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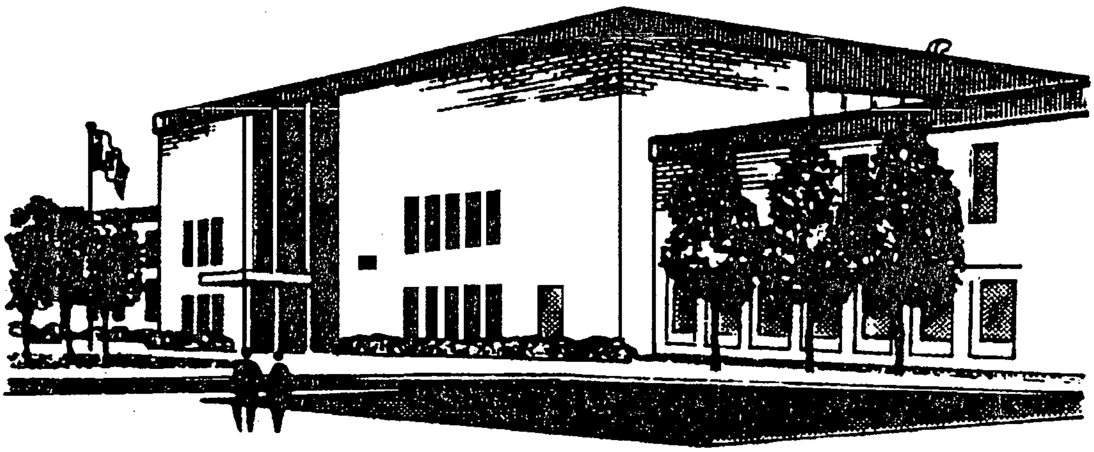
Exhaust Emissions from an Urban Transit Bus Powered by a Diesel/Natural Gas Dual-Fuel System

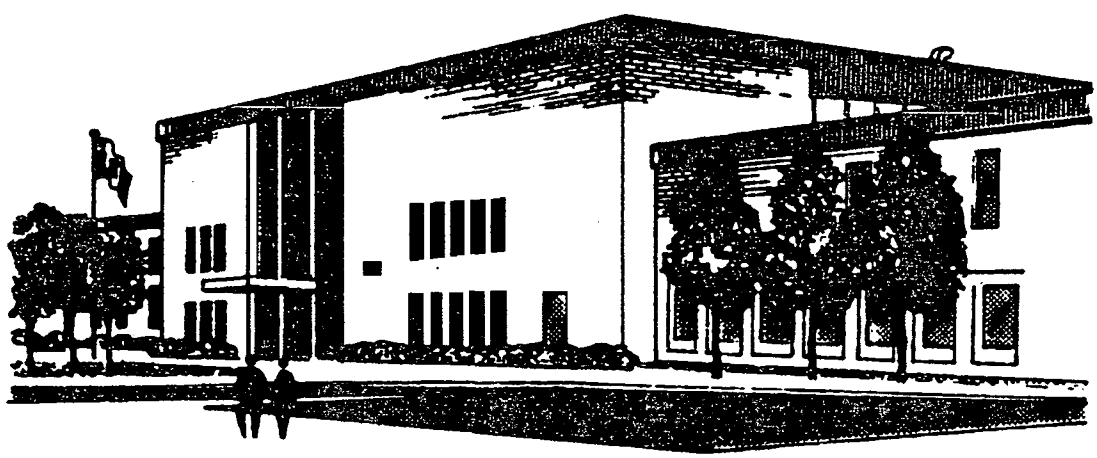


MSED REPORT #94-10
ENVIRONMENTAL TECHNOLOGY CENTRE
MOBILE SOURCES EMISSIONS DIVISION

Environment Canada
Environnement Canada

Canada

Exhaust Emissions from an Urban Transit Bus Powered by a Diesel/Natural Gas Dual-Fuel System



MSED REPORT #94-10

Prepared By: Greg Rideout
Preapred for: BC Transit

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Abstract

The exhaust emission rates of the regulated compounds, as well other unregulated components of the exhaust, were determined for an urban transit bus which had been converted to operate on either diesel or diesel-natural gas. The exhaust emission tests were conducted on a heavy duty chassis dynamometer capable of simulating the inertia weight and road loads that urban buses are subjected to during normal on-road operation. The emissions of total hydrocarbons, methane, carbon monoxide, carbon dioxide, oxides of nitrogen, carbonyls, and total particulate were determined for the bus over various transient chassis dynamometer driving cycles. The test cycles included in the project were the Central Business District (CBD), the New York Bus Cycle (NYBUS), and New York Bus Composite Cycle (NYBCOMP). Arterial, and Commuter Cycles.

Background

The emissions from urban transit buses have been considered a significant source of ambient air pollutants such as particulate matter and nitrogen oxides, for several years. These vehicles are quite visible to the urban population and hence their emissions of smoke and other odorous compounds are perceived as obvious contributors to urban air quality problems. In recent years stringent emission standards have been introduced which limit the emission rates from new engines, while for the in-service engines emission limiting legislation is scheduled for implementation in the United States in 1994.

Engine manufacturers have been investigating a number of options in the areas of engine design, fuel management, exhaust aftertreatment, and alternative fuels, to reduce emissions from new engines to the levels dictated by legislation. However, this activity does not provide a solution to the numerous in-use diesel engines, particularly those that operate in densely populated areas such as urban centers where the emissions will have a widespread effect on the general public. For the in-use segment of the heavy duty engine applications, the potential emission reduction opportunities which have been investigated include retrofit exhaust aftertreatment systems such as diesel catalytic converters and particulate traps, and the conversion of the diesel engine to alternative fuels.

In this study, the Mobile Sources Emissions Division of Environment Canada, conducted exhaust emission tests on an urban transit bus which had been converted to operate on a combination of diesel and natural gas. The system (Mark VII) as designed by Pro-Staff Fuels Ltd. allows the engine to operate in a dual-fuel mode on both diesel and natural gas simultaneously, as well as being operated as a mono-fuel diesel engine.

The testing was carried out as part of a demonstration program of the Mark VII system conducted by BC Transit . Funding for the emissions testing was contributed by Natural Resouces Canada, and also by the MSED of Environment Canada. The objective of the test program was to determine the potential emission reductions of the dual fuel system, and also to determine if the system would comply with the California Air Resources Board certification requirements for the aftermarket section

The following report describes the procedures and results of the emissions testing program.

Vehicle and Fuel Description

The test vehicle was an in-use city transit bus powered by a conventional diesel fuelled engine typical of the year of manufacture. The chassis was a 1978 GMC "New Look" forty foot bus, equipped with a Detroit Diesel 6V71 normally aspirated engine.

