Environment Canada
Conservation & Protection

Emissions from Two Diesel Fueled Urban Transit Buses

Technical Report

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1.0 EXECUTIVE SUMMARY

In December 1990, Environment Canada's Mobile Source Emissions Division (MSED) was contracted by Ontario Bus Industries Inc. (OBI) to participate in a joint project to characterize the exhaust emissions from two, diesel fueled, urban transit buses.

The project had several objectives. The main objective was to obtain a better understanding of the relationship between chassis and engine emissions testing and to create a baseline for future projects with similar vehicle/engine configurations operating on fuels other than diesel. Other objectives of the project included; an investigation into the vehicle loading and duty cycle effect upon emission rates from the vehicle and the effect of engine horsepower on the emissions performance under identical operation conditions. The final goal of the project was to reproduce emission tests which had been conducted previously at another facility.

The vehicles were 1990 ORION 45 Passenger City Buses, powered by the diesel fueled, Cummins in-line, 6-cylinder, turbocharged L-10 engine. Prior to installing the engines in the vehicles, they had undergone emissions certification at the Southwest Research Institute (SwRI) in San Antonio Texas. The results of the engine emissions certification tests are presented here with the permission of the Ontario Bus Industries Inc.

During the testing at the Environment Canada facility, the emission rates of hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), aldehydes (HCOH) and total particulate (PM), were determined over various driving cycles. The test cycles which were implemented for the project included the EPA Heavy Duty Chassis Transient Cycle (HDTC), the Central Business District Cycle, the New York Bus Cycle (non-freeway) and the New York Bus Composite Cycle.

This paper describes the gaseous and particulate emission results from all of the above testing and compares the results of the HDTC tests to those obtained during the engine emissions certification tests.

2.0 INTRODUCTION

Exhaust emissions from urban transit buses have been considered a significant source of ambient air pollutants for some time. These vehicles are quite visible to the urban population and hence their emissions of smoke and odorous compounds are perceived as obvious contributors to air pollution problems.

The US Environmental Protection Agency (US EPA) considered the problem serious enough to introduce very stringent emissions standards. As of 1988 all engines in vehicles with a gross vehicle weