Interim Report No. 1

DEMONSTRATION OF LOW CAPITAL TECHNOLOGIES TO REDUCE DIESEL BUS ENGINE EMISSIONS

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February 1994
JHR 94-223 Project 90-7

This research was sponsored by the Joint Highway Research Advisory Council (JHRAC) of the University of Connecticut and the Connecticut Department of Transportation and was carried out in the Civil Engineering Department of the University of Connecticut.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
JHR 94-223		

4. Title and Subtitle

Demonstration of Low Capital Technologies to Reduce Diesel Bus Engine Emissions

5. Report Date

February 1994

6. Performing Organization Code

7. Author(s)

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8. Performing Organization Report No.

JHR 94-223

9. Performing Organization Name and Address

University of Connecticut
Department of Civil Engineering
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10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

Connecticut Department of Transportation
280 West Street
Rocky Hill, CT 06067-0207

13. Type of Report and Period Covered

Interim Report No. 1

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report summarizes the measurement methods and preliminary findings on the data gathered from December 1992 through April 1993 for five test buses to assess the viability of various engine and exhaust system modifications. The prototype vehicle is an MCI L'Autobus 1992 model with a Detroit Diesel Series 92, two-stroke, scavenging type engine. Four other vehicles were modified with ceramic coating of the piston heads, crowns, and valves, or particulate traps in the exhaust streams, or a combination. One vehicle is ceramic coated, trapped, and uses an impregnated catalyst. Since the engine is a scavenging type, excess air mixes with products of combustion. Therefore, the data is converted from part per million to the engine specific grams per brake horsepower-hour. Particulates are indirectly measured through an opacity meter that measures the amount of light passed through the exhaust stream (0% = clear, 100% = blocked). Preliminary results show that properly maintained traps are effective in reducing opacity; however, they show a noticeable reduction in fuel economy. The traps also proved to be costly to maintain and showed no effect on opacity when in need of maintenance. Emission data exhibits no systematically noticeable trends other than NO_x being slightly higher and UHC/CO being slightly lower in ceramic coated engines. It is suspected to be attributed to the insulating effect of the coating, causing higher combustion temperatures. Due to the limited sample size of each type, namely one, statistically meaningful data cannot be gathered. Consequently data may be flawed by the random nature of the testing. The recommendation for future testing is to remove the traps and to add another baseline bus to give three base buses and three ceramic coated. This will improve the statistical significance of the data.

17. Key Words	18. Distribution Statement
Bus, Diesel, Emissions, Ceramic Coating, Catalytic Coating, Soot, Traps	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	48	

Form DOT F 1700.7 (8-72)

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

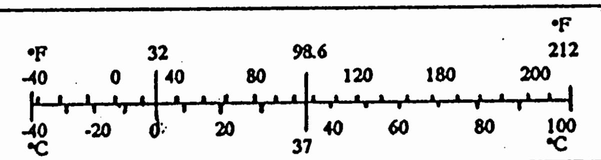
NOTE: Volumes greator than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

*SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



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I. Introduction

The genesis of this project was around the end of 1990 when the Connecticut Department of Transportation (through Mr. T. Kirker) approached the University of Connecticut through JHRAC to monitor and assess the benefits of several low cost modifications of diesel engines that would be used in buses operated by Connecticut Transit in the Hartford area. Accordingly, a proposal prepared by Professors E.K. Dabora and B.M. Cetegen in November 1990 was submitted to ConnDOT outlining the role of UConn in the project.

Because of delays in funding, UConn did not get officially involved in the project until December 1991. In the meantime, UConn was periodically in contact with CT Transit in an advisory capacity for the instrumentation needed to conduct the testing. Accordingly, a major instrument was purchased by CT Transit, namely the Nicolet Rega 7000 Analyzer that is used for pollutant measurements.

Specifically the modified bus engines that are to be assessed are listed below:

AT9253	Standard Engine
AT9254	Ceramic Coating - FCS, Seaworthy Systems
AT9255	Ceramic Coating + Donaldson's Particulate Trap
AT9256	Ceramic Coating impregnated with catalyst + Particulate Trap
AT9257	Trap Only

Again, through many delays, these buses were not received by CT Transit until July-August 1992 and finally were put in service in November of 1992.

This report gives an account of the measurement techniques and some **preliminary** measurement results that have been acquired since the buses went into operation. It should be indicated that refinements in the measurement technique were continuously made in order to obtain as accurate data as possible. At times our measurements have been hampered by procurement delays as well as the recent breakdown of the Nicolet analyzer.

II. Measurement Procedures

Opacity Measurements:

Opacity measurements are made using an optical smoke opacity meter. The opacity meter used for this study is a "Wager" model P-6IL. The principle of operation is to pass the exhaust gas stream in a duct between a light source and a photo detector unit. Attenuation of the light by the smoky gas is then related to the smoke density and measured as percent opacity on the analog meter. The unit consists of a light unit, a receiving unit, a control unit, calibrating devices, and a readout unit. The unit is also equipped with an air purge system. The readout unit has two scales (0-100% and 0-20% scales). For the opacity tests, the buses are placed on the chassis dynamometer, chained for safety, and connected to the smoke sampling system. The sampling system has a pipe directly connected to the engine exhaust. This pipe is pressure fit to a flexible pipe and inserted into the entrance cone of the opacity device. Since the opacity system inlet is larger than the exhaust pipe, the gap is sealed with a blanket of insulation material to prevent any leakage of air into the exhaust stream to be measured.

Initial testing procedures were planned to simulate the EPA test cycles described in the National Code of Federal Regulations (CFR-40) which consists of an acceleration mode and a lugging mode. Since the engines operate at idle approximately 50% of engine hours, opacity at idle was also important. See "Test Plan for CT Transit/UCONN Alternate Engine Technologies Study" in Appendix A. After the initial opacity runs, it was concluded that opacity at a steady state RPM is negligible. Therefore, opacity measurements at idle were discarded from the test plan. The lugging mode requires the engine to be loaded as RPM decreases from maximum to idle. The chassis dynamometer at CT Transit is neither programmable nor can it be set up for transient test cycles as might be required for EPA test cycles. We attempted to load the engine to 100% at full throttle and unload as a driver decreased throttle position. There was no consistency in the performance of this test due to human error. In addition, the opacity was found to be much greater for the acceleration test. For these two reasons, the lugging mode test was dropped from the plans and opacity testing was performed in acceleration mode only.

The same repeatability problem was exhibited in the acceleration test, since the driver was accelerating from idle to full throttle using the foot pedal, thus introducing a human error to the test. This problem was alleviated using existing engine computer control interface on the test buses (computer interface is further elaborated on in the section of "Road Data Measurements"). The computer software developed for this project by "Specialty Electronics" was modified to linearly increase RPM over a desired period between two desired engine speeds. Starting from 3/3/93, data were obtained using the computer to accurately accelerate the buses. To simulate load, the buses are put in gear for the acceleration tests. It was found that smoking was negligible at low engine loads (not in gear) during the acceleration tests. Initial acceleration tests were carried out in five second acceleration of the engine from idle to the maximum RPM with bus rear wheels turning on the chassis dynamometer.

Recently, a 10-second acceleration test was included.

The data retrieval method was initially to record data every second on the data acquisition system at CT Transit. This is the smallest time increment possible with the data acquisition system presently in place. Opacity data was plotted versus time over approximately 12 seconds; the five second test period and a 6-7 second purge period that showed sizable opacity readings. A detailed look at the opacity profile during this period showed that the one-second printing interval can miss the features of the actual profile. For this reason, the opacity meter output was recorded on a strip chart recorder to capture the whole opacity profile.

A chart recorder from UConn was installed and all data after 4/30/93 reflects that taken using the chart recorder. The area under the opacity versus time plots were calculated by numerical integration and they represent the total smoke yield during the acceleration period. The opacity test results are discussed later in this report.

Gaseous Emissions Measurements:

Gaseous emissions were measured using the "Nicolet" Rega 7000 system. The principle of operation is based FTIR (Fourier Transform Infrared Spectroscopy) spectrometer to detect gaseous species. This system consists of an optical bench, sampling system, and data analyzing computer. Analysis of the data received is performed by the REGA software package. The method for quantitative analysis of composition of mixtures is based on three principles. The first is that the components should absorb light in the frequencies measurable by the spectrometer. The elemental species do not obey this statement, and that is the reason elemental species such as oxygen (O_2) must be measured separately. The second principle is that the components in a mixture should absorb light at different wavelengths, which the products of combustion do in most part. The third principle is that for a given path length, the amount of light absorbed by each species increased with concentration, which is the method of measurement. The exhaust gas is introduced into the bench from a bag sample and data is collected for 64 seconds. The 64 data points are then statistically manipulated by the computer and displayed as the average concentrations and associated error readings (see Appendix B for sample output sheet).

The buses are placed on the chassis dynamometer, chained for safety, and bag samples are taken at the three steady state points. The sampling system has a pipe directly connected to the exhaust with a permanent sampling port close to bus exhaust port as shown in Figure 1. A 3/8" copper tube connects the sampling port, first to a condenser to remove the moisture in the exhaust, then to a carbon filter to remove soot, then to the suction side of the pump, and finally into an EPA approved mylar sampling bag. The sample bags were thoroughly evacuated (first evacuated then flushed with nitrogen then re-evacuated) before testing. The bags were then moved to the control room and connected to the analyzer. The initial tests were performed without the condenser, which arrived at CT Transit in late January 1993. Nicolet recommends the use of a condenser since excess water vapor creates interference for the spectrometric measurement. An oxygen meter was also added to the test procedures in late January 1993. It was found that excess oxygen was leaking into the sampling system since most of the devices are on the suction side of the pump. Quick connect fittings that are designed for positive pressure piping were discarded, and the whole new sampling train was reworked in February 1993 with leak-proof fittings. This showed a reduction of approximately 1-3% oxygen.

Testing procedure was to take three bag samples: one at idle (no load), one at cruise RPM with approximately 50% load applied, and one at maximum RPM with 100% load applied. Testing procedures can be found in Appendix A. The species of interest are: carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), and hydrocarbons (HC). The analyzer was set up for a method to look for the aforementioned species and water (H_2O), carbon dioxide (CO_2), and nitrous oxide (N_2O). The nitrous oxide was found to be negligibly small. It is known that the two cycle 92 series Detroit-Diesel engines are of scavenging type, meaning that an air blower facilitates the removal of combustion products from the cylinder. The amount of oxygen in the exhaust stream is thus much higher than that in four-stroke engines. Because of this dilution effect, it was decided to analyze emission data on the basis of grams per brake horsepower hours. The equation used for this purpose is derived from a carbon balance (i.e., all carbon in the fuel appears as CO and CO_2 in the exhaust stream. Fraction of carbon as soot is negligible.) This equation can be written as:

$$GPBHP = \frac{m_f \ (m_c/m_f) \ (X_{sp})X_{CO+CO2}) \ M_{sp}}{M_c W}$$

where: GPBHP = grams per brake horsepower hour of the species of interest;

m_f = fuel of mass flow rate (gms/hr);

m_c/m_f = mass of carbon per unit mass of fuel taken as 0.874 for diesel fuel;

X_{sp}/X_{CO+CO2} = mole fraction of species of interest per mole fraction of CO + CO_2;

M_{sp} = molecular weight of species of interest;

W = brake horsepower

M_c = atomic weight of carbon

The emission data were collected on a biweekly schedule and input into a computer program to convert the measured concentrations to GPBHP [see copy of spreadsheet for emission data in Appendix C]. The data were then plotted as a bar chart for each test period. The averages of all data were also determined over time for this report. The torque value was obtained from an engine performance curve no. E4-8067-32-130 from Detroit Diesel, the engine manufacturer. The torque was then converted to BHP with the standard equations for shaft motion.

Road Data Measurements:

Road data were gathered using lap-top computers system installed on all five test buses directly behind the driver. A special housing was made for the computers, isolating them from vibration and allowing for ventilation. The housing is mounted on the driver's side of the panel behind the driver; ventilation holes are located to limit water damage. The software was developed by "Specialty Electronics" for the DDEC engine and modified for this project. Hardware consisted of an 80286-processor lap-top computer interfaced to the DDEC by a special cable. The software allows for detailed configuration of data acquisition parameters, time intervals for data acquisition, and trip files. The program was configured to obtain the following data: road speed (MHP), percent accelerator pedal position (TPS), percent engine load (LOAD), fuel consumption rate (GPS), engine speed (RPM), engine coolant temperature (ETS), and instantaneous fuel economy (MPG). Engine data originally were collected at a frequency of 1 Hz. But due to disk space limitations and the purposes for which the data were to be used, the frequency was decreased to 0.033 Hz. Road trip data were stored every time the bus engines were switched off. Trip data were acquired and averaged monthly to monitor fuel economy trends and total engine miles and hours. Road data are presently available on floppy disks.

III. Preliminary Test Results

The test results reported in this section cover the test period from 12/92 to 4/93. These results are preliminary in nature and therefore should not be used to deduce definite conclusions yet (see Recommendations). In the following, the test results are presented in the following order: Opacity measurements, Gaseous Emission Measurements and Fuel Economy. In order to facilitate comparisons later on, the following are the modifications on each test bus:

Bus No. AT9253:	Baseline Unit
Bus No. AT9254:	Ceramic coated engine parts (cylinder head, piston crown and valve stems)
Bus No. AT9255:	Ceramic coated engine parts and particulate trap
Bus No. AT9256:	Ceramic coated engine parts impregnated with catalyst and particulate trap
Bus No. AT9257:	Particulate Trap only

Opacity Test Results:

Figure 2 shows the typical opacity profile during a five-second acceleration test for the baseline bus (AT9253) and the ceramic coated bus (AT9254) from a recent test. In these tests, although the acceleration period of the engine was five seconds, the opacity measurements are obtained until smoke clears out of the long exhaust pipe leading to the opacity detector (see Figure 1). These measurements are interpreted in two ways. The first is the maximum peak opacity during the test period, shown in Figure 2 as O_{max}. These maximum readings are summarized in Figure 3 for all the test periods from 12/92 to 3/93. Three bars for each bus represent the minimum, average and maximum values of the peak opacity readings during this time. The average is the simple arithmetic average of all peak opacities from different test periods. The average peak opacity readings indicate that the ceramic coated bus has a higher opacity than the baseline bus. The two buses equipped with particulate traps (AT9255 and AT9256) show lower opacities. The AT9257 unit has the highest opacity, which is indicative of problems with the soot trap. In fact, this bus has shown a dramatic increase in opacity in recent tests. In earlier tests, the opacity of this bus was at comparable values to other trap buses as shown in Figure 4. However, the ceramic coated bus (AT9254) appears to be higher than all other units including the baseline bus.