The diesel fuel used during the testing was a low sulphur content fuel provided by BC Transit. This was the same fuel used by their fleet. The natural gas was obtained from a commercial supplier in the vacinity of the MSED laboratory. The following tables provide a brief description of the vehicle used in this study and also properties of the diesel fuel and compressed natural gas as obtained from BC Transit and Consumers Gas.

Table 1. Vehicle Specifications

Test Vehicle	GMC Urban Transit Bus
Model year	1,978
Curb weight (lbs)	21,540
Engine	DDC 6V-71NA
Number of cylinders	6
Exhaust Aftertreatment	None
Transmission	Automatic, 3 speed
Air Intake	Normally Aspirated
Test Inertia Weight (pounds)	26,800
Test Road Load Horsepower	88.76 (@ 50 mph)

Table 2a Comparative Fuel Specifications for Commercial and Certification Diesel*

ITEM	BC Transit	Certification Type 2-D
Cetane	41.5	42-50
Distillation range:		
IPB F	350.6	340-400
10% Point, F	384.8	400-460
50% Point, F	424.4	470-540
90& Point, F	500	550-610
EP, F	550.4	580-660
Gravity, API		33-37
Total Sulfur	0.05	0.2-0.5
Hydrocarbon Composition		
Aromatics %		27
Paraffins, Napthenes, Olefins		remainder
Flashpoint F (min)	100.4	130
Viscosity, Centistokes	1.3 - 2.4	2.0-3.2

* USEPA Code of Federal Regulation 86-113-87

Typically, the transit company from which the test vehicle was obtained operate on a Type 1-D fuel . The properties of this fuel listed in the table above, were very similar to that of the emissions certification reference fuel. Therefore, efforts were not directed toward ensuring that the test vehicle was evaluated with the certification fuel. .

Table 2b. Natural Gas Composition

Constituent	Volume Percent
Methane	94.93
Ethane	2.56
Propane	0.21
Butane	0.02
Iso-Butane	0.03
Pentane	0.01
Iso-Pentane	0.01
Hexanes +	trace
Nitrogen	1.65
Carbon Dioxide	0.58

Facility and Equipment Description

Gaseous Emissions Measurement and Analytical Techniques

Gaseous and particulate emissions were obtained using a large single dilution CVS, which utilized a stainless steel tunnel ten inches in diameter, and one hundred inches in effective length, coupled to a secondary dilution tunnel which enabled particulate collection in accordance with accepted test procedures [1,2]. The flow rate in the main tunnel was 1500 SCFM during the studies. The raw exhaust from the vehicle was transferred from the exhaust pipe of the bus to the dilution system through a flexible stainless steel pipe 20 feet in length and 4 inches in diameter.

The gaseous sampling zone of the dilution system was equipped with three probes. One sample probe was used to draw sample from the tunnel to tedlar bags for analysis. The other probes directed samples of the dilute exhaust through heated lines (375 F) to silica gel cartridges, which had been treated prior to testing with 2,4 dinitrophenylhydrazine (DNPH) for carbonyl collection. A dedicated heated probe upstream of this zone was used for continuous collection of sample for total hydrocarbon measurement. A second probe in the same area of the heated probe, was used to direct a sample from the main tunnel to the secondary tunnel, where a second dilution occurred and sample was drawn through 70mm teflon coated glass fiber filters for particulate collection.

In determining the total hydrocarbons, a heated probe, filter, and sample line system, was used to direct a sample of the diluted exhaust from the dilution tunnel to a heated Flame Ionization Detector (HFID). The total hydrocarbon emissions were continuously measured throughout each test, and integrated to provide the emission rate over each test. The temperature of the heated components was maintained at approximately 191 degrees Celcius.

The emission rates of CO, CO2, and NOx, were determined by collecting a proportional sample of the dilute exhaust in tedlar "bags" and analyzing the contents of the bag using nondispersive infrared instruments (for CO and CO2) and a chemiluminescence instrument (for NOx).

The carbonyls in the dilute exhaust were collected on the DNPH coated cartridges. This method measures the phenylhydrzone derivatives, which are formed by the reaction of the DNPH solution and the carbonyls, and are a function of the carbonyl concentration in the dilute exhaust. Measurement of the derivatives was determined using High Performance Liquid Chromatography.

During each of the tests, samples of the dilute exhaust were collected in seperate tedlar bags and subjected to analysis by gas chromatography to quantify the amount of methane which was emitted. This also facilitated the determination of the non-methane hydrocarbon emission rate.

The light hydrocarbon (LHC) method employs a Hewlett Packard 5890 Series II gas chromatograph with an FID. The instrument is controlled and data is acquired and analysed via the Hewlett Packard 3365 Series II DOS ChemStation. A manually controlled valve injection of the gas sample is made directly on-column. A Valco 6 port heated valve is used. Details of analytical conditions are summarised in the table below.

Table 3. Light Hydrocarbon Analytical Conditions

Analytical Column	J&W Scientific GS-Q PLOT 30 m long 0.53 mm i.d.
GC Temperature Program	40 °C hold 1.1 min 25°C/min to 130 °C hold 2.3 min FID temperature 180 °C
Injection Valve	Valco WT series 6 port, 2 position 0.25 mL sample loop operating temperature 65 °C

The target species for the LHC method are summarized in Table 4. The method is calibrated between 15 and .15 ppmV for each component, except Methane which is calibrated in the range .15 to 300 ppmV. The detection limit for the C_2-C_4 compounds is approximately 0.03 ppmC and for Methane is 0.09 ppmC.

Table 4. Target List of Detailed Light Hydrocarbon Analysis

Methane
Ethylene
Acetylene
Ethane
Propylene
Propane
Propyne
n-Butane

Chassis Dynamometer Description

The chassis dynamometer used in the study was a Clayton Heavy Duty Vehicle Emission Dynamometer with twin rolls (split) 8.65 inches in diameter, 120 inches in length, and 20 inches between roll centers. Inertia simulation was selected through mechanical flywheels with electric compensation, while Road Load was simulated by an 300 horsepower electric DC motor. Maximum inertia and road load of the system is 45000 pounds, and 150 horsepower at 50 miles per hour.

The rotating speed of the dynamometer rolls during a vehicle emissions test is measured by a pulse counter, which communicates this information to a microprocessor controller. The controller translates the pulses into the linear speed of the vehicle and it is displayed on a video screen as a cursor. The vehicle driver then uses the cursor to follow a selected speed versus time trace. In this way, the vehicle may be operated over a selected transient operation or driving cycle.

The chassis dynamometer testing procedures followed for this type of emissions testing are outlined in a USEPA report entitled "Recommended Practise for Determining Exhaust Emissions from Heavy Duty Vehicles Under Transient Conditions" [1]. The exhaust sampling and vehicle test procedures were very similar to those described for light duty emissions certification [2]. The electronic programming feature of the dynamometer controller allows for a speed-power curve for each test vehicle. To calculate the curve the following equation was applied [3]:

$$RLP = F * 0.67 * (H - 0.75) * W * (V/50)^3 + 0.00125 * LVW * (V/50)$$

where:

RLP = Road Load Power in Horsepower

F = 1.00 for tractor trailers, 0.85 for urban buses

H = Average maximum height in feet

W = Average maximum width in feet

LVW= Loaded Vehicle Weight in Pounds

V = Vehicle Speed (mph)

According to the procedure recommended by the US EPA, the inerta setting for the bus should be equal to the sum of the empty bus weight, half passenger load and the driver at 150 pounds each, and the equivalent inertia of the non-rotating wheel assemblies.

Driving Cycles

The driving cycles or traces used for the exhaust emissions testing during most of the studies reported here were the the Central Business District (CBD), the New York Bus Cycle (NYBUS), and New York Bus Composite Cycle (NYBCOMP), Arterial, and Commuter Cycles.

Table 5 provides details of the test cycles while graphical representations of the speed versus time data for these driving cycles have been enclosed in the appendices of the report.

TABLE 5. Exhaust Emission Test Cycles

Test	Duration (seconds)	Distance (miles)	Average Speed mph
CBD	600	2.06	12.37
New York Bus	600	0.65	3.89
New York Bus Comp	600	2.51	8.77
Arterial	373	2	19
Commuter	359	4	40

Test Procedure

The test procedures which were followed for the exhaust emission testing of the heavy duty vehicle were outlined in the US-EPA report entitled "Recommended Practise for Determining Exhaust Emissions from Heavy-Duty Vehicles Under Transient Conditions". The calculations of exhaust emissions and fuel economy were performed in accordance with the US-EPA Code of Federal Regulation, Schedule 40, Part 86.

The bus was located on the dynamometer with the drive wheels cradled between the twin rolls of the dyno. Wheel chocks were placed in front of the vehicles steering wheels, and chain restraints located in the test cell floor were attached to the rear frame assembly of the vehicle as a safety precaution. The exhaust outlet pipe of the vehicle was connected to a heated, 4 inch diameter 20 feet in length, flexible stainless steel pipe, which was also connected to the inlet of the dilution tunnel. Fans were located in the vacinity of the drive wheels to create air flow across the tires and remove the heat generated by the tire to dynamometer roll contact.

During each of the test days the vehicle was brought to operating temperature by operating the vehicle at various steady state speeds. Following the warm-up the emission tests were conducted as hot starts. Driver variability was eliminated from the results by using the same technician for all of the vehicle testing. In general three repeats of each driving cycle were conducted in series, with a 3 minute "soak" between each repitition. Where it was identified that additional tests were required on a particular cycle, additional tests were conducted after an engine warm-up.

The bus was first tested in its diesel only configuration. The results of this testing were to be considered as the baseline emissions of the bus. At the conclusion of the baseline testing the bus was prepared for emissions testing in the dual fuel operating mode. Representatives of Pro-Staff Fuels Ltd. were permitted to conduct brake stalls on the bus in the dual fuel configuration as a check on the operation of the fueling system. A request was made by Pro-Staff Fuels Ltd to conduct full power tests of the bus on the emissions dynamometer, however it was not possible to accomodate this request due to the dynamometer design.

Results and Discussion

Exhaust emission tests were conducted on an urban transit bus over various transient driving cycles. The following section provides the summarized results of this testing while the complete body of results are enclosed in the appendices of the report.

During the course of the testing it was observed that during the Commuter and Arterial test cycles there was excessive heat build up in the tires. The temperature was sufficient to cause the tire tread to seperate from the main body of the tire. It was decided upon consultation with BC Transit and the California Air Resources Board, to omit these test cycles from the test program.

Regulated Emissions

Tables 6, through 12 list the emission rates of the regulated emissions (THC, CO, NOx, and particulate matter), for all repeats for each of the driving cycles used in the study.

The abbreviations used for the measured exhaust components have been defined earlier in the report with the exception of HCOH which refers to formaldehyde. Exhaust emission rates were calculated as described in a report entitled Calculation of Emissions and Fuel Economy When Using Alternative Fuels[4].

The non-methane hydrocarbons during the dual fuel operation were determined by correcting the total hydrocarbon analysis from the flame ionization detector for the methane concentration in the sample as determined by gas chromatography. It was assumed that the methane component of the exhaust hydrocarbons during the diesel testing were at ambient levels therefore the total hydrocarbon emission rate was presented as the non-methane hydrocarbon emission.

Table 6. Diesel Emission Rates Central Business District

Test	NMHC grams/mile	CO grams/mile	NOx grams/mile	CO_2 grams/mile	PM grams/mile	HCOH mg/mile
1	4.05	33.34	33.49	2,917.51	1.76	335.56
2	4.5	29.04	35.72	2,933.34	1.62	360.52
3	4.25	35.01	34.16	2,991.73	1.98	370.88
4	4.16	29.15	33.06	2,866.47	1.62	368.46
Average	4.24	31.64	34.11	2,927.26	1.75	333.86
Std Dev.	0.19	3.01	1.17	51.59	0.17	46.05
+10%	4.66	34.8	37.52		1.92	
-10%	3.82	28.47	30.7		1.57	
cv%	4.6	9.52	3.42		9.68	

Table 7. Diesel Emission Rates, New York Bus Cycle

Test	NMHC grams/mile	CO grams/mile	NOx grams/mile	CO_2 grams/mile	PM grams/mile	HCOH mg/mile
1	8.68	81.48	73.17	5,191.62	2.49	489.38
2	8.66	70.77	73.23	4,974.57	2.43	470.8
3	8.9	73.48	74	5,048.77	2.62	429.41
Average	8.75	75.36	73.47	5,071.65	2.51	463.2
Std Dev.	0.14	5.52	0.46	110.32	0.09	30.7
+10%	9.62	82.9	80.81		2.77	
-10%	7.87	67.83	66.12		2.26	
cv%	1.56	7.32	0.63		3.73	

Table 8. Diesel Emission Rates, New York Bus Composite Cycle

Test	NMHC grams/mile	CO grams/mile	NOx grams/mile	CO_2 grams/mile	PM grams/mile	HCOH mg/mile
1	4.81	20.04	35.6	2,571.88	1.71	286.24
2	4.8	21.75	36.11	2,601.72	1.75	306.03
3	4.62	20.94	36.27	2,617.02	1.72	286.17
Average	4.74	20.91	35.99	2,596.87	1.73	292.81
Std Dev.	0.11	0.86	0.35	22.96	0.03	11.45
+10%	5.22	23	39.59		1.9	
-10%	4.27	18.82	32.39		1.55	
cv%	2.24	4.09	0.97		1.48	

Table 9. CNG-Diesel Emission Rates, Central Business District Cycle

Test	NMHC grams/mile	CO grams/mile	NOx grams/mile	CO_2 grams/mile	PM grams/mile	HCOH mg/mile
1	3.99	61.84	33.49	2,917.51	2.25	1,794.32
2	19.92	85.83	35.72	2,933.34	1.94	1,853.25
3	21.28	97.54	34.16	2,991.73	1.82	1,838.8
4	8.13	63.26	36.93	2,511.52	2.15	
5	7.68	65.96	45.52	2,813.66	3.24	
6	8.67	64.27	42.22	2,654.6	3	
Average	11.61	73.12	38.01	2,803.73	2.4	1,828.79
Std Dev.	7.17	14.91	4.81	185.91	0.58	30.71
+10%	12.77	80.43	41.81		2.64	
-10%	10.45	65.81	34.21		2.16	
cv%	61.72	20.4	12.66		24.37	

Table 10. CNG-Diesel Emission Rates, New York Bus Cycle

Test	NMHC grams/mile	CO grams/mile	NOx grams/mile	CO_2 grams/mile	PM grams/mile	HCOH mg/mile
1	5.07	97.59	67.28	4,784	2.58	1,494.17
2	9.68	94.16	62.23	4,538	2.56	1,854.66
3	13.43	149.05	62.44	4,585	3.13	2,055.17
4	9.81	150.51	70.49	4,620	2.97	
5	8.81	183.73	79.51	4,862.75	3.32	
6	11.52	149.18	78.62	4,655.85	2.77	
Average	9.06	131.69	69.69	4,689.94	2.84	1,801.33
Std Dev.	3.11	35.13	7.03	120.91	0.3	284.28
+10%	9.96	144.86	76.66		3.13	
-10%	8.15	118.52	62.72		2.56	
cv%	34.33	26.68	10.09		10.59	

Table 11. CNG-Diesel Emission Rates, New York Bus Composite Cycle

Test	NMHC grams/mile	CO grams/mile	NOx grams/mile	CO_2 grams/mile	PM grams/mile	HCOH mg/mile
1	7.24	73.84	39.77	2,689.72	2.69	1,434.31
2	15.05	93.32	34.71	2,382.67	2.11	1,814.2
3	8.49	93.38	36.37	2,479.48	2.12	1,554.29
4	9.67	53.41	36.81	2,519.94	2.53	
5	9.84	100.39	39.72	2,615.95	2.59	
6	10.7	80.48	42.68	2,623.75	2.45	
Average	10.17	82.47	38.34	2,551.92	2.41	1,601.93
Std Dev.	2.68	17.21	2.9	112.4	0.24	195.84
+10%	11.18	90.72	42.18		2.66	
-10%	9.15	74.22	34.51		2.17	
cv%	26.35	20.87	7.58		10.09	

Discussion

The baseline tests of the vehicle yeilded emission rates comparable to those measured by the MSED in previous studies of buses powered by the DDC 6V71 engine. This indicates that the engine was operating in a normal fashion during the baseline tests. The Table below provides comparison data from three of these buses and the BC Transit Bus over the Central Business District Cycle.

Table 12. Diesel Bus Emissions

Emission grams/mile	Bus 1	Bus 2	Bus 3	BC Transit
THC	4.29	3.74	3.61	4.24
CO	8.94	23.1	58.95	31.64
NOx	46.78	35.79	30.56	34.11
CO2	3,009	3,301	3,112.74	2,927.26
PM	1.14	2.17	2.92	1.75

In addition, the test to test repeatability of the diesel testing was observed to be within the standard guide (coefficient of variance) used the Mobile Sources Emissions Division which uses the limits of 10 - 15%, 20%, and <8% , for total hydrocarbons, carbon monoxide, and oxides of nitrogen respectively.

The testing of the dual fuel system yielded results with a lower level of repeatability when compared to the diesel baseline tests. Therefore additional tests were conducted to increase the database. The exhaust constitiuents displaying the largest degree of variability was the non-methane hydrocarbons and carbon monoxide. Each of these emissions are formed primarily through incomplete combustion of the fuel by the engine.

The following Figures compare the emissions from the baseline diesel operation of the bus to those from the dual fuel configuration.

