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Federal Methanol Fleet Project
Final Report

B.H. West
R.N. McGill
S.L. Hillis
J.W. Hodgson

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FEDERAL METHANOL FLEET PROJECT
FINAL REPORT

B. H. West
R. N. McGill
S. L. Hillis*
J. W. Hodgson*

*University of Tennessee

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ABSTRACT

The Federal Methanol Fleet Project concluded with the termination of data collection from the three fleet sites in February 1991. The Lawrence Berkeley Laboratory (LBL) completed five years of operation, Argonne National Laboratory (ANL) completed its fourth year in the project, and Oak Ridge National Laboratory (ORNL) completed its third. Twenty of the thirty-nine vehicles in the fleet were powered by fuel methanol (typically M85, 85% methanol, 15% unleaded gasoline, although the LBL fleet used M88), and the remaining control vehicles were comparable gasoline vehicles. Over 2.2 million km (1.4 million miles) were accumulated on the fleet vehicles in routine government service. Data collected over the years have included vehicle mileage and fuel economy, engine oil analysis, emissions, vehicle maintenance, and driver acceptance.

Fuel economies (on an energy basis) of the methanol and gasoline vehicles of the same type were comparable throughout the fleet testing. Engine oil analysis has revealed higher accumulation rates of iron and other metals in the oil of the methanol vehicles, although no significant engine damage has been attributed to the higher metal content. Vehicles of both fuel types have experienced degradation in their emission control systems, however, the methanol vehicles seem to have degraded their catalytic converters at a higher rate. The methanol vehicles have required more maintenance than their gasoline counterparts, in most cases, although the higher levels of maintenance cannot be attributed to "fuel-related" repairs. According to the daily driver logs and results from several surveys, drivers of the fleet vehicles at all three sites were generally satisfied with the methanol vehicles.

PREFACE

This report is the last in a series of yearly reports on the results from the Federal Methanol Fleet project. Each of the nine previous reports details the annual results from one of the three fleet sites. This final report is somewhat brief, therefore readers are encouraged to refer to the previous nine reports for rigorous details. All of these other reports in the series should be referred to in order to benefit from the entire context of the project, and to avoid the risk of possibly misreading limited results from only one report.

A brief review of some of the philosophies and practices implemented in this project are presented below in order to further reduce the possibility of data being taken out of context.

* This project resulted from a congressional appropriation in Fiscal Year 1985 and the associated mandate to begin to place methanol-fueled vehicles into government fleets and assess their performance. Funds for these purposes have totalled approximately $2.4 million through Fiscal Year 1992.

* It was decided to use the best available "proven" technology for converting vehicles to methanol since it was impossible in 1985 to obtain methanol vehicles from original equipment manufacturers (OEMs). The intent was to acquire methanol converted vehicles from as many "proven" aftermarket companies as funds would permit ("proven" meaning that the aftermarket company possessed a demonstrated record of successful conversions of gasoline vehicles to methanol).

* It was decided to operate the methanol vehicles in all cases alongside baseline gasoline vehicles for comparison. This required the acquisition of the gasoline vehicles also.

* While it was desirable to achieve the lowest possible emissions with the converted methanol vehicles, it was recognized that this would be an expensive proposition because rigorous engineering and development would be necessary in order to accomplish this goal. Because of this, the methanol vehicles were not optimized for lowest emissions. Instead, the philosophy was to acquire the vehicles, measure their emissions, and track their performance over time. The important comparison would be how emissions change over time and not how they would compare to the lowest attainable. Emissions measured immediately after methanol conversions would serve as the baseline for comparison.

* All the vehicles in the project were to be used in routine fleet service within the organizations to which they were to be assigned. This limited the extent to which very specialized tests or driving cycles could be utilized. On the other hand, the vehicles would experience a "real-world" environment, and it is within that context that they have been evaluated.

FEDERAL METHANOL FLEET PROJECT
FINAL REPORT

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INTRODUCTION

The Federal Methanol Fleet (FMF) was a Congressionally mandated program initiated in 1985 to place methanol vehicles into routine government service. Oak Ridge National Laboratory (ORNL) has had project management responsibility for the project and has collected and disseminated data from all three fleet sites. The three sites are the Lawrence Berkeley Laboratory (LBL), the Argonne National Laboratory (ANL), and the Oak Ridge National Laboratory (ORNL). Over the past six years, nine reports (1-9)* have detailed the fleet operation and results. This final summary report will be somewhat brief, and will focus mainly on results. The reader is encouraged to refer to the earlier reports for more detail. Short descriptions of the individual fleets are presented below.

LAWRENCE BERKELEY LABORATORY FLEET

The LBL fleet was the first pressed into operation in the spring of 1985 with the methanol conversion of five relatively new 1984 Chevrolet Citations with carburetted 2.8L V-6 engines. The conversion was performed by the Bank of America, in the San Francisco, California area. The Bank of America had previously performed conversions on similar cars for their own use. The conversion essentially consisted of replacing components which were not methanol compatible, and changing the air/fuel ratio via carburetor alterations (the stock compression ratio was maintained). A more detailed description of the LBL conversion can be found in Reference 1.

The five gasoline control vehicles were comparable 1984 Citations commandeered from the central motor pool. These vehicles had each accumulated roughly 32-48,000 km (20-30,000 miles) in government service before being assigned to the FMF. All the FMF vehicles were used for transportation around the LBL site, into and around Berkeley and Oakland, and to and from Lawrence Livermore Laboratory or the Stanford Linear Accelerator Center in Palo Alto. The fuel used at LBL was nominally M88 (88 volume % methanol, 12% unleaded gasoline), although it was varied seasonally between M86 and M90. A refueling tank was installed on-site at the LBL motor pool area. Commercial refueling sites were also available to the drivers in the Bay area, many of which provided the more common M85 blend.

ARGONNE NATIONAL LABORATORY FLEET

Ten vehicles were converted to M85 operation in the late fall of 1986 for the ANL fleet. Five 1986 Ford Crown Victoria security vehicles with port fuel injected 5.0L V-8 engines, and five

*Numbers in parentheses denote references at the end of the report.

1986 Chevrolet S-10 pickup trucks with throttle-body injected 2.5L four cylinder engines were converted by Alcohol Energy Systems, Inc. of Santa Clara, California. The control vehicles at ANL consisted of four similar gasoline Fords and five similar gasoline Chevrolets. The total fleet, therefore, consisted of nineteen vehicles. An M85 refueling tank and dispensing pump were installed at the ANL refueling site. This was the only place that the methanol vehicles were refueled.

The Argonne site, near Chicago, was chosen as the cold-weather test site for the Federal Methanol Fleet, and the methanol vehicles assigned there were equipped with special cold-start systems. The system on the Chevrolets started the engine on gasoline (from a separate auxiliary fuel tank) when the coolant temperature was below 0°C (32°F), and would automatically switch over to methanol fuel operation after about 30 seconds. The system on the Fords used only the methanol fuel, was provided by Ford, and is proprietary and cannot be discussed in detail. All nineteen vehicles were also equipped with block heaters for use in extremely cold weather. The conversions of the ANL vehicles involved not only replacing non-methanol compatible components and adjustment of air/fuel ratios, but also installation of the cold-start systems and high compression pistons. The Chevrolets' compression ratios were increased from 9.0 to 10.5, and the Fords' from 9.2 to 11.2. (A more detailed discussion of the ANL conversions can be found in Reference 5.)

OAK RIDGE NATIONAL LABORATORY FLEET

Data collection for the ORNL fleet began with the receipt of five 1987 gasoline powered 3.8L turbo Buick Regals in the summer of 1987. Five similar cars were converted to M85 operation by the Michigan Automotive Research Corporation, in Ann Arbor, Michigan, and were received in Oak Ridge in the late fall of 1987. The methanol conversion involved replacement of non-methanol compatible components, and changes to the engine control module (ECM) and other hardware to obtain the proper air/fuel ratio. Except for a minor spark timing adjustment by the ECM at cold-start, the methanol Buicks had no special cold-start systems. The conversion is discussed in detail in Reference 8.

The Buicks at ORNL were used for routine fleet service in and around the three DOE sites in Oak Ridge, Tennessee. An M85 refueling tank was located at one of the three sites, and was the only place that the methanol vehicles could be refueled, although on a few occasions, methanol fuel drums were shipped to strategic locations to allow longer highway trips.

FINDINGS AND OBSERVATIONS

FLEET UTILIZATION AND FUEL CONSUMPTION

Tables 1 through 4 show the mileage accumulation, average trip mileage, and fuel economy for the aggregates of each vehicle type from each of the three fleets over the course of the project. The LBL Chevrolet data are given in Table 1, the ANL Chevrolet and Ford data in Tables 2 and 3, respectively, and the ORNL Buick data in Table 4. Note in Tables 2 and 3 that the average trip lengths for the methanol and gasoline vehicles were very nearly the same (for both the Chevrolets and the Fords) at ANL and, as such, the fuel economies (on an energy basis) were also very comparable. This results from the fact that the gasoline and methanol vehicles of each type were used in nearly identical service. While the higher compression ratios in the methanol vehicles would be expected to contribute to improved fuel economy, there is little or no apparent improvement. Reasons for this disparity are not clear. The LBL methanol Chevrolets, on the other hand, suffered a 17 percent lower fuel economy than their gasoline counterparts.

Table 1. LBL Fleet Utilization Data
Summary of five years

Chevrolet Citations

	Total miles[a]	Average miles/trip[ab]	Fuel economy mpg[b]	Fuel economy km/GJ[bc]
Methanol vehicles				
1st year	36,864	36	11.4	274
2nd year	35,958	38	11.7	281
3rd year	30,440	38	10.9	260
4th year	25,388	31	11.2	269
5th year	15,062	23	9.9	238
All years	143,712	34	11.1	267
Gasoline vehicles				
1st year	74,329	57	24.1	318
2nd year	63,812	46	24.9	329
3rd year	43,057	38	21.5	284
4th year	Not in service			
5th year	Not in service			
All years	181,198	48	23.6	312

[a]To convert miles to km, multiply by 1.609

[b]Based on total quantities for five vehicles.

[c]Based on methanol lower heating value of 56,560 Btu/gal and gasoline lower heating value of 115,400 Btu/gal; M88 lower heating value equals 63,620 Btu/gal (17.73 GJ/m^3).

Table 2. ANL Fleet Utilization Data for Chevrolets
Summary of four years

	Total miles[a]	Average miles/trip[ab]	Fuel economy mpg[b]	Fuel economy km/GJ[bc]
Methanol vehicles				
1st year	43,035	16	9.6	224
2nd year	30,550	19	9.0	211
3rd year	32,009	17	9.0	211
4th year	30,825	16	8.6	201
All years	136,419	17	9.1	211
Gasoline vehicles				
1st year	46,426	16	16.9	219
2nd year	35,944	18	17.2	227
3rd year	35,186	15	16.4	216
4th year	38,265	18	14.3	189
All years	155,821	16	16.0	212

[a]To convert miles to km, multiply by 1.609

[b]Based on total quantities for five vehicles.

[c]Based on methanol lower heating value of 56,560 Btu/gal and gasoline lower heating value of 115,400 Btu/gal; M85 lower heating value equals 65,390 Btu/gal (18.22 GJ/m^3).

Table 3. ANL Fleet Utilization Data for Fords
Summary of four years

	Total miles[a]	Average miles/trip[ab]	Fuel economy mpg[b]	Fuel economy km/GJ[bc]
Methanol vehicles				
1st year	97,389	11	6.2	145
2nd year	75,915	28	6.2	145
3rd year	63,034	28	6.1	143
4th year	70,191	56	5.6	130
All years	306,529	20	6.0	140
Gasoline vehicles				
1st year	114,496	11	10.5	139
2nd year	57,274	25	10.5	139
3rd year	42,734	30	10.4	138
4th year	58,148	49	9.5	126
All years	272,652	17	10.2	135

[a]To convert miles to km, multiply by 1.609

[b]Based on total quantities for five methanol vehicles, four gasoline vehicles.

[c]Based on methanol lower heating value of 56,560 Btu/gal and gasoline lower heating value of 115,400 Btu/gal; M85 lower heating value equals 65,390 Btu/gal (18.22 GJ/m^3).

Table 4. ORNL Fleet Utilization Data
Summary of three years

	Total miles[a]	Average miles/trip[ab]	Fuel economy mpg[b]	Fuel economy km/GJ[bc]
Methanol vehicles				
1st year	31,681	11	9.8	224
2nd year	25,133	9	9.5	222
3rd year	24,305	10	9.1	213
All years	81,119	10	9.5	222
Gasoline vehicles				
1st year	64,480	18	19.1	253
2nd year	31,509	15	17.5	232
3rd year	31,715	12	17.5	232
All years	127,704	16	18.3	242

[a]To convert miles to km, multiply by 1.609

[b]Based on total quantities for five vehicles.

[c]Based on methanol lower heating value of 56,560 Btu/gal and gasoline lower heating value of 115,400 Btu/gal; M85 lower heating value equals 65,390 Btu/gal (18.22 GJ/m^3).

