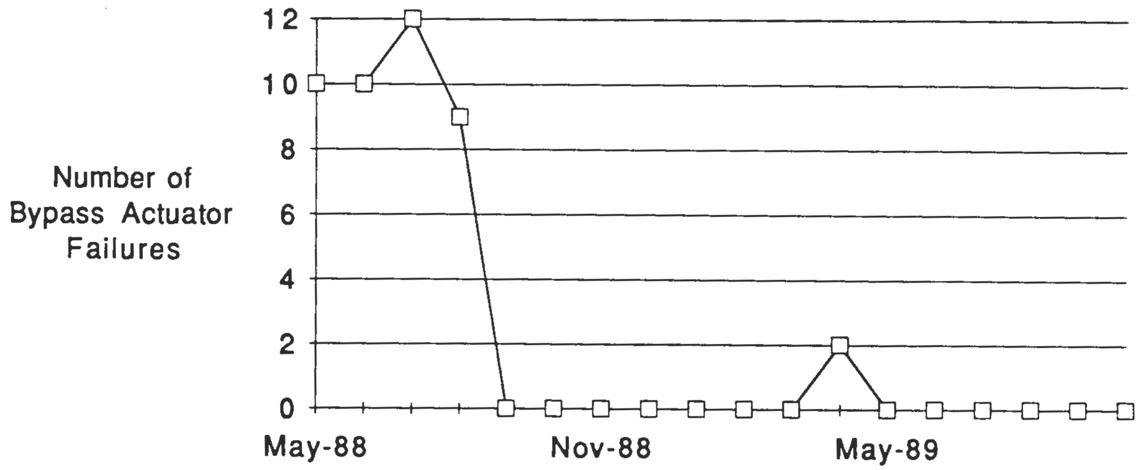

FIGURE 12. NUMBER OF BYPASS ACTUATOR FAILURES AT NEW YORK TRIBORO

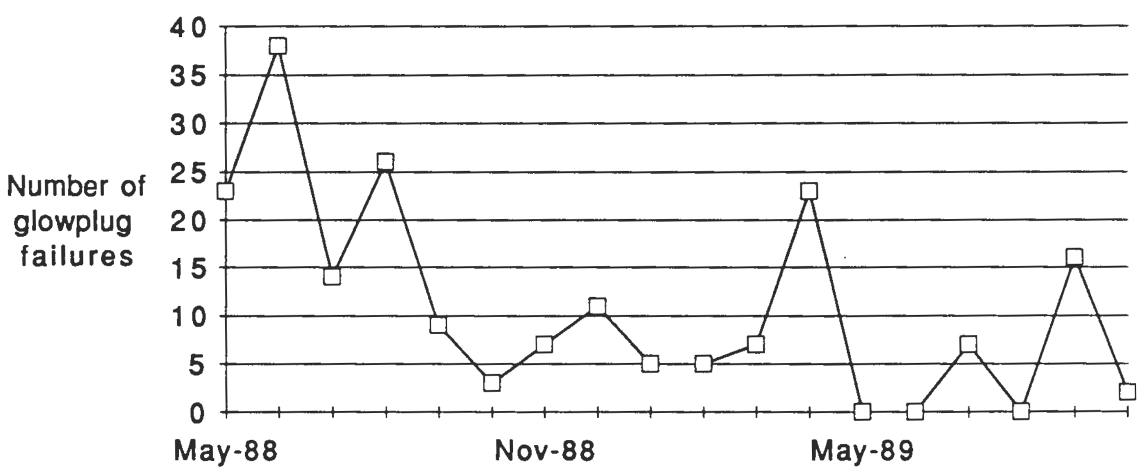

FIGURE 13. NUMBER OF GLOWPLUG FAILURES AT NEW YORK TRIBORO

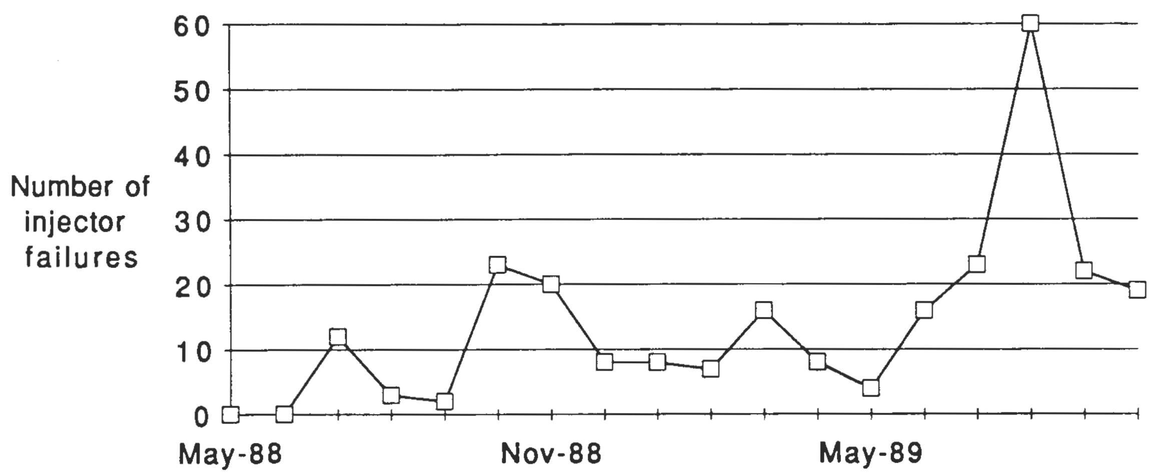

FIGURE 14. NUMBER OF FUEL INJECTOR FAILURES AT NEW YORK TRIBORO

3.6.6 Safety, Health, and Accident Reports

There have been no safety incidents, accidents, or worker's compensation claims for the demonstration fleet at Triboro during the 18 months of the demonstration covered by this report.

3.7 Denver RTD

3.7.1 Demonstration Site Introduction

The largest city in the rocky mountain west and the high plains region, Denver is situated at an altitude of 5,280 feet. The city is approximately ten miles east of the foothills of the rocky mountains on relatively flat land. The suburbs of Denver occupy the foothills, and some of Denver RTD's buses regularly operate at altitudes above 10,000 feet. Some mountain passes to the west of Denver exceed 14,000 feet in elevation.

The climate in Denver is dry, averaging about 14 inches per year of precipitation. Summers are hot and dry, with daily maximum average temperatures above 85°F. Winters are mild, with maximum daily temperatures usually in the 40's. The 1984 census showed 1.8 million people in the consolidated metropolitan statistical area.

The Denver Regional Transportation District (RTD) methanol demonstration began in June of 1989 with five TMC methanol buses and five Neoplan diesel control buses.

3.7.2 Bus Specifications

As listed in Table 1, the Denver RTD demonstration involves five methanol buses and five diesel control buses. The demonstration fleet began revenue service in June of 1988. The methanol buses are TMC coaches with DDC methanol fueled 6V-92 engines. The diesel control buses are substantially different; they are 1987 Neoplans with DDC 9V-92 engines. Although both are 40 foot heavy-duty transit buses with DDC 6V-92 engines, differences in weight, gearing, brakes, and suspension are significant. Complete detailed specifications for both bus types are given in Appendix A, Tables A5 and A6.

3.7.3 Bus Routing

The methanol and diesel control buses are assigned to a set of nine routes with CBD type service. Instead of running side-by-side pairs of methanol and diesel control buses together, the buses are rotated through halves of the blocks in a given route every four weeks. For example, the five methanol buses will serve block Nos. 1 though 4 of route No. 28 for four weeks while the five diesel control buses serve blocks Nos. 5 through 8 of the same route. After four weeks, the methanol buses switch to blocks 5 through 8 of that route while the diesel control buses travel blocks 1 through 4. This results in both fleets seeing the same service every eight weeks. A complete description of the routes used is contained in Appendix B, Table B3.

3.7.4 Consumables

Denver RTD does not own and operate a methanol fueling facility. The methanol buses are driven by RTD personnel to a local contractor facility for fueling. The contractor adds 5¢ per gallon surcharge for fueling in addition to the fuel price. This surcharge is included in all fuel cost figures reported for Denver.

In the first 9 months of the demonstration at Denver, the methanol buses have used 11 percent more fuel, on an equivalent basis, than the diesel control buses. Table 12 shows all the consumables data for Denver. Figure 15 shows the equivalent fuel economy at Denver RTD. Figure 16 shows the equivalent fuel costs at Denver.

3.7.5 Maintenance

Denver RTD reports roadcalls for the methanol and diesel control fleets as an indicator of reliability. As shown in Table 13, the methanol buses have experienced about 50 percent more roadcalls than the diesel control buses. The general reliability of the methanol engines is not satisfactory because of fuel injector failures. Denver experienced a complete engine failure on a methanol bus in February, 1990. At 29,000 miles, the engine seized. Teardown inspection revealed that the three left bank (lower bank) cylinders had seized, and all three right bank (upper bank) cylinders showed excessive wear, with no crosshatching visible at the top of the cylinder liner. Although the cause of the condition has not been established, such a

TABLE 12. DENVER FUEL TABLE

		Jun-89	Jul-89	Aug-89	Sep-89	Oct-89	Nov-89
1. Total Fleet Miles	(M) (D)	11,600 16,400	13,700 12,100	19,400 20,000	15,900 14,800	19,600 17,800	17,500 21,900
2. Total Fleet Fuel Usage (in Gallons)	(M) (D)	7,501 4,444	8,429 3,046	10,596 5,187	11,537 3,756	12,133 4,382	11,515 5,425
3. Average Fleet Miles Per Gallon	(M) (D)	1.55 3.69	1.63 3.97	1.83 3.86	1.38 3.94	1.62 4.06	1.52 4.04
4. Average Fleet Miles Per Energy Equivalent	(M)	3.53	3.71	4.17	3.14	3.68	3.47
5. Percent Less Miles Per Energy Equivalent for Methanol		4%	7%	-8%	20%	9%	14%
6. Average MPG Ratio (D/M)		2.39	2.44	2.11	2.86	2.51	2.66
7. Fuel Cost Per Gallon	(M) (D)	\$ 0.780 \$ 0.520	\$ 0.740 \$ 0.480	\$ 0.710 \$ 0.520	\$ 0.640 \$ 0.590	\$ 0.570 \$ 0.610	\$ 0.550 \$ 0.650
8. Fuel Cost Per Mile, Average Bus	(M) (D)	\$ 0.50 \$ 0.14	\$ 0.46 \$ 0.12	\$ 0.39 \$ 0.13	\$ 0.46 \$ 0.15	\$ 0.35 \$ 0.15	\$ 0.36 \$ 0.16
9. Fuel Cost for Total Fleet Miles	(M) (D)	\$ 5,851 \$ 2,311	\$ 6,237 \$ 1,462	\$ 7,523 \$ 2,697	\$ 7,384 \$ 2,216	\$ 6,916 \$ 2,673	\$ 6,333 \$ 3,526

TABLE 12. DENVER FUEL TABLE (CONTINUED)

		Dec-89	Jan-90	Feb-90
1. Total Fleet Miles	(M)	14,900	16,700	16,400
	(D)	22,200	19,800	17,800
2. Total Fleet Fuel Usage (in Gallons)	(M)	10,678	10,592	9,742
	(D)	5,183	4,650	4,288
3. Average Fleet Miles Per Gallon	(M)	1.40	1.58	1.68
	(D)	4.28	4.26	4.15
4. Average Fleet Miles Per Energy Equivalent	(M)	3.18	3.59	3.84
5. Percent Less Miles Per Energy Equivalent for Methanol		26%	16%	8%
6. Average MPG Ratio (D/M)		3.07	2.70	2.47
7. Fuel Cost Per Gallon	(M)	$ 0.550	$ 0.600	$ 0.670
	(D)	$ 0.660	$ 0.680	$ 0.570
8. Fuel Cost Per Mile, Average Bus	(M)	$ 0.39	$ 0.38	$ 0.40
	(D)	$ 0.15	$ 0.16	$ 0.14
9. Fuel Cost for Total Fleet Miles	(M)	$ 5,873	$ 6,355	$ 6,527
	(D)	$ 3,421	$ 3,162	$ 2,444

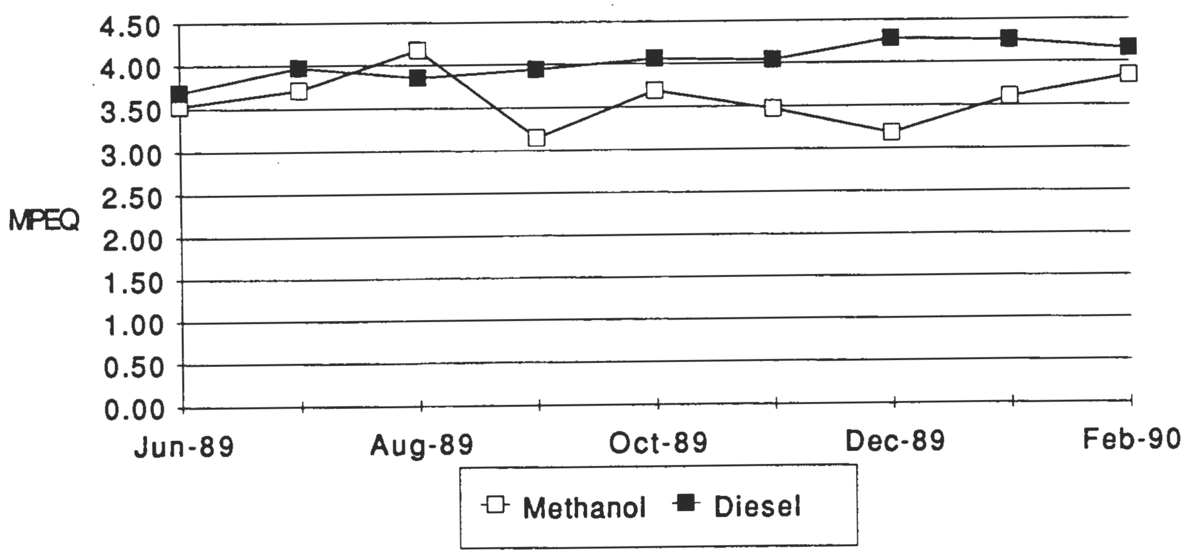

FIGURE 15. EQUIVALENT FUEL ECONOMY AT DENVER RTD

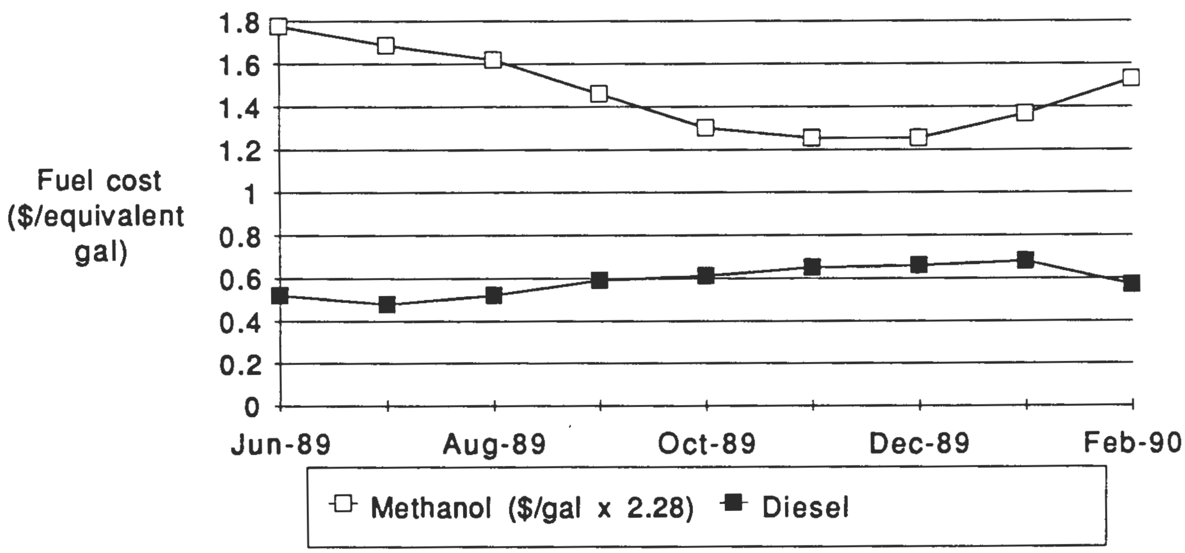

FIGURE 16. EQUIVALENT FUEL COSTS AT DENVER RTD

TABLE 13. DENVER FUEL AND MAINTENANCE TABLE

		Jun-89	Jul-89	Aug-89	Sep-89	Oct-89	Nov-89
1. Total Fleet Miles	(M)	11,600	13,700	19,400	15,900	19,600	17,500
	(D)	16,400	12,100	20,000	14,800	17,800	21,900
2. Number of Roadcalls	(M)	8	12	18	10	9	5
	(D)	5	4	9	11	9	4
3. Average Miles Between Roadcalls	(M)	1,450	1,142	1,078	1,590	2,178	3,500
	(D)	3,280	3,025	2,222	1,345	1,978	5,475
4. Total Fleet Parts Cost	(M)	$ 7,955	$11,345	$10,554	$ 9,614	$13,893	$ 5,916
	(D)	$ 1,975	$ 481	$ 1,711	$ 2,152	$ 2,239	$ 1,648
5. Total Fleet Labor Hours	(M)	476	510	398	319	496	385
	(D)	221	145	181	245	203	235
6. Average Labor Hours Per Mile	(M)	0.04	0.04	0.02	0.02	0.03	0.02
	(D)	0.01	0.01	0.01	0.02	0.01	0.01
7. Total Fleet Labor Cost	(M)	$ 8,934	$ 9,562	$ 7,469	$ 5,978	$ 9,307	$ 7,221
	(D)	$ 4,142	$ 2,721	$ 3,391	$ 4,598	$ 3,813	$ 4,409
8. Parts Cost Per Mile, Average Bus	(M)	$ 0.69	$ 0.83	$ 0.54	$ 0.60	$ 0.71	$ 0.34
	(D)	$ 0.12	$ 0.04	$ 0.09	$ 0.15	$ 0.13	$ 0.08
9. Labor Cost Per Mile, Average Bus	(M)	$ 0.77	$ 0.70	$ 0.39	$ 0.38	$ 0.47	$ 0.41
	(D)	$ 0.25	$ 0.22	$ 0.17	$ 0.31	$ 0.21	$ 0.20
10. Total Cost Per Mile, Average Bus (Maintenance, Parts, and Fuel)	(M)	$ 1.96	$ 1.98	$ 1.32	$ 1.45	$ 1.54	$ 1.11
	(D)	$ 0.51	$ 0.39	$ 0.39	$ 0.61	$ 0.49	$ 0.44
11. Average Labor Rate, $ Per Hour	(M)	$ 18.77	$ 18.75	$ 18.77	$ 18.74	$ 18.76	$ 18.76
	(D)	$ 18.74	$ 18.77	$ 18.73	$ 18.77	$ 18.78	$ 18.76

TABLE 13. DENVER FUEL AND MAINTENANCE TABLE (CONTINUED)

		Dec-89	Jan-90	Feb-90
1. Total Fleet Miles	(M) (D)	14,900 22,200	16,700 19,800	16,400 17,800
2. Number of Roadcalls	(M) (D)	9 7	7 1	6 5
3. Average Miles Between Roadcalls	(M) (D)	1,656 3,171	2,386 19,800	2,733 3,560
4. Total Fleet Parts Cost	(M) (D)	$ 7,899 $ 2,016	$11,089 $ 1,990	$11,750 $ 1,593
5. Total Fleet Labor Hours	(M) (D)	356 232	369 202	346 240
6. Average Labor Hours Per Mile	(M) (D)	0.02 0.01	0.02 0.01	0.02 0.01
7. Total Fleet Labor Cost	(M) (D)	$ 6,671 $ 4,341	$ 6,921 $ 3,784	$ 6,492 $ 4,499
8. Parts Cost Per Mile, Average Bus	(M) (D)	$ 0.53 $ 0.09	$ 0.66 $ 0.10	$ 0.72 $ 0.09
9. Labor Cost Per Mile, Average Bus	(M) (D)	$ 0.45 $ 0.20	$ 0.41 $ 0.19	$ 0.40 $ 0.25
10. Total Cost Per Mile, Average Bus (Maintenance, Parts, and Fuel)	(M) (D)	$ 1.37 $ 0.44	$ 1.46 $ 0.45	$ 1.51 $ 0.48
11. Average Labor Rate, $ Per Hour	(M) (D)	$ 18.74 $ 18.71	$ 18.76 $ 18.73	$ 18.76 $ 18.75

failure is consistent with the expected results of excessive methanol washing lube oil from the cylinder liners. The Golden Gate demonstration reported that lower bank injectors failed more often, and this Denver engine had the lower bank cylinders seized. Figure 17 shows the roadcalls for the demonstration fleet. The data for January, 1990, show only one diesel roadcall for an average 19,800 miles between diesel roadcalls. Denver is also able to report total parts costs and total labor costs for the methanol and diesel control fleets. This accurately captures for the first time the total difference in operating cost between the methanol and diesel control buses.

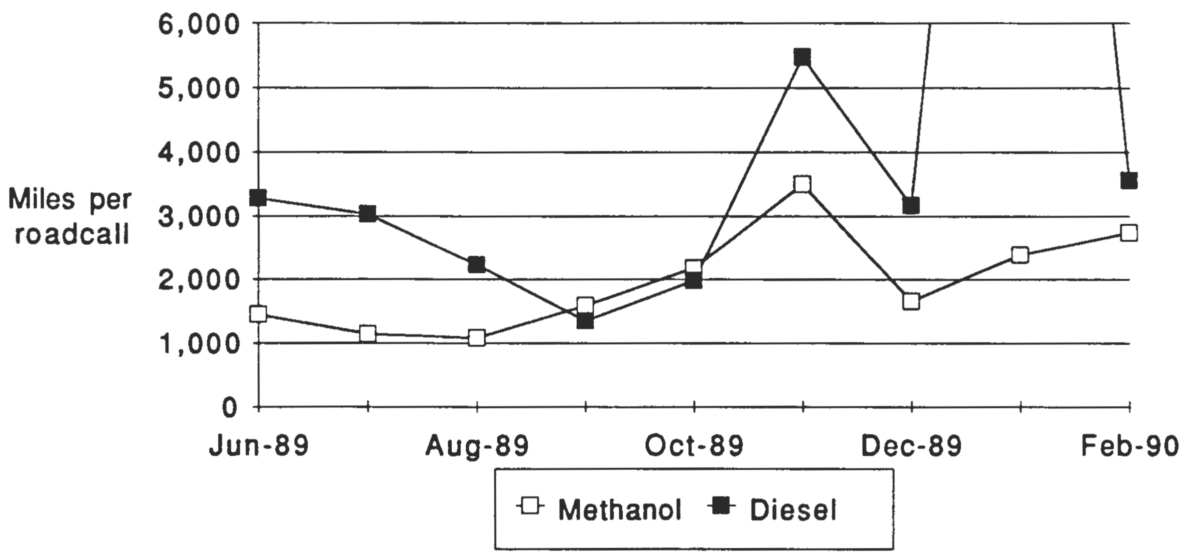

FIGURE 17. MILES BETWEEN ROADCALLS AT DENVER RTD

Figures 18, 19, and 20 show the cost per mile for parts, labor, and fuel for the buses, all to the same scale. Figure 21 shows the sum of these costs as total cost per mile averaged over the program to date. This figure shows that the total operating cost for the methanol buses at Denver is about four times the operating cost for the diesel buses. The large cost difference is mainly caused by the high number of fuel injector failures. If the parts cost and labor cost of the methanol buses can be improved to equal that of the diesel buses, the overall cost ratio will fall from 4:1 to 1.6:1. The 60 percent additional cost which remains for methanol is the fuel differential at today's prices. Figure 22 shows the monthly mileages.

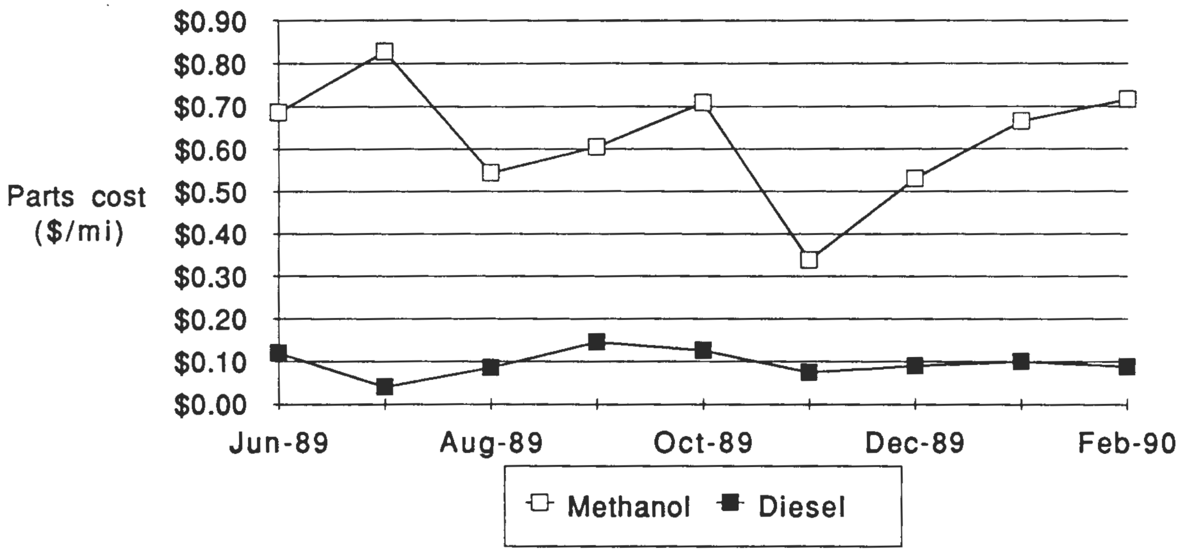

FIGURE 18. PARTS COSTS PER MILE AT DENVER RTD

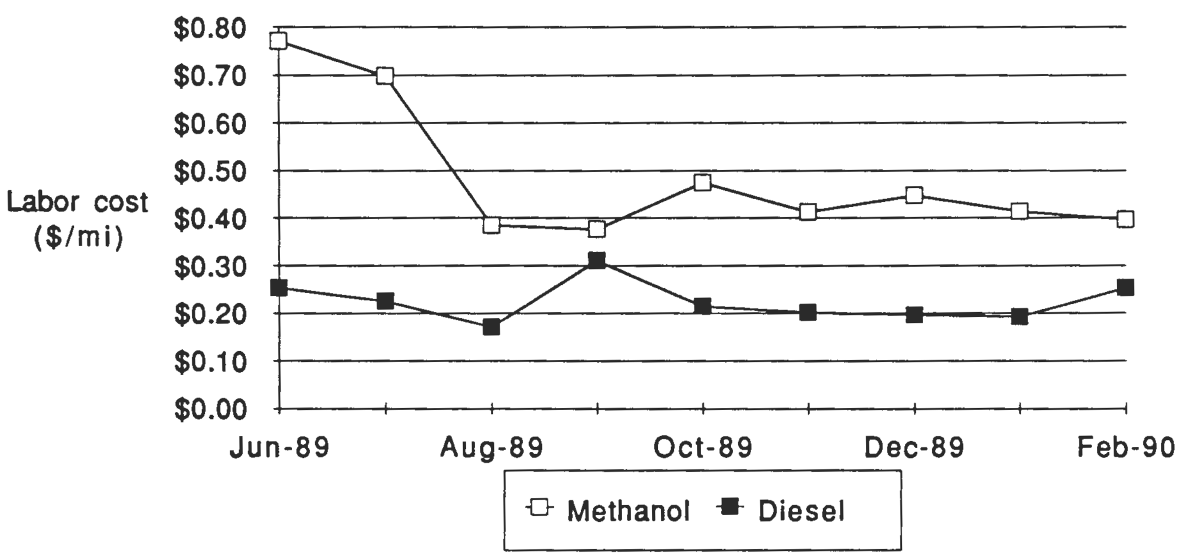

FIGURE 19. LABOR COSTS PER MILE AT DENVER RTD

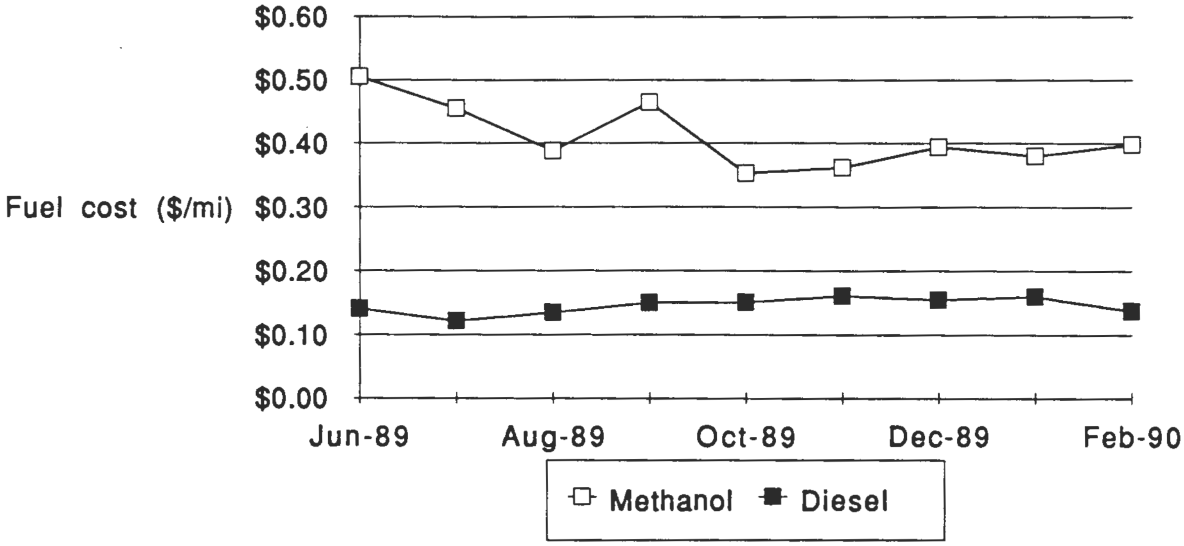

FIGURE 20. FUEL COSTS PER MILE AT DENVER RTD

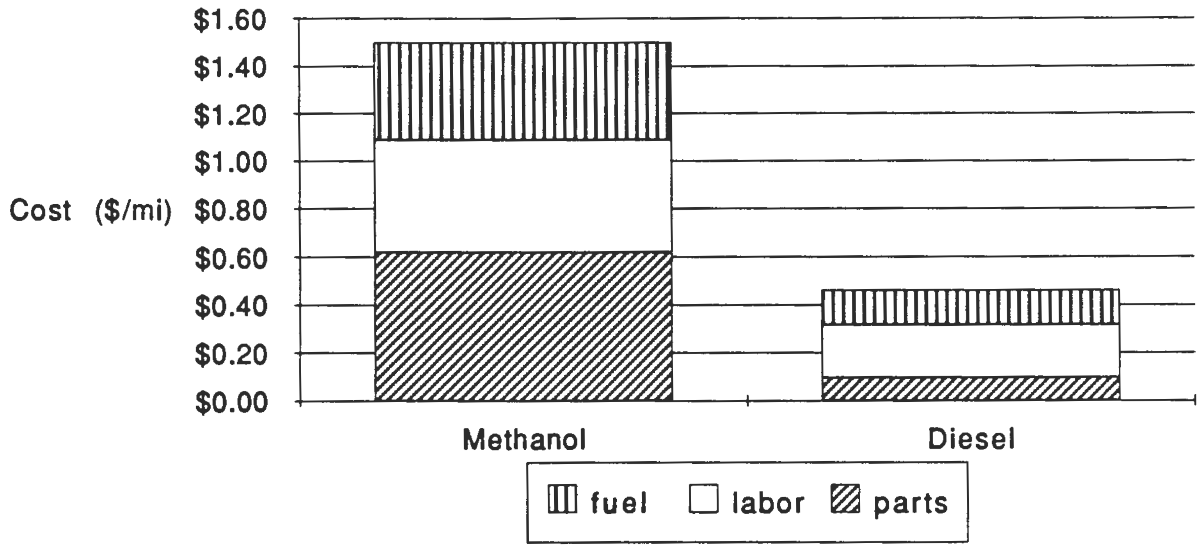

FIGURE 21. TOTAL COSTS PER MILE AT DENVER RTD

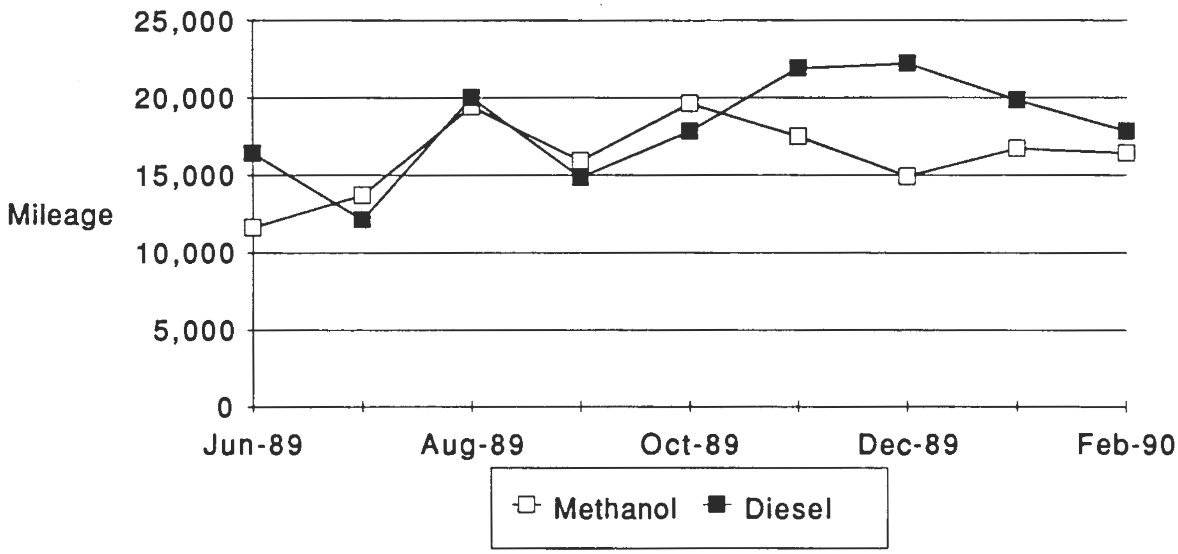

FIGURE 22. MONTHLY FLEET MILES AT DENVER

3.8 SCRTD

3.8.1 Demonstration Site Introduction

Los Angeles, in southern California, is the third largest city in the U.S. As a coastal city, its elevation begins at sea level and climbs to 5,080 feet atop Mt. Lukens. Temperatures average 57.5°F in winter, and 70°F in summer. The climate is dry, averaging 12.6 inches of precipitation annually. Although snow has fallen in Los Angeles, it is exceedingly rare. High levels of traffic congestion and air pollution are characteristics of the greater metropolitan area. The 1984 census population was 12.4 million for the consolidated metropolitan statistical area.

The Southern California Rapid Transit District (SCRTD) methanol demonstration began in June, 1989. The demonstration includes 30 methanol-fueled TMC buses and 30 diesel-fueled TMC control buses. All 60 demonstration buses are powered by DDC 6V-92TA (diesel) and 6V-92TA-M (methanol) engines. The delivery of the 30 methanol buses is extending over a several month period, and is still one bus short of completion as of January, 1990. As each new methanol bus is placed in revenue service for the demonstration, a diesel control bus is added to the demonstration fleet.

3.8.2 Bus Specification

The specifications for the SCRTD methanol buses is exactly the same as for the Denver buses, as they are all from the same manufacturing run and purchase contract. This specification is in Appendix A, Table A5.

3.8.3 Bus Routing

SCRTD assigns the methanol buses arbitrarily to routes in its service area. Although route descriptions have not been provided by SCRTD, policy prescribes that each methanol bus remain paired with a single diesel control bus. This assures that diesel control fleet and the methanol fleet are assigned to identical routings.

3.8.4 Consumables

In the seven month period between July of 89 and January of 90, the SCRTD methanol buses averaged approximately 24 percent fewer miles per gallon, on an energy equivalent basis, than the diesel control buses. Table 13 shows the totals and averages for fuel mileage at SCRTD, while Table 14 shows the complete data. Figure 23 shows the fuel consumption on an energy equivalent basis.

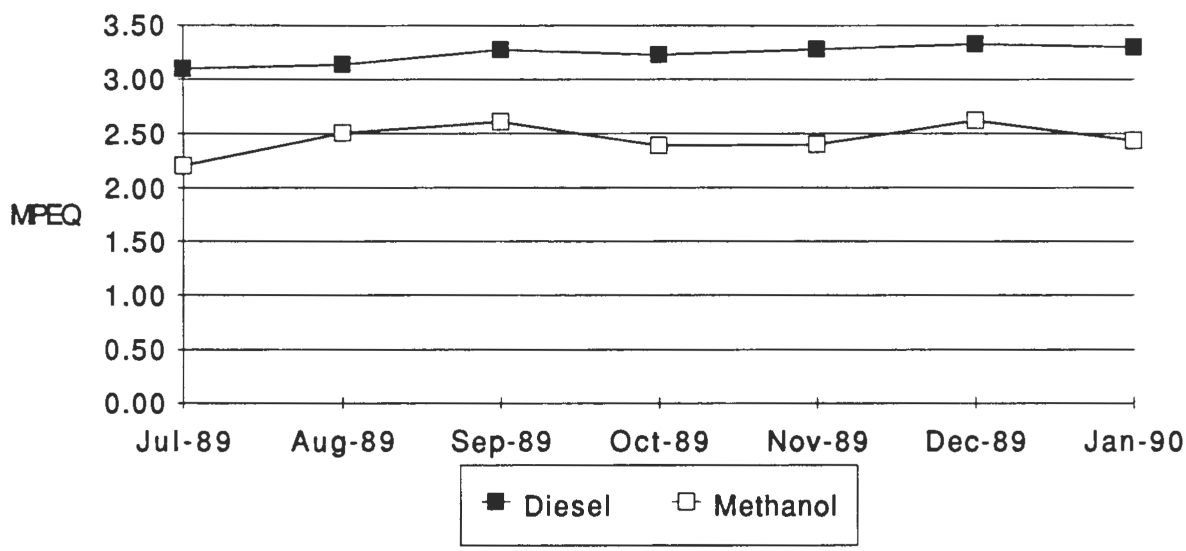

FIGURE 23. MILES PER ENERGY EQUIVALENT GALLON AT SCRTD

3.8.5. Unscheduled Maintenance

The maintenance data reported by SCRTD consists of miles traveled for both methanol and diesel control buses, methanol engine repairs, and number of methanol related roadcalls to date.

The methanol buses have accumulated one-third less miles than the diesel control buses. Upon entering revenue service, each methanol bus was paired with a diesel control bus. The two buses are always assigned together on the route chosen arbitrarily each day. This arrangement makes the total

TABLE 14. FUEL CONSUMPTION AT SCRTD FROM JULY 1989 THROUGH JANUARY 1990

		Jul-89	Aug-89	Sep-89	Oct-89	Nov-89	Dec-89	Jan-90
1. Total Fleet Miles	(M)	13,577	33,258	40,775	42,868	43,667	47,978	52,026
	(D)	22,697	46,382	55,170	58,824	64,927	84,081	81,132
2. Average Fleet Miles Per Gallon	(M)	0.97	1.10	1.14	1.05	1.05	1.15	1.07
	(D)	3.09	3.14	3.27	3.23	3.28	3.32	3.30
3. Methanol Equivalent MPEQ	(M)	2.20	2.50	2.61	2.38	2.40	2.62	2.43
4. Number of Buses in Fleet	(M)	10	17	18	22	29	29	30
	(D)	8	17	18	22	30	30	30
5. Average Miles Per Bus	(M)	1,358	1,956	2,265	1,949	1,506	1,654	1,734
	(D)	2,837	2,728	3,065	2,674	2,164	2,803	2,704
6. Total Cumulative Fleet Miles	(M)	13,577	46,835	87,610	130,478	174,145	222,123	274,149
	(D)	22,697	69,079	124,249	183,073	248,000	332,081	413,213

fleet miles a good indicator of relative availability of the diesel and methanol fleets. The SCRTD buses have only been able to provide two-thirds of the revenue service miles that the identically-dispatched diesel control fleet has provided.

Table 14 shows the SCRTD fuel data, and Table 15 shows the maintenance data. During the first seven months of operation, the SCRTD methanol engines have had 424 injector failures for an average of 647 miles between injector failures. Figure 24 shows the SCRTD injector failures. The data show no clear trend over the seven months for injector failure rates.

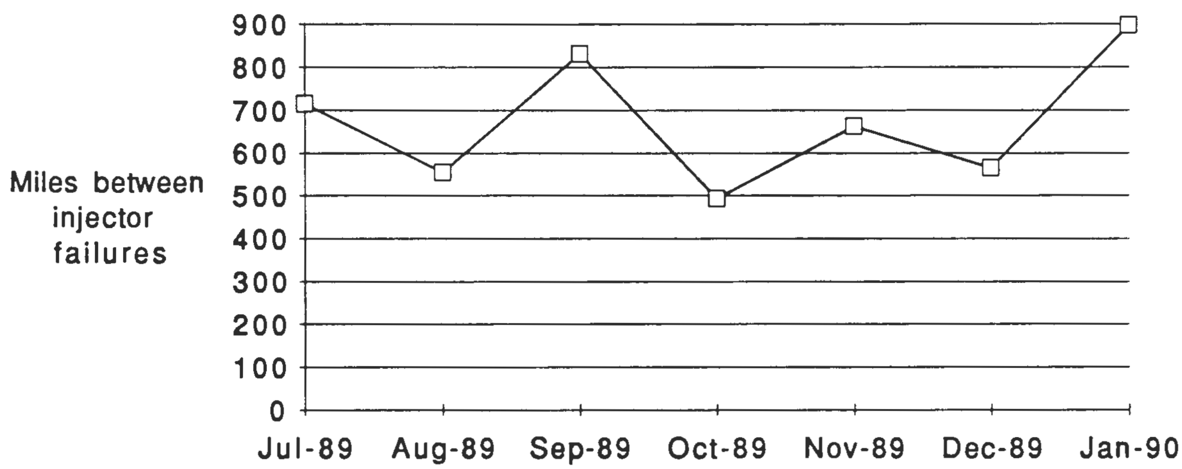

FIGURE 24. MILES BETWEEN METHANOL FUEL INJECTOR FAILURES AT SCRTD

Similarly, the miles between glowplug failures, shown in Figure 25, exhibit no clear trend. Figure 26 shows the miles between fuel filter failures. This data indicates that fuel filter reliability is deteriorating over time and is stabilizing at about 3,500 miles between fuel filter failures.

TABLE 15. SCRTD MAINTENANCE DATA FOR
JULY 1989 THROUGH JANUARY 1990

	Jul-89	Aug-89	Sep-89	Oct-89	Nov-89	Dec-89	Jan-90
1. Total Methanol Fuel Miles	13,577	33,258	40,775	42,868	43,667	47,978	52,026
2. Number of Glowplug Failures	6	19	10	13	8	43	66
3. Number of Glowplug Controller Failures	1	5	2	12	1	4	7
4. Number of Injector Failures	19	60	49	87	66	85	58
5. Number of Fuel Filter Failures	2	15	6	13	10	16	14
6. Number of Other Failures	1	5	3	5	1	6	5
7. Average Miles Between Glowplug Failures	2,263	1,750	4,078	3,298	5,458	1,116	788
8. Average Miles Between Glowplug Controller Failures	13,577	6,652	20,388	3,572	43,667	11,995	7,432
9. Average Miles Between Injector Failures	715	554	832	493	662	564	897
10. Average Miles Between Fuel Filter Failures	6,789	2,217	6,796	3,298	4,367	2,999	3,716
11. Average Miles Between Other Failures	13,577	6,652	13,592	8,574	43,667	7,996	10,405
12. Average Miles Between All Failures	468	320	583	330	508	312	347
13. Total Cumulative Fleet Miles	13,577	46,835	87,610	130,478	174,145	222,123	274,149

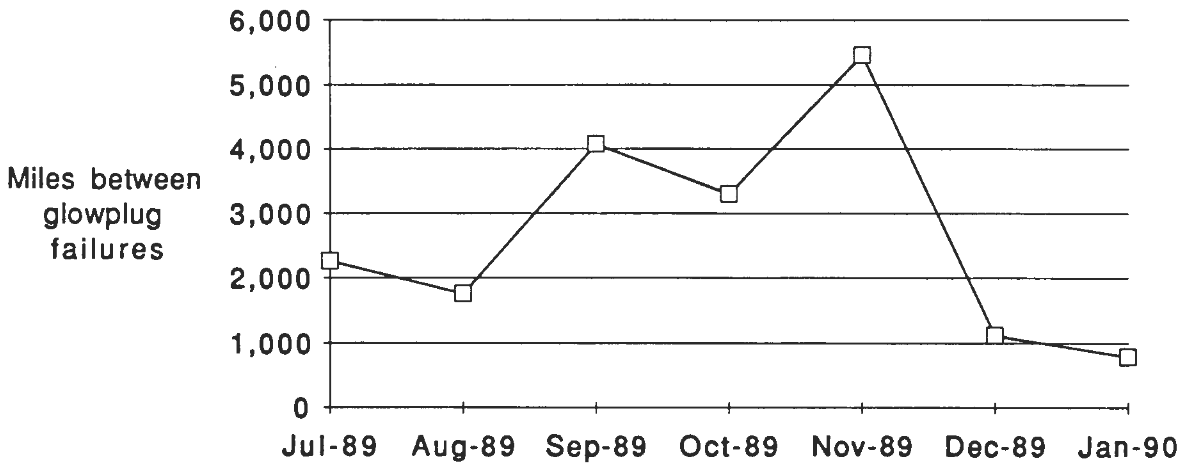

FIGURE 25. MILES BETWEEN METHANOL GLOWPLUG FAILURES AT SCRTD

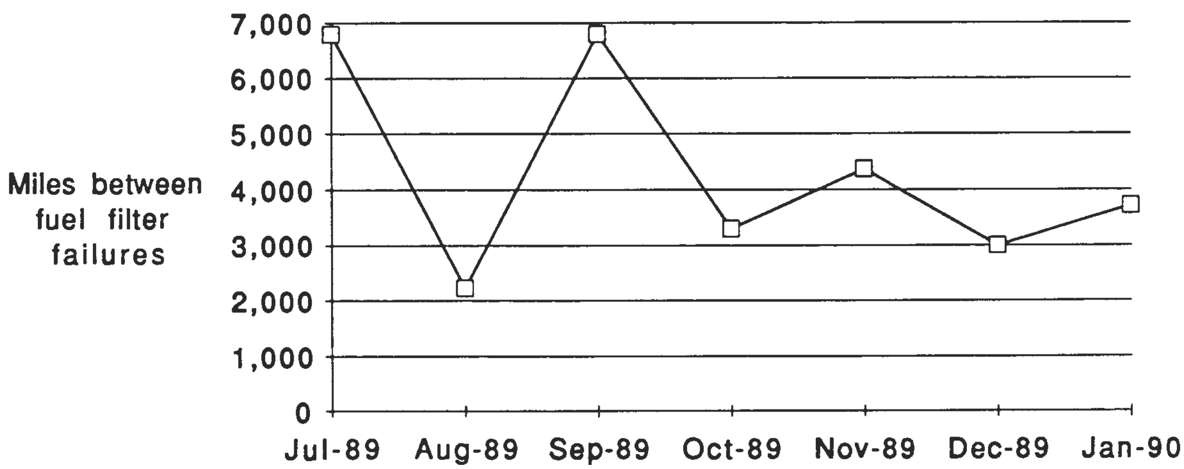

FIGURE 26. MILES BETWEEN METHANOL FUEL FILTER FAILURES AT SCRTD

SCRTD reports 185 methanol-related roadcalls to date, for an average of just under 1,500 miles between roadcalls. SCRTD also reports that 12 methanol engines have suffered major failures (i.e., crankshaft, main bearing, connecting rods, pistons, blocks, cylinder head, or camshaft) of some sort, mostly due to main bearing failure. The cause of these failures have not been determined, but the information reported by SCRTD is consistent with the expected results of excessive methanol present in the engine to dilute or wash away lube oil.

3.9 Other Methanol Bus Operators

3.9.1 Golden Gate Transit District

The Golden Gate Transit District (GGTD) in San Rafael, California, obtained one GM methanol bus in December 1983 and one M.A.N. bus in June of 1984. The buses were subjected to a test program, and were placed into revenue service in September of 1984. A detailed report[8] on the first year of revenue operations was provided for this summary which covers the period of June 1984 through October 1985.

3.9.1.1 Bus Specifications. The GM bus is an RTS-04, powered by one of the first prototype methanol 6V-92TA engines. The M.A.N. methanol bus is a European SÜ 240 coach with a D2566FMUH engine. This engine is naturally aspirated, four stroke, high compression, stratified charge, direct injected, with spark ignition.

The control buses are a GM diesel with 6V-92 engine and a M.A.N. diesel coach with a D2566MUH engine.

3.9.1.2 Fuel Usage Comparisons. Controlled fuel economy testing was performed on the buses upon receipt. The results showed that the methanol buses provided fuel economy within 3 percent of the diesel buses on an energy equivalent basis, except at idle. At idle, the methanol buses burned approximately 50 percent more fuel, on an energy equivalent basis, than the diesel buses.

During the first year of revenue service, the GM methanol bus accumulated 27,800 miles, and the M.A.N. methanol bus accumulated 36,000 miles. Table 16 shows the totals and averages for fuel usage.

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[8] Methanol Fueled Transit Bus Demonstration, Phase I Technical Analysis, October, 1986. Prepared for California Energy Commission, Developmental Division, by Stephan Unnasch and Michael Jackson, Acurex Corporation, Environmental Systems Division.

TABLE 16. TOTALS AND AVERAGES OF FUEL CONSUMPTION AT GOLDEN GATE FROM SEPTEMBER 1984 THROUGH OCTOBER 1985

	GM Diesel	GM Methanol	M.A.N. Diesel	M.A.N. Methanol
1. Total Mileage	25,774	20,903	34,509	31,633
2. Total Fuel Used (Gallons	6,316	14,693	6,203	13,265
3. Average Miles Per Gallon	4.08	1.42	5.56	2.38
4. Average MPEQ	4.08	3.24	5.56	5.43

It shows that the GM methanol bus averaged just over 20 percent fewer miles per gallon, on an energy equivalent basis, than the GM diesel bus. The M.A.N. methanol bus averaged almost the same (within 3 percent) miles per gallon as the diesel M.A.N. bus on an energy equivalent basis. Because these are one vehicle "fleets", caution should be used when comparing the methanol and diesel control buses; the individual conditions of the control buses greatly influence the comparison.

3.9.1.3 Unscheduled Maintenance. The initial GGTD experience with the GM methanol bus was very troublesome. The DDC methanol engine was the first in service in a bus, and the first experimental configurations were unsatisfactory. After seven months of testing and modification, the bus was put into revenue service. The M.A.N. methanol engine was a more mature design. M.A.N. has been working on heavy duty methanol engines since the early 1970's, and had operated methanol buses in New Zealand and West Germany. The initial M.A.N. reliability and overall reliability have been much better than the G.M. methanol bus. The M.A.N. methanol reliability problems are due mostly to frequent spark plug changes. The GGTD experience showed the spark plugs to usually last over 4,000 miles, but begin to fail at 5,000 miles. Table 17 shows the total fuel injector, glowplug and spark plug failures for the methanol buses.

TABLE 17. TOTAL METHANOL ENGINE GLOWPLUG, FUEL INJECTOR, AND SPARK PLUG FAILURES AT GOLDEN GATE FROM SEPTEMBER 1984 THROUGH OCTOBER 1985

	GM Methanol	M.A.N. Methanol
1. Total Injector Failures	30	N/A
2. Total Glowplug Failures	37	N/A
3. Total Spark Plug Failures	N/A	66 (11 sets of 6)

3.9.1.4 Total Life Cycle Costs. A life cycle cost analysis was performed on the two GGTD methanol buses. The results are somewhat unrealistic because they include a very high purchase cost for the buses. The GGTD methanol buses were very expensive ($310,000 for the GM, and $230,620 for the M.A.N.) because they were essentially hand-built experimental vehicles. Similarly, fuel costs are difficult to predict, and this 1986 analysis was based upon a diesel fuel cost of 34.3¢ per gallon, and a lowest methanol price of 62.8¢ per gallon and a highest methanol price of 79.4¢ per gallon. The results find the cost per mile of the methanol buses to be from 145% to 237% of diesel costs. The analysis was a present-value analysis, and is documented in complete detail in the program report.

3.9.2 Riverside Transit Agency

The Riverside Transit Agency (RTA) in Riverside, California is currently operating three methanol powered buses. Riverside is located approximately 50 miles east of Los Angeles, and is considered one of the South Coast Air Quality Management District's worst air polluted areas. RTA is operating its methanol buses for a three year demonstration project sponsored by the California Air Resources Board and General Motors Corporation.

RTA has retrofitted three 1982 GMC buses for methanol operation. The conversion included outfitting the buses with DDEC I and ATEC I control systems. The buses were placed in revenue service on April 8, 1988, and were still in operation in March of 1990. The three Riverside methanol buses have experienced poor fuel injector and glowplug performance, although both components are reported to have had significant reliability improvements in recent months.

3.9.3 Jacksonville Transportation Authority

The Jacksonville Transportation Authority (JTA) in Jacksonville, Florida, operated three methanol buses under the sponsorship of the Florida Department of Transportation and UMTA. Revenue operation of these buses began in June, 1986, and was terminated in October of 1988. Jacksonville is located at the northeast corner of Florida. The subtropical climate does not normally provide snow, although Jacksonville does receive 40-60 inches of annual rain. Typical daytime high temperatures are in the low 80's in August and in the mid 40's in January.

3.9.3.1 Bus Specifications. JTA converted three 1964 G.M.C. 40 foot buses for methanol use. The buses were equipped with 6V-71 engines. The buses were put into revenue service on March 14, 1988. The buses had previously been configured to burn methanol with castor oil added to improve lubricity. The castor oil fouled the engines severely with deposits, requiring all three engines to be disassembled and rebuilt. After reworking the engines, the buses were run on methanol with an additive from ICI called "AVOCET", which improves lubricity and ignition and inhibits corrosion. The final configuration of the JTA methanol buses was unique in that they had neither glow plugs nor spark plugs. The use of "AVOCET" methanol additive in the fuel enabled the fuel mixture to auto-ignite like diesel fuel.

3.9.3.2 Consumables. Florida D.O.T. provided fuel use data covering the period of March through August of 1988. These buses were fueled with 98 percent methanol and 2 percent "AVOCET" brand additive. Only data on fuel consumption were reported for the three methanol buses; no data were provided for diesel buses or for oil consumption. These data are presented in Table 18. Table 18 shows the methanol bus fuel usage, while Figure 5 shows the ratio of the actual MPG's of the three methanol buses to the fleetwide diesel bus average.

TABLE 18. FUEL CONSUMPTION FOR JACKSONVILLE TRANSIT AUTHORITY METHANOL BUS ONLY

	APR 1988	MAY 1988	JUN 1988	JUL 1988	AUG 1988
1. Total Fleet Mileage (Miles)	3,082	3,316	2,733	3,719	4,418
2. Average Bus Mileage (Miles)	1,027	1,105	911	1,240	1,473
3. Average Miles Per Gallon (MPG)	1.15	1.05	1.02	1.09	1.14
4. Average Miles Per Energy Equivalent (MPEQ)	2.62	2.39	2.32	2.49	2.60
5. Fuel Cost Per Gallon ($)	0.78	0.78	0.78	N/A	N/A

3.9.3.3 Safety, Health, and Accident Reports. Jacksonville experienced three fires in their methanol buses, all in revenue service. No one was injured in any fire. One of the fires has been attributed to an electrical system failure unrelated to the use of methanol fuel.

The two methanol related fires were exhaust stack fires, where unburned fuel in the exhaust ignited in the final portion of the exhaust system. Both fires caused damage to body panels near the exhaust pipe.

The first methanol exhaust fire occurred in December, 1986, when the buses were burning the methanol/castor oil mixture. The second exhaust fire occurred in October of 1989. This bus was burning methanol with two percent Avocet.

The electrical fire occurred in August of 1988, and was determined to be unrelated to the use of methanol.

4.0 EMISSIONS

The measurement of vehicle emissions is possible using many techniques and methods. Small changes in test conditions and measurement methods can make large differences in results. Results from different test methods cannot, in general, be related to each other.

The only method that the U.S. EPA accepts as evidence of compliance with its 1991 regulations is an engine dynamometer test. The engine is run over a specific set of varying speeds and loads, and the emissions are measured in grams per brake·horsepower·hour (g/bhp·hr). This testing is usually done by the engine manufacturer.

Another common method of emissions testing is with a chassis dynamometer. There are only a few such facilities available in the U.S. capable of handling a heavy-duty transit bus which are also capable of subjecting the vehicle to transient loading.

There is much evidence to suggest that the majority of vehicle emissions occur during acceleration and deceleration. Therefore, any sort of steady-state testing (such as the commonly performed 13-mode test) will probably give emissions results much lower than a transient test. The 13-mode test has previously been used as the federal EPA test standard for heavy duty engines.

Emissions data for the methanol bus engines is available only from a few sources. Chevron Research Company tested both an M.A.N. and a GM bus with its heavy duty chassis dynamometer facility. Results were published in grams per hour and in grams per mile, therefore no conclusions can be drawn as to whether these buses met the 1991 standards in grams per brake·hp·hr. On the transient cycles, the DDC-6V92-TAM produced significantly lower NO_x, particulates, and carbon monoxide than a diesel bus. Hydrocarbons and formaldehyde were higher for the methanol engine.

The New York State Department of Environmental Protection is producing test data on the Triboro buses using a chassis dynamometer facility. This facility is operating a unique transient cycle that uses only low speed and low load conditions. The results of this testing cannot be correlated with the 1991 EPA standards. These tests show reduced NO_x and particulates for the methanol buses. The hydrocarbon, carbon monoxide, and formaldehyde emissions levels vary depending upon the type and condition of the catalytic converter.

The Detroit Diesel Company has run the EPA engine dynamometer certification procedure on several versions of the 6V-92TAM methanol engine. DDC states that the production engine has met the 1991 standards without a catalytic converter, and exceeded the 1991 standards with a catalytic converter.

5.0 FINDINGS

The first 2½ years of data have been reviewed, and the following findings are made:

1. The M.A.N. methanol buses are providing essentially the same amount of revenue service miles per year as diesel buses. This demonstrates that methanol buses are capable of serving routes with the same number of vehicles as today's diesel buses. There is no need to increase the bus spares ratio for mature methanol technology. This is based upon the Seattle data.

2. Methanol buses are significantly more expensive to operate, with existing technology, than diesel buses. It should be noted that the maintenance mechanics are highly experienced with diesel buses and have little methanol bus experience. This is based on all demonstration sites.

3. The M.A.N. methanol fuel injectors provide the same reliability as M.A.N. diesel fuel injectors. This is based upon the Seattle data.

4. The DDC fuel injectors provide unacceptably poor life and reliability, and their failure may seriously damage major engine components. A fuel additive recently developed by DDC and Lubrizol offers a potential solution to this problem. This is based upon all demonstration sites except Seattle.

5. Methanol fuel can be used safely in a transit environment. This is based upon all demonstration data.

6. Methanol buses show significant reductions in regulated emissions. DDC states that they have met and exceeded 1991 EPA

standards with their methanol engine. This is based upon all existing emissions data.

7. Methanol buses are well accepted by the drivers, mechanics, and the general public. This is based upon all demonstration sites.

8. There is no fundamental property of methanol engines which prevents them from having reliability equivalent to diesel engines. The M.A.N. and DDC engines in this demonstration each show a solution to one of the two outstanding methanol engine reliability problems. The M.A.N. engines have reliable methanol fuel injectors, and the recent DDC engines have reliable ignition-assisting glowplugs. There is no basic reason that a methanol engine cannot be built with both reliable fuel injectors and reliable ignition aids. This is based upon all demonstration sites.

9. As this report is written, rapid engineering advances are being made toward resolving the costly high maintenance items for methanol engines. When these engineering improvements are complete, methanol buses will only suffer a fuel cost penalty compared with diesel. At current fuel prices, the fuel cost differences will result in a total cost per mile ratio of 1.6 to 1. This is based on Denver's reported cost data and the maintenance data from all demonstration sites.

APPENDIX A

BUS SPECIFICATIONS

This appendix contains the detailed specifications for both the diesel and methanol buses used in the formal demonstration. The four tables specify the Seattle Metro methanol buses, the Seattle Metro diesel buses, the Triboro methanol buses, and the Triboro diesel buses.