The test procedures were reviewed to make sure that the results were not influenced by the test procedures. Several improvements to the opacity tests were made as discussed in the previous section. In recent tests, the whole opacity profiles were integrated as shown in Figure 2. The integrated opacity readings are shown in Figure 5 for the 5/4/93 test of all buses. In this one test, the integrated opacity of the ceramic coated bus appears to be slightly lower than that of the baseline bus. However, it should be remembered that there will be statistical variations from one test to another, and continuing tests will build up these long time averages. This interpretation of the data from a very limited sample of buses (namely one of each) is also flawed in the sense that a statistically meaningful comparison cannot be obtained. When these results were obtained, we presented our findings to Seaworthy Systems (Matthew Winkler and Maxwell Warren) in a meeting at UConn. At this meeting, there was some concern that the poor fuel injector performance may be the cause of this behavior (before the tests started, this unit apparently had a faulty injector). Subsequently, the fuel injectors of this bus were checked and no problems were detected with the fuel injection system. At the time of this report writing, there appears no other reason for the high opacity observed in the ceramic coated bus. The high opacity from one of the trap buses (AT9257) is related to the faulty operation of the trap and CT Transit has been notified of this problem.

Gaseous Emission Results:

While the main concern currently in Diesel engines is the minimization or elimination of soot, other pollutants are of importance in view of the amended clean air act which places restrictions on NO_x, CO and unburned hydrocarbons (UHC). As a reference, Table I shows the standards for the 1993 engines.

Table I

1993 Federal Heavy-duty Urban Bus Engine Emission Standards

NO_x	5.0(*)
UHC	1.3
CO	15.5

(*) grams per brake horsepower hour

Figure 6 shows the average NO_x data for the period of 12/1/92 - 3/5/93. The test results at three different engine speeds are shown for each of the five engines. The baseline engine appears to produce the least NO_x emission according to these data. The ceramic coated engine (AT9254) shows a rather large increase in the NO_x levels. While this is suspected due to the higher combustion temperatures as a result of the insulating effect of the ceramic coating, the magnitude of this increase is somewhat surprising. This may be related to the abnormality of this engine as pointed out earlier. On the average, all other engines are within or slightly above the standards.

Figure 7 shows the hydrocarbon emissions. The ceramic coated engine (AT9254) appears to be the lowest in UHC emissions. This trend is consistent with NO_x trend in that higher temperature combustion will result in lower UHC emissions while producing higher levels of NO_x. Another surprising result is the emissions from the bus AT9255 bus. In terms of all emissions except soot (or opacity) it should give the same results as Bus AT9254. Yet, it shows higher UHC emissions. While this anomaly cannot be explained at present, it can be seen that the level of UHC emission is within the standards. This observation applies also to the CO emissions shown in Figure 8.

Overall Fuel Economy Results

The fuel economy in miles per gallon of fuel (MPG) was obtained from onboard computer data that are available from all five test buses. In addition, CT Transit monitors the fuel consumption in their whole fleet with additional breakdown on the AT project buses. Figure 9 shows the fuel economy for the test buses. The baseline (AT9253) and ceramic coated buses (AT9254) have higher values of MPG than the other three buses that have particulate traps. The main reason for this behavior is that the idle speed for trap buses is higher than the other two (700 rpm versus 600 rpm). Considering these buses in regular service spend between 55 to 59% of their operation at idle (see Table 2), it is expected that trap buses have a lower fuel economy. However, this is an artifact rather than the desired on-road fuel economy. Comparison of the baseline bus to the ceramic coated bus shows a slow improvement of fuel economy with time for the baseline bus. In contrast, a slow deterioration of the fuel economy is observed for the ceramic coated bus. Figure 10 shows the CT Transit data for a fleet of 22 buses in addition to the test buses. The variations in fuel economy appear to be similar in the overlapping time period between January 1993 and April 1993. The lower fuel economy of the trap buses is also observed in these data.

IV. Recommendations for Future Testing

The test buses will continue to be evaluated at biweekly intervals to obtain long time averaged data. However, due to limited sample size, statistically meaningful test results will be difficult to obtain. Namely, it would be desirable, for example, to have at least three baseline buses and three buses with the same modifications as the other four buses. This would enable us to get number averages in addition to the time averages on one bus. The disadvantage of having only one test bus is that the results will be directly affected by operational abnormalities of the test bus which we may be observing in the reported tests. It is also realized that the additional expense is an issue. This matter will be discussed with CT Transit and ConnDOT.

V. Appendices

A. Test Plan
B. Sample Nicolet Instrument Data Output
C. Gas Emission Test Data
D. Test Results Added for the period through August 1993, when this report was revised.

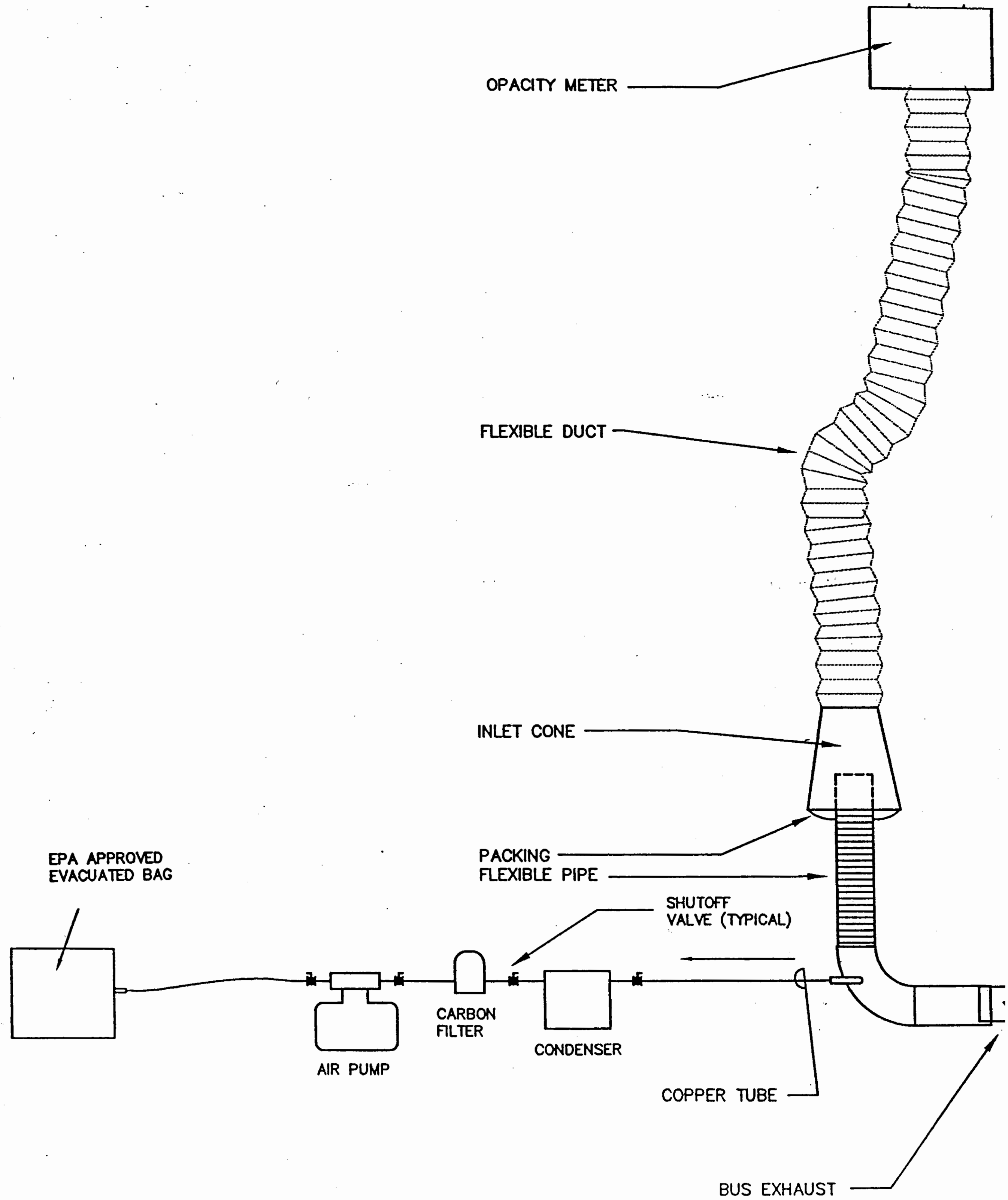
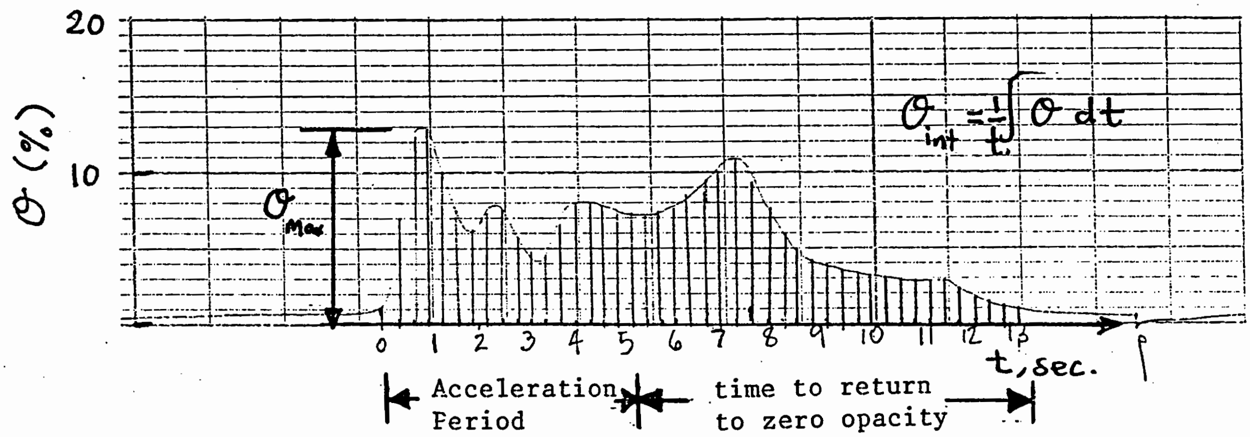


Figure 1. Bus exhaust emission sampling system

BASELINE BUS (9253AT)



CERAMIC COATED BUS (9254AT)

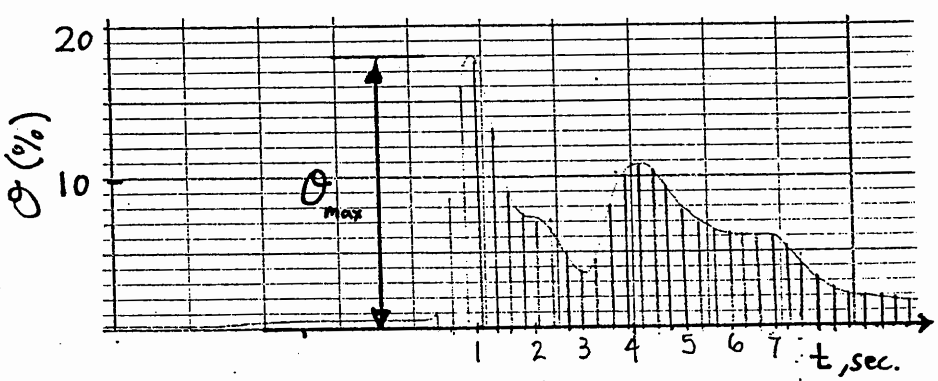


Figure 2. Bus exhaust opacity as a function of time during 5 sec acceleration test for baseline and ceramic coated busses

Average Maximum Opacity, 12/1/92 - 3/5/93

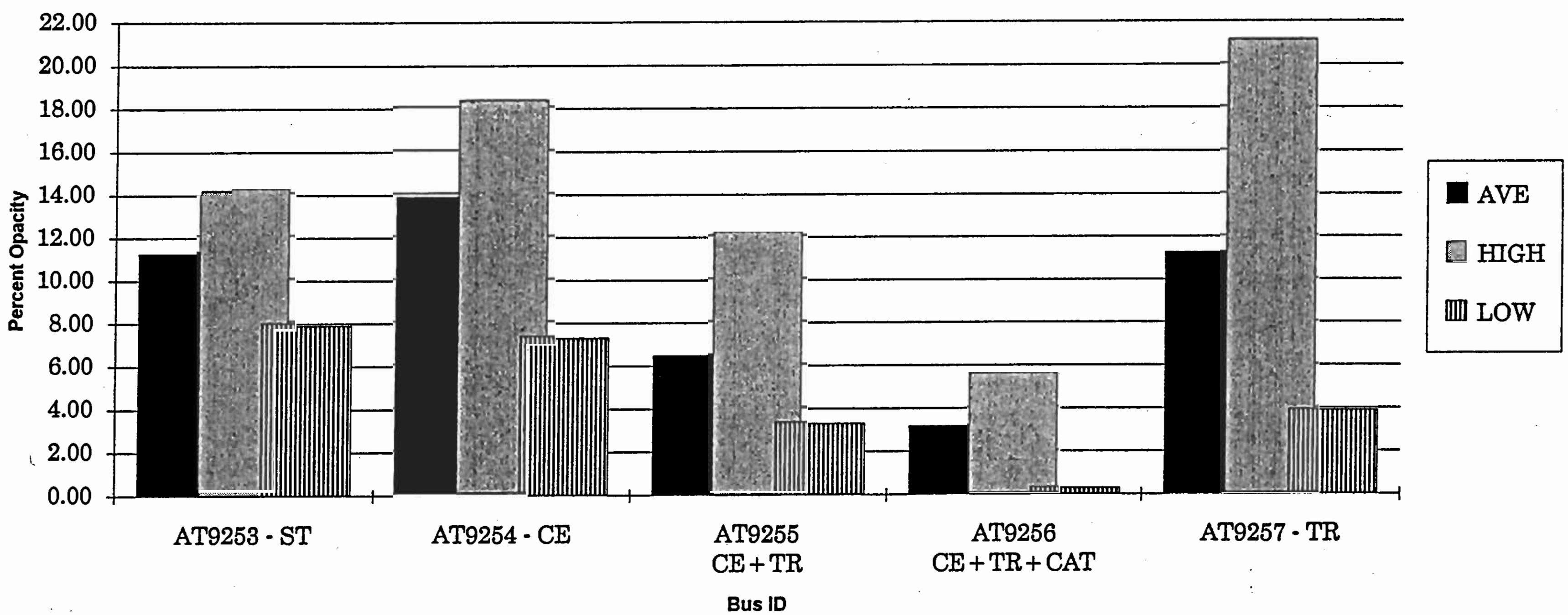


Figure 3. The peak opacity values for the test buses during the whole test period. High = highest peak value, AVE = average of all tests, LOW = lowest peak value. ST - Standard, CE - Ceramic,

Opacity Peak Values - Acceleration Test (Period Ending 2-5)