This lower fuel economy can probably be attributed to the longer average trip lengths of the gasoline cars. Albeit to a lesser extent, a similar observation can be made regarding the Buicks at ORNL as shown in Table 4.

EMISSIONS TESTS

Background

As stated in the Preface, the goal of the FMF Project was not necessarily to produce low emission methanol vehicles. The methanol vehicles used in the project were retrofitted, and it was realized that a tremendous amount of engineering would be required to achieve low emissions. As a result, it was decided to measure the vehicles' emissions soon after conversion to methanol, and then track their performance over time. Again, full details have been provided in previous reports (1,3,5-8), and only highlights will be presented here.

The OEM emission control system components (EGR valves, catalysts, fuel vapor recovery systems, etc.) remained intact on all of the converted methanol vehicles. However, mechanical changes (increased compression ratios, larger injectors, larger carburetor jets) and engine control system changes (revised EGR schedules, spark timing revisions, injector pulse width revisions) were made and would be expected to influence the emissions. Since emission reduction was not the focus of the fleet operation, converted vehicles, in some cases, had higher emissions after conversion than before. The emission values reported should not be taken as being representative of what should be expected from methanol-fueled vehicles that are converted or manufactured with emissions as an important conversion parameter. In fact, vehicles converted to M85 use by engineering students in competitions have achieved emissions well below the applicable EPA limits (10-12). Also, OEMs are currently manufacturing flexible or variable-fuel-vehicles (FFVs, VFVs), which are meeting all applicable standards. The authors believe that the FMF emissions reported can be useful in terms of changes in emission levels that may arise as vehicles accumulate service time and mileage. In at least two cases, interesting comparisons between methanol and gasoline catalyst deterioration have resulted from the test program.

During the period of this demonstration project, emission testing of methanol-fueled vehicles was a developing technology. As a result, testing procedures used during the fleet program were not consistent as the program progressed. In particular, techniques for measuring the aldehydes, the unburned methanol, and the other organic gases in the exhaust were in a state of flux. This is associated with the fact that the flame ionization detector (FID) typically used to measure unburned hydrocarbons from gasoline-fueled vehicles has essentially no response to aldehydes and only partial response to unburned methanol. In addition, even when a procedure was developed for handling these exhaust constituents, the emission testing laboratory doing the tests might not have been equipped to conduct the testing according to procedures recommended by the Environmental Protection Agency (EPA) (13). Fortunately, the impact of the FID response is negligible in terms of the CO (carbon monoxide) and NO_x (oxides of nitrogen) measurements, so these quantities can be reported with a high degree of confidence. The organic gases in the exhaust have been reported as OMHCE (Organic Material Hydrocarbon Equivalent) - defined by the EPA (13). In order to report the OMHCE in situations where direct measurements of the methanol in the exhaust were not made, a method of estimating the OMHCE (the ORNL protocol) was developed and appears to give satisfactory agreement with OMHCE values derived from actual methanol measurements (6).

Because the three fleet locations were widely scattered and because the vehicle conversions were conducted by a variety of contractors, several different laboratories were used for the emissions tests, as shown in Table 5. Since the results of the

Table 5. Laboratories Used for Emissions Testing

Argonne National Laboratory:	
Chevrolet S10s	Conversion: Alcohol Energy Systems
Round 1 Testing:	Bay Area Emission Lab[a]
Round 2 Testing:	Amoco Research Center[a]
Round 3 Testing:	Amoco Research Center[b,c]
Ford Crown Victorias	Conversion: Alcohol Energy Systems
Round 1 Testing:	Bay Area Emissions Lab[a]
Round 2 Testing:	Amoco Research Center[a]
Round 3 Testing:	Amoco Research Center[b,c]
Lawrence Berkeley Laboratory:	
Chevrolet Citations	Conversion: Bank of America
Round 1 Testing:	University of Santa Clara[a]
Round 2 Testing:	Northern California Emissions Lab[a]
Oak Ridge National Laboratory:	
Buick Regals	Conversion: Michigan Automotive Research Corp.
Round 1 Testing:	EPA-Ann Arbor[b,c]
Additional Testing:	EPA-Research Triangle Park[b,c]

[a]Methanol was not measured directly
[b]Methanol was measured directly
[c]Formaldehyde was measured directly

individual tests have been reported elsewhere (1,3,5-8), they will not all be repeated here. The intent is to highlight what are considered to be some of the more interesting findings from the data.

Catalyst Deterioration

All the converted vehicles retained the OEM catalysts which were, of course, designed for service on vehicles fueled with gasoline. It is important to note that catalyst suppliers would probably recommend using catalysts tailored specifically for methanol on these vehicles. Nevertheless, it is worthwhile to examine some of the emissions results obtained from this program.

Chevrolet Citations - Two of the Citations at Lawrence Berkeley Laboratory were tested for emissions after accumulating over 32,000 km (20,000 miles) of service on methanol. Vehicle 754 was tested three times to check the consistency of the testing, and then tested again after having the catalyst replaced. The results are shown in Table 6. A similar procedure was used on vehicle 753 with the exception that no repeatability tests were conducted. The results are shown in Table 7.

Table 6. Emissions From Chevrolet Citation 754

Odometer (miles)[a]	Condition	FTP Emissions (g/mile) CO	OMHCE	NO_x
1,669	Initial Test	2.38	0.59	1.06
28,110	After Tune-up	2.88	0.27	1.16
28,623	Re-test	1.71	0.23	1.16
28,642	Re-test	2.38	0.23	1.13
28,858	New Catalyst	1.39	0.12	1.00

[a]To convert miles to km, multiply by 1.609

Table 7. Emissions From Chevrolet Citation 753

Odometer (miles)[a]	Condition	FTP Emissions (g/mile) CO	OMHCE	NO_x
1,475	Initial Test	1.87	0.98	0.66
23,344	After Tune-up	1.88	0.24	1.06
24,152	New Catalyst	0.84	0.16	0.81

[a]To convert miles to km, multiply by 1.609

The OMHCE and NO_x values for vehicle 754 (Table 6) were fairly repeatable, but the CO data were not. The initial tests on both vehicles were conducted at a test facility different from the one used for the later tests. Comparing the initial test values with those from later tests raises the possibility that the effects observed may have been associated with the testing facility rather than the vehicle condition. On the other hand, comparing the data before and after the installation of a replacement catalyst raises the possibility that the replacement catalyst was inherently more effective than the original catalyst.

If one accepts the premise that there was no effect associated with testing at different facilities, then the catalysts showed no appreciable change in CO conversion efficiency, an increase in the OMHCE conversion efficiency, and a slight loss in the NO_x conversion efficiency. Comparing the results from the same laboratory for the used and the new catalysts would indicate increased efficiency for the new catalyst over the old one with the possible inference that the catalyst had deteriorated with use. In either case, however, the deterioration was not severe and the results from the Citation tests do not

suggest a major problem with the catalysts within the use patterns experienced by these vehicles.

Ford Crown Victorias - The final round of emission testing conducted on the ANL Fords led to some very interesting results. A methanol vehicle was tested with its original catalyst (a re-test was conducted to get some indication of repeatability) along with a gasoline Ford Crown Victoria (which was not part of the FMF). The catalysts from the two vehicles were then switched and another test run on each vehicle. The results are shown in Table 8. Formaldehyde (HCOH) emissions were measured directly and are also shown in this table.

Table 8. Emissions from Ford Crown Victorias

Odometer (miles)*	Condition	FTP Emissions (g/mile) CO	OMHCE	NO_x	HCOH
Methanol vehicle					
53,300	Original Catalyst	2.39	0.63	0.45	0.312
53,300	Re-test	2.35	0.66	0.43	0.299
58,400	Gasoline Catalyst	0.76	0.27	0.37	0.060
Gasoline vehicle					
40,200	Original Catalyst	1.34	0.40	0.89	0.021
40,200	Re-test	1.39	0.38	0.90	0.022
40,800	Methanol Catalyst	4.12	0.91	0.97	0.021

*To convert miles to km, multiply by 1.609

Clearly the catalyst that had been on the methanol-fueled vehicle showed deteriorated performance in terms of its ability to oxidize CO and OMHCE. The catalyst that had been on the gasoline vehicle, after installation on the methanol vehicle, brought the emissions well within the EPA requirements for new vehicles (3.4 g/mile CO; 0.41 g/mile HC; 1.0 g/mile NO_x). The catalyst swap reduced the aldehyde emissions from around 300 mg/mile (0.3 g/mile) to 60 mg/mile. For comparison, California has adopted a 15 mg/mile formaldehyde standard for Low-Emission Vehicles (LEVs), and an 8 mg/mile standard for Ultra Low Emission Vehicles (ULEVs) (14). While these aldehyde standards are difficult to achieve, M85-fueled vehicles have nonetheless been capable of meeting or surpassing the ULEV standard for aldehydes in student competitions (10-12). The NO_x reduction efficiency of the catalyst from the methanol Ford did not appear to have seriously deteriorated with use, although this inference can not be made conclusively since raw engine exhaust emissions were not measured (i.e., the methanol engine's raw exhaust may be inherently low in NO_x).

Buick Regals - The emissions testing on the Buick Regals was not thoroughly extended beyond the initial round of testing, but some preliminary testing was done on one vehicle (9394). This particular vehicle had exhibited rather high emissions during testing conducted immediately following its conversion to M85 fuel use (8). Prior to an anticipated second round of testing (that was precluded by scheduling and budget constraints) the vehicle was subjected to emissions testing that revealed additional deterioration of the emission values. In order to gain some understanding of the results, a new OEM catalytic converter was obtained and further testing was conducted. The results are shown in Table 9. The installation of a new catalyst clearly had a significant effect on the CO and OMHCE emissions (the catalyst had actually accumulated about 800 km of service by the time the emission test was conducted).

The old catalyst that was removed from the vehicle had deposits on the inlet side of the monolith that were removed for analysis. The analysis results indicated that the deposits were probably associated with the oil used in this engine. The catalyst was returned to the manufacturer for evaluation where

Table 9. Emissions From Buick Regal 9394

Odometer (miles)*	Condition	FTP emissions (g/mile) CO	OMHCE	NO_x
323	After Conversion	3.72	0.19	1.18
362	Repeat	5.13	0.23	1.18
401	Repeat	6.00	0.32	1.19
13,200	Original Catalyst	16.1	0.69	0.63
15,900	New Catalyst	6.29	0.25	0.77

*To convert miles to km, multiply by 1.609

tests conducted using gasoline engine exhaust showed no significant deterioration of the catalyst efficiency.

It is speculated that the unburned methanol in the exhaust from methanol-fueled engines might possibly result in the formation of CO in the catalytic converter as the methanol dissociates into CO and hydrogen. As the catalyst ages, the relative amounts of CO formation may increase (as opposed to the complete oxidation of the methanol).

Based on the emissions testing results, it is clear that there may be air quality implications associated with catalyst aging on some M85-fueled vehicles. The data are insufficient to support any conclusions as to what causes the deterioration of catalyst performance but there is some reason to suspect lubricant involvement in the process.

ENGINE OIL ANALYSIS

Fleet Service

The engine oil in all FMF vehicles was changed nominally at 4800 km intervals (6400 km at LBL), and sampled at nominal 1600 km intervals for laboratory analysis of iron, lead, copper, and other wear metal content, as well as for total base number, water content, etc. Normally, linear regressions have been performed on the wear metals data to provide an *accumulation rate* (the slope of the best-fit line of metal concentration as a function of distance travelled since the last oil change). This was done on a yearly basis and it was noted that iron accumulation rates in the methanol vehicles' oil were greater than those of the gasoline vehicles. Year-to-year however, the iron accumulation rates usually decreased, for both fuel types.

Later in the project, linear regressions were performed on subsets of the data partitioned by calendar quarter or season, and it was noted that seasonal variations did occur, as shown for the ORNL methanol and gasoline Buicks in Figure 1.

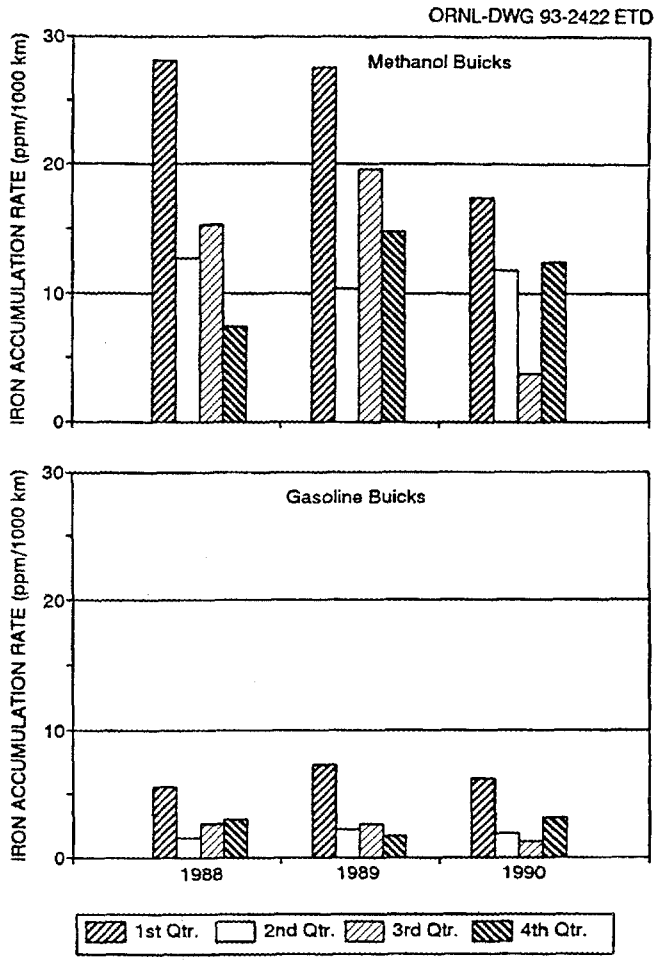

Figure 1. Iron accumulation rate in ORNL Buicks as a function of quarter.