Figure 1. Central Business District Cycle Emissions g/mile

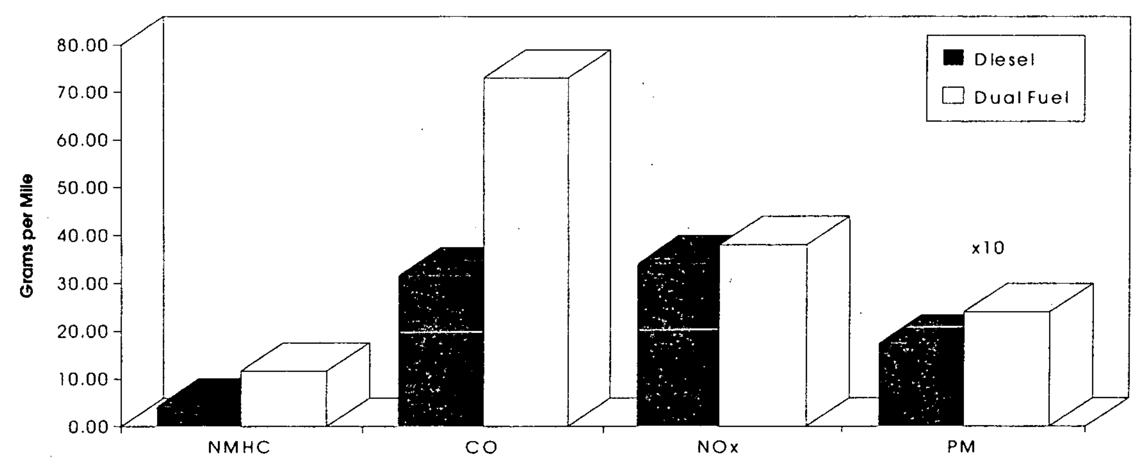


Figure 2. New York Bus Cycle Emissions g/mile

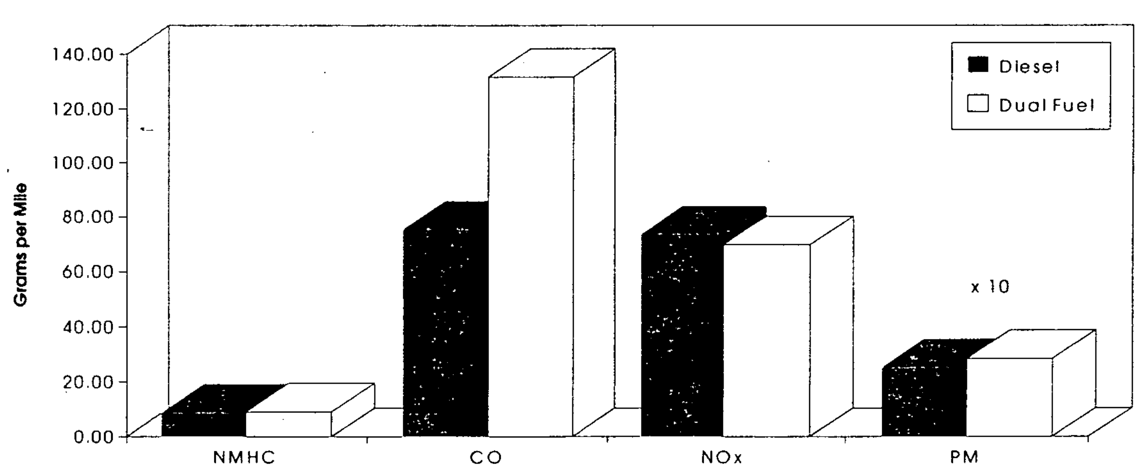


Figure 3. New York Bus Composite Emissions g/mile

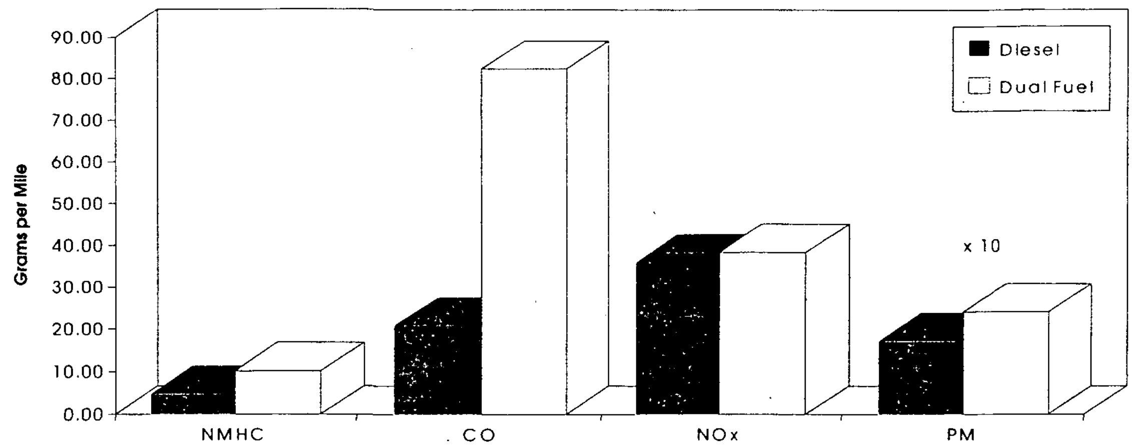
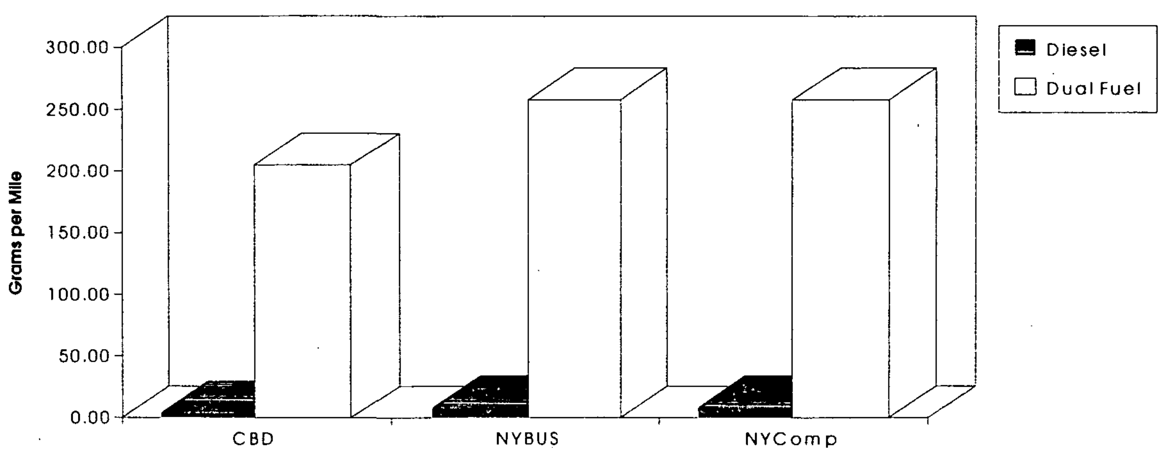


Figure 4. Total Hydrocarbon Emissions, g/mile



Inspection of these results indicate that total hydrocarbons were significantly increased during operation with the dual fuel system. The total hydrocarbon emissions from the dual fuel system were on average 40 times greater than that of the baseline levels, with methane comprising 95% of the total.

Comparing the non-methane hydrocarbon and carbon monoxide emisisons over the three cycles indicates that the dual fuel system emission rates were, on average, two and three times greater with the dual fuel system. The nitrogen oxide emission rates observed from the bus were similar for the baseline and dual-fuel system, however on average the dual fuel system emission rate was 4% greater than the baseline. The particulate mass emission rate was 30% greater with the dual fuel system. Formaldehyde emissions from the dual fuel system were 5 to 7 times higher than the levels produced by the diesel operation of the bus. This result would be expected since partial oxidation of the methane would result in formaldehyde formation.

Summary

The Mobile Sources Emission Division of Environment Canad performed heavy duty chassis dynamometer emissions testing on a standard forty foot urban transit bus while operating on diesel, and also in a dual (CNG-Diesel) fuel mode. The testing was conducted in support of a demonstration program involving BC Transit, Natural Resources Canada, and Pro-Staff Fuels. The objective of the emissions test program was to determine and compare the emissions from the bus while in the standard diesel configuration, and while operating with the dual fuel, diesel natural gas fumigation system. The results of the testing were also intended to determine the exceptability of the dual fuel system with respect to the requirements of the California Air Resources Board.

The main observations resulting from these tests were;

- The diesel baseline emission results were similar to those measured from this engine type in previous studies conducted by the MSED.
- The dual-fuel system emission results did not produce the same level of repeatability observed from the baseline tests.
- Total Hydrocarbon emissions were 40 times higher with the dual-fuel compared to the baseline, with methane comprising 95% of the total during the dual-fuel tests.
- Non-methane hydrocarbon emissions were on average 2 times greater during the dual-fuel tests compared to the baseline levels.
- Formaldehyde emissions were 5 to 7 times higher with the dual-fuel system compared to the diesel baseline.
- Carbon monoxide emission levels were on average 3 times greater during the dual-fuel tests compared to the baseline levels.
- NOx emissions were similar between the baseline and the dual-fuel tests, however the dual-fuel system emission rates were increased on average by 4%.
- Particulate emission levels were increased by 30% with the dual-fuel system.