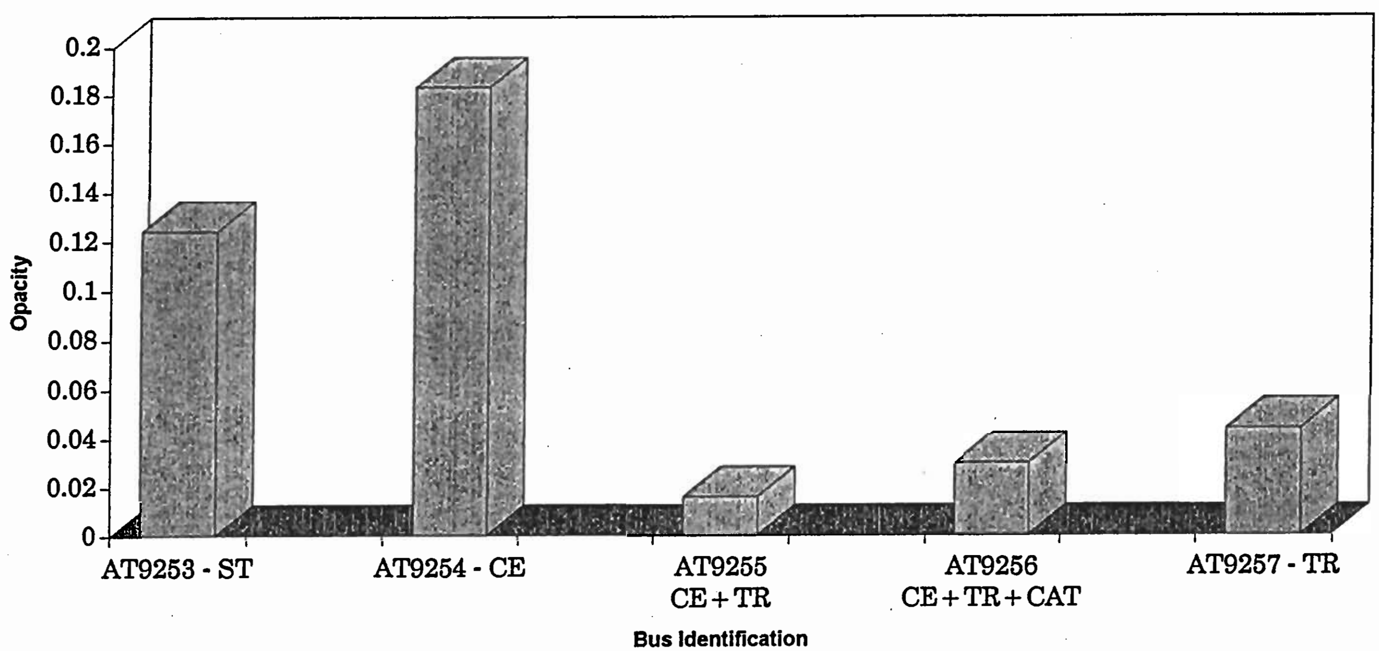


Figure 4. Peak opacity values in test periods before 2/5/93.
ST - Standard, CE - Ceramic, TR - Trap, CAT - Catalyst

Integrated Average Opacity, 5/4/93 Test

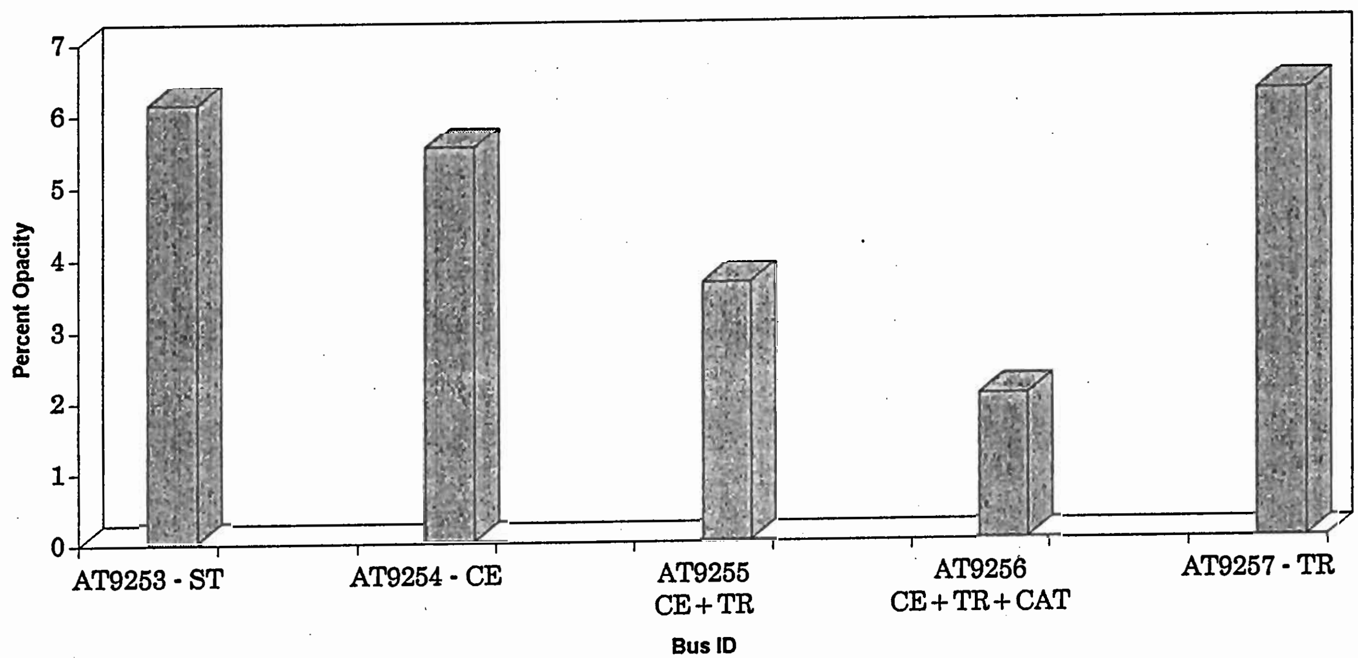


Figure 5. Total opacity yield (time integral of opacity) during 5 second acceleration test for the test on 5/4/93. ST - Standard, CE - Ceramic,

Average Oxides of Nitrogen (NOx), 12/1/92 - 3/5/93

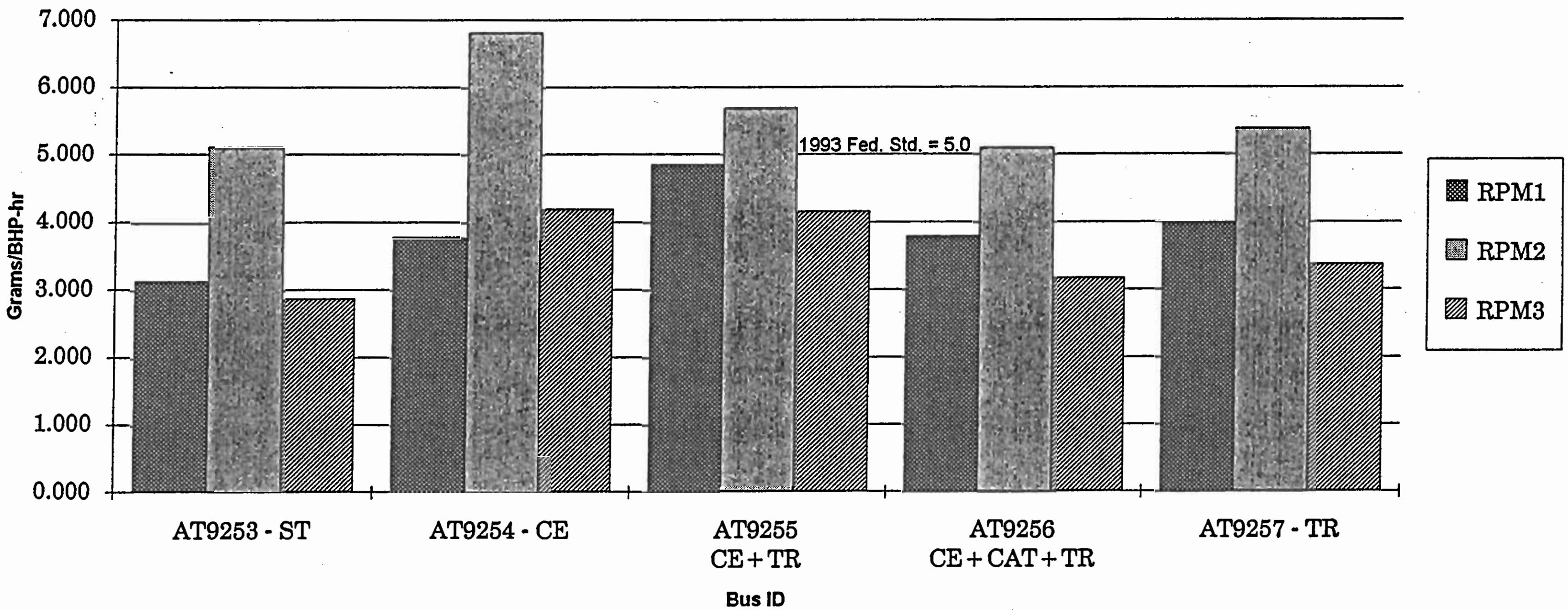


Figure 6. Emission of NOx for test buses averaged over the whole test period. ST - Standard, CE - Ceramic, TR - Trap, CAT - Catalyst

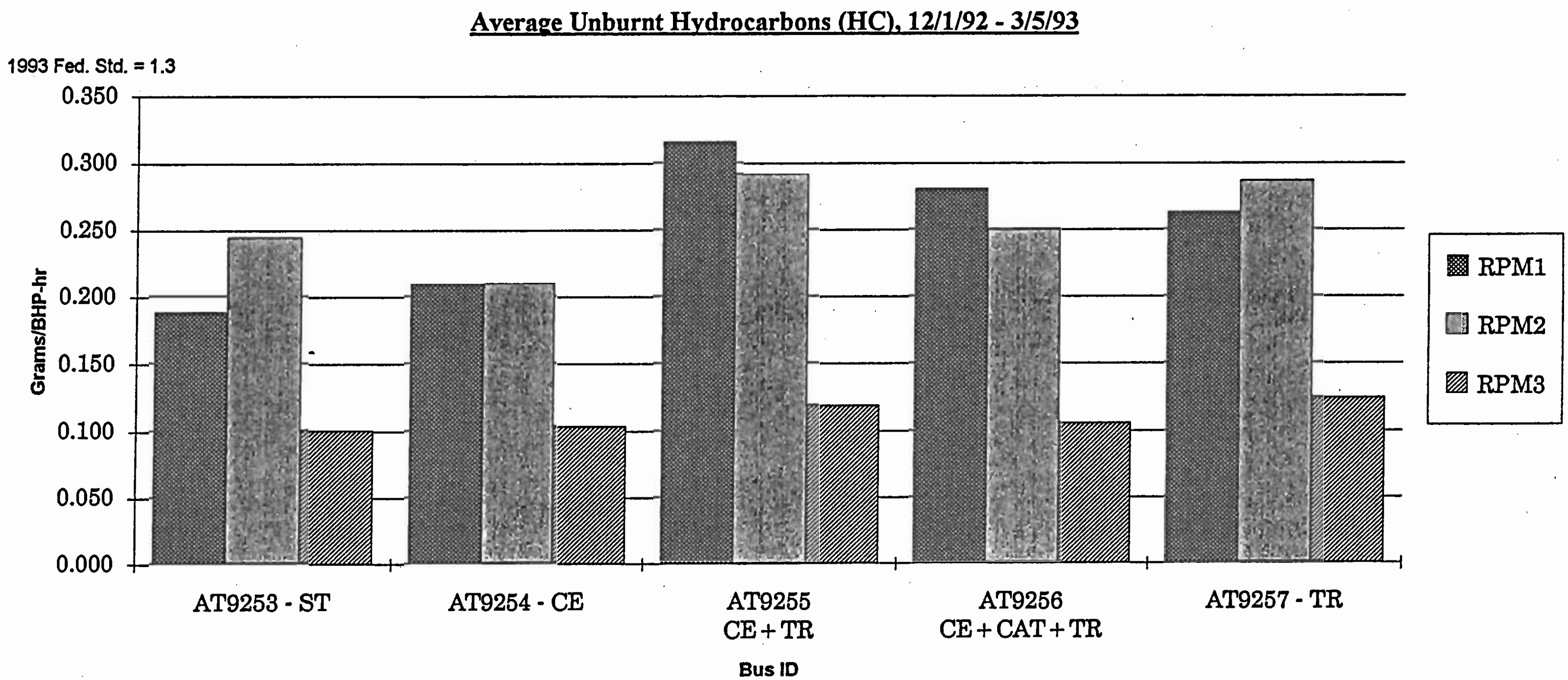


Figure 7. Emission of unburnt hydrocarbons for the test buses over

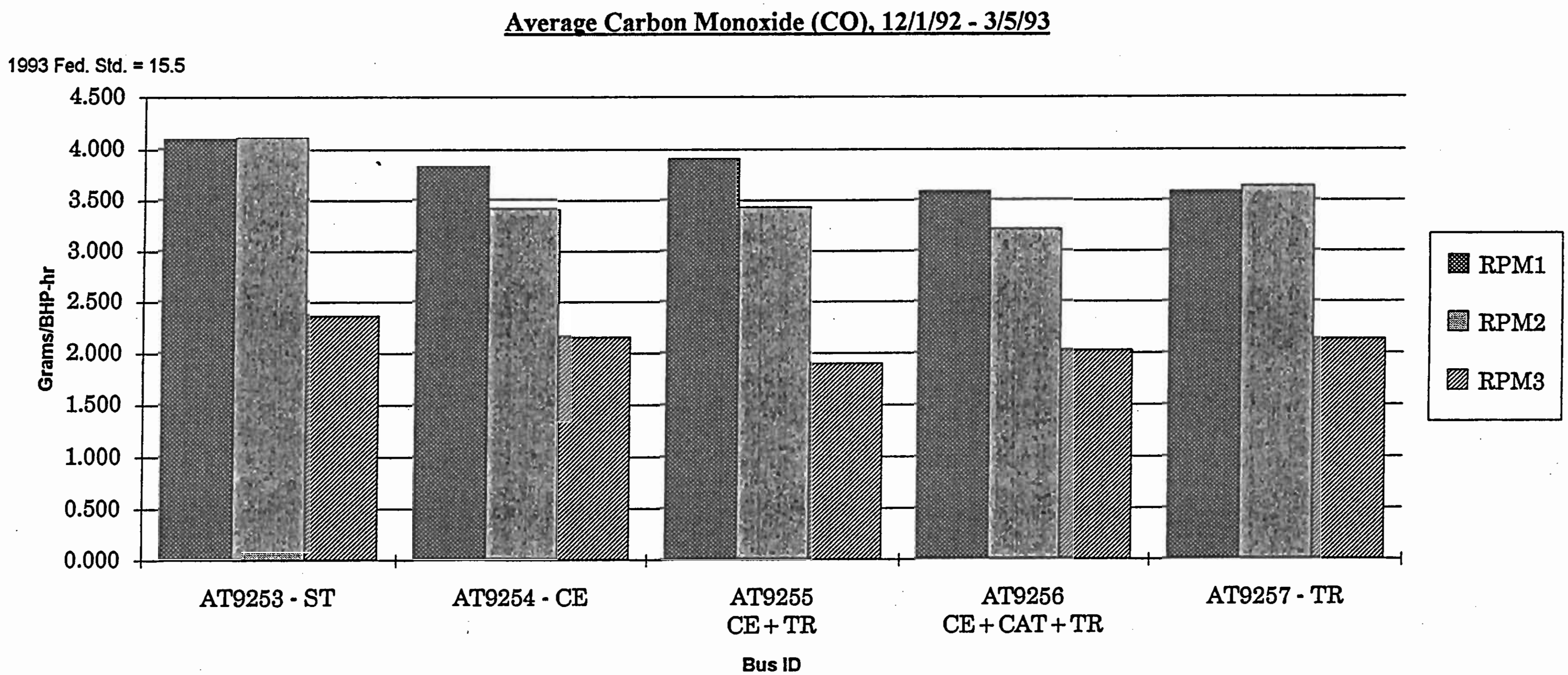


Figure 8. Emission of carbon monoxide for the test buses averaged over the whole test period. ST - Standard, CE - Ceramic, TR - Trap, CAT - Catalyst