TABLE A1. SEATTLE METRO METHANOL BUS SPECIFICATIONS

Transit Agency Seattle Metro Bus Number 3150 to 3159

Bus Manufacturer M.A.N. Model Number SL40102LM

Accumulated Mileage at Start of Demonstration 6209 Miles (Average Bus)

Length, ft.	40'1"	
Width, in.	102"	
Height, in.	120"	
Passenger seats, no.	44	
Engine Type:	4 Stroke Spark Ignition	*
Manufacturer	M.A.N.	
Model Number	M2566LUH	*
Power, bhp	279 bhp	
Fuel Injector Type:	BOSCH #PES6 P130 A720LV16379	*
Size	2683-2799 psi, 0.036 inch spray hole diameter	*
Fuel Type	Neat Methanol	*
Fuel Pump(s): Type	Electrical Y580700151 43.5 psi Mechanical BOSCH Double Acting 14.5 psi	*
Fuel System:	M.A.N.	
Tank Capacity, gallons	266 Volume & 250 Usable	*
Fillpipe Flame Arrestor	Yes ____ No ✓	
Vent Flame Arrestor	Yes ✓ No ____	
Fueling System:		
Manufacturer		
Type		
Model Number		

NOTE: * Indicates a specification difference between the methanol and diesel buses

TABLE A1. SEATTLE METRO METHANOL BUS SPECIFICATIONS (CONTINUED)

Bus Number 3150-3159

Generator:	Delco Remy	
Output at Normal Idle	Amps ____ Volts ____	
Maximum Rating	Amps 270 Volts 28	
Starter Type:	Electrical √ Air ____	*
Manufacturer	BOSCH	*
Model	KB	*
Heating System Type:	Forced Air Hot Water	
Capacity, btu/hr		
Air Conditioning:	None	
System Capacity, btu/hr	N/A	
Compressor Manufacturer	N/A	
Compressor Model Number	N/A	
Air Compressor:		
Manufacturer	WABCO 35.67 cu. in.	
Model Number	4110338062	
Capacity, cubic ft/min	20.5 CFM @ 145 psi	
Transmission Type:	Automatic - Hydraulic	
Manufacturer	Renk	
Model Number	Doromat 874B	
Converter Torque Multiplication	811.2 ft. lbs. @ 1600 rpm (2200 rpm max)	
Retarder Type:	Integral - Hydraulic	
Manufacturer	Renk	
Model Number		

NOTE: * Indicates a specification difference between the methanol and diesel buses

TABLE A1. SEATTLE METRO METHANOL BUS SPECIFICATIONS (CONTINUED)

Bus Number 3150-3159

Brakes, Type:	Drum "S" CAM	
Manufacturer	M.A.N.	
Drive Axle:		
Manufacturer	M.A.N.	
Model Number		
Axle Ratio	5.22	
Tires:		
Manufacturer	Firestone	
Type	Bias Ply - Tubeless	
Size	12.5 x 22.5	
Curb Weight:		
Front Axle	10,700 lbs.	
Rear Axle	18,040 lbs.	
Total	28,740 lbs.	*
Seated Load Weight:		
Front Axle		
Rear Axle		
Total	35,340 lbs.	*
Other attributes or features: (wheelchair lifts, wheelchair position, bicycle racks, etc.)	1. Wheelchair lift - front door	

NOTE: *Indicates a specification difference between the methanol and diesel buses

TABLE A2. SEATTLE METRO DIESEL BUS SPECIFICATIONS

Transit Agency ___Seattle Metro___ Bus Number ___3137 to 3146___

Bus Manufacturer ___M.A.N.___ Model Number ___SL40102L___

Accumulated Mileage at Start of Demonstration ___44779 Miles___ (Average Bus)

Length, ft.	40'1"	
Width, in.	102"	
Height, in.	120"	
Passenger seats, no.	44	
Engine Type:	4 Stroke #2566 MLUH/US/240	*
Manufacturer	M.A.N.	
Model Number	D2566MLUH	*
Power, bhp	257 bhp	
Fuel Injector Type:	BOSCH #PES6 P120 A720LS388	*
Size	3480-3596 psi, 0.029 inch spray hole diameter	*
Fuel Type	#2 Diesel	*
uel Pump(s): Type	Electrical ___ Mechanical ___BOSCH___	*
Fuel System:	M.A.N.	
Tank Capacity, gallons	133 Volume & 125 Usable	*
Fueling System:		
Manufacturer		
Type		
Model Number		
Generator:	Delco Remy	
Output at Normal Idle	Amps ___ Volts ___	
Maximum Rating	Amps ___270___ Volts ___28___	

NOTE: *Indicates a specification difference between the methanol and diesel buses

TABLE A2. SEATTLE METRO DIESEL BUS SPECIFICATIONS (CONTINUED)

Bus Number 3137-3146

Starter Type:	Electrical ______ Air ___√___ *
Manufacturer	Ingersoll Rand *
Model	SS350GB03R85-1537 *
Heating System Type:	Forced Air Hot Water
Capacity, btu/hr	
Air Conditioning:	None
System Capacity, btu/hr	N/A
Compressor Manufacturer	N/A
Compressor Model Number	N/A
Air Compressor:	
Manufacturer	WABCO 35.67 cu. in.
Model Number	4110338062
Capacity, cubic ft/min	20.5 CFM @ 145 psi
Transmission Type:	Automatic - Hydraulic
Manufacturer	Renk
Model Number	Doromat 874B
Converter Torque Multiplication	811.2 ft. lbs. @ 1600 rpm (2200 rpm max)
Retarder Type:	Integral - Hydraulic
Manufacturer	Renk
Model Number	
Brakes, Type:	Drum "S" CAM
Manufacturer	M.A.N.
Drive Axle:	

NOTE: *Indicates a specification difference between the methanol and diesel buses

TABLE A2. SEATTLE METRO DIESEL BUS SPECIFICATIONS (CONTINUED)

Bus Number 3137-3146

Manufacturer	M.A.N.	
Model Number		
Axle Ratio	5.22	
Tires:		
Manufacturer	Firestone	
Type	Bias Ply - Tubeless	
Size	12.5 x 22.5	
Curb Weight:		
Front Axle	10,100 lbs.	
Rear Axle	17,700 lbs.	
Total	27,800 lbs.	*
Seated Load Weight:		
Front Axle		
Rear Axle		
Total	34,400 lbs.	*
Other attributes or features: (wheelchair lifts, wheelchair position, bicycle racks, etc.	1. Wheelchair lift - front door	
	2. Diesel engine starting aid - Kold Ban International, Ltd. (KBI) Fluid Starting System	*

NOTE: *Indicates a specification difference between the methanol and diesel buses

TABLE A3. TRIBORO METHANOL BUS SPECIFICATIONS

Transit Agency: Triboro Coach Co. Bus Number: M-5

Bus Manufacturer: G.M.C. Model Number: T80206

Accumulated Mileage at Start of Demonstration: 466 Miles (Average Bus)

Length, ft.	40 Ft
Width, in.	102 In Wide
Height, in.	119 In
Passenger seats, no.	Seats 46 Stands 35
Engine Type:	Methanol
Manufacturer	Detroit Diesel
Model Number	6V92
Power, bhp	253 bhp (until Feb 90) 277 bhp (after Feb 90)
Fuel Injector Type:	Electronic (DDEC)
Size	7mm Plunger
Fuel Type	Methanol
Fuel Pump(s): Type	Electrical X Mechanical ____
Fuel System:	Self Prime
Tank Capacity, gallons	2 Tanks - 125 Gallons - 159 Gallons
Fillpipe Flame Arrestor	Yes X No ____
Vent Flame Arrestor	Yes X No ____
Fueling System:	Posi - Lock
Manufacturer	Emcc - Weaton
Type	Dry - Disconnect
Model Number	G-2256

TABLE A3. TRIBORO METHANOL BUS SPECIFICATIONS (CONTINUED)

Bus Number 718

Generator:	Delco - Series 50 D.W.
Output at Normal Idle A 1800	Amps 165 Volts 28 VDC
Maximum Rating A 300	Amps 250 Volts 28 VDC
Starter Type:	Electrical X Air ____
Manufacturer	Delco
Model	Series 42 MT Type 400
Heating System Type:	Climate Control
Capacity, btu/hr	32,000
Air Conditioning:	Climate Control
System Capacity, btu/hr	32,000
Compressor Manufacturer	Trane Co.
Compressor Model Number	G, 4 Cylinder, Com 1967
Air Compressor:	2 Cylinder - Water Cooled - Engine Oil
Manufacturer	Bendix - Westinghouse
Model Number	Tru-Flo 700
Capacity, cubic ft/min	15.5
Transmission Type:	Toque Converter and Planetary Gearing
Manufacturer	Detroit Diesel Allison
Model Number	V-731
Converter Torque Multiplication	3.43 - 1

TABLE A3. TRIBORO METHANOL BUS SPECIFICATIONS (CONTINUED)

Bus Number 718

Retarder Type:	
Manufacturer	
Model Number	
Brakes, Type:	Air - Wedge
Manufacturer	Rockwell
Drive Axle:	Angle Spiral Bevel
Manufacturer	Rockwell
Model Number	
Axle Ratio V-6 Engine	5 1/8 - 1 or 5 3/8 - 1
Tires:	
Manufacturer	Goodyear
Type	Bias Load H
Size	12.5 x 22.5
Curb Weight:	
Front Axle	
Rear Axle	
Total	
Seated Load Weight:	
Front Axle	
Rear Axle	
Total	

TABLE A3. TRIBORO METHANOL BUS SPECIFICATIONS (CONTINUED)

Bus Number 718

Other attributes or features: (wheelchair lifts, wheelchair position, bicycle racks, any items that make this bus different from the other test or control buses)	1. Wheelchair Lift 2. Combination Silver/Platinum Catalyst

TABLE A4. TRIBORO DIESEL BUS SPECIFICATIONS

Transit Agency Triboro Coach Co. Bus Number 718

Bus Manufacturer G.M.C. Model Number T80206

Accumulated Mileage at Start of Demonstration 28,468 Miles (Average Bus)

Length, ft.	40 Ft
Width, in.	102 In Wide
Height, in.	119 In
Passenger seats, no.	Seats 46 Stands 35
Engine Type:	Diesel
Manufacturer	Detroit Diesel
Model Number	6V92 Silver
Power, bhp	277 bhp
Fuel Injector Type:	Mechanical
Size	9-.0050
Fuel Type	Diesel
Fuel Pump(s): Type	Electrical ____ Mechanical X
Fuel System:	2 Line Engine Mounted Pump
Tank Capacity, gallons	125 Gallons
Fueling System:	Conventional
Manufacturer	
Type	
Model Number	
Generator:	Delco - Series 50 D.W.
Output at Normal Idle A 1800	Amps 165 Volts 28 VDC
Maximum Rating A 300	Amps 250 Volts 28 VDC

TABLE A4. TRIBORO DIESEL BUS SPECIFICATIONS (CONTINUED)

Bus Number 718

Starter Type:	Electrical X Air ____
Manufacturer	Delco
Model	Series 42 MT Type 400
Heating System Type:	Climate Control
Capacity, btu/hr	32,000
Air Conditioning:	Climate Control
System Capacity, btu/hr	32,000
Compressor Manufacturer	Trane Co.
Compressor Model Number	G, 4 Cylinder, Com 1967
Air Compressor:	2 Cylinder - Water Cooled - Engine Oil
Manufacturer	Bendix - Westinghouse
Model Number	Tu-Flo 700
Capacity, cubic ft/min	15.5
Transmission Type:	Toque Converter - Planetary Gearing
Manufacturer	Detroit Diesel Allison
Model Number	V-730
Converter Torque Multiplication	3.43 - 1
Retarder Type:	
Manufacturer	
Model Number	
Brakes, Type:	Air - Wedge
Manufacturer	Rockwell

TABLE A4. TRIBORO DIESEL BUS SPECIFICATIONS (CONTINUED)

Bus Number 718

Drive Axle:	Angle Spiral Bevel
Manufacturer	Rockwell
Model Number	
Axle Ratio V-6 Engine	5 1/8 - 1 or 5 3/8 - 1
Tires:	
Manufacturer	Goodyear
Type	Bias Load Range H
Size	12.5 x 22.5
Curb Weight:	
Front Axle	13,400 lbs.
Rear Axle	23,500 lbs.
Total	36,900 lbs.
Seated Load Weight:	
Front Axle	13,400 lbs.
Rear Axle	23,500 lbs.
Total	36,900 lbs.
Other attributes or features: (wheelchair lifts, wheelchair position, bicycle racks, any items that make this bus different from the other test or control buses)	