These results are similar to those described in the literature from other exhaust emission studies of diesel - natural gas fumigation engines[5]. Based upon these findings it may be concluded that in general the emissions deteriorated when operated in the dual-fuel mode.

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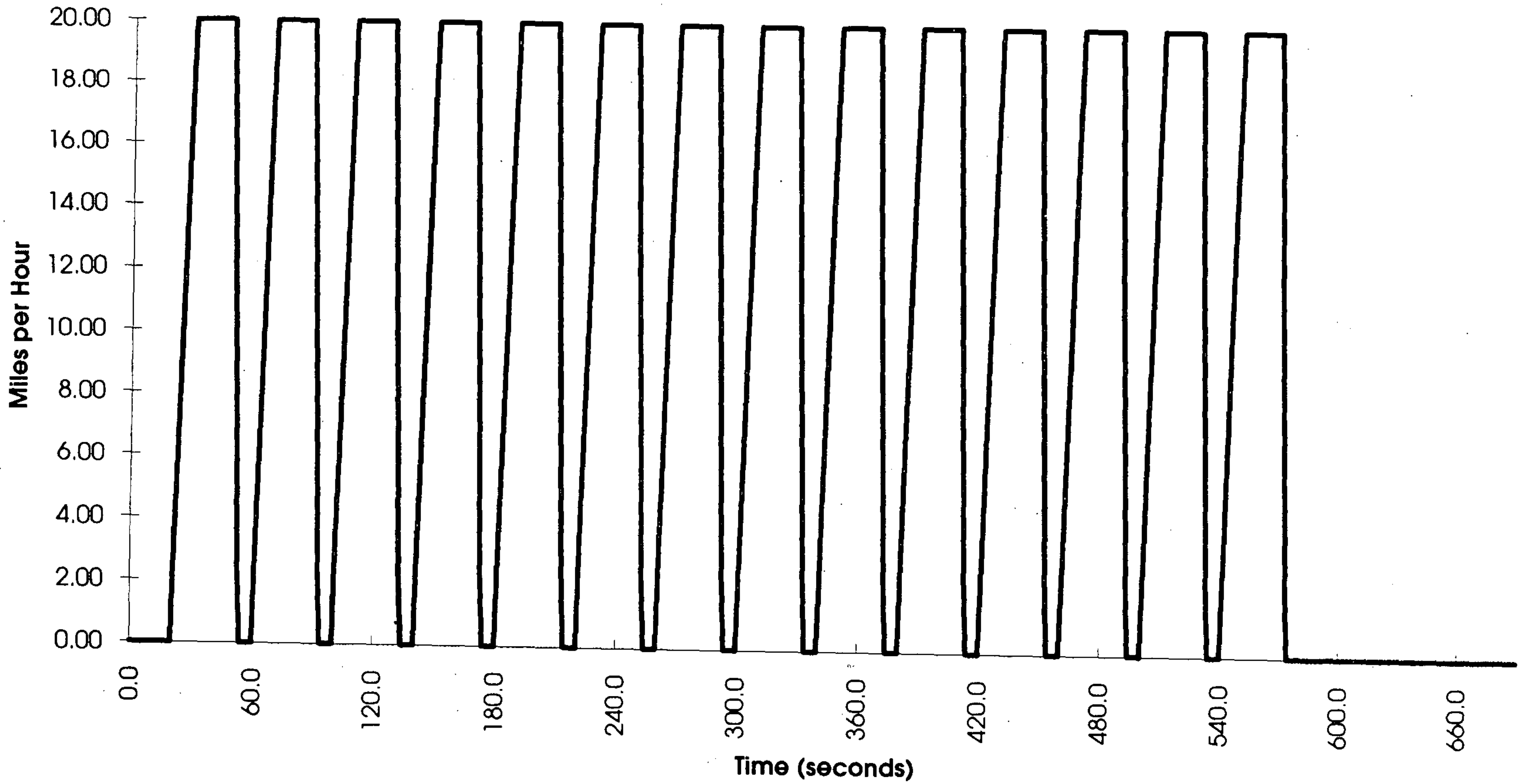
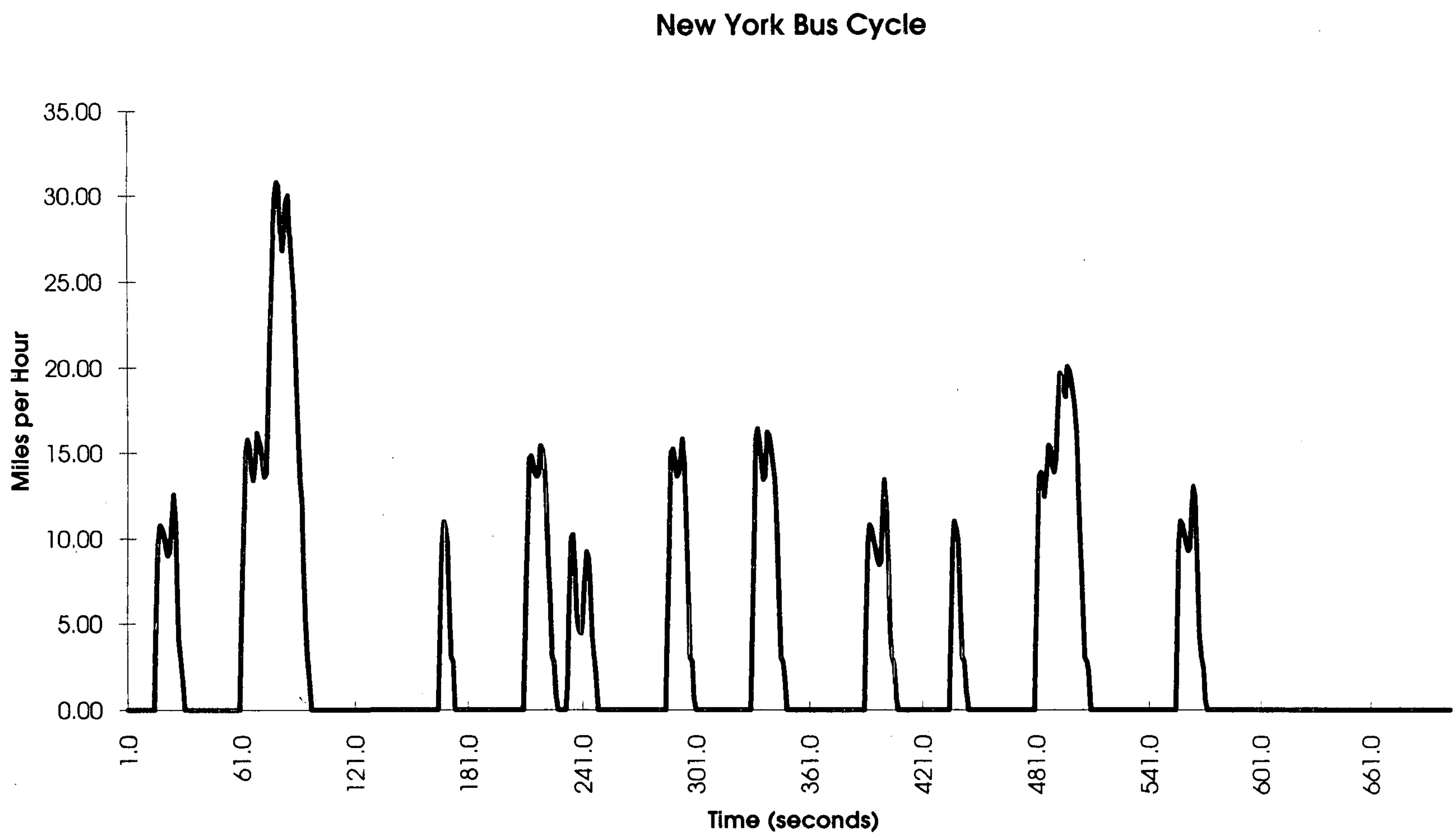
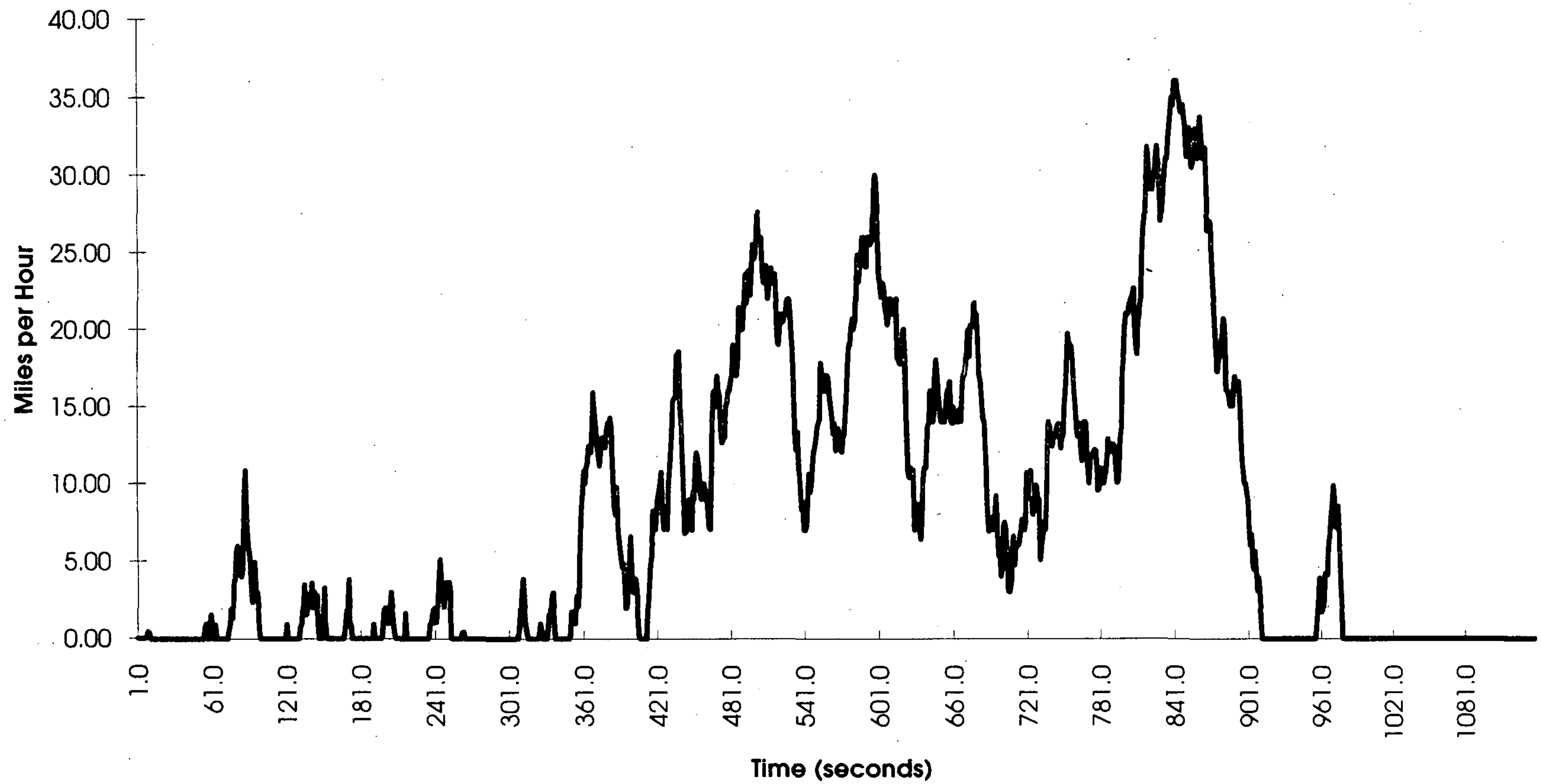
Although this paper has been supported by Environment Canada it has not been vetted for policy implications and therefore does not necessarily reflect the views or policies of Environment Canada nor does the mention of any trade names, commercial products, or organisations imply endorsement by Environment Canada.