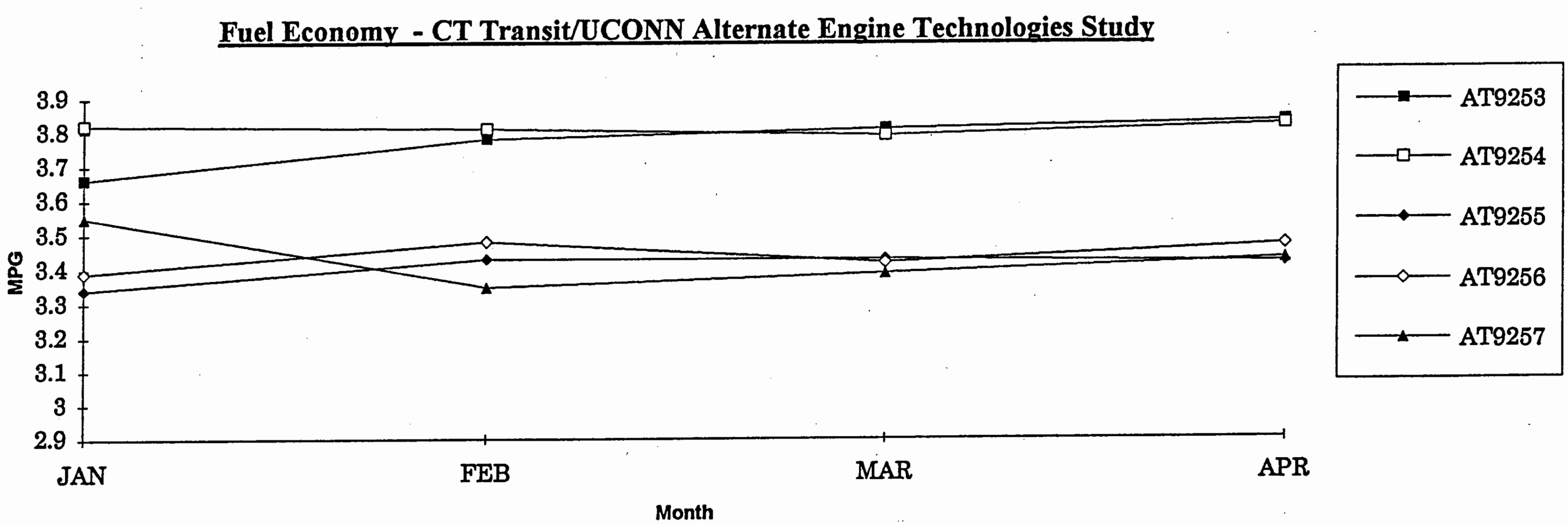


Figure 9. Fuel economy as a function of time for the test buses.
AT53 - Standard, AT54 - Ceramic, AT55 - Ceramic and Trap,

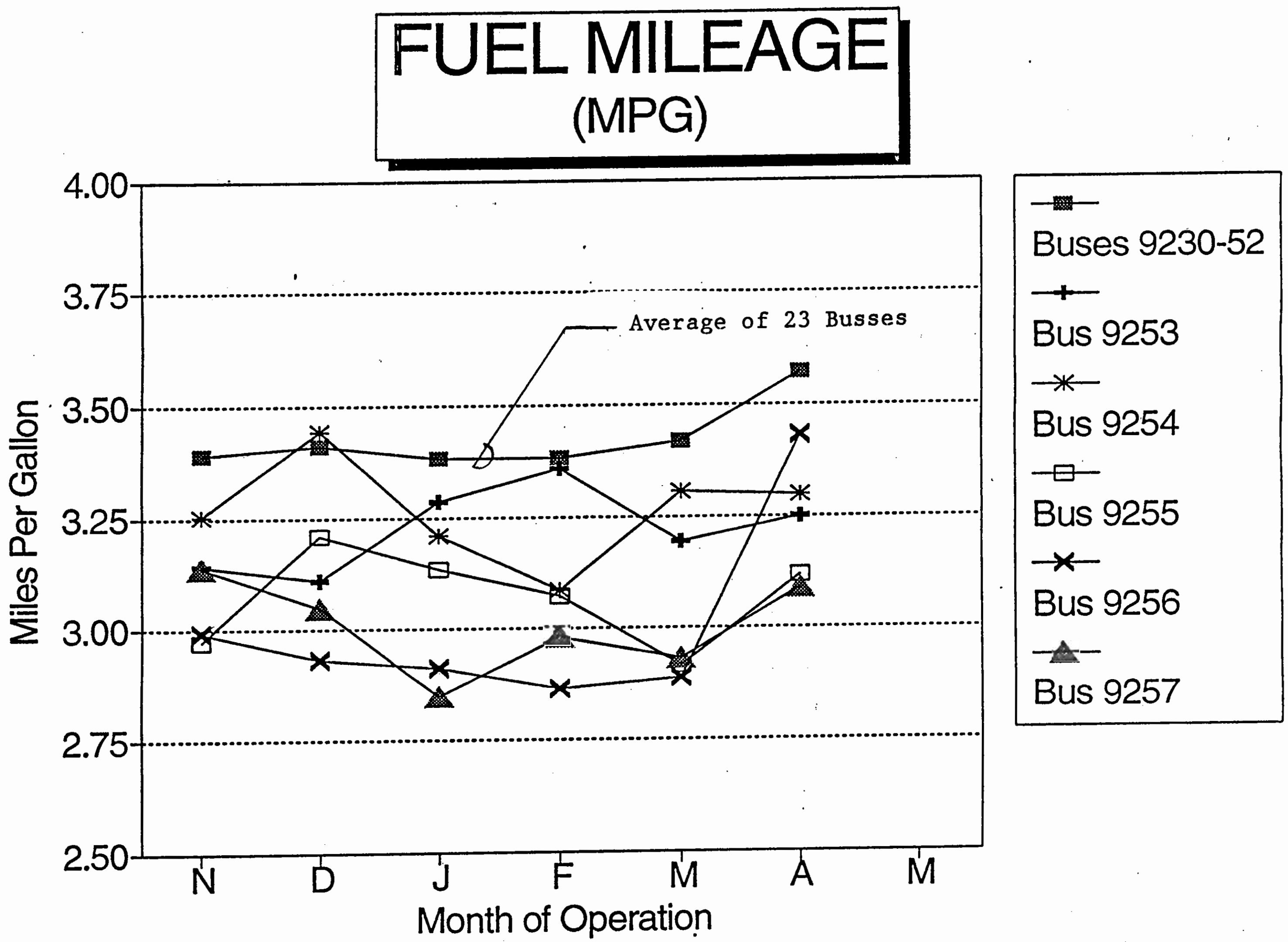


Figure 10. Connecticut Transit Fuel Mileage data for a fleet of buses and the test program buses

Table II

CT TRANSIT/UCONN ALTERNATE ENGINE TECHNOLOGY STUDY

DATA COMPARISON - 2/5/93 vs. 1/22/93

Date: 2/10/93

File:COMP2-10.XLS

RPM 1 = 600, 700 (AT55,56,57)
RPM 2 = 1075, 1175(AT55,56,57)
RPM 3 = 2150

Bus I.D.		AT9253 - ST		AT9254 - CE		AT9255 CE+TR		AT9256 CE+TR+C		AT9257 - TR	
Date		1/22/93	2/5/93	1/22/93	2/5/93	1/22/93	2/5/93	1/22/93	2/5/93	1/22/93	2/5/93
% Idle		57.02		55.69		57.62		58.92		56.76	
Ave. MPG		3.66		3.82		3.34		3.39		3.55	
Mileage		5449		6676		5914	7850	5994		7423	8479
HC(ppm)	RPM 1	6.74	4.48	6.13	5.47	8.55	5.90	9.70	5.68	5.15	6.84
	RPM 2	5.07	4.43	5.76	5.80	8.04	5.82	6.67	7.32	6.83	6.62
	RPM 3	3.43	2.55	3.91	4.17	5.52	4.16	3.81	4.80	4.80	4.93
NOx(ppm)	RPM 1	181.40	143.81	192.55	207.12	207.78	230.18	160.17	180.35	177.89	218.37
	RPM 2	216.14	200.64'	271.93	293.61	264.70	287.99	231.13	273.19	227.53	252.86
	RPM 3	211.93	214.75	299.30	314.39	338.75	325.45	164.59	327.47	190.17	343.85
CO(ppm)	RPM 1	325.42	328.33	275.55	253.65	258.37	268.00	263.91	257.80	272.42	265.44
	RPM 2	250.56	248.31	251.95	249.01	252.76	248.17	247.75	254.46	251.79	254.51
	RPM 3	241.68	238.24	240.06	239.66	243.15	242.64	248.33	242.52	258.98	245.63

Maximum Opacity (%) Observed

Acceleration Mode II	3.2% - 12.4%	16.9% - 18.3%	8.20% - 1.6%	5.60% - 0.30%	5.9% - 4.4%
Lugging Mode	0.20% - 2.7%	0.10% - 0.3%	0.00% - 0.00%	0.30% - 0.30%	0.20% - 0.00%
	0.124	0.183	0.016	0.03	0.044

Trap Hours per Regeneration

Trap 1	N/A	N/A	5.04 - 5.03	3.03 - 3.17	7.44 - 7.21
Trap 2	N/A	N/A	3.65 - 3.53	3.28 - 3.38	5.85 - 5.98

TEST PLAN FOR CT TRANSIT/UCONN ALTERNATE ENGINE TECHNOLOGIES STUDY

Test Buses

Bus	I.D. No.	Ceramic coated	Particulate trap	Catalyst
Bus I	9253AT	No	No	No
Bus II	9254AT	Yes	No	No
Bus III	9255AT	Yes	Yes	No
Bus IV	9256AT	Yes	Yes	Yes
Bus V	9257AT	No	Yes	No

I. Measurements

A. Exhaust Gas Emissions
   1. Water (H_2O)
   2. Carbon Monoxide (CO)
   3. Carbon Dioxide (CO_2)
   4. Nitric Oxide (NO)
   5. Nitrogen Dioxide (NO_2)
   6. Hydrocarbons (HC)

B. Opacity Measurements (0-100%)

C. Particulate Trap Regeneration Data

D. Instruments to be used
   1. Emissions: 'Nicolet' Rega 7000 Fourier Transform Infrared Exhaust Analyzer
   2. Opacity: 'Wager' Model P-6 Smoke Opacity Meter.

II. Test Procedures

A. Emissions Test Points
   1. Idle" 600 RPM (700 RPM for Trap Bus), No load applied.
   2. Cruise: 1075 RPM @ 25% rated maximum Hp (40 bhp).
   3. Shift speed: 1780 RPM @ 99% rated maximum Hp (215 bhp).

B. Emission Test
   1. Extract samples from bus exhaust and fill evacuated EPA bags
   2. Analyze with 'Nicolet' Rega 7000, save to files and print results.

C. Opacity Test Points
   1. Idle: 600 RPM (700 RPM for trap buses), No load applied.
   2. Acceleration Mode
      a. Idle rpm to Idle rpm + 200 in 3 seconds. Opacity meter records and prints data at a frequency of 1 Hz minimum. **Note: This test was deleted. No significantly measurable values are obtained at this condition.**
      b. Idle rpm to 1780 Rpm in 5 seconds. Opacity meter records data at 1 Hz. Also, save data on strip chart recorder.

3. Lugging Mode: 1780 RPM @ 0 load down to Idle rpm (in 30 seconds) while gradually loading to maximum wheel hp. OM recor date at 1Hz. **Note: This test was deleted due to the limited ability to control the chassis dynamometer.**

D. Filter Regeneration: Record mileage, date and time of filter regeneration for trap buses.

E. Frequency: Test all 5 buses bi-weekly starting with the commencement of bus operation.

IV. Bus Data Acquisition

A. Hardware. 5 Lap top computers with 5 MB RAM and 30 MB hard dri to be located on the buses by CT Transit. No computer interface required by driver.

B. Software: "Specialty Electronic" DDR Data reader for Detroit Diesel DDEC II Engine control computer. Data files to be downloaded by UCONN as required.

C. Data To Be Recorded

1. Road Speed (MPH)
2. Percent Accelerator Pedal Position (TPS)
3. Percent Engine Load (LOAD)
4. Fuel Consumption Rate (GPS)
5. Engine Speed (RPM)
6. Engine Coolant Temperature (ETS)
7. Rated Horsepower (BHP)
8. Instantaneous Miles Per Gallon (MPG)

D. Frequency

1. Engine data: At a frequency of 10 Hz, save to computers ha drive.
2. Road data: At a frequency of 10 Hz, save to computers hard drive.