Note that the iron accumulation rates for the methanol vehicles are generally an order of magnitude higher than those for the gasoline vehicles in a given quarter. Note also that the highest accumulation rates occurred in the first (winter) quarter, for both vehicle types. Cold-engine service is known to accelerate engine wear, and hot weather can also accelerate engine wear when combined with high load service (15-17). These facts may partially account for the some of the high iron accumulation rates evident in Figure 1. The results do indicate that there are variations in iron accumulation with changes in ambient temperature.

Figure 2 shows the quarterly iron accumulation rates for the methanol and gasoline Citations at LBL for four years (4). Note again that

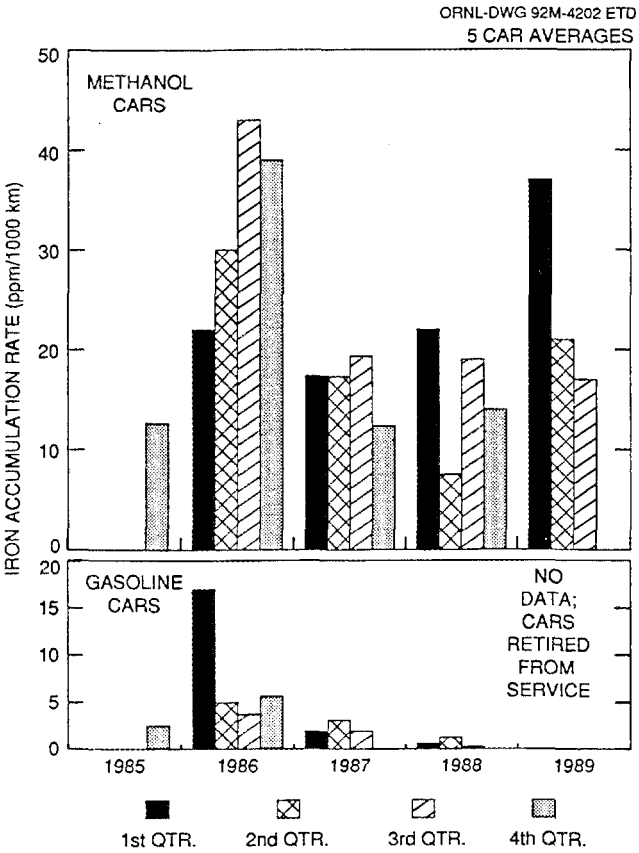

Figure 2. Iron accumulation rate in LBL Chevrolet Citations as a function of quarter.

the accumulation rates in the methanol vehicles are considerably higher than those in the gasoline vehicles. While there is significant variability in the quarterly accumulation rates in the methanol vehicles, the seasonal trends are not as obvious as for the ORNL Buicks, due probably to the milder climate in the Berkeley area. Although there is little variation in ambient temperature at the LBL site, vehicle use patterns from quarter-to-quarter might have differed somewhat, possibly contributing to the variations in iron accumulation noted in the figure. Unfortunately, little data other than trip length were gathered on how the vehicles were driven (e.g., short-trips with repeated cold starts, or high temperature/high load).

The highest iron accumulation rate in the gasoline Citations occurred in the first quarter of 1986. One might attribute this apparent wear to "green engine break-in," however it is important to recognize that the gasoline cars each had over 32,000 km (20,000 miles) on their odometers. The cause of the higher accumulation rate at that time in the vehicle's life is unknown. It is important to note that the iron accumulation rates for the gasoline vehicles prior to being commandeered into the FMF are completely unknown. An interesting observation is that the gasoline car iron accumulation rates generally decline with increasing age.

Figure 3 shows the seasonal iron accumulation rates for the ANL Chevrolets. Because the Chicago area has an extended colder climate, seasons were defined for the ANL site rather than simply using the calendar quarters. The seasons used consisted of a four-month winter, a three-month spring and fall, and a two month summer. The winter season includes two and one-

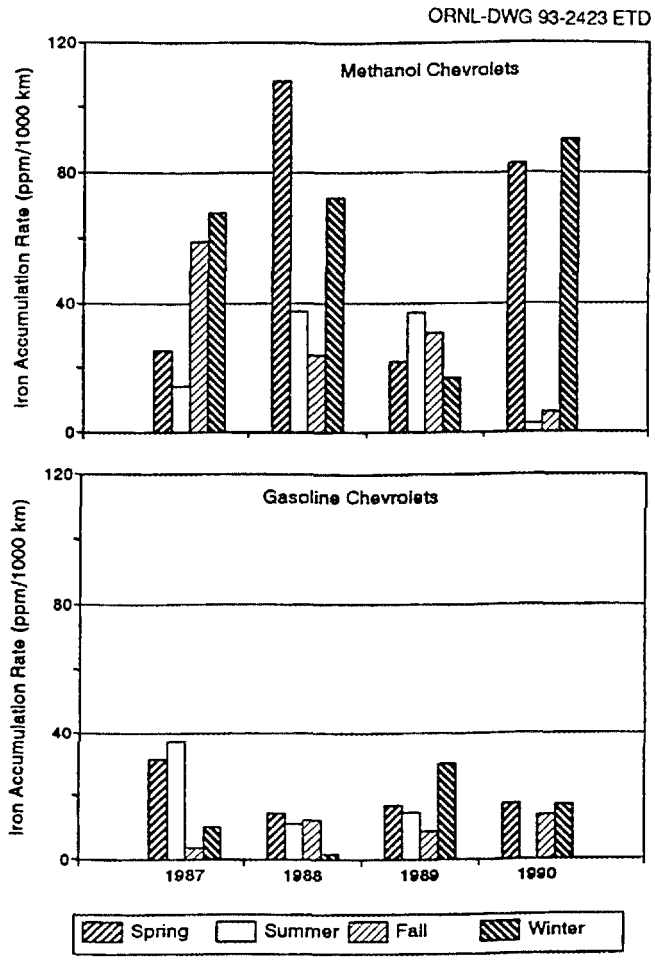

Figure 3. Iron accumulation rate in ANL Chevrolets as a function of season.

half months of the subsequent year (i.e., winter 1990 includes January, February, and half of March 1991). Note in the figure that while the methanol-vehicle iron accumulation rates are considerably higher than those of the gasoline counterparts, the least difference can be noted for 1989. While the methanol-Chevrolet iron accumulation rates generally decreased with age (except for a couple of high seasons), the gasoline-vehicle rates remained relatively constant. The majority of the highest rates for both vehicle types are in the spring and winter seasons.

The seasonal iron accumulation rates for the ANL Fords are shown in Figure 4. Except for the peak in the summer of 1989, the iron accumulation rates for the methanol Fords show a general decrease following the winter of 1987. The iron accumulation in the gasoline Fords, on the other hand, seem to have increased with age up to the spring of 1989, and then leveled off. Reasons for these phenomena are not known.

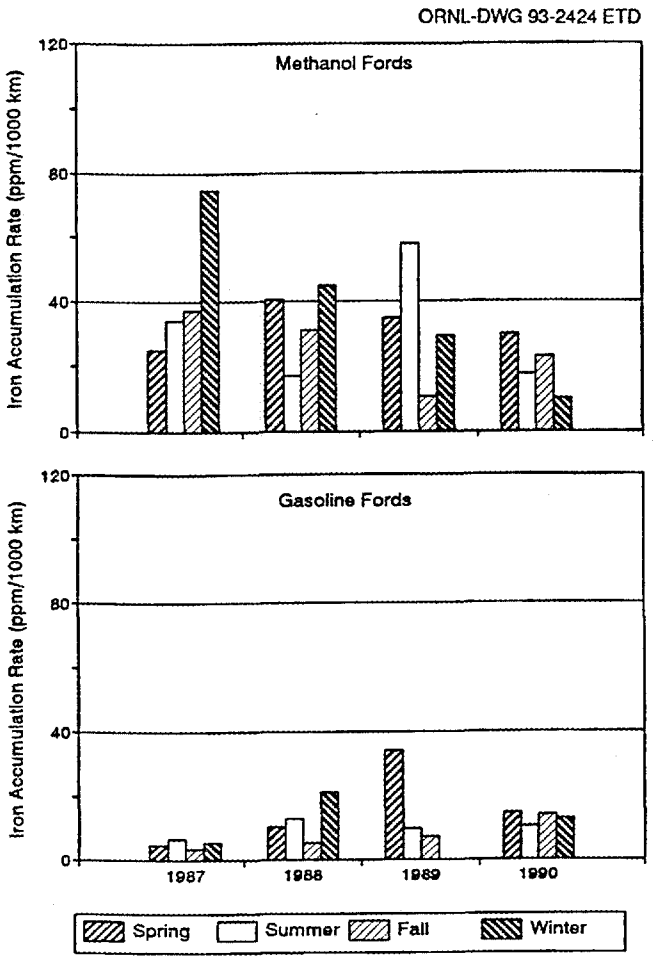

Figure 4. Iron accumulation rate in ANL Fords as a function of season.

The data base created in this project shows that, in most cases, the iron accumulation rate is higher in the methanol vehicles. The limited budget of the project did not allow investigating whether or not the higher iron accumulation rates were actually caused by significant increases in engine wear. However, with the interest and assistance of industry, some of the ANL Ford engines were examined in a cooperative effort between DOE, Lubrizol, and Ford. The surplused engines were provided by ANL and DOE, and Lubrizol and Ford cooperated on the disassemblies and inspections. Three of the methanol engines and one gasoline engine were examined.

Although the pistons and rings in the methanol engines were not the same as those in the OEM gasoline vehicle, the findings of the inspections are still of interest. The methanol Ford engines experienced increased piston ring wear apparently caused by calcium deposits in the top ring groove. The average compression ring side clearance for the methanol engines ranged from 0.16 to 0.30 mm, while that of the gasoline engine was 0.13 mm. The oil used in the methanol engines contained relatively high calcium for an automotive oil formulation, although not higher than that used in many diesel formulations (15,18). The gasoline vehicles used a standard, manufacturer-recommended, 10W-30 engine oil that is routinely stocked by ANL. Calcium deposits were also evident on the methanol-engine piston crowns and valve tulips.

While all four engines showed signs of high cylinder bore wear, the gasoline engine, contrary to expectations, actually had worse wear near top dead center. The M85 engines, on the other hand, showed more evidence of rusting. Surface roughness measurements showed the cylinder bores of all four engines to be similar, although the corroded crankshaft journals of the M85 engines

were not as smooth as those of the gasoline engine. The gasoline engine had more sludge and varnish deposits than did the methanol-fueled engines (19).

Short-Trip Testing

From late-winter to mid-summer of 1990, two of the ORNL Buicks were subjected to severe short-trip service to determine the harmful effects of two types of cold-start, short-trip service on the lubricating oil being used in the methanol vehicles. One methanol and one gasoline vehicle were removed from routine fleet service for the testing.

The first phase of the two-part experiment investigated the effects of severe short-trip driving in which large amounts of methanol and water were allowed to collect in the oil of the methanol vehicle. In the second phase, the trip length was increased to the point that the oil became warm enough to remove (evaporate) the methanol.

The ORNL FMF methanol vehicles' oil was supplied by Lubrizol, Inc. and was formulated as shown in Table 10. This oil is essentially the same as the oil referred to as "modified T" by Chamberlin and Gordon (15). While the gasoline vehicles in fleet service used a commercially available motor oil, both of the test vehicles used the Lubrizol oil formulation for the short-trip experiments.

Table 10. Oil Formulation Used in Methanol Vehicles at ORNL

SAE Viscosity Grade	10W-30
Viscosities	10.37 cSt at 100°C
	69.5 cSt at 40°C
	3450 cP at -20°C
TAN	4.3 (measured)
TBN	8.7 (theoretical) 9.0-9.8 (measured)
Sulfated Ash	1.1%
Elements	0.05% Calcium
	0.15% Magnesium
	0.20% Zinc
	0.11% Phosphorus

Introduction - As previously noted, a problem area for lubrication of methanol vehicles is short-trip, cold-engine service (15,17,19-24). Under these cold-engine conditions, unburned fuel, condensed water, and other combustion products enter the crankcase by blow-by and become diluted in the relatively cool oil. Under normal driving conditions in which the oil is allowed to warm to temperatures above about 60°C, many of these contaminants evaporate and are thus removed. The presence of methanol and water in the lubricating oil can remove additives, cause the formation of emulsions, impair lubrication, and increase corrosion. These problems are of special concern for methanol-fueled engines because combustion of M85 produces about 90% more water than does gasoline combustion (for equivalent energy release). Methanol and water are miscible with each other but form emulsions in engine oil. Gasoline, on the other hand, is miscible with engine oil.

Experiment - In preparation for the experiment, two of the Buicks (one methanol and one gasoline) were outfitted with thermocouples and other instrumentation. The two vehicles were chosen from the fleet of ten based on the criterion of nearly equal odometer mileage. The gasoline Buick began the experiment with 29,240 km and the methanol Buick with 27,040 km.

Prior to the start of the experiment, each vehicle's oil sump was "double-flushed" (i.e., the oil was changed twice in each vehicle). First each vehicle's oil and filter were changed. Each vehicle was then driven approximately 13 km and the oil and filter were changed again. Following the second change, the vehicles were driven 0.5 km and parked until actual testing began.

Type K thermocouples were inserted through the sides of the vehicles' oil pans to measure sump

temperature, and into the water jackets at the pump outlet to measure coolant temperature. Thermocouples were also mounted on each vehicle's radio antenna to measure the ambient air temperature. The vehicles' stock cam-position-sensor signals were employed to measure engine speed/revolutions. A Campbell Scientific 21X micrologger was used in each vehicle to monitor, process, and record all of the above signals.

Oil Analysis - The oil from each vehicle was sampled and analyzed periodically throughout the experiment. Samples were drawn through the dipstick tubes using a small hand pump and polyethylene tubing. Fresh tubing was used for each sample. The properties measured and the methods used are shown in Table 11. Although the samples were tested for glycol content, glycol results are not presented because the levels were undetectable in all samples.

Table 11. Methods used in oil analysis

Quantity	Abbreviation	Method
Total base number	TBN	ASTM D 2896
Total acid number	TAN	ASTM D 664
Pentane insolubles	PIN	ASTM D 893
Glycol content (percent)	-	GLYTEC Test Kit
Water dilution (percent)	-	ASTM D 1744 (Karl Fischer)
Gasoline dilution (percent)	-	ASTM D 3525
Methanol dilution (percent)	-	Packed column gas chromatography
Metals concentration (parts per million, ppm)	-	Rotating disk optical emission
Oxidation stability (minutes)	DSC	Differential scanning calorimetry at 175°C and 4.14 MPa O_2 pressure

Procedures - The details of cumulative distance driven and sample intervals for the phases can be found in Figures 5 and 6. Phase 1, shown schematically in Figure 5, consisted of 40 short trips that averaged 1.5 km in length, followed by a single

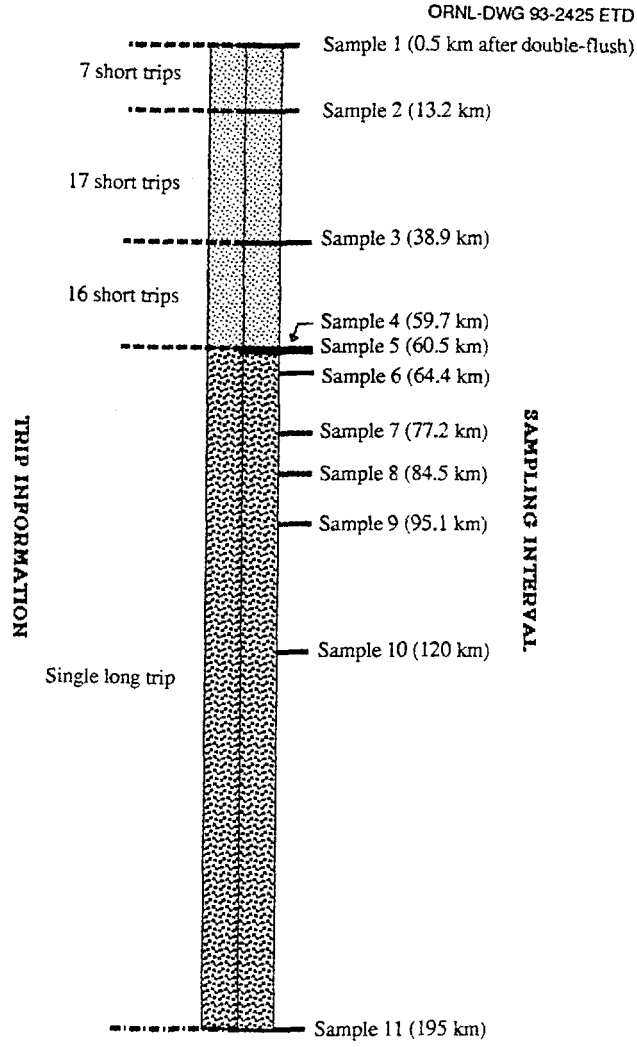

Figure 5. Phase 1 schematic diagram.

135 km trip of highway driving. Phase 2, shown in Figure 6, began with 735 km of fleet service and highway driving, and was followed by the longer 2.7-km short trips. Phase 2 short-trip testing ended with a 37-km highway trip.

During both phases of the short-trip testing, the vehicles were started at the same instant, driven simultaneously, and shutdown at the same instant. Drivers switched cars every trip in an attempt to equalize any small operator variations. Given that the methanol vehicle was prone to longer cranking times on cool days, the driver of the gasoline vehicle was instructed to wait until the methanol vehicle was starting before initiating cranking. This process helped to ensure that each vehicle experienced

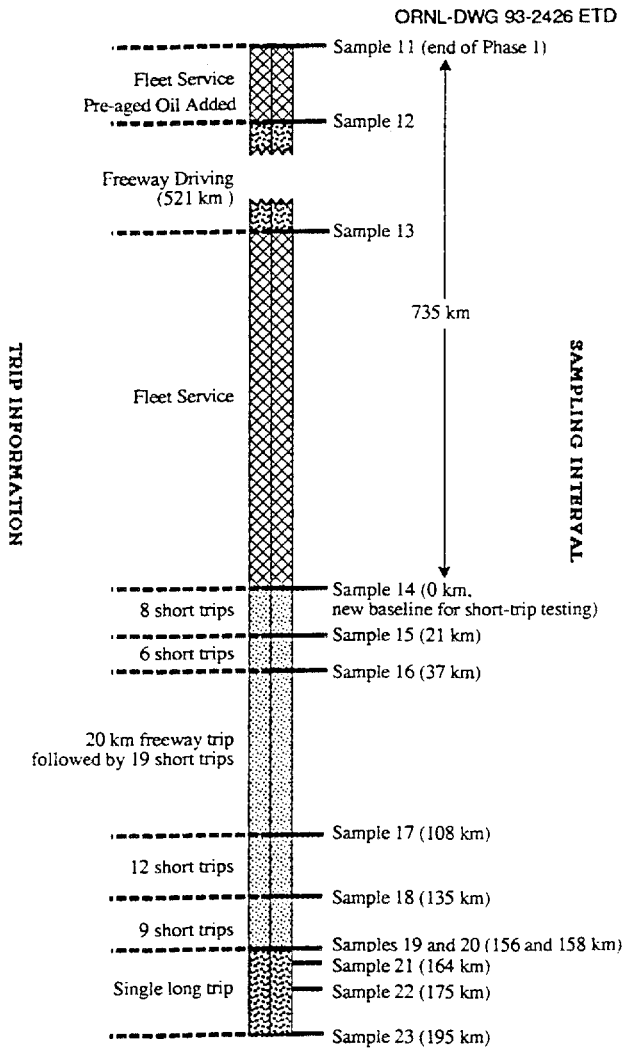

Figure 6. Phase 2 schematic diagram.

approximately the same number of engine cycles throughout the short-trip testing. Unfortunately, an open circuit in the cam-position-sensor signal of the methanol vehicle precluded obtaining the revolutions data during the single long trip of Phase 1. However, for the period for which revolutions were measured, the total number of revolutions were within 2% of each other (the methanol vehicle being slightly higher). During the Phase 2 short-trip testing and the subsequent long trip, the methanol vehicle's engine revolutions were about 6% higher than that of the gasoline engine. The reason for the higher number of engine cycles was probably related to the methanol vehicle's engine control module (ECM) which was reprogrammed for slightly higher idle speed under cold engine conditions. This was not considered to be an important factor, however, because the transmissions were in gear and the vehicles were being driven at the same speed during cold engine operation.

Phase 1 - The initial plan for Phase 1 was to complete two 2-km trips per day until 40 trips had been completed. However, unseasonably warm temperatures called for shorter trips and precluded making a second trip on most days. Nonetheless, forty trips were completed, totaling only 60 km.

Because the objectives of the experiment were to determine the deleterious effects of volatile contaminants in the engine oil and the effects of oil temperature on the level of contaminants and rates of degradation, it was decided that one shorter trip per day would be more prudent than two 2-km trips, in order to avoid boiling off appreciable amounts of volatile contaminants. While colder ambient temperatures and longer trips would have been preferred, the extremely short trips were the best means available to ensure that the vehicles' oil temperatures remained low.

Pre-aged Makeup Oil - Following the Phase 1 long trip (during which several oil samples were taken) and before the beginning of the Phase 2 testing, a similar volume (about 1.1 liters) of pre-aged make-up oil was added to each vehicle. The pre-aged oil was obtained from another methanol Buick that had accumulated about 2700 km on its oil in typical fleet service. The oil was taken from one of the methanol Buicks because these were the only cars available that were using the oil formulation being tested (the other gasoline FMF cars used commercially available oil).

Pre-aged make-up oil was added in lieu of fresh oil to minimize any significant improvement in the oils' protective properties. Ideally, oils used for this purpose would be pre-aged in similar vehicles driven under similar service conditions for the same distances (25). However, no such oil was available. The test vehicles had each accumulated 195 km at

the time the make-up oil was added. Based on the literature, it was reasonable to assume that the short-trip service would be 10-15 times more detrimental to the oil than combined highway/city driving for the same distance. Therefore, the oil with 2700 km of fleet service was considered appropriate.

The analysis results for the pre-aged make-up oil are shown in Table 12. Also shown are the analysis results for the fresh oil and the samples drawn from each of the test vehicles prior to and following the pre-aged oil addition. Note that the oxidation stability (DSC) of the pre-aged oil is only 4 minutes. Although considerably lower than expected, the exact type of service to which this vehicle had been subjected was unknown. It is clear that the addition of pre-aged make-up oil did not improve the condition of the oil in the vehicles' sumps. In fact, the results in Table 12 indicate that the used-oil addition actually resulted in degradation of the resultant sump contents.

Table 12. Analysis results for fresh, pre-aged, and test vehicle oil samples before and after oil addition

Sample	TAN	TBN	PIN	gasoline dil'n (%)	methanol dil'n (%)	water dil'n (%)	iron conc. (ppm)	DSC (min)
Fresh oil (2 sample average)	4.3	9.4	0.0	0	0	0.07	0	96
Pre-aged oil (2 sample average)	8.7	3.7	0.6	1	<1	0.12	100	4
				Methanol	Vehicle			
Before oil add (sample 11)	4.1	11.7	<0.1	<1	<1	0.08	60	55
After oil add (sample 12)	7.5	8.5	<0.1	<1	<1	0.17	60	45
After highway (sample 13)	8.3	9.5	<0.1	2	<1	0.21	70	26
				Gasoline	Vehicle			
Before oil add (sample 11)	3.3	11.0	<0.1	4	0	0.07	30	47
After oil add (sample 12)	7.7	8.5	<0.1	2	0	0.15	50	33
After highway (sample 13)	7.2	9.2	<0.1	2	0	0.16	60	25

Phase 2 - Following the addition of make-up oil, both vehicles were driven 702 km before beginning the longer short-trip service. Again, the types of service are depicted in Figure 6. Table 12 shows the analysis results for samples taken after the 521 km of highway driving. On inspection of the oxidation stabilities, it is apparent that the oils were further degraded by the highway driving, although their total base numbers improved slightly. The vehicles were not driven "side-by-side" during portions of this period of fleet and highway service. They did, however, see nearly identical service and accumulated identical mileage.

The Phase 2 short-trip testing, like that of Phase 1, was initially designed to be comprised of 40 short trips. However, an unavoidable trip to the garage after 14 short trips interrupted the experiment. This interruption is indicated in Figure 6 as the 20-km trip after Sample 16. Following this intermittent long trip, 40 more short trips were made.

Discussion of Phase 1 - In Phase 1 of the experiment, the trips were sufficiently short that the sump temperatures did not exceed 60°C except in the long trip at the end. Surprisingly, the methanol vehicle's oil temperature was consistently higher than that of the gasoline vehicle even though the coolant temperature was actually lower, as shown for a typical short-trip in Figure 7. Lower coolant temperatures would be expected in the methanol vehicle due to methanol's slightly lower flame temperature and much higher latent heat of vaporization. By the same reasoning, lower oil temperatures would be expected. One possible explanation for the higher oil temperatures is that there may have been a higher level of hot blow-by gases in the crankcase of the methanol vehicle caused by increased cylinder bore and ring wear.