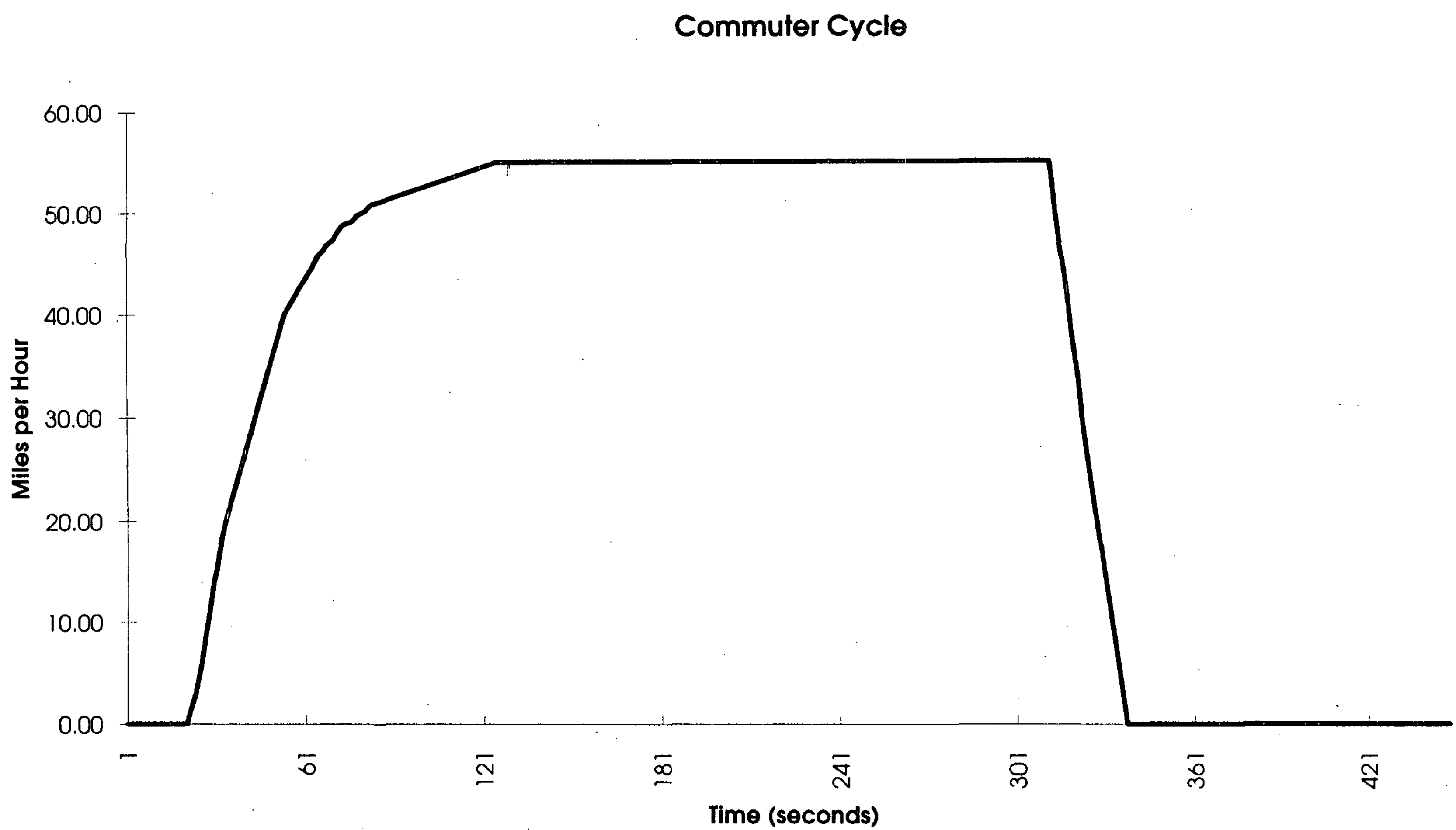
Central Business District Cycle



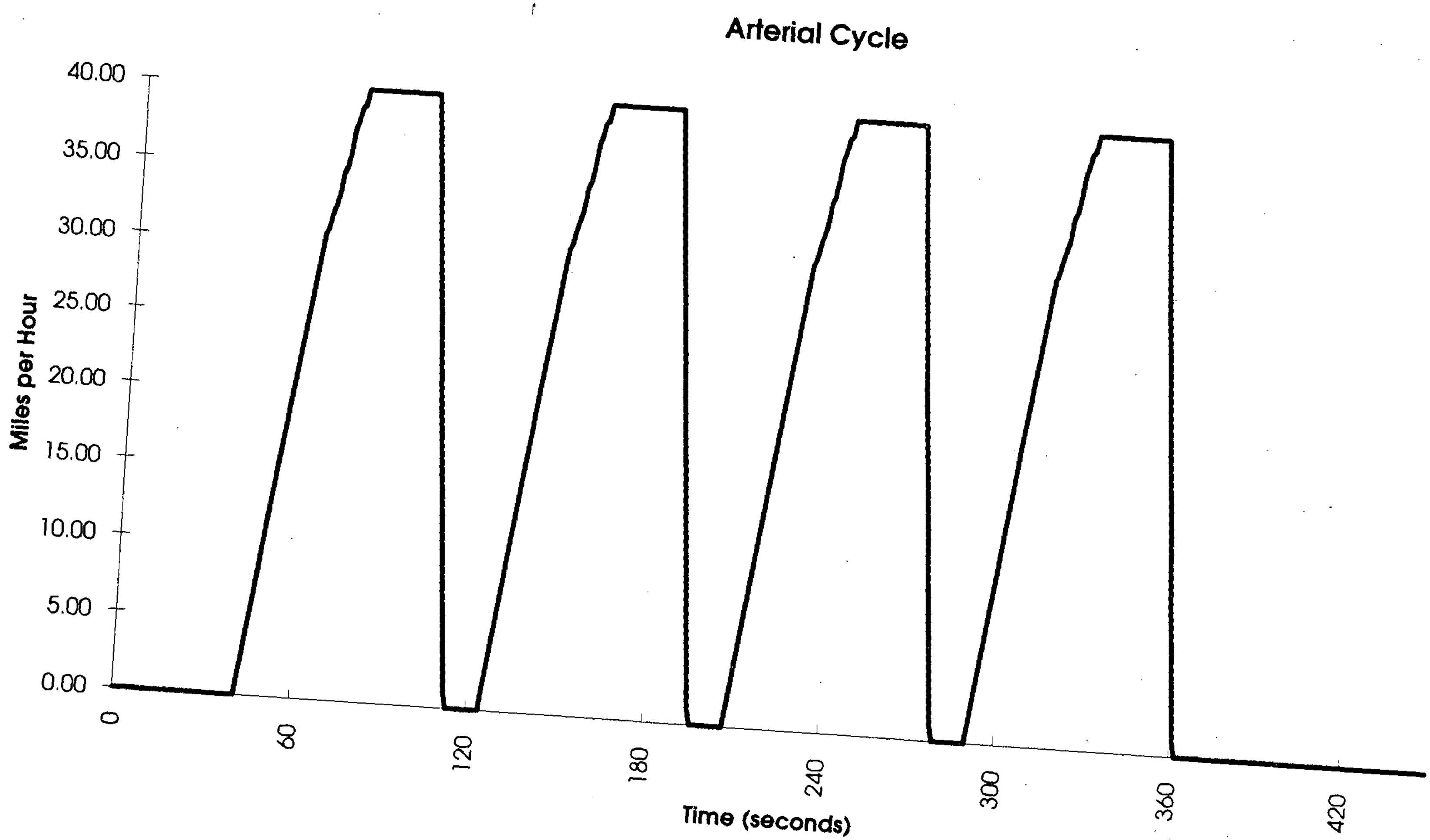

New York Bus Cycle
Miles per Hour
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1.0
61.0
121.0
181.0
241.0
301.0
361.0
421.0
481.0
541.0
601.0
661.0
Time (seconds)

New York Bus Composite Cycle





Commuter Cycle
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Miles per Hour
1
61
121
181
241
301
361
421
Time (seconds)



Arterial Cycle
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Miles per Hour
0
60
120
180
240
300
360
420
Time (seconds)