TABLE A5. DENVER RTD AND SCRTD METHANOL BUS SPECIFICATION

Transit Agency RTD & SCRTD

Bus Manufacturer TMC Model Number RTS6

Date of Purchase May 15, 1989

Accumulated Mileage at Start of Demonstration Approximately 1,000

Length, ft.	40 ft.
Width, in.	102 in.
Height, in.	119 in.
Passenger seats, no.	43 21/22
Engine Type:	6V-92TA DDECII
Manufacturer	DDC
Model Number	8-673A2M
Power, bhp	253 bhp (until Feb 90) 277 (after Feb 90)
Fuel Injector Type:	112440 253 hp
Size	125-135 mm^3/1,000 Strokes at Std.
Fuel Type	Methanol
Fuel Pump(s): Type	Electrical x Mechanical ____
Fuel System:	Stainless Steel
Tank Capacity, gallons	285 Gallons
Fillpipe Flame Arrestor	Yes ____ No x
Vent Flame Arrestor	Yes x No ____
Fueling System:	
Manufacturer	EMCO-Wheaton
Type	Dry Break
Model Number	G-3266-105

TABLE A5. DENVER RTD AND SCRTD METHANOL BUS SPECIFICATION (CONTINUED)

Generator:	
Output at Normal Idle	Amps 190 Volts 27
Maximum Rating	Amps 205 Volts 28
Starter Type:	Electrical x Air ____
Manufacturer	Delco-Remy
Model	1990447
Heating System Type:	
Capacity, btu/hr	90,000 BTU
Air Conditioning:	Vapor
System Capacity, btu/hr	100,000 BTU
Compressor Manufacturer	Vapor
Compressor Model Number	CROG 1500 2C
Air Compressor:	
Manufacturer	Bendix
Model Number	10471B
Capacity, cubic ft/min	15.5 ft^3/1,250 rpm
Transmission Type:	
Manufacturer	Allison
Model Number	V-731
Converter Torque Multiplication	3.43:1 TC470
Retarder Type:	
Manufacturer	None
Model Number	

TABLE A5. DENVER RTD AND SCRTD METHANOL BUS SPECIFICATION (CONTINUED)

Brakes, Type:	Wedge
Manufacturer	Rockwell
Drive Axle:	
Manufacturer	Rockwell
Model Number	597733RDC18
Axle Ratio	5.13:1
Tires:	
Manufacturer	Goodyear
Type	City Cruiser
Size	12.5 x 22.5
Curb Weight:	
Front Axle	9,540 lbs
Rear Axle	18,980 lbs.
Total	28,560 lbs.
Seated Load Weight:	
Front Axle	12,690 lbs.
Rear Axle	22,280 lbs.
Total	34,970 lbs.
Other attributes or features: (wheelchair lifts, wheelchair position, bicycle racks, etc.)	Rear Door Wheelchair Lift

TABLE A6. DENVER RTD DIESEL BUS SPECIFICATION

Transit Agency: RTD

Bus Number: 5201C to 5205C

Bus Manufacturer: Neoplan

Model Number: EC

Vehicle Identification Number (VIN): IN9TA12A8HL013532

Date of Purchase: October 9, 1987

Accumulated Mileage at Start of Demonstration: Approximately 100,000

Length, ft.	40 ft.
Width, in.	102 in.
Height, in.	120 in.
Passenger seats, no.	43 $^{20}/_{23}$
Engine Type:	6V-92TA DDECI
Manufacturer	DDC
Model Number	8067-7A28
Power, bhp	277 bhp
Fuel Injector Type:	5234915 277 hp
Size	90-95 mm^3/1,000 Strokes at Std. Duration
Fuel Type	Diesel #2
Fuel Pump(s): Type	Electrical ______ Mechanical x
Fuel System:	Steel
Tank Capacity, gallons	125 Gallons
Fueling System:	
Manufacturer	EMCO-Wheaton
Type	Dry Break
Model Number	G-2266-105

TABLE A6. DENVER RTD DIESEL BUS SPECIFICATION (CONTINUED)

Bus Number 5201C to 5205C

Generator:	1117706 Delco Remy
Output at Normal Idle	Amps ______ Volts 27v
Maximum Rating	Amps ______ Volts 2 v
Starter Type:	Electrical ____ Air x
Manufacturer	Ingersoll-Rand
Model	SS350EE03R31-02F
Heating System Type:	
Capacity, btu/hr	108,000
Air Conditioning:	AC 19D
System Capacity, btu/hr	96,000
Compressor Manufacturer	Bock
Compressor Model Number	FK-4
Air Compressor:	
Manufacturer	Bendix
Model Number	103918
Capacity, cubic ft/min	15.5 ft^3/1,250 rpm
Transmission Type:	
Manufacturer	Allison
Model Number	HTB-748
Converter Torque Multiplication	2.21:1 T 495
Retarder Type:	Hydraulic Output
Manufacturer	Allison
Model Number	HTB-748

TABLE A6. DENVER RTD DIESEL BUS SPECIFICATION (CONTINUED)

Bus Number 5201C to 5205C

Brakes, Type:	S-CAM
Manufacturer	Perrot
Drive Axle:	
Manufacturer	ZF
Model Number	A-130
Axle Ratio	4.67:1
Tires:	
Manufacturer	Goodyear
Type	City Cruiser
Size	12.5 x 22.5
Curb Weight:	
Front Axle	9,960 lbs
Rear Axle	18,720 lbs.
Total	28,680 lbs.
Seated Load Weight:	
Front Axle	12,960 lbs.
Rear Axle	22,170 lbs.
Total	35,130 lbs.
Other attributes or features: (wheelchair lifts, wheelchair position, bicycle racks, etc.)	Front Door Lift-U Wheelchair Lift

APPENDIX B

ROUTE DESCRIPTIONS

This appendix contains information on the routes used by the demonstration fleets at Seattle Metro and Triboro. Every route has both a methanol bus and a diesel control bus operating on it.

TABLE B1. ROUTES USED BY DEMONSTRATION FLEET AT SEATTLE METRO

Route No.	Approximate Average Weekday Schedule Speed (MPH)	Approximate Round Trip Length (Miles)*	Average Seasonal Load Factor	Peak No. of Buses on Route	Comments
6	13.2	28.3 and 23.4 and 19.4	.7332	7	
11	10.9	9.1	.4947	7	Very Steep Grades
17	15.5	42.6 and 37.8 and 16.3	.7289	9	
25	11.9	21.1 and 8.1	.4798	8	Very Steep Grades
28	12.9	27.4 and 22.3 and 21.1	.0525	8	
30	12.7	9.4	.2306	1	
32	12.1	15.5	.6870	1	
33	11.4	25.2 and 21.5 and 20.5	.3651	6	
37	13.6	31.0 and 22.49 and 11.9	.1845	6	
46	14.6	13.4	.6769	2	
48	11.1	28.5	.5317	4	
60	9.6	14.1	.3949	3	
62	12.9	20.5	.2135	3	
65	17.3	23.6	.3496	2	
78	16.3	15.3	.4399	3	
118	14.7	25.8 and 21.4 and 18.0	.5820	5	
360	23.5	27.4	.8125	1	Express of Route 6
370	16.7	44.8	.6020	3	Freeway Operation

* Different mileages indicate different versions of the same route.

TABLE B2. ROUTES USED BY DEMONSTRATION FLEET AT TRIBORO

Route No.	Approximate Average Weekday Schedule Speed (MPH)	Approximate Round Trip Length (Miles)	Peak No. of Buses On Route
Q-19A	9.64	5.3	13
Q-23	10.59	8.0	14
Q-33	10.56	4.4	9
Q-38	12.11	7.0	11
Q-39	10.42	7.0	17
Q-72	10.94	5.7	5

TABLE B3. ROUTES USED BY DEMONSTRATION BUSES AT DENVER RTD

ROUTE	# OF BLOCKS AM	# OF BLOCKS BASE	# OF BLOCKS PM	DIVISION (GARAGE)
28	8	4	8	Platte
31	8	4	8	Platte
32	8	4	8	Platte
38	5	4	8	Platte
68X	2			Platte
76X	1			Platte
44	8	4	8	Platte
52	7	4	6	Platte
82X	1		2	Platte

We are proposing that four buses from each group of control buses be assigned to four blocks in one of these route groups for a continuous period of four weeks, i.e., methanol buses on Route 28, blocks 1 - 4, diesels on blocks 5 - 8, etc. Then, at the end of the four weeks, the diesels would rotate to blocks 1 - 4 and the methanols would rotate to blocks 5 - 8. This pattern would continue until all of these routes had been exhausted.

APPENDIX C

ENERGY CONTENT OF METHANOL AND DIESEL FUEL

This appendix contains a detailed discussion of the different energy contents of methanol and diesel fuel and provides the rational for the basis on which they are compared in this study. This appendix was written by Michael Murphy of the Fuels and Combustion Technology Section of Battelle.

In comparing the performance of combustion equipment operating on different fuels, it is desirable to compare the output in terms of the energy content of the fuel and not just in terms of the mass or volume of fuel used.

The following text discusses the way the energy content of fuels is specified and compares the energy content of methanol and diesel fuel.

Heating Values of Fuels

The term "heat of combustion" is defined as the amount of heat released when a fuel is completely burned and the combustion products returned to the initial temperature.*

The expressions "calorific value" and "heating value" are used synonymously with the expression "heat of combustion". However, in thermodynamic terms, further definition is necessary, because the initial state of the fuel (solid, liquid, or gas), the final state of the combustion products (pressure or volume equal to initial), and the final state of the water in the combustion products (liquid or gas) all affect the amount of energy released and so must also be specified.

If the final pressure is equal to the initial pressure, the heat obtained from the fuel is called the enthalpy of combustion. If the final volume is equal to the initial volume, the heat obtained from the fuel is called the internal energy of combustion. Where the volume of the combustion products is different from that of the reactants, that volume change could be used to do work and, because of the first law of thermodynamics relating work and heat, the heating values under constant volume are different from those under constant pressure.

For the purpose of comparing the performance of combustion equipment whose inlet and exhaust flows are both open to the atmosphere (as is the case in a furnace or a vehicle) the heating value at constant pressure, or the enthalpy of combustion, is the more relevant measure of heating value.

If the products of combustion are cooled to the usual initial temperature of 25 C, water formed from the combustion of the hydrogen in the

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* The consistent SI units for heating value are kJ/kg or MJ/kg. Note that volumetric heating value, kJ/L is the product of the heating value, kJ/kg and the fuel density in kg/L: $\frac{kJ}{kg} \times \frac{kg}{L} = \frac{kJ}{L}$

fuel will condense and add its latent heat to the heat released through the combustion reaction. For this reason, such heating values are called the gross or higher heating values.

Since the latent heat of the water is not always considered recoverable, a correction can be made to reduce the gross heating value to a net, or lower heating value. This lower heating value represents the energy derived from the combustion reaction alone. In order to make this correction, the chemical composition of the fuel must be known so that the amount of water formed can be calculated, and the heat of condensation for that quantity of water obtained from tables of thermodynamic data and subtracted.

In North America, it is the near universal custom that the term heating value means higher heating value, even if it is not specifically identified as the higher heating value. In Europe, it is the custom to use lower heating values, again, often without so specifying.

The fact that both customs are in simultaneous use indicates that neither is clearly "right" nor clearly "wrong". The Europeans feel that using the higher heating value and counting the latent heat of the water is unrealistic, since in practical equipment (such as an internal combustion engine on a vehicle) the latent heat of the water in the exhaust can never be recovered. North Americans point out that, in calculating efficiencies, the actual equipment performance should be compared to the best possible performance, which would include the energy content of the product water and that moreover, if the lower heating value is used for combustion equipment in which condensation does take place (such as residential condensing furnaces) unrealistic efficiencies greater than 100 percent are obtained.

In summary, different heating values are obtained for combustion at constant pressure and at constant volume, for the same fuel in a liquid or gaseous state, and for combustion products containing either liquid or gaseous water. Thus, there are a total of eight different heating values for methanol, a chemically-pure substance whose thermodynamic properties are well-known. Many authors are sloppy in identifying the exact heating value they use. Others are undoubtedly ignorant of the differences. The result can be a great deal of confusion. All four constant pressure heating values for methanol have been quoted in the methanol-engine literature.

Measuring Heating Values

For pure chemical substances (such as methanol) the heat of combustion can be conveniently calculated from tables of thermodynamic data. However, for mixtures of indeterminate composition (such as diesel fuel) the heating value must be determined experimentally.