The Phase 1 oil and ambient temperatures are shown in Figure 8. The oil data up to 60 km are the peak temperatures reached during the daily short trips. From 60 km to 195 km (single long trip), the oil temperatures are those recorded each time a sample was taken. Again, the higher methanol vehicle oil temperatures are quite apparent.

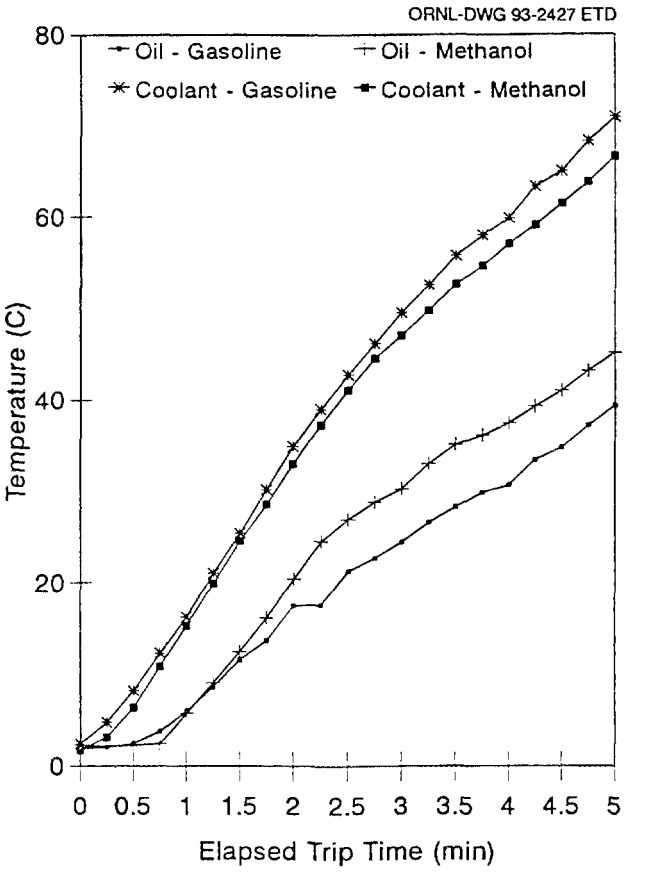

Figure 7. Methanol and gasoline vehicle oil and coolant temperatures for a typical short-trip.

Warmer oil temperatures notwithstanding, the methanol vehicle's oil still accumulated a larger volume of volatile contamination. Figure 9 shows the total volatile contamination (sum of water, gasoline, and methanol dilution) in the oil of each vehicle. Note that the peak volatile content of the methanol vehicle is more than double that of the gasoline vehicle.

Figure 10 shows the fuel and water contamination separately for the methanol vehicle, and Figure 11 shows the same information for the gasoline vehicle. The gasoline vehicle's fuel dilution peaked at about 12% with only a few percent of water dilution. The fuel contamination only dropped to 5% after the 135 km of freeway driving at elevated temperatures.

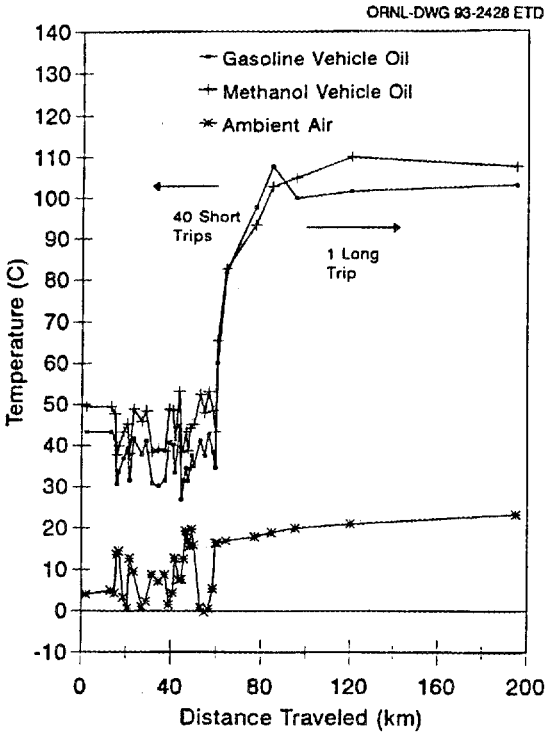

Figure 8. Phase 1 ambient and oil temperatures for both vehicles.

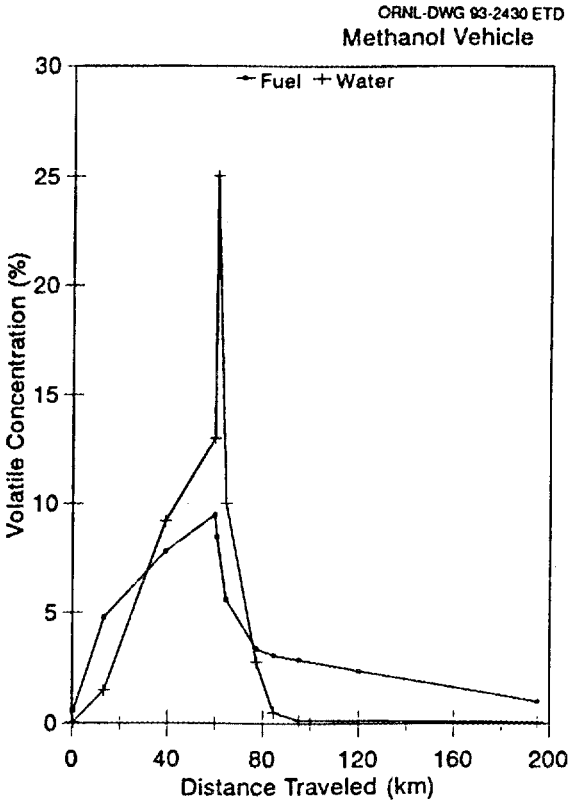

Figure 10. Phase 1 fuel and water dilution in methanol vehicle's oil.

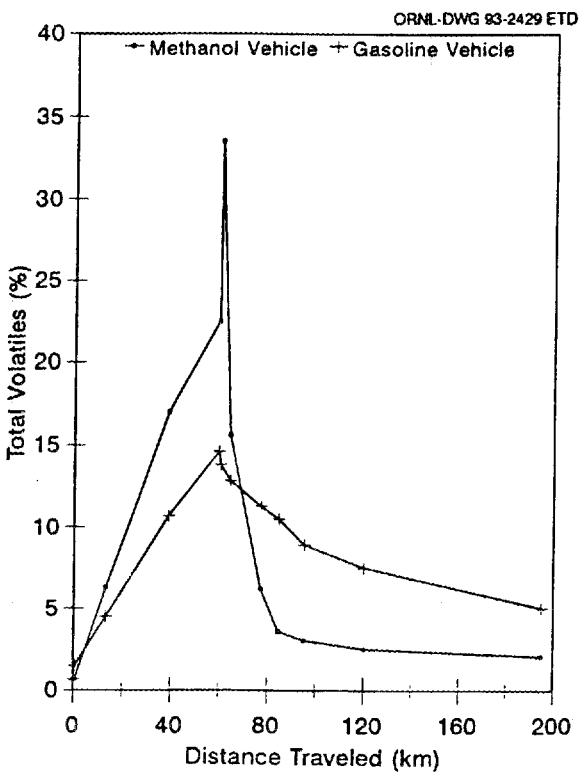

Figure 9. Phase 1 total volatile contamination in oil for both vehicles.

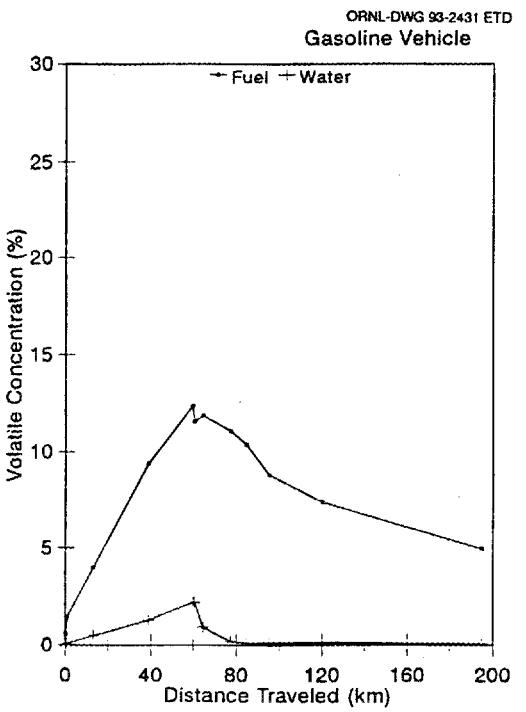

Figure 11. Phase 1 fuel and water dilution in gasoline vehicle's oil.

The oil readily forms an emulsion with high levels of water and/or methanol, as shown in Figure 12. The first four samples were taken during the 40 short trips. Note that at Sample 3 the specimens look similar, but that at Sample 4 the methanol vehicle's oil is much more emulsified. The long trip included a one-hour "hot-soak," and totaled over four hours in duration. The methanol vehicle's oil had much higher water dilution than did the gasoline vehicle's oil, although the fuel dilution (methanol *and* gasoline combined) peaked at a slightly lower level. While the water boiled off rather quickly in both vehicles, the fuel contamination in the gasoline vehicle's oil was removed at a much slower rate due to its wide boiling range (typically 25-215°C). Vaporization of fuel in the methanol vehicle's oil occurred quickly at first, due to the single boiling point of methanol (65°C), but the gasoline portion of the fuel was removed at a slower rate.

The change in TBN is shown in Figure 13. The TBN decreases substantially in both vehicles during the short-trip testing and rebounds during the long trip. The high TBN value shown for the methanol vehicle at about 100 km is not understood, although the sample was noted to have been "gummy." The contents of this sample were apparently quite alkaline; however, it is most unlikely that the vehicle's entire sump had such a TBN at that time. Results for total acid number are not shown because there was very little variation throughout Phase 1.

The TBN values at the beginning of the short trip testing are quite different. The gasoline vehicle's TBN was much higher than that of the

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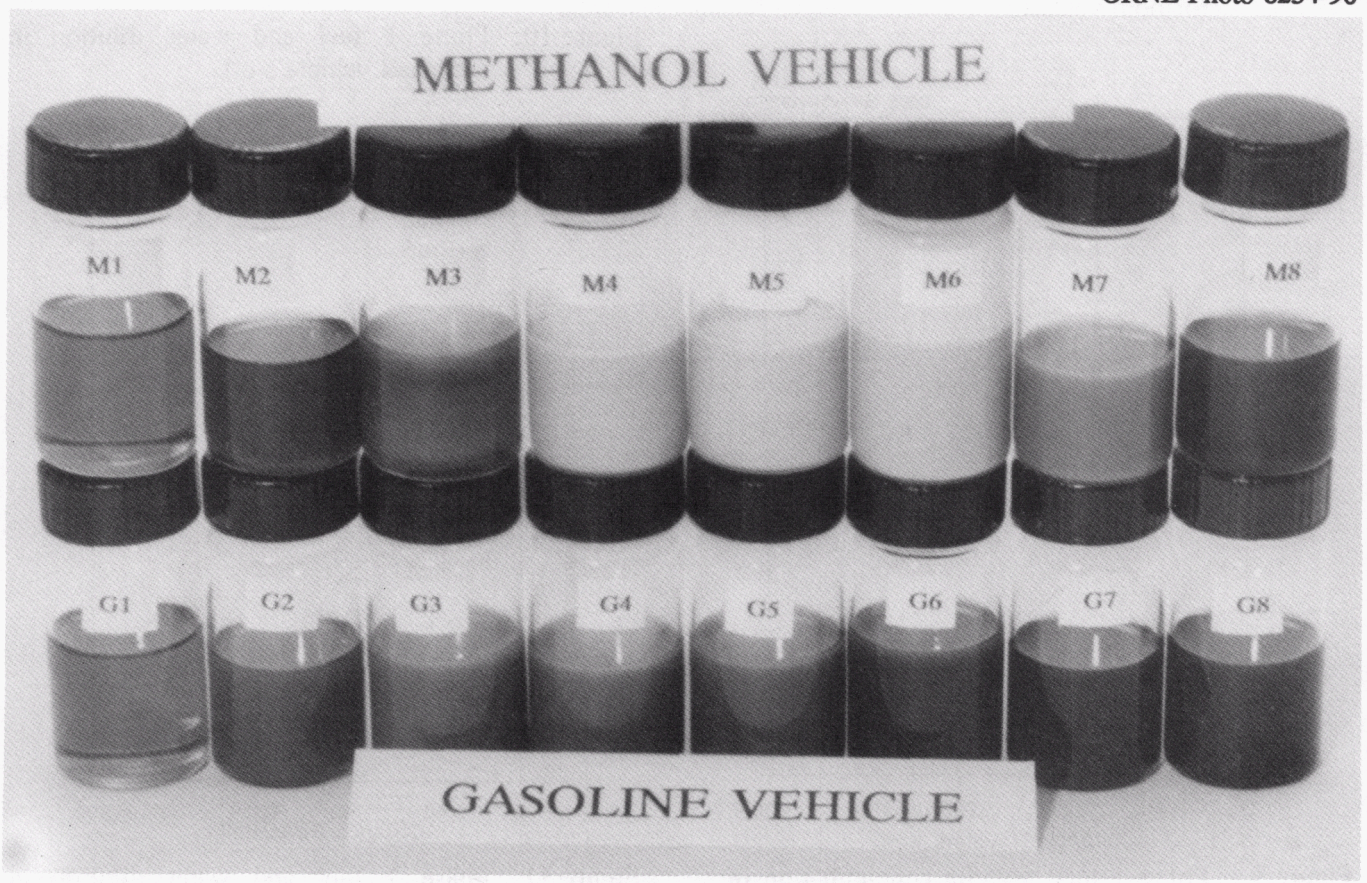

Figure 12. Phase 1 oil samples.