V. Quality Assurance Procedure

A. Calibrate 'Nicolet' Rega 700 weekly before and after testing with Carbon Monoxide test gas.

APPENDIX B

SAMPLE NICOLET INSTRUMENT DATA OUTPUT

```
GA 7000 version 0.8F
pyright (C) 1991 Nicolet Instrument Corporation

 Jan =

mperature (C) =  185.0
essure (Torr) =  650.0
thlength (cm) =  384.0

thod #  3 - RAW CELL/UCONN STUDY loaded
e LCI interface  740 type bench

58_0114_C
llect data for     1 files

ta collection started at  14:59:36
```

#	Name	Concentration		Error		
1	H2O	14138.29	+/-	1209.63	ppm	****
2	COHI	250.56	+/-	10.14	ppm	****
3	COLO	53.79	+/-	5.56	ppm	***
4	CO2	16772.77	+/-	586.48	ppm	****
5	NO	95.74	+/-	5.92	ppm	****
6	NO2	120.40	+/-	16.67	ppm	***
7	N2O	.00	+/-	1.05	ppm	
8	HCONT	5.07	+/-	.96	ppm	***

APPENDIX C

[illegible] GAS EMISSION TEST DATA

Emissions Calculations - CTransit/UCONN Alternate Engine Technologies Study

Testing Period: 12/1/92 - 1/1/93

By: W. Mark Gendron, UCONN

Bus ID	RPM	Fuel rate	Fuel rate	% max T	Torque	BHP	CO2	CO		NO		NO2		Total NOx	HC	
		gal/hr	lb/hr		ft-lbs	hp	PPM	PPM	GPBHP	PPM	GPBHP	PPM	GPBHP	GPBHP	PPM	GPBHP
AT9253	600	0.59	3.94	18	144.0	16.5	17664	410.89	5.046	76.06	1.001	73.53	1.806	2.807	5.48	0.197
	1075	1.67	11.16	22	189.2	38.7	17096	256.74	3.949	97.93	1.614	109.5	3.368	4.982	4.73	0.213
	2083	15.82	105.75	98	679.1	269.3	36793	245.38	2.408	100.59	1.058	57.67	1.132	2.190	3.56	0.102
AT9254	600	0.6	4.01	18	144.0	16.5	15656	270.47	3.833	76.62	1.164	73.31	2.078	3.242	5.32	0.221
	1075	1.44	9.63	22	189.2	38.7	18880	251.29	3.023	108.93	1.404	146.01	3.513	4.917	5.16	0.182
	2113	15.72	105.08	98	679.1	273.2	40052	248.44	2.195	92.53	0.876	61.21	1.082	1.958	3.81	0.099
AT9255	700	0.86	5.75	18	147.6	19.7	16800	259.11	4.109	61.88	1.052	109.89	3.486	4.537	6.76	0.314
	1175	1.76	11.76	22	193.6	43.3	17253	254.08	3.650	95.02	1.462	144.81	4.160	5.623	7.44	0.313
	2114	15.74	105.21	98	679.1	273.4	43981	246.09	1.983	169.3	1.462	154.23	2.485	3.947	4.69	0.111
AT9256	700	0.82	5.48	18	147.6	19.7	16102	259.73	4.095	78.6	1.328	77.02	2.429	3.757	6.18	0.285
	1170	1.69	11.30	22	193.6	43.1	17750	253.3	3.412	91.34	1.318	129.45	3.488	4.806	6.9	0.272
	2048	15.48	103.48	98	679.1	264.8	40691	253.81	2.243	101.58	0.962	60.5	1.069	2.031	5.4	0.140
AT9257	700	0.74	4.95	18	147.6	19.7	18388	277.22	3.458	104.01	1.390	94.79	2.365	3.755	8.04	0.294
	1175	1.80	12.03	22	193.6	43.3	19627	256.58	3.319	114.36	1.585	124.75	3.227	4.812	7.65	0.290
	2103	16.21	108.36	98	679.1	271.9	48093	254.28	1.940	152.84	1.250	75.4	1.151	2.400	6.92	0.155

Notes:
1. GPBHP - Grams per BrakeHorse Power hour
2. PPM - Parts Per Million
3. AT9253 - Base Diesel Engine, AT9254 - Ceramic coated, AT9255 - Ceramic coated w/trap
   AT9256 - Ceramic coated w/catalyst & trap, AT9257 - Base bus w/trap only

Emissions Calculations - CTransit/UCONN Alternate Engine Technologies Study
Testing Period: 1/1/93 - 1/22/93
By: W. Mark Gendron, UCONN

Bus ID	RPM	Fuel rate	Fuel rate	% max T	Torque	BHP	CO2	CO		NO		NO2		Total NOx	HC	
		gal/hr	lb/hr		ft-lbs	hp	PPM	PPM	GPBHP	PPM	GPBHP	PPM	GPBHP	GPBHP	PPM	GPBHP
AT9253	600	0.59	3.94	18	144.0	16.5	18593	325.42	3.818	94.91	1.193	86.46	2.029	3.222	6.74	0.232
	1075	1.67	11.16	22	189.2	38.7	16772	250.56	3.928	95.74	1.608	120.4	3.775	5.384	5.07	0.233
	2083	15.82	105.75	98	679.1	269.3	37530	241.68	2.326	109.24	1.126	102.69	1.976	3.103	3.43	0.097
AT9254	600	0.60	4.01	18	144.0	16.5	18774	275.55	3.265	89.43	1.135	103.12	2.444	3.579	6.13	0.213
	1075	1.44	9.63	22	189.2	38.7	18559	251.95	3.082	106.57	1.397	165.36	4.046	5.443	5.76	0.206
	2113	15.72	105.08	98	679.1	273.2	38260	240.06	2.220	131.94	1.307	167.36	3.096	4.403	3.91	0.106
AT9255	700	0.86	5.75	18	147.6	19.7	17621	258.37	3.910	86	1.394	121.78	3.686	5.080	8.55	0.379
	1175	1.76	11.76	22	193.6	43.3	18325	252.76	3.422	91.39	1.326	173.31	4.692	6.018	8.04	0.319
	2114	15.74	105.21	98	679.1	273.4	43829	243.15	1.966	146.84	1.272	191.91	3.103	4.376	5.52	0.131
AT9256	700	0.82	5.48	18	147.6	19.7	18378	263.91	3.652	79.12	1.173	81.05	2.243	3.416	9.7	0.393
	1170	1.69	11.30	22	193.6	43.1	18479	247.75	3.208	116.47	1.616	114.66	2.970	4.586	6.67	0.253
	2048	15.48	103.48	98	679.1	264.8	36616	248.33	2.437	111.59	1.173	53	1.040	2.214	3.81	0.109
AT9257	700	0.74	4.95	18	147.6	19.7	18560	272.42	3.368	63.55	0.842	114.34	2.827	3.669	5.15	0.186
	1175	1.80	12.03	22	193.6	43.3	17436	251.76	3.661	98.7	1.538	128.83	3.747	5.284	6.83	0.291
	2103	16.21	108.36	98	679.1	271.9	47094	258.98	2.018	113.54	0.948	76.63	1.194	2.142	4.8	0.110

Notes:
1. GPBHP - Grams per BrakeHorse Power hour
2. PPM - Parts Per Million
3. AT9253 - Base Diesel Engine, AT9254 - Ceramic coated, AT9255 - Ceramic coated w/trap
   AT9256 - Ceramic coated w/catalyst & trap, AT9257 - Base bus w/trap only

<u>Emissions Calculations - CTransit/UCONN Alternate Engine Technologies Study</u>

Testing Period: 1/22/93 - 2/5/93

By: W. Mark Gendron, UCONN

Bus ID	RPM	Fuel rate	Fuel rate	% max T	Torque	BHP	CO2	CO		NO		NO2		Total NOx	HC	
		gal/hr	lb/hr		ft-lbs	hp	PPM	PPM	GPBHP	PPM	GPBHP	PPM	GPBHP	GPBHP	PPM	GPBHP
AT53	600	0.59	3.94	18	144.0	16.5	14205	328.33	5.015	70.93	1.161	72.88	2.226	3.387	4.48	0.200
	1075	1.67	11.16	22	189.2	38.7	14782	248.31	4.409	90.39	1.720	110.25	3.915	5.635	4.43	0.230
	2083	15.82	105.75	98	679.1	269.3	35917	238.24	2.395	114.77	1.236	99.98	2.010	3.247	2.55	0.075
AT54	600	0.60	4.01	18	144.0	16.5	16346	253.65	3.449	117.25	1.708	89.87	2.444	4.152	5.47	0.218
	1075	1.44	9.63	22	189.2	38.7	16581	249.01	3.405	144.56	2.118	149.05	4.076	6.194	5.8	0.232
	2113	15.72	105.08	98	679.1	273.2	35941	239.66	2.359	179.25	1.890	135.14	2.660	4.550	4.17	0.120
AT55	700	0.86	5.75	18	147.6	19.7	20068	268	3.566	112.6	1.605	117.58	3.129	4.734	5.9	0.230
	1175	1.76	11.76	22	193.6	43.3	20505	248.17	3.007	124.55	1.617	163.44	3.961	5.578	5.82	0.207
	2114	15.74	105.21	98	679.1	273.4	44282	242.64	1.942	151.03	1.295	174.42	2.792	4.087	4.16	0.098
AT56	700	0.82	5.48	18	147.6	19.7	15559	257.8	4.205	75.34	1.317	105.01	3.425	4.742	5.68	0.271
	1170	1.69	11.30	22	193.6	43.1	19637	254.46	3.102	107.07	1.399	166.12	4.051	5.449	7.32	0.261
	2048	15.48	103.48	98	679.1	264.8	47112	242.52	1.853	135.98	1.113	191.49	2.926	4.039	4.8	0.107
AT57	700	0.74	4.95	18	147.6	19.7	16128	265.44	3.769	129.89	1.976	88.48	2.513	4.489	6.84	0.284
	1175	1.80	12.03	22	193.6	43.3	16447	254.51	3.919	135.35	2.233	117.51	3.619	5.853	6.62	0.299
	2103	16.21	108.36	98	679.1	271.9	41868	245.63	2.152	198.29	1.861	145.56	2.550	4.411	4.93	0.126

Notes:

1. GPBHP - Grams per BrakeHorse Power hour
2. PPM - Parts Per Million
3. AT9253 - Base Diesel Engine, AT9254 - Ceramic coated, AT9255 - Ceramic coated w/trap
   AT9256 - Ceramic coated w/catalyst & trap, AT9257 - Base bus w/trap only

Emissions Calculations - CTransit/UCONN Alternate Engine Technologies Study

Testing Period: 2/5/93 - 2/19/93

By: W. Mark Gendron, UCONN

Bus ID	RPM	O2	Fuel rate	Fuel rate	% max T	Torque	BHP	CO2	CO		NO		NO2		Total NOx	HC	
		%	gal/hr	lb/hr		ft-lbs	hp	PPM	PPM	GPBHP	PPM	GPBHP	PPM	GPBHP	GPBHP	PPM	GPBHP
AT9253	600	17.5	0.59	3.94	18	144.0	16.5	23908	264.41	2.428	119.56	1.176	103.94	1.909	3.085	6.17	0.166
	1075	18.7	1.67	11.16	22	189.2	38.7	14766	249.3	4.431	119.38	2.273	88.52	3.147	5.420	6.91	0.360
	2083	15.7	15.82	105.75	98	679.1	269.3	37670	243.71	2.337	177.26	1.821	58.03	1.113	2.934	4.6	0.129
AT9254	600	18.9	0.60	4.01	18	144.0	16.5	13669	255.52	4.142	99.37	1.726	68.74	2.229	3.954	4.6	0.218
	1075	18.8	1.44	9.63	22	189.2	38.7	15159	248.14	3.706	140.52	2.249	119.25	3.562	5.811	5.76	0.252
	2113	16.0	15.72	105.08	98	679.1	273.2	35462	238	2.374	171.39	1.832	129.18	2.577	4.408	3.82	0.112
AT9255	700	18.5	0.86	5.75	18	147.6	19.7	16196	257.04	4.227	113.98	2.008	95.88	3.153	5.162	7.43	0.358
	1175	18.4	1.76	11.76	22	193.6	43.3	16956	250.62	3.663	151.48	2.372	116.11	3.394	5.766	7.92	0.339
	2114	15.2	15.74	105.21	98	679.1	273.4	41350	242.22	2.075	265.39	2.436	97.33	1.668	4.104	5.97	0.150
AT9256	700	18.9	0.82	5.48	18	147.6	19.7	18806	249.07	3.372	81.71	1.185	102.25	2.769	3.954	5.74	0.228
	1170	18.0	1.69	11.30	22	193.6	43.1	19830	249.85	3.018	112.91	1.461	166.26	4.016	5.477	6.74	0.238
	2048	18.0	15.48	103.48	98	679.1	264.8	42565	243	2.054	134.3	1.216	156.7	2.649	3.865	3.84	0.095
AT9257	700	18.4	0.74	4.95	18	147.6	19.7	17027	261.91	3.527	116.15	1.676	83.74	2.255	3.931	6.05	0.239
	1175	18.2	1.80	12.03	22	193.6	43.3	17648	249.32	3.583	128.07	1.972	117.08	3.365	5.337	5.82	0.245
	2103	16.1	16.21	108.36	98	679.1	271.9	32736	238.88	2.673	152.87	1.832	108.3	2.423	4.256	4.1	0.134

Notes:

1. GPBHP - Grams per BrakeHorse Power hour
2. PPM - Parts Per Million
3. AT9253 - Base Diesel Engine, AT9254 - Ceramic coated, AT9255 - Ceramic coated w/trap
   AT9256 - Ceramic coated w/catalyst & trap, AT9257 - Base bus w/trap only

Emissions Calculations - CTransit/UCONN Alternate Engine Technologies Study
Testing Period: 2/19/93 - 3/5/93
By: W. Mark Gendron, UCONN

Bus ID	RPM	O2	Fuel rate	Fuel rate	% max T	Torque	BHP	CO2	CO		NO		NO2		Total NOx	HC	
		%	gal/hr	lb/hr		ft-lbs	hp	PPM	PPM	GPBHP	PPM	GPBHP	PPM	GPBHP	GPBHP	PPM	GPBHP
AT9253	600	18.1	0.59	3.94	18	144.0	16.5	17965	344.79	4.180	76.37	0.992	92.77	2.249	3.241	3.22	0.114
	1075	18.1	1.67	11.16	22	189.2	38.7	17702	258.62	3.843	91.15	1.451	91.13	2.708	4.159	4.2	0.183
	2083	14.1	15.82	105.75	98	679.1	269.3										
AT9254	600	19.2	0.60	4.01	18	144.0	16.5	12505	253.37	4.483	83.64	1.586	67.28	2.381	3.966	3.4	0.176
	1075	18.7	1.44	9.63	22	189.2	38.7	14663	248.73	3.839	107.77	1.782	132.84	4.100	5.882	3.95	0.179
	2113	13.2	15.72	105.08	98	679.1	273.2	52705	243.71	1.639	162.15	1.168	188.51	2.535	3.704	4.15	0.082
AT9255	700	18.2	0.86	5.75	18	147.6	19.7	18371	256.88	3.731	102.36	1.593	110.35	3.206	4.798	6.94	0.295
	1175	18.4	1.76	11.76	22	193.6	43.3	18011	249.19	3.432	132.15	1.950	128.1	3.528	5.478	6.93	0.280
	2114	13.3	15.74	105.21	98	679.1	273.4	56934	250.31	1.560	307.96	2.056	179.25	2.234	4.290	5.68	0.104
AT9256	700	17.6	0.82	5.48	18	147.6	19.7	24115	243.22	2.576	94.91	1.077	95.51	2.023	3.100	4.28	0.133
	1170	18.4	1.69	11.30	22	193.6	43.1	17617	244.84	3.324	98.13	1.428	139.43	3.786	5.214	5.65	0.225
	2048	16.8	15.48	103.48	98	679.1	264.8	57264	244.42	1.538	199.15	1.342	188.22	2.368	3.710	4.2	0.077
AT9257	700	18.7	0.74	4.95	18	147.6	19.7	15867	261.66	3.777	102.4	1.584	87.02	2.512	4.096	7.37	0.312
	1175	18.4	1.80	12.03	22	193.6	43.3	17342	252.51	3.691	127.36	1.995	124.61	3.643	5.638	7.25	0.310
	2103	14.4	16.21	108.36	98	679.1	271.9	47963	247.95	1.897	297.13	2.436	79.32	1.214	3.650	4.34	0.097