An apparatus called a bomb calorimeter is used to determine heating values. This device is simply a closed vessel immersed in water in which a small amount of fuel is burned with oxygen and the resulting temperature rise of the water measured. The bomb calorimeter determination of heating value is relatively expensive, and requires many calibrations and corrections. For example, combustion in the bomb calorimeter takes place under constant volume, not under constant pressure and so yields the internal energy of combustion. In order to obtain the more relevant enthalpy of combustion, the volume change of the combustion reaction and the energy associated with that volume change must be computed from the chemical composition of the fuel.

Because of these measurement complexities, heating values are not generally used in commercial fuel specifications despite the fact that the entire purpose of a fuel is to provide energy. Instead, other fuel properties, which correlate well with heating value are usually specified.

[Note that the above comments hold for both alcohol and hydrocarbon (petroleum) fuel.]

Heating Value of Methanol

The constant-pressure, higher heating value of liquid methanol at 25 C and 1 atm is 22,700 kJ/kg. The lower heating value under the same conditions is 19,960 kJ/kg.

For example, in the physical properties section of the Seattle Metro methanol fuel specification, the heat of combustion of liquid methanol is given as 5420 cal/gm which is equal to the higher heating value listed above of 22,700 kJ/kg.

Heating Value of Diesel Fuel

Diesel fuel is not a pure substance, but a mixture of hundreds of similar (but different) hydrocarbons. Only an actual test using a bomb calorimeter can yield the true heating value of a diesel fuel.

However, in practice, because of the similarities of the various hydrocarbons in diesel fuel, and because the properties of similar hydrocarbons tend to correlate well with density, the diesel fuel density can be used to predict the heating value. Over the years, various correlations have been developed. The U.S. Bureau of Mines developed the following correlation:

$$HHV = 51916 * [8792 (specific * gravity)^2] kJ/kg$$

Because fuel specific gravity (or "gravity") is often measured with a hydrometer, a ballasted glass tube which floats to different heights depending on the density of the fuel and which has a thermometer-like scale, the custom grew up of stating the fuel density in "degrees". The American Petroleum Institute has defined these degrees such that:

$$deg\ API = 141.5/Sp\ Gr - 131.5$$

For example, using the fuel density of 30 deg API (Sp Gr = 0.876), the above correlation between heating value and fuel density predicts a higher heating value of 45,170 kJ/kg. A diesel fuel with a density equal to the national average of 0.850 kg/L would have a higher heating value of 45,560 kJ/kg.

A more recent, improved correlation between fuel oil density and heating value is given in (1.). According to this correlation, a diesel fuel with a density equal to the national average would have a higher heating value of 44,890 kJ/kg and lower heating value of 42,120 kJ/kg.

Ratio of Methanol and Diesel Fuel Heating Values

Comparing the higher heating value of methanol, above, with the average higher heating value of diesel fuel yields a ratio of 2.01. This ratio may be used to calculate "energy equivalent" weights of the two fuels.

By using the density of methanol of 0.791 kg/L and the density of the national average diesel fuel of 0.850 kg/L, one can calculate a ratio of volumetric higher heating values, 2.16. If the lower heating values are used, the ratio is 2.28. It is this ratio that should be used to calculate equivalent fuel mileage for the two fuels.

Literature Values

Several multipliers for converting methanol fuel usage to equivalent diesel fuel usage have already appeared in the literature. An SAE paper by the research department of Caterpillar describing a methanol-powered bulldozer[2] used a multiplier of 2.28, corresponding to the lower heating value (LHV) ratio. A comparison of the emissions from two methanol-powered buses[3] used a multiplier of 2.17, corresponding to the higher heating value (HHV) ratio. A paper on the California Energy Commission demonstration[4] used a multiplier of 2.32, again a LHV ratio.

Further Refinement

Strictly speaking, in studying vehicles we are interested in the work output of the engine and not the heat output. Thus, the use of heating values is inappropriate. The appropriate thermodynamic measure of energy content for measuring the potential of a fuel to do work is the Gibbs free energy. This more subtle concept is generally numerically nearly equal (within 10 percent) to the enthalpy of combustion (heating value). For methanol, the lower Gibbs free energy of combustion differs from the lower enthalpy of combustion by 6.8 percent. For octane, the difference between the enthalpy of combustion and the Gibbs free energy of combustion is 2.0 percent. Thus, the diesel energy/methanol energy ratio for the two fuels based on the

Gibbs free energy of combustion is about four percent less than the ratio based on the enthalpy of combustion.

The thermodynamic data necessary to calculate the Gibbs energy of complex fuels, such as diesel fuel, are very difficult to obtain. A value of the Gibbs free energy of diesel fuel was not located. Thus, the Gibbs energy, although rigorously correct, is seldom used to compare fuel values. However, one should note that use of the "wrong" thermodynamic measure of the maximum possible work obtainable from fuels, namely the enthalpy of combustion, can lead to minor errors.

REFERENCES

1. Fuel Oil Manual, 4th edition, Paul F. Schmidt, 1985, page 47.

2. "A Neat Methanol Direct Injection Combustion System for Heavy-Duty Applications", SAE Paper 861169, (1986).

3. "Emissions from Two Methanol-Powered Buses", SAE Paper 860305, (1986).

4. "Transit Bus Operation with Methanol Fuel", SAE Paper 850216, (1985).

APPENDIX D

DRIVER SURVEY QUESTIONNAIRE

This appendix contains a copy of the questionnaire that was given to Seattle Metro drivers to gauge driver reaction to the methanol buses.

DRIVER SURVEY

Based upon your experience driving both types of buses, please check only one response per question. THERE ARE THREE POSSIBLE answers to most of the following questions:

1. Does the methanol bus start more easily when cold than the diesel bus?

   Yes _____ No (Opposite is true) _____ The same _____

2. Does the methanol bus start more easily when hot than the diesel bus?

   Yes _____ No (Opposite is true) _____ The same _____

3. Does the methanol bus have a greater tendency to stall out in "drive" when cold than the diesel bus?

   Yes _____ No (Opposite is true) _____ The same _____

4. Does the methanol bus have a greater tendency to stall out in "drive" when hot than the diesel bus?

   Yes _____ No (Opposite is true) _____ The same _____

5. Does the methanol bus idle smoother in "neutral" than the diesel bus after warm-up?

   Yes _____ No (Opposite is true) _____ The same _____

6. Does the methanol bus idle better in "drive" with service brakes applied than the diesel bus?

   Yes _____ No (Opposite is true) _____ The same _____

7. Does the methanol bus have more delay in responding to depression of the accelerator than the diesel bus?

   Yes _____ No (Opposite is true) _____ The same _____

8. Does the methanol bus have smoother acceleration after the bus is in motion than the diesel bus?

   Yes _____ No (Opposite is true) _____ The same _____

9. Does the methanol bus accelerate faster than the diesel bus?

   Yes _____ No (Opposite is true) _____ The same _____

10. Is it easier to maintain your schedule with the methanol bus than with the diesel bus?

Yes _____ No (Opposite is true) _____ The same _____

11. Do you feel the methanol bus is quieter to drive than the diesel bus?

Yes _____ No (Opposite is true) _____ The same _____

12. Do you feel the passengers like the methanol bus better than the diesel bus?

Yes _____ No (Opposite is true) _____ The same _____

13. Do you feel safer driving the methanol bus than driving the diesel bus?

Yes _____ No (Opposite is true) _____ The same _____

14. Overall, do you prefer to drive the methanol bus instead of the diesel bus?

Yes _____ No (Opposite is true) _____ The same _____

15. Do you write up the methanol bus for repairs more often than the diesel bus?

Yes _____ No (Opposite is true) _____ The same _____

16. Indicate the number of times you have driven the methanol bus.

More than 100 _____ 10 to 100 _____ Less than 10 _____

17. Indicate your years of bus driving experience.

More than 10 _____ 5 to 10 _____ 1 to 5 _____ Less than 1 _____

18. In the space below, feel free to elaborate upon any of the responses to the questions above or any other opinions you may have concerning the methanol bus compared to the diesel bus:

____

____

____

____

Thank you very much for your participation in this survey.

APPENDIX E

SELECTED BIBLIOGRAPHY OF REPORTS AND ARTICLES ON METHANOL

SELECTED BIBLIOGRAPHY OF REPORTS AND ARTICLES ON METHANOL

Urban Mass Transportation Administrators

(1) King, R.D. and Francis, G.A., "Plan for Methanol Bus Data Collection", UMTA, Office of Bus and Paratransit Systems, August 25, 1987.

(2) Murphy, M., "Data Collection on Methanol Vapor Exposure", UMTA, Office of Bus and Paratransit Systems, November, 1987.

(3) Turanski, A.J., "Methanol Bus Program, First Semiannual Data Analysis Report", UMTA, Office of Bus and Paratransit Systems, March 31, 1988.

(4) Murphy, M. and Pine, R., "Training Manual for Methanol Fuel Use In Transit Operations", UMTA-IT-06-0322-88-2, July 1988.

(5) Murphy, M. and Krenelka, T., "Methanol Vapor Measurements in a Vehicle Maintenance Pit at Seattle Metro Ryerson Base", UMTA, Office of Technical Assistance and Safety, October, 1988.

(6) Krenelka, T., Turanski, A.J., and Murphy, M. "Methanol Bus Program, Data Analysis Report, UMTA-IT-06-0322-88-3, October, 1988.

(7) Francis, G.A. and King, R.D., "Proving Ground Comparison of M.A.N. Methanol and Diesel Transit Buses", UMTA-IT-06-0322-88-4, October, 1988.

(8) Shippard, W.J. and Hillman, M.E.D., "Methanol Price Outlook", UMTA, April 18, 1989.

(9) Murphy, M.J. and Krenelka, T., "Methanol Vapor Exposure Measurement at Denver RTD", UMTA, Office of Engineering Evaluation, October, 1989.

(10) Murphy, M.J. and Pine, R. "Methanol Use Training Manual", UMTA-OH-06-0056-90-1, XXX.

Environmental Protection Agency

(11) Fanick, E.R. and Smith, L.R., "Survey of Safety Related Additives for Methanol Fuel", EPA 46013-84-016, November, 1984.

(12) Guidance on Estimating Motor Vehicle Emission Reductions from the Use of Alternative Fuels and Fuel Blends", U.S. EPA, EPA-AA-TSS-PA-87-4, January 29, 1988.

(13) Alson, J.A., "The Emission Characteristics of Methanol and Compressed Natural Gas in Light Vehicles", U.S. EPA, APCA Paper No. 88-99.3, June, 1988.

(14) "Emission Standards for Methanol Fueled Motor Vehicles and Motor Vehicle Engines", EPA Final Rulemaking, Federal Register Part 86, No. 68, 14426 - 14613, April 11, 1989.

(15) "Analysis of Economic and Environmental Effects of Methanol as an Automotive Fuel", U.S. EPA, Special Report, Office of Mobile Sources, September, 1989.

Other

(16) Unnasch, S. and Jackson, M.D., "Methanol-Fueled Transit Bus Demonstration, Phase 1, Technical Analyses, California Energy Commission, October, 1986.

(17) Lawson, A., Simmons, E.W., Athey, J.A.B., "Safety Aspects of the Use of Alcohol Fuels in Road Vehicles", Celanese Canada, Inc., Marc 1987.

(18) "Automotive Methanol Vapors and Human Health: An Evaluation of Existing Scientific Information and Issues for Future Research" Special Report, Health Effects Institute, May, 1987.

(19) Ullman, T., Hare, C., and Baines, T., "Emissions from Direct-Injected Heavy-Duty Methanol-Fueled Coach Engines (One Dual-Injection and One Spark-Ignited) and a Comparable Diesel Engine", SAE 820966.

(20) Gill, A.P., "Design Choices for 1990's Low Emission Diesel Engine", SAE Paper 880350, 1988.

(21) Richards, R.R. and Sibley, J.E., "Diesel Engine Emission Controls for the 1990's", SAE Paper 880346, 1988.

(22) Methanol-Seattle Metro 1988 Operating Experience, prepared for and presented at APTA Eastern Alternative Fuels Workshop, May 24, 1989, by Jim Boon, Metro Transit, Seattle, Washington.

(23) Dif iglio, C., "Methanol and Energy Security: Cost, Feedstock, and Source of Supply, Conference Paper, Methanol As An Alternative Fuel Choice: An Assessment, December 4, 1989.

(24) "Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel", U.S. EPA, Special REport, Office of Mobile Sources, September, 1989.

(25) "Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector; DOE/PE-0093, November, 1989.