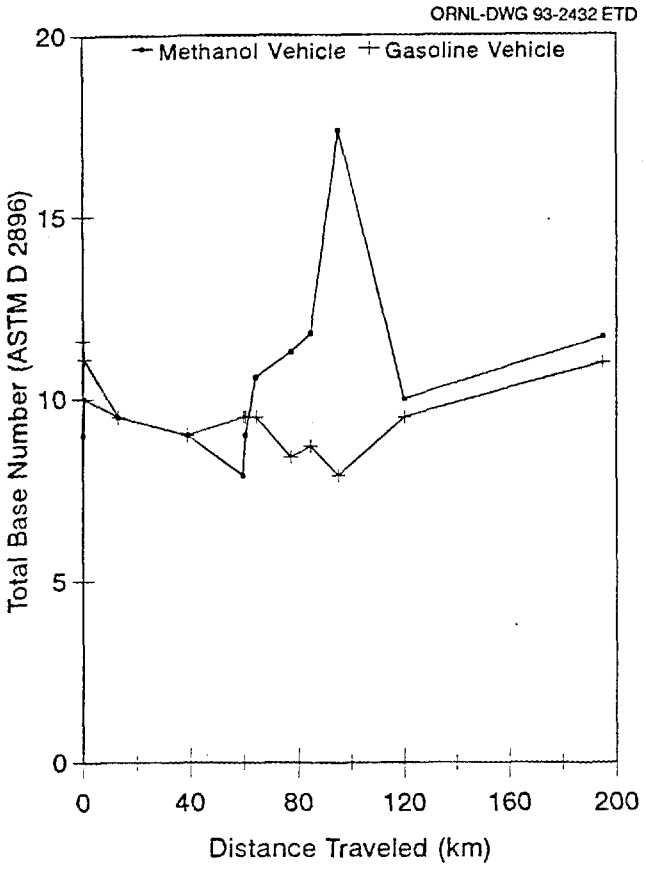

Figure 13. Phase 1 total base number for both vehicles.

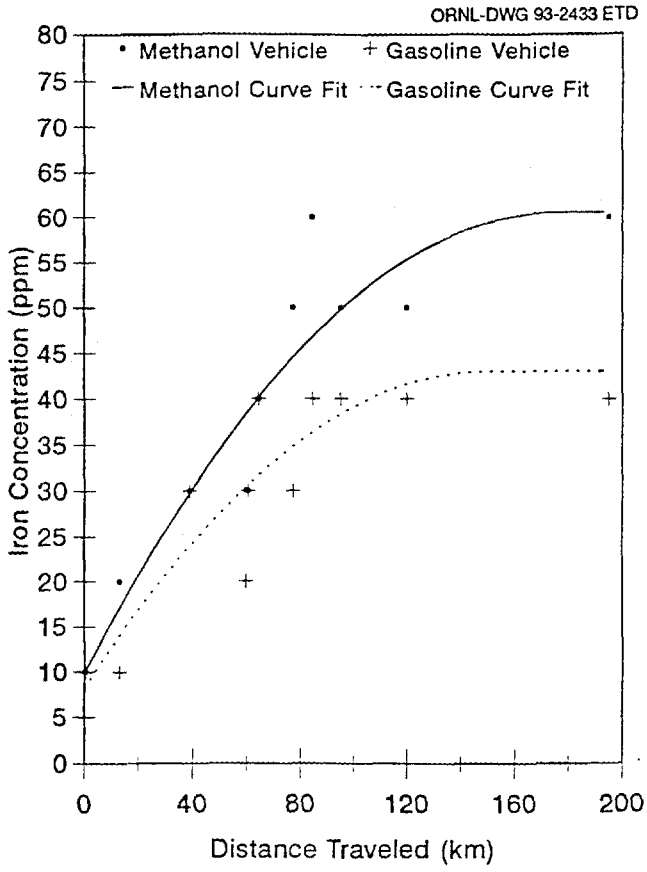

Figure 14. Phase 1 iron concentrations in both vehicles' oil.

methanol vehicle. Reasons for this are not clear. It may be possible that, despite the double-flush oil-change, some residue from the bottom of the oil pans could have contaminated the samples. Unfortunately, the oil drains were not sampled prior to the double-flush.

Figure 14 shows the iron concentrations measured in each vehicle's oil throughout Phase 1. The curve fits shown are quadratic regressions. A quadratic method was used because the iron accumulation rates appeared to level off during the long trip. Figure 14 shows that the iron accumulation rate for the methanol vehicle was higher than that for the gasoline vehicle. Although both curves appear to level off at about the same distance, the methanol vehicle's final iron level was about 20 ppm higher than that of the gasoline vehicle.

Linear regressions were also performed, using only the first 8 values of the Phase 1 data. During the short trip testing, and early in the long trip, the iron accumulation rate for the gasoline vehicle was 335 ppm/1000 km which is over 30 times higher than the highest seen in any winter quarter (Figure 1). The methanol vehicle's oil accumulated iron at a rate of 490 ppm/1000 km which is about 17 times higher than the highest iron accumulation rate shown in Figure 1.

Discussion of Phase 2 - When the short-trip testing portion of Phase 2 began, each vehicle had accumulated 930 km since the double-flush oil change at the beginning of Phase 1. Sample 14 was drawn to obtain a new baseline and short-trip testing was resumed with longer 2.7-km trips. The average ambient temperature was warmer during this period.

Figure 15 shows the oil and ambient air temperatures as functions of distance for the last segment of Phase 2. Figure 16 shows the total volatile contamination for both vehicles. During this period, there was no accumulation of methanol, so the sum of fuel and water includes only water and gasoline. The inadvertent long trip after the first 14 short trips is apparent by the increased level of the oil temperatures at about 40 km. During the longer (2.7-km) short-trip testing, the methanol vehicle's oil was again warmer than that of the gasoline vehicle, but by a smaller margin. The sump temperatures during this phase were still relatively low, rarely exceeding 70°C. Note that the peak volatile contamination for the gasoline vehicle is about double that for the methanol vehicle for this warmer short-trip service. The long trip began at 158 km and ended at 195 km.

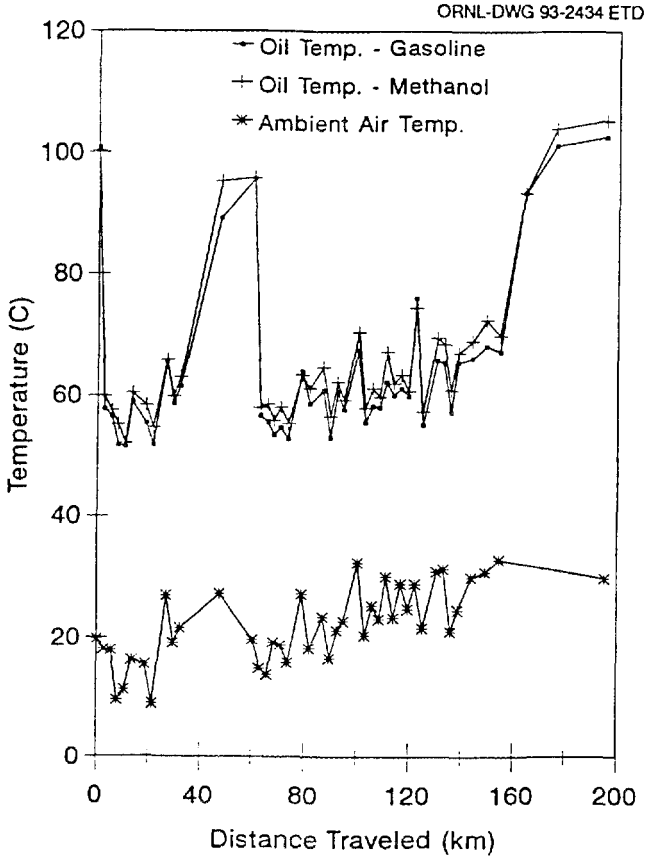

Figure 15. Phase 2 ambient and oil temperatures for both vehicles.

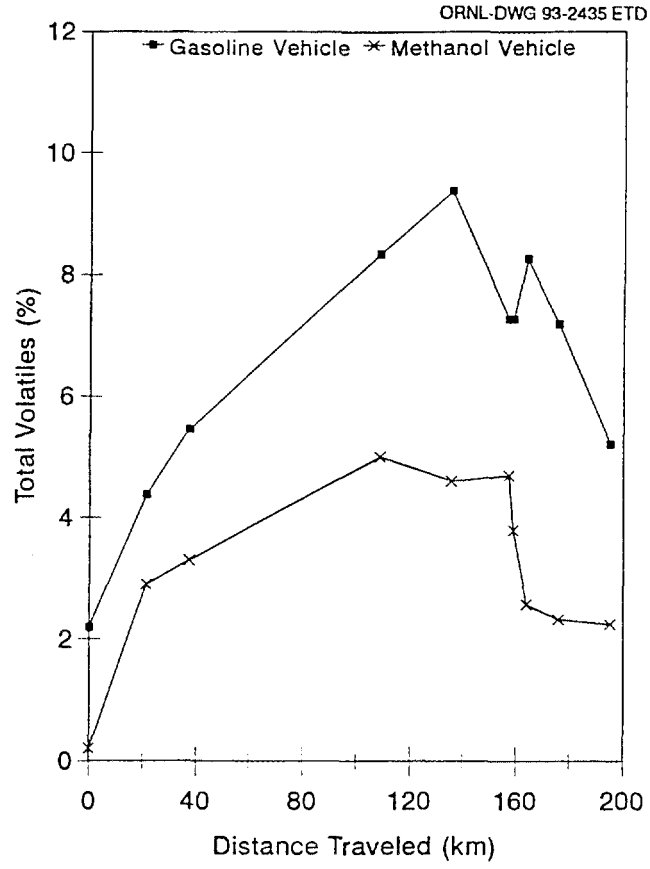

Figure 16. Phase 2 total volatile contamination in oil for both vehicles.

Figure 17 shows the water and fuel dilution for the methanol vehicle and Figure 18 shows the same information for the gasoline vehicle. The warmer sump temperatures precluded any methanol dilution during this phase, however the methanol vehicle's oil still accumulated 2% gasoline. There was very little water dilution in the gasoline vehicle's oil. During the long trip, the volatiles in the methanol vehicle's oil (being mostly water) were removed at a much higher rate at first. In fact, the gasoline concentration in the methanol vehicle's oil was still 2% at the end of the long trip. The vehicles were obviously not driven far enough to remove all of the volatile contamination. Given the warmer sump temperatures and the appearance of the oil (samples were not analyzed until all work was completed), it was thought that 37 km would be a sufficiently long trip.

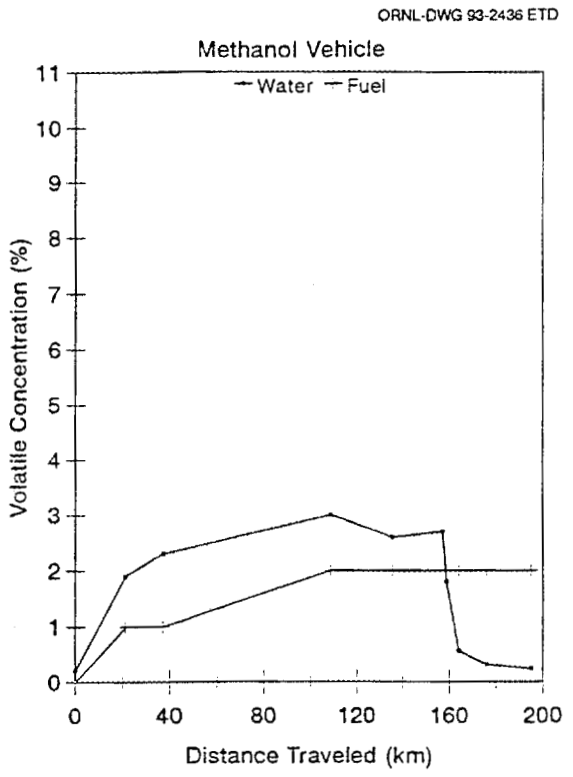

Figure 17. Phase 2 fuel and water dilution in methanol vehicle's oil.

The TBN results for Phase 2 are shown in Figure 19. The figure shows that there was a near-steady decrease in the TBN of the gasoline vehicle's oil for this period. The methanol vehicle's TBN followed a similar trend, but increased rapidly to its end-of-Phase-1 value during the long trip.