Notes:
1. GPBHP - Grams per BrakeHorse Power hour
2. PPM - Parts Per Million
3. AT9253 - Base Diesel Engine, AT9254 - Ceramic coated, AT9255 - Ceramic coated w/trap
   AT9256 - Ceramic coated w/catalyst & trap, AT9257 - Base bus w/trap only

APPENDIX D

Test Results Added for the period through August 1993

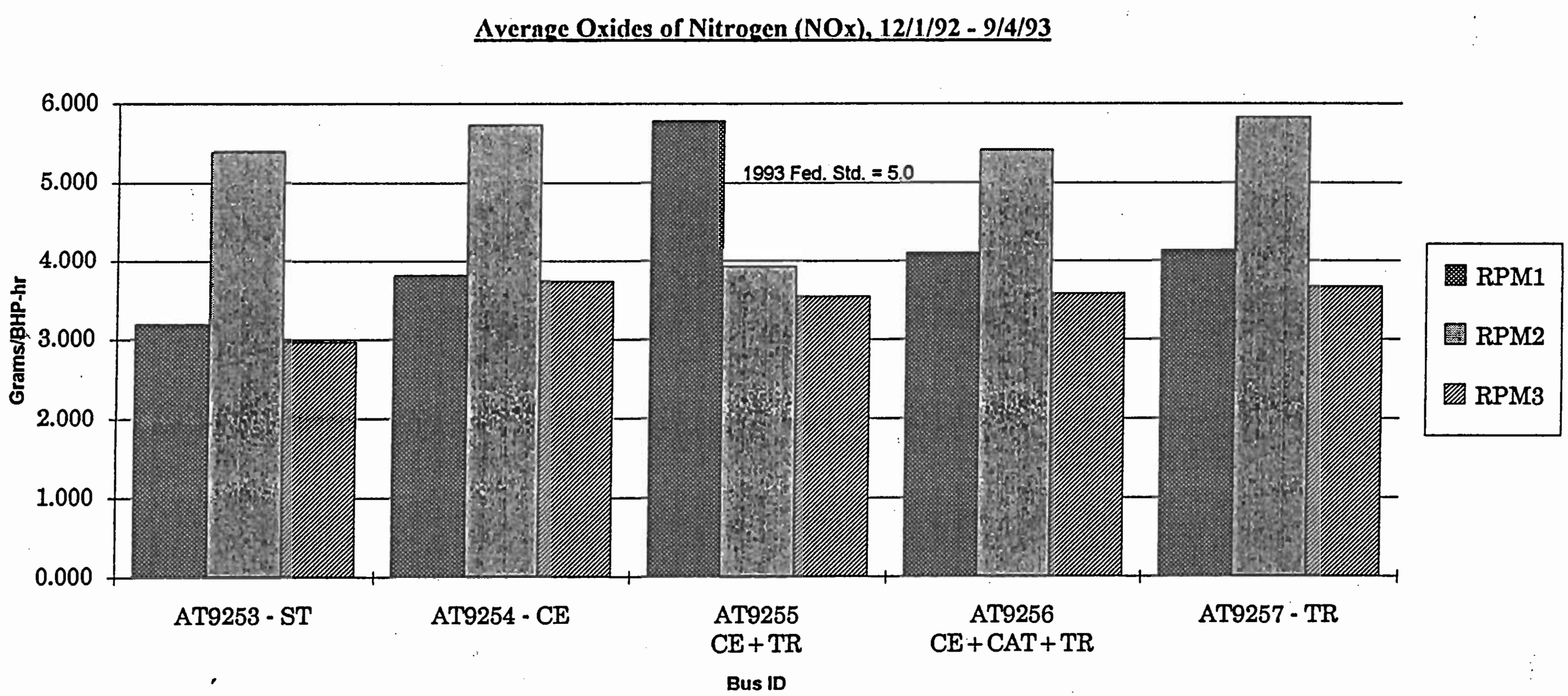


Figure 6. Emission of NOx for test buses averaged over the whole test period. ST - Standard, CE - Ceramic, TR - Trap, CAT - Catalyst

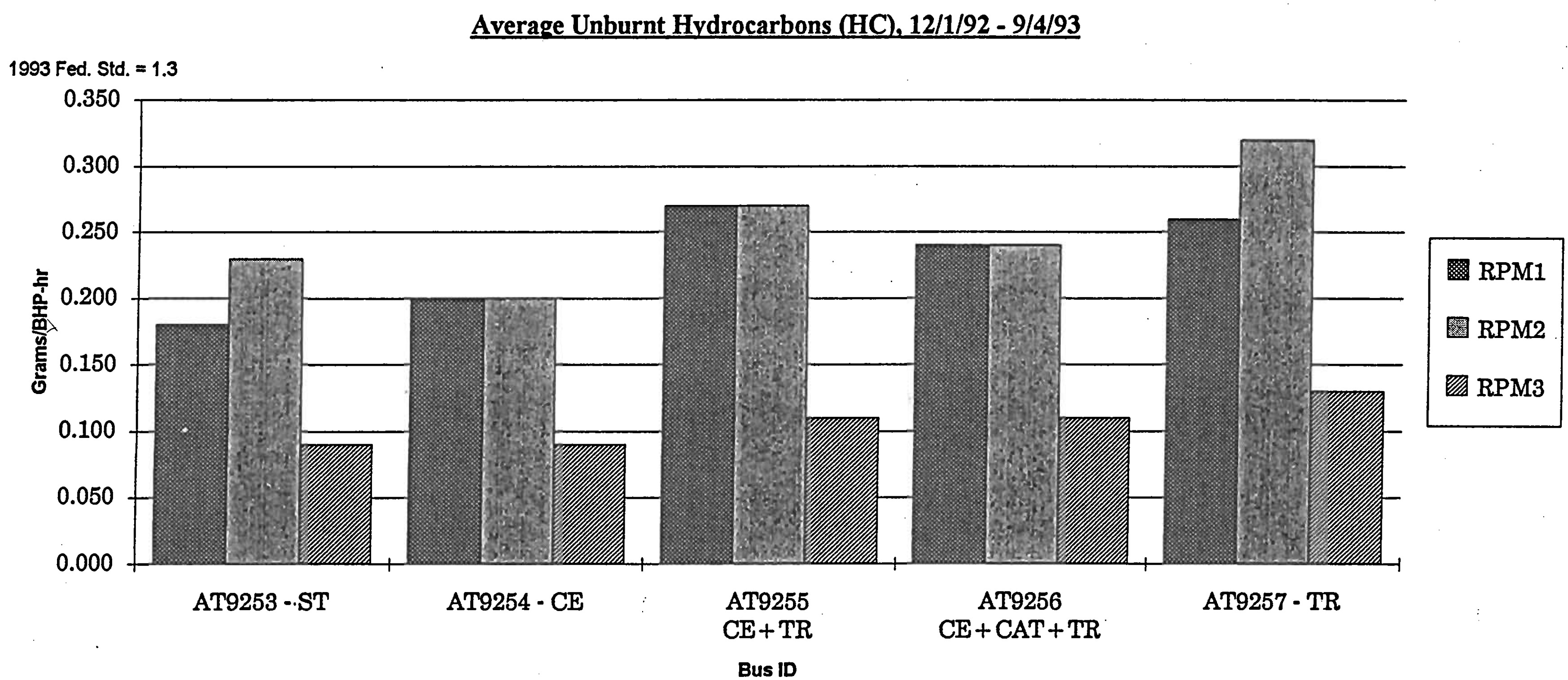


Figure 7. Emission of unburnt hydrocarbons for the test buses over

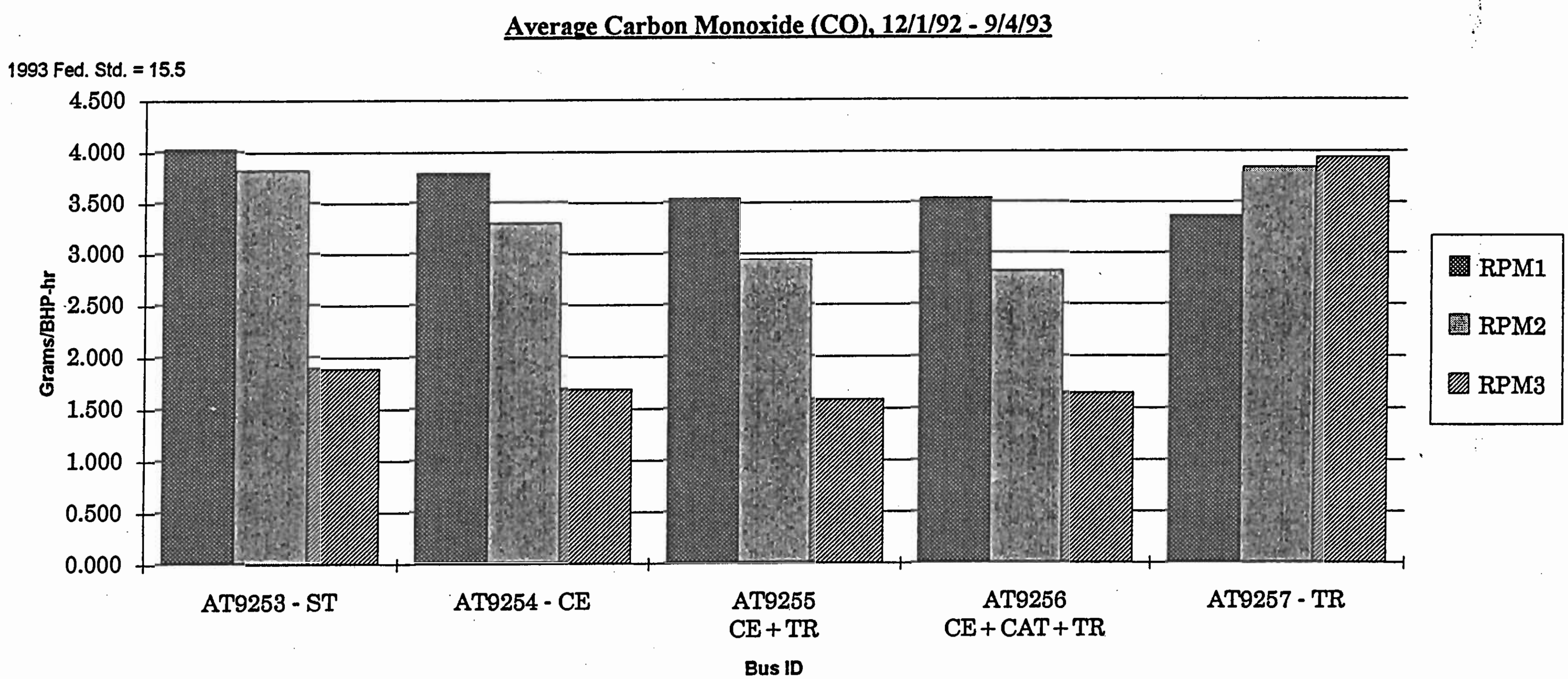


Figure 8. Emission of carbon monoxide for the test buses averaged over the whole test period. ST - Standard, CE - Ceramic, TR - Trap, CAT - Catalyst