The iron levels for both vehicles were nearly constant throughout the short-trip portion of Phase 2, as shown in Figure 20. Linear regressions of the data produced a negative iron accumulation rate for the gasoline vehicle, which merely reflects the uncertainty (± 5 ppm) in the measurements. The methanol vehicle's regression shows an increasing trend, largely because of the last two data points. The iron accumulation rate for the methanol vehicle, calculated as described above, was 74 ppm/1000 km. Although considerably lower than the 490 ppm/1000 km found in Phase 1, 74 ppm/1000 km is still more than double any rate shown in Figure 1 (from three years of fleet service). These and other results are presented in more detail in Reference 26.

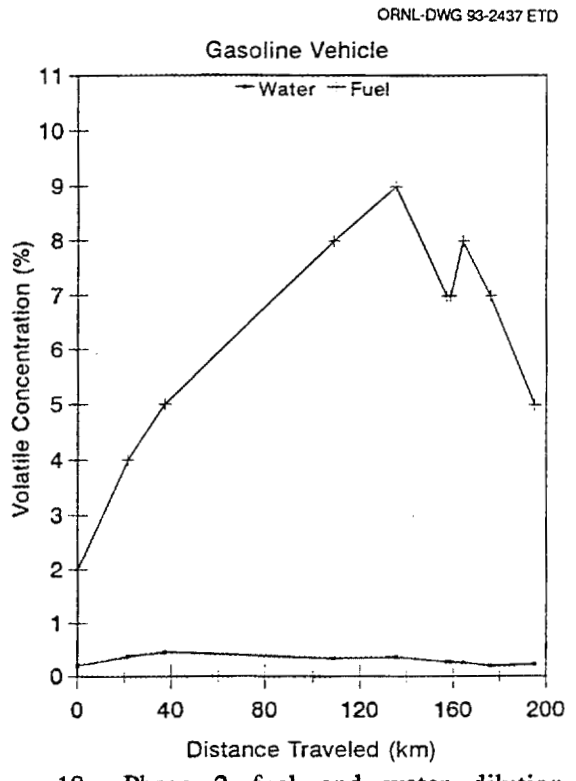

Figure 18. Phase 2 fuel and water dilution in gasoline vehicle's oil.

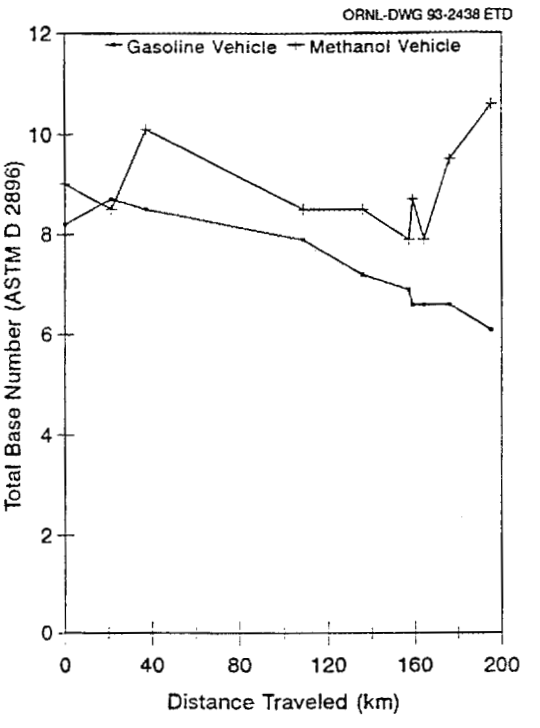

Figure 19. Phase 2 total base number for both vehicles.

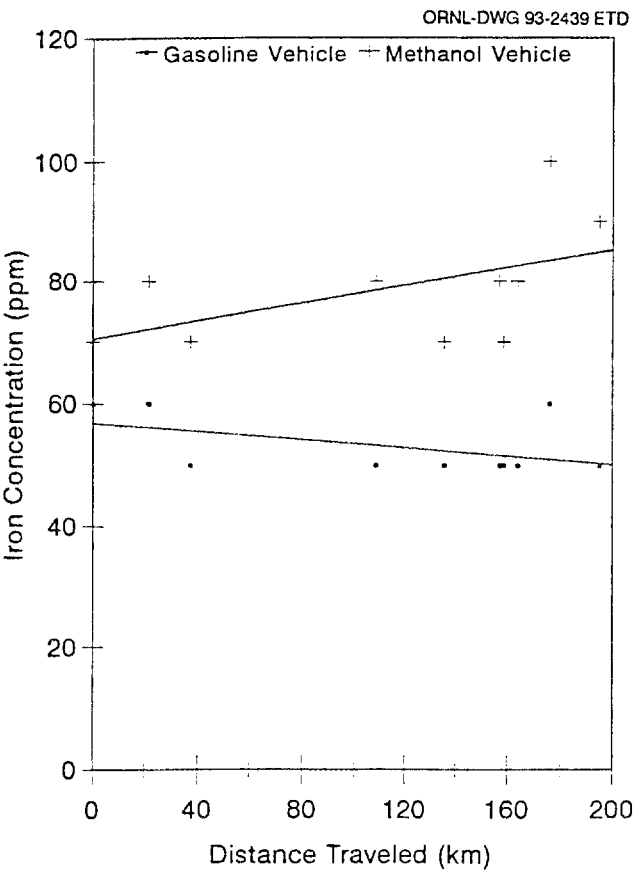

Figure 20. Phase 2 iron concentrations in both vehicles' oil.

COMPARISON OF MAINTENANCE AND SERVICE

The data collected over the course of this project showed that the methanol vehicles generally required more overall maintenance than their gasoline counterparts, something one might expect for development or prototype vehicles. The maintenance data were examined to determine what percentage of the maintenance was "fuel-related" (i.e., corrective or preventative maintenance which could be traced to the fuel or fuel system). Although the methanol vehicles did have higher fuel-related maintenance than did the gasoline cars, the fuel-related incidents did not always account for the greater amount of overall maintenance. In other words, the methanol vehicles were sent to the shop more frequently, but not due to fuel-related problems. The authors believe that the drivers were more sensitive to mechanical problems in the "special" methanol vehicles and requested maintenance for them on occasions that might have been dismissed for a gasoline vehicle.

For illustrative purposes, Figure 21 shows the maintenance frequency (maintenance events per 1000 km) and intensity (labor hours per 1000 km) for the Chevrolet S10 pickup trucks at ANL for the first three years of operation. The figure shows that, although the maintenance frequency for the methanol vehicles rose slightly each year, it stayed relatively constant for the gasoline vehicles. The methanol vehicles' maintenance intensity increased markedly each year while that of the gasoline vehicles increased only slightly.

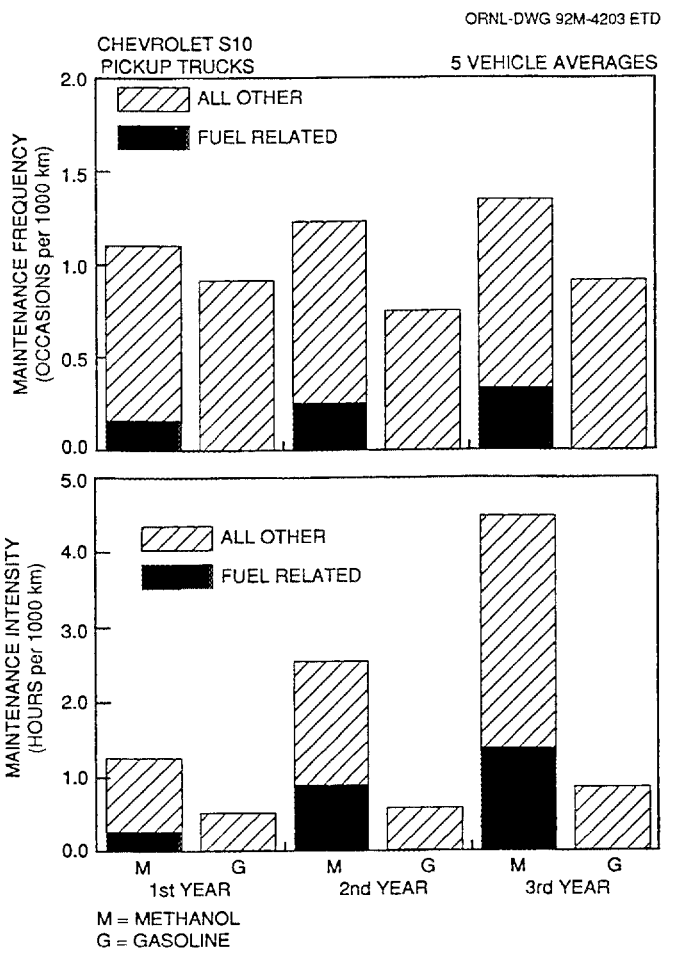

Figure 21. Maintenance frequency and intensity for ANL Chevrolets.

Similar information is presented in Figure 22 for the Fords at ANL. The maintenance frequency for the methanol Fords increased slightly each year while that for the gasoline Fords was relatively constant. The maintenance intensity increased each year for both fuel types, although at a higher rate for the methanol Fords. Once again, note that the fuel-related maintenance does not account for the greater overall maintenance of the methanol Chevrolets or Fords, although the "all other" categories for the methanol and gasoline Fords are more equitable.

Figure 23 shows similar information for the Buicks at ORNL for their first two years of operation, and similar conclusions can be drawn. In some cases, however, the gasoline vehicles actually required more maintenance in the "all other" category. The maintenance history for the LBL Citations is presented in Figure 24. Note that for all years at LBL the "all other" categories of both maintenance frequency and intensity are smaller for the gasoline vehicles. This fact reenforces the belief that drivers have a propensity to request service more frequently on an atypical vehicle.

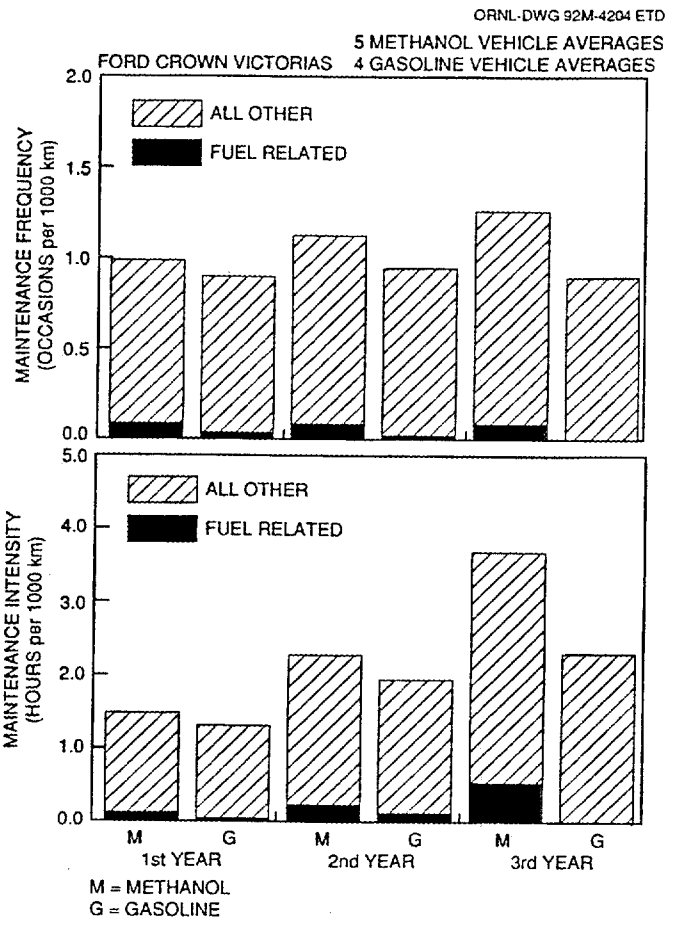

Figure 22. Maintenance frequency and intensity for ANL Fords.

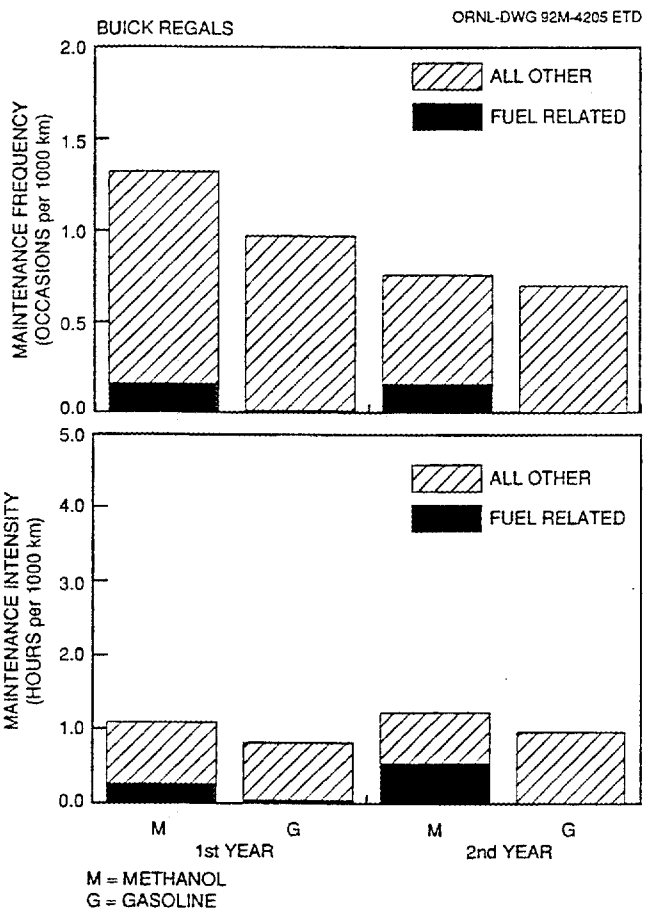

Figure 23. Maintenance frequency and intensity for ORNL Buicks.

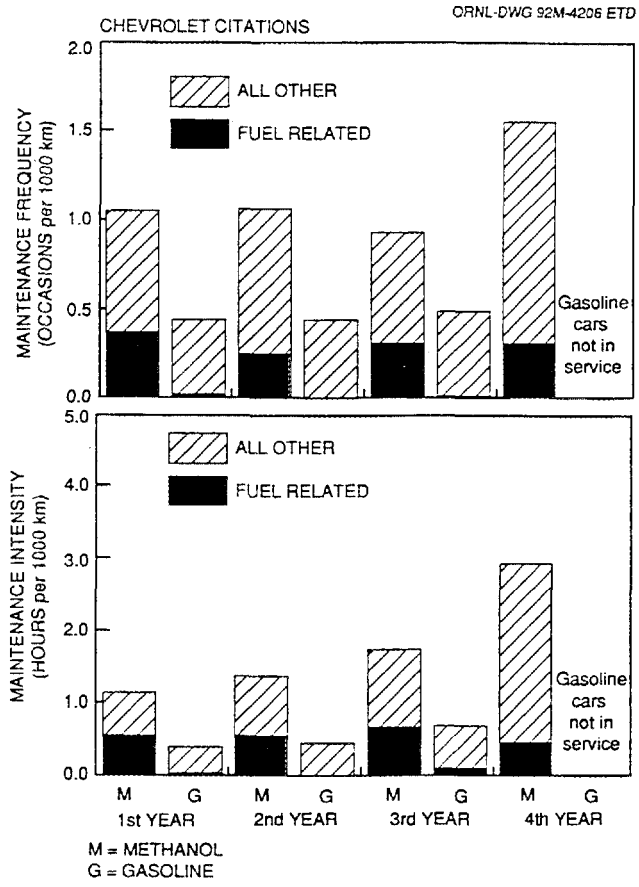

Figure 24. Maintenance frequency and intensity for LBL Chevrolet Citations.

DRIVER SATISFACTION

Response From Driver Logs

For the duration of the project, drivers at all three sites were asked to evaluate the vehicles' ease of starting and driveability for each trip by making a check mark under either "Good," "Average," or "Poor" in the vehicle's trip log. Drivers at ANL were also asked to estimate the ambient temperature and to check either "5°F or less," "6°F to 40°F," or "Greater than 40°F." These estimates were intended to give some indication of the vehicles' performance as a function of weather. In general, the gasoline vehicles at all three sites received slightly higher marks than the methanol vehicles, although ratings for both vehicle types were quite high; ease of starting and driveability at all sites were rated as "Average" or "Good" over 50% of the time. The cold start systems on the methanol vehicles at ANL apparently performed well. The ratings of ease of starting in colder weather were not highly different from those in milder temperatures. The ORNL fleet showed the greatest seasonal variation in ease of starting ratings, probably as a result of the lack of sophisticated cold-start systems on the methanol vehicles and the freezing and below freezing weather encountered in the Oak Ridge winters. The LBL fleet showed very little seasonal variation in driver satisfaction. Figure 25 shows the average of the first daily ease-of-starting ratings for the methanol vehicles at all three sites as a function of month of the year. Numerical values were assigned to "Good," "Average," and "Poor" so that averages could be computed. The first rating of each day was assumed to be a true "cold start," because the vehicle would have had several hours of "soaking" at the ambient temperature. This might not be universally true in the case of the Fords at ANL, because they were used around-the-clock as security vehicles. The figure shows the average for each month for 2, 3, or 4 years, for the ORNL, ANL, and LBL fleets, respectively. Note that the ORNL Buicks showed the greatest variance, with better ratings in the warmer months and poorer ratings in

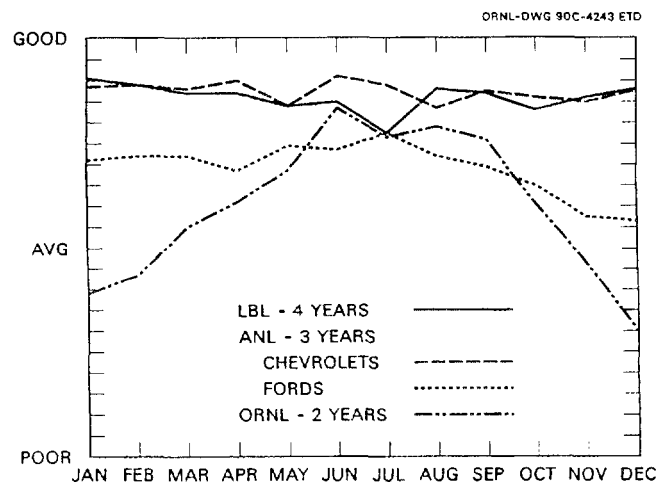

Figure 25. Average ease of starting ratings for first daily start as a function of month.

colder months. This trend is not as apparent for the LBL Citations, perhaps because of the milder climate, and the ANL Fords and Chevrolets show less variation due to their cold-start systems. Note that the ANL Chevrolets received better ratings than did the ANL Fords. This could be due, at least in part, to the fact that the Chevrolets used a gasoline cold-start system, while the Fords' system used only the M85 fuel. Because the same drivers did not operate both vehicle types at ANL, absolute comparisons should not be made. For the same reason, site-to-site comparisons should not be made.

Response From Driver Surveys

Survey forms were sent to randomly selected drivers at all three test sites on four separate occasions. The LBL drivers were surveyed twice and the ANL and ORNL drivers were each surveyed once. The overall response rate for all four surveys was 50%. Response from three of the surveys was 50% or greater, but that from the second survey at LBL was only 39% (probably a result of loss of interest in the then-three-year-old project). The survey results show percentages of responses to particular questions and any comments given by the respondents. The results of the individual surveys are presented in their entirety in References 1, 3, 6, and 9.

In general, the surveys indicated a reasonable level of acceptance of the methanol vehicles at all three sites. In both LBL surveys over 50% of respondents said that for the methanol vehicles, the ease of starting, performance during warm-up, and performance when warmed-up were "about the same" as that of the gasoline vehicles. In the first survey, 67% of respondents at LBL said overall performance was the same, while only 49% gave this response in the second survey. Ratings of driveability declined with vehicle age, and several drivers at LBL complained that the methanol vehicles stalled frequently or had poor acceleration. In response to these complaints, the vehicles were usually sent to the garage for adjustments to the carburetor, which generally constituted nearly half of the "fuel-related" maintenance on the Citations. Similar adjustments were not required on the fuel-injected cars at the other FMF sites. It is not likely that future OEM methanol vehicles will have carburetted engines.

The ANL drivers rated the performance of the methanol Chevrolets as "about the same" or "better" than the gasoline vehicles over 50% of the time during warm-up and 78% of the time after being fully warmed up. The Fords were not rated quite as high with ratings of "equal" or "better" two-thirds of the time after warm-up, and "equal" only 30% of the time during warm-up.

Nearly half of the ANL Chevrolet drivers responded that they would consider buying a methanol vehicle and only 17% of the Ford drivers would consider buying one. Many of the comments received dealt with drivers' concerns over fuel economy (miles per gallon) and range, fuel availability, and driveability in cold weather. Many drivers indicated that they liked the improved performance of the methanol engines, provided that details such as cold-start and range could be addressed.

The Buick Regals at ORNL were probably the most well-received vehicles in the FMF. Over 50% of respondents indicated that the methanol Buicks started about the same as, or better than, the gasoline Buicks. Seventy-three percent of respondents revealed that the methanol vehicles' performance during the warm-up period was the same or better than their gasoline counterparts, while 94% had these responses for warmed-up operation. The ORNL drivers also indicated high satisfaction with driveability and range (the methanol Buicks had 30 gallon fuel tanks).

The responses from driver surveys and the daily driver logs indicated a generally high level of acceptance of the FMF vehicles. While there were some complaints about driveability, ease of starting, and range, most of these problems can be attributed to the prototype nature of the retrofitted vehicles, or to the relatively small fuel tanks on some of the methanol vehicles.

SUMMARY AND CONCLUSIONS

The Federal Methanol Fleet (FMF) Project concluded with the termination of data collection in 1991. Twenty methanol-fueled vehicles were operated in tandem with 19 comparable gasoline vehicles at three DOE sites. These three test sites included the Lawrence Berkeley Laboratory (LBL), the Argonne National Laboratory (ANL), and the Oak Ridge National Laboratory (ORNL). The 39 vehicles accumulated over 2.2 million km in routine fleet service. Data collected over the years have included vehicle mileage and fuel economy, engine oil analysis, emissions, maintenance, and driver acceptance.

The gasoline vehicles at LBL and ORNL were generally driven 40 to 60% further per trip than their methanol counterparts, which resulted in 4-17% higher fuel economy (on an energy basis). Use patterns at ANL were more equitable, and as such, the fuel economies of ANL methanol vehicles were about the same as their gasoline counterparts.

Emissions from some of the gasoline control vehicles and the retrofitted methanol vehicles were measured several times throughout the project. While the emissions of both methanol and gasoline vehicles tended to increase with age, there was evidence of more rapid catalyst degradation on some of the methanol-fueled vehicles. While the methanol vehicles in this project were not optimized for methanol fuel use, it is likely that optimized OEM methanol vehicles will need to employ different catalyst formulations than those used for typical gasoline vehicles.

Evaluations of engine oil from the fleet vehicles have generally indicated higher levels of iron contamination in the oil of the methanol vehicles. Seasonal variations in iron accumulation rate have also been apparent, suggesting that engine wear is increased in colder weather, or under high-temperature, high-load service. While the iron accumulation rates in the methanol vehicles have been as much as an order of magnitude higher than those of their gasoline counterparts in some cases, increased or more apparent engine damage has been difficult to assess. Disassembly of three methanol engines and one gasoline engine from the ANL fleet did confirm some wear patterns typical to methanol engines (such as high cylinder bore wear and corrosion), but contrary to expectations, the gasoline engine had an even higher level of bore wear.

Maintenance records have generally indicated a higher maintenance frequency and intensity for the methanol vehicles at all sites. Fuel-related maintenance was higher for the methanol vehicles in all cases, and given that the methanol vehicles were retrofitted, or development-type vehicles, this would be expected. It is interesting to note, however, that the fuel-related maintenance could not always account for the higher level of maintenance. In other words, the methanol vehicles were sent to the garage more frequently, but not due to fuel-related problems. The authors believe that drivers were more sensitive to mechanical problems in the more uncommon methanol vehicles, and requested maintenance on occasions that they may have overlooked in a gasoline vehicle.

Drivers at all three fleet sites were asked to fill out a daily driver log each time they drove one of the FMF vehicles indicating their satisfaction with the vehicle's ease of starting and driveability. Drivers were also surveyed on four different occasions and asked more detailed questions about their satisfaction with the FMF vehicles. Data from the driver logs indicated that the methanol cars were well-received, although the gasoline vehicles generally received better ratings, especially in colder seasons. Respondents to most of the surveys indicated a relatively high level of satisfaction with the methanol vehicles. Typical complaints were related to driveability, ease of starting, and range. Most of these complaints can be attributed to the prototype nature of the vehicles, and the relatively small fuel tanks on most of the methanol vehicles.

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ACRONYMS AND NOMENCLATURE

ANL	Argonne National Laboratory
CO	Carbon monoxide
DOE	Department of Energy
DSC	Differential scanning calorimeter, a measure of oxidation stability (minutes)
ECM	Engine control module
EGR	Exhaust gas recirculation
EPA	Environmental Protection Agency
FID	Flame ionization detector
FMF	Federal Methanol Fleet
FTP	Federal test procedure (for determining motor vehicle emissions)
g	Gram
GJ	Gigajoule (10^9 Joules)
HCOH	Formaldehyde
km	Kilometer
LBL	Lawrence Berkeley Laboratory
M85	Fuel methanol, 85% methanol, 15% unleaded gasoline or other hydrocarbon additive
mpg	Miles per gallon
NO_x	Oxides of nitrogen (nitrogen dioxide, NO_2, and nitric oxide, NO)
OEM	Original equipment manufacturer
OMHCE	Organic material hydrocarbon equivalent
ORNL	Oak Ridge National Laboratory
TBN	Total base number, a measure of alkaline reserve

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41. R. P. Larsen, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439

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