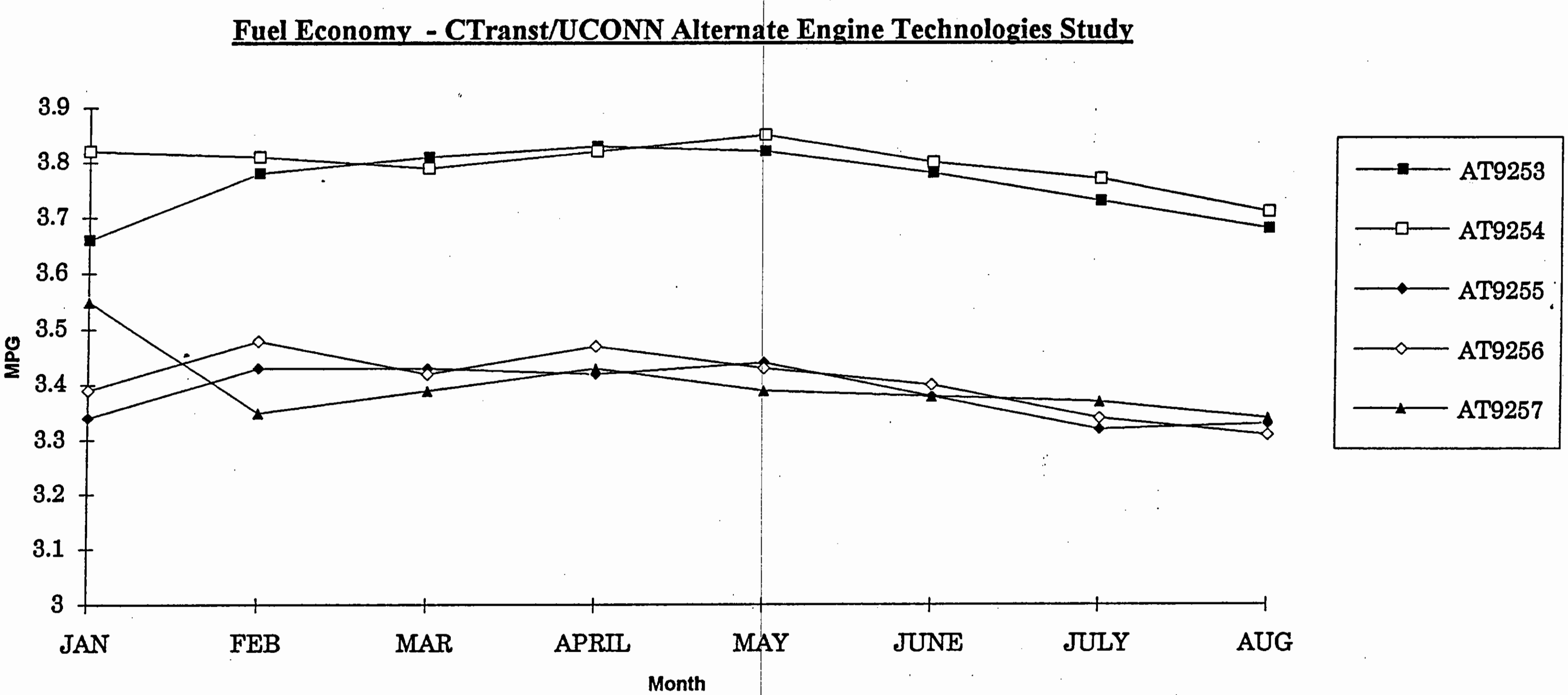
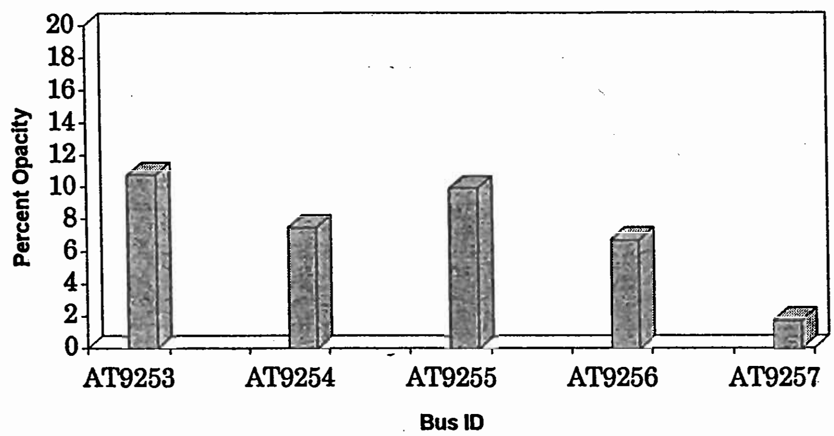
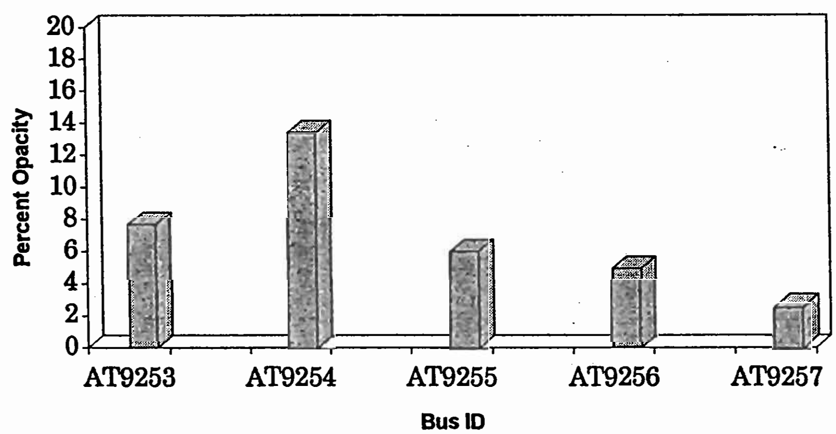


Figure 9. Fuel economy as a function of time for the test buses.
AT53 - Standard, AT54 - Ceramic, AT55 - Ceramic and Trap,

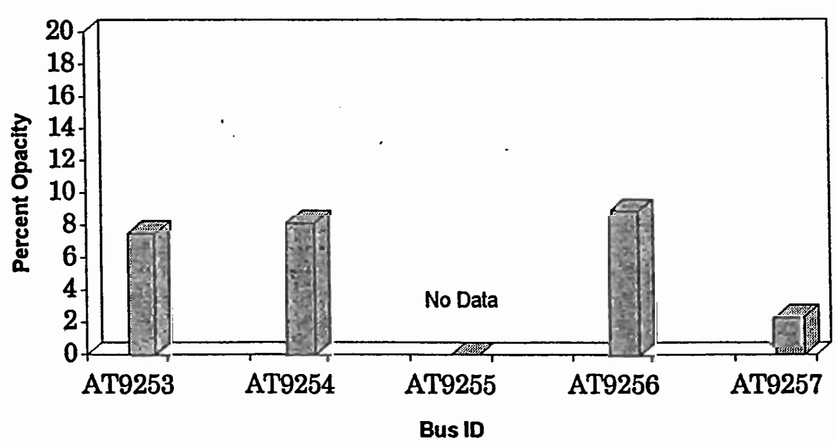
Integrated Average Opacity, 8/5/93 Test



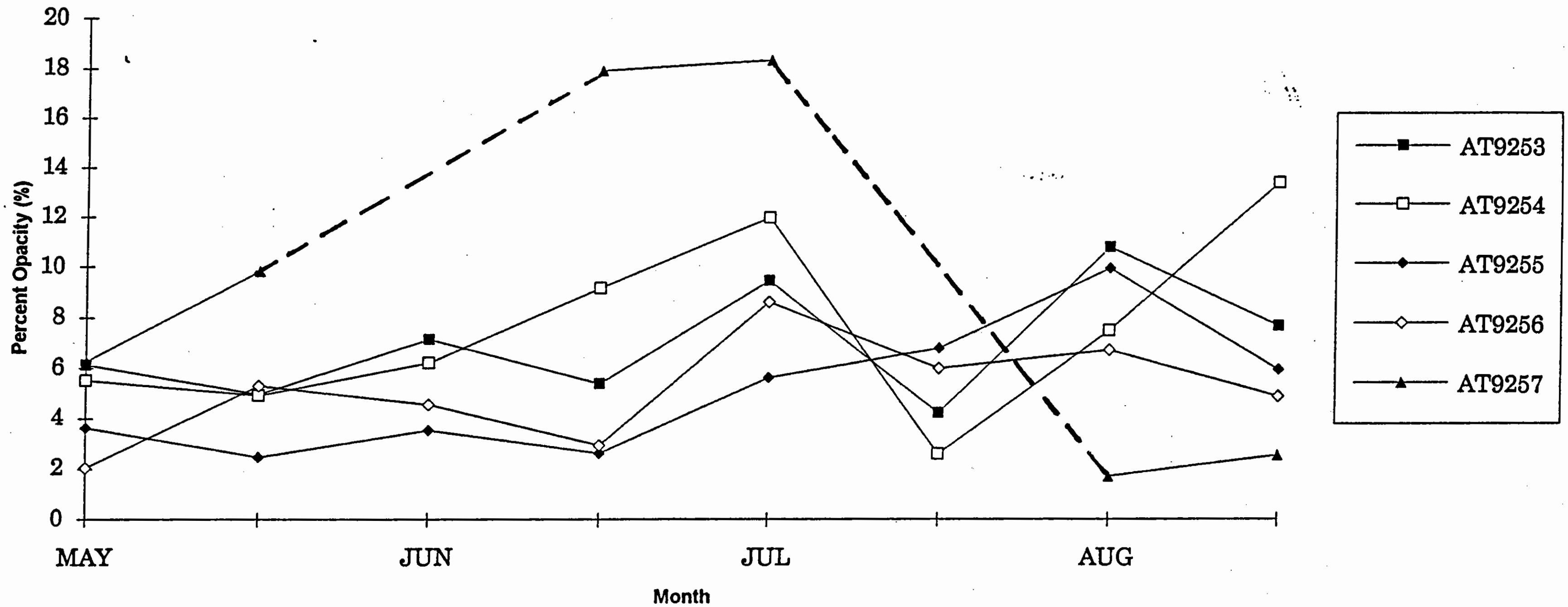
Integrated Average Opacity, 8/19/93 Test



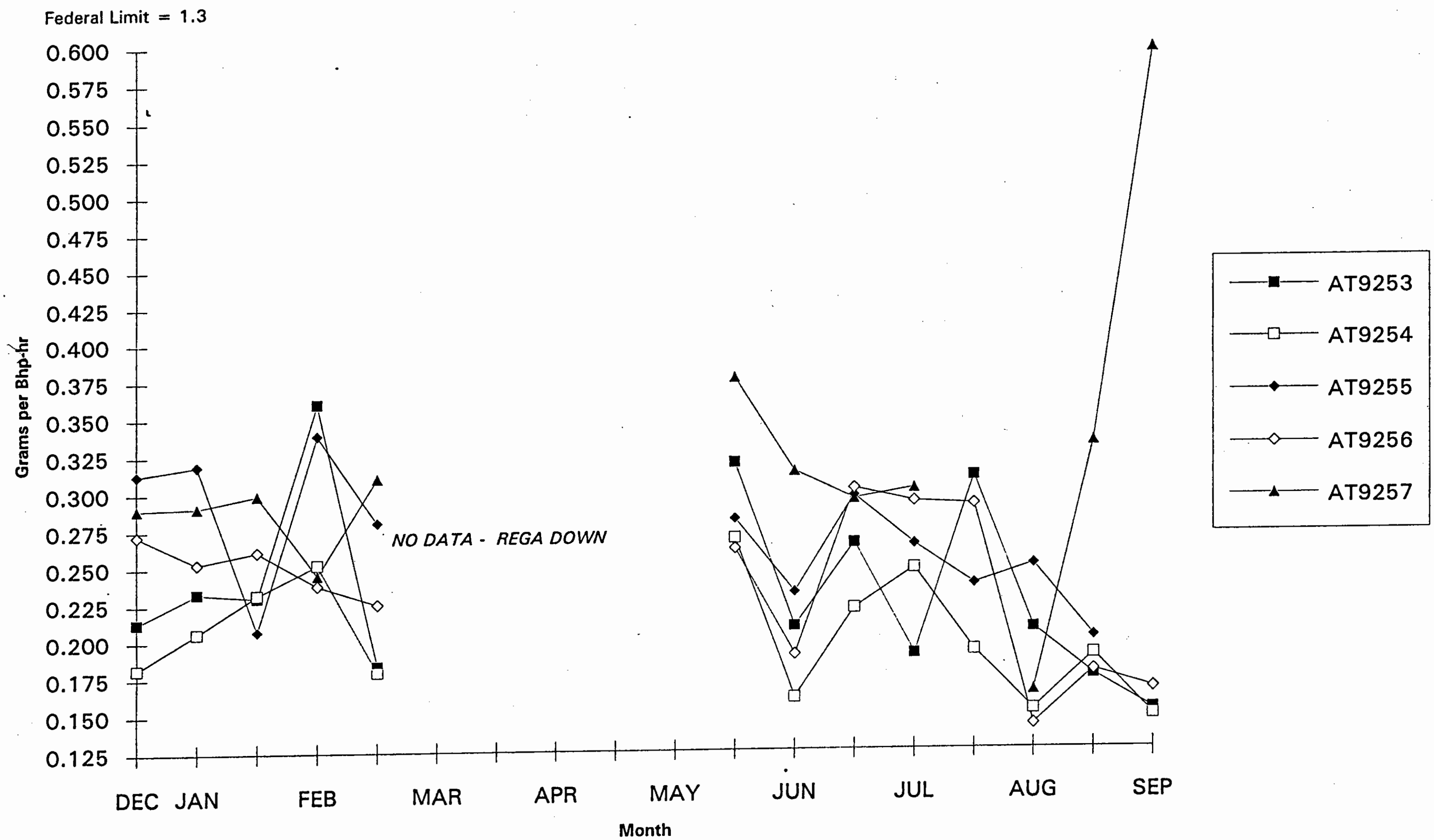
Integrated Average Opacity, 9/2/93 Test



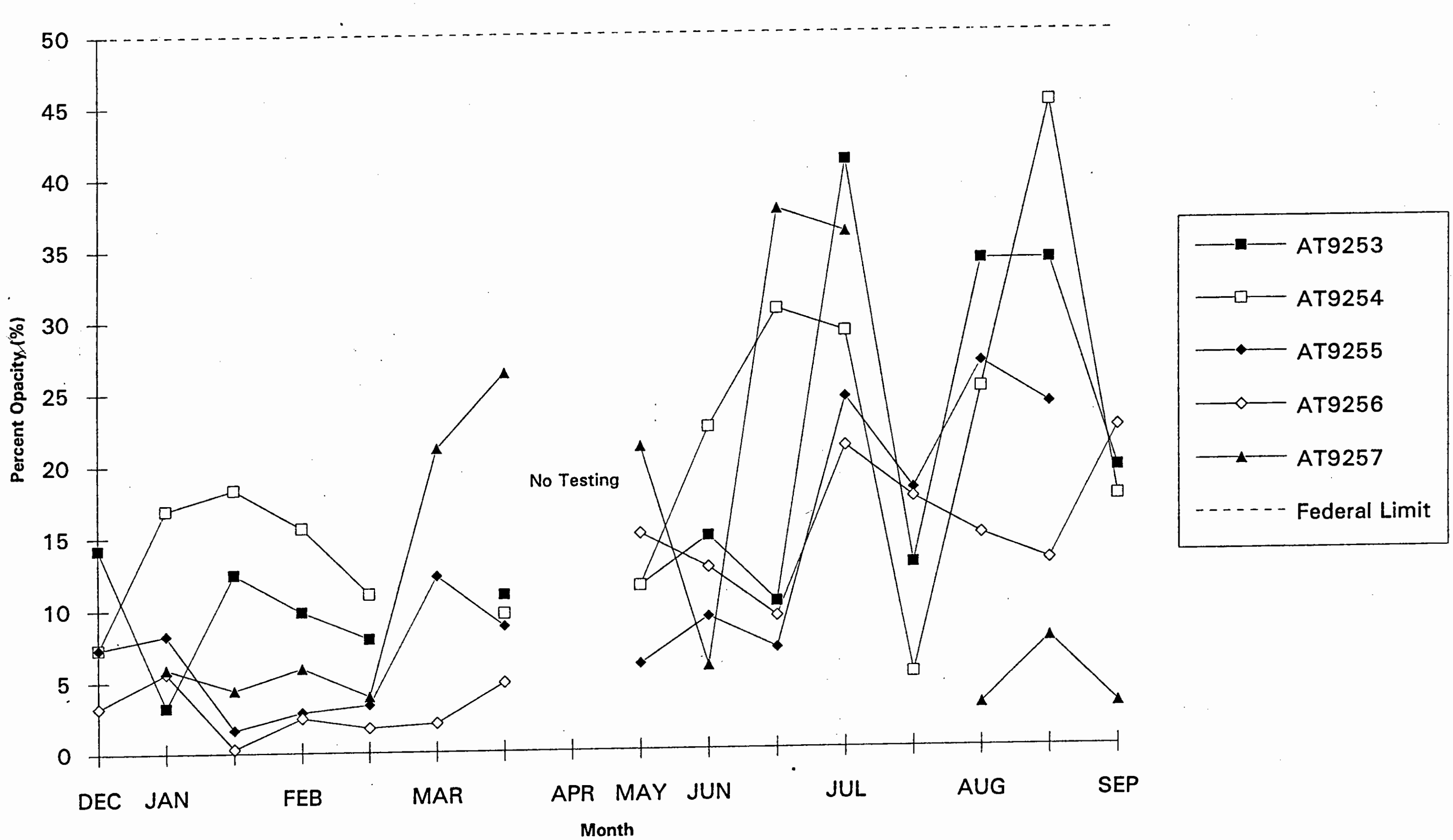
Integrated Average Opacity History, 5/1/93-present



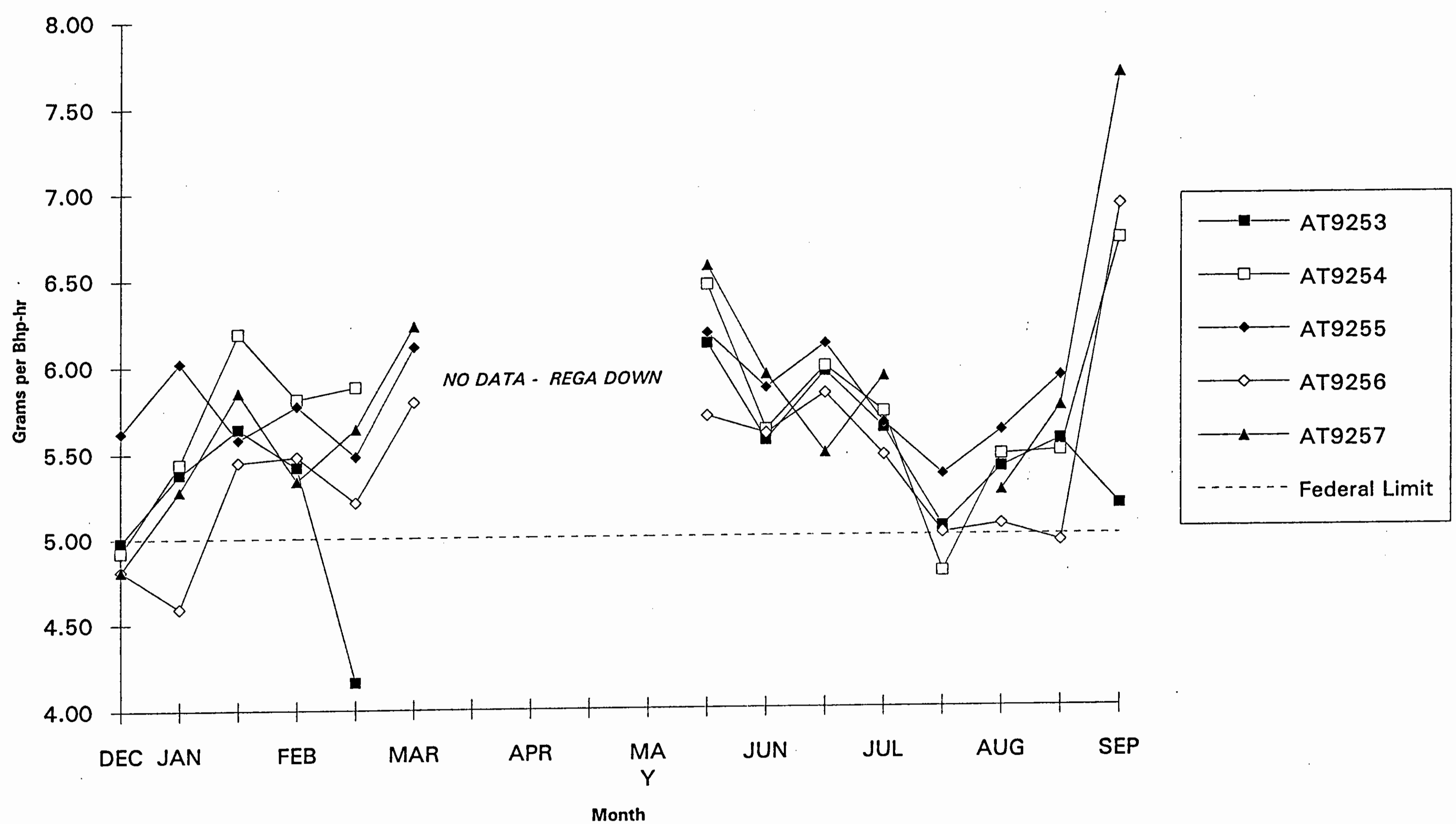
Unburnt Hydrocarbon (HC) History - Cruise Condition



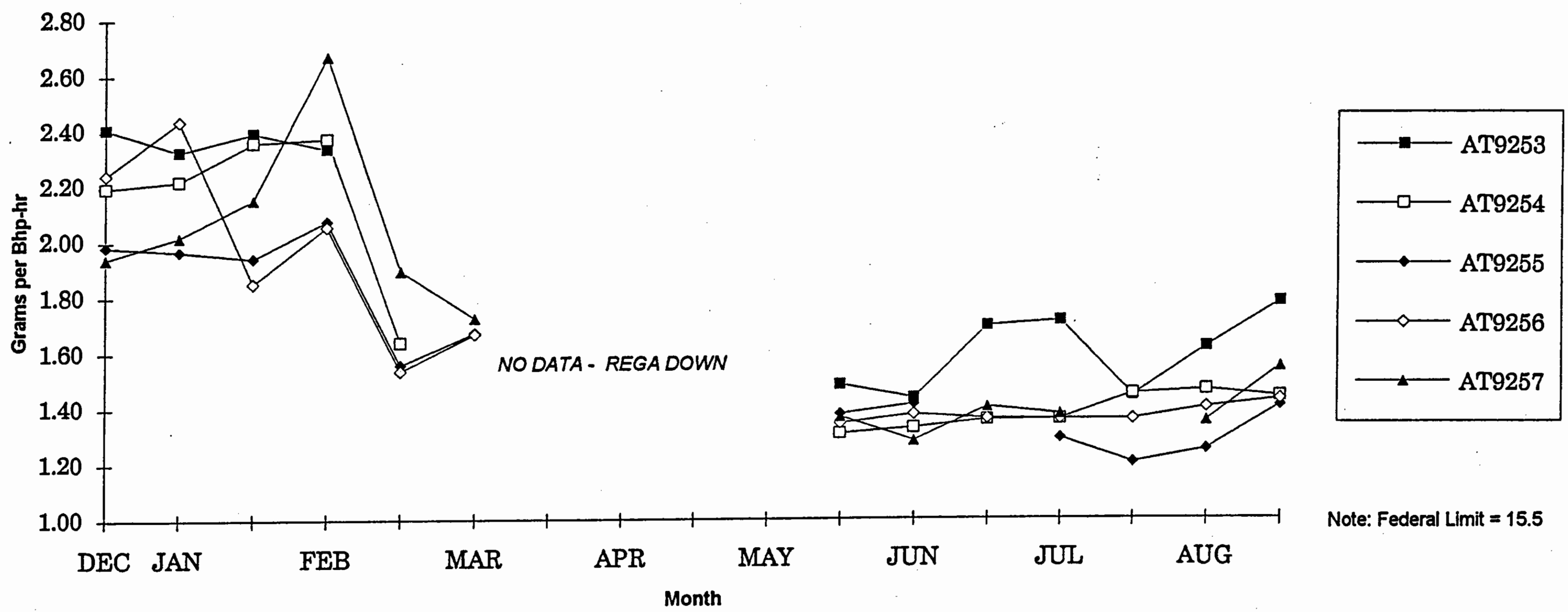
Maximum Opacity History



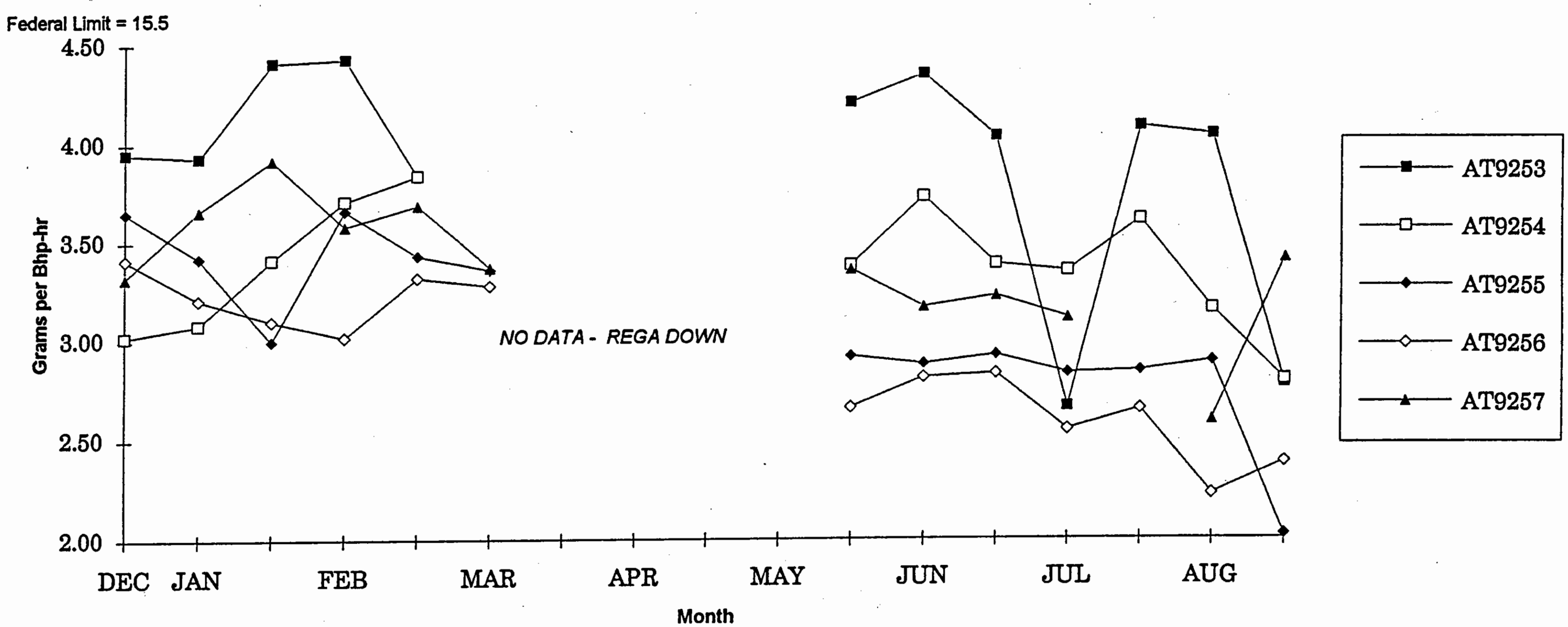
Oxides of Nitrogen (NOx) History - Cruise RPM

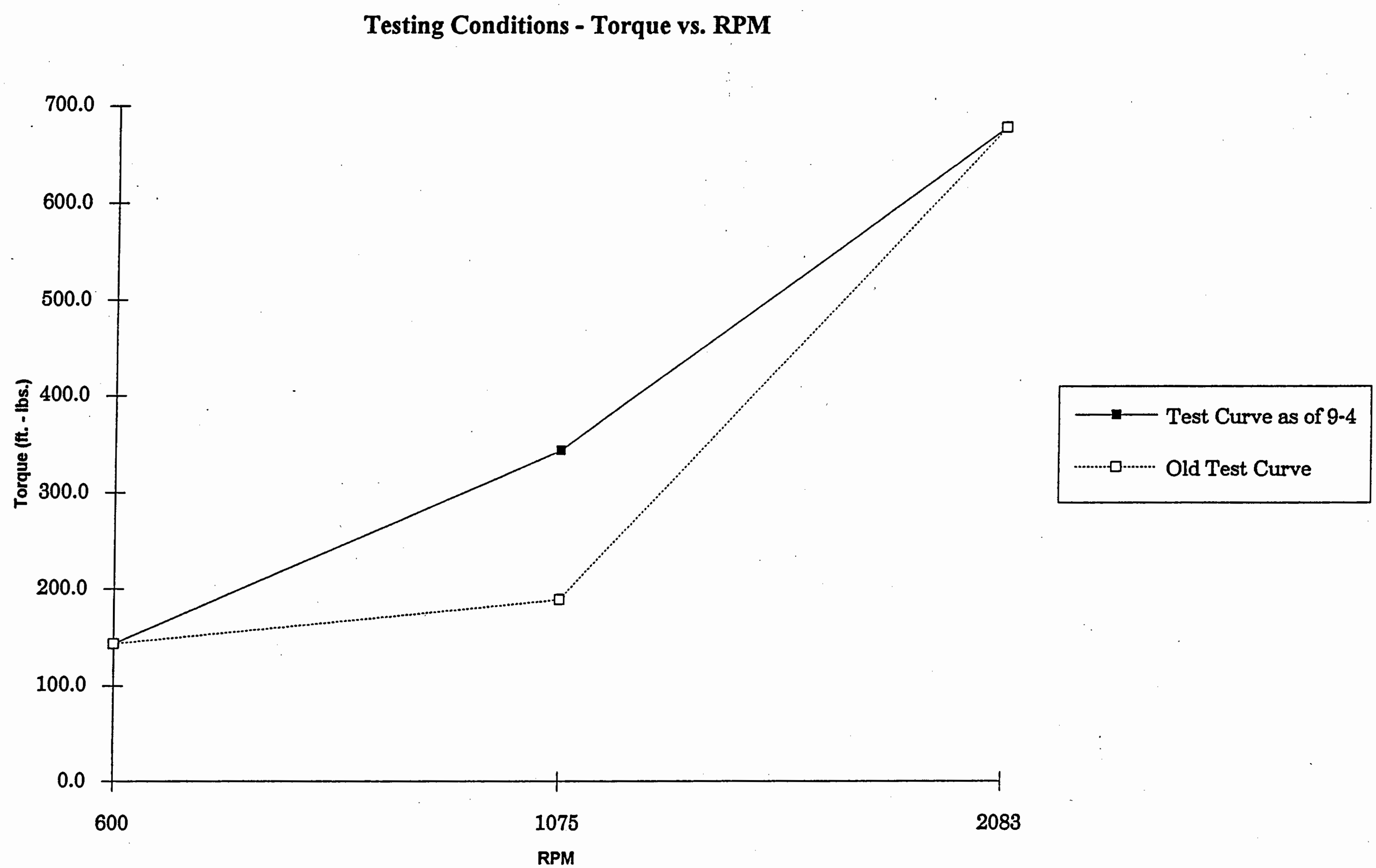


Carbon Monoxide (CO) History - Full Load Condition



Carbon Monoxide (CO) History - Cruise Condition





Testing Conditions - Torque vs. RPM
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
Torque (ft. - lbs.)
600
1075
2083
RPM
Test Curve as of 9-4
Old Test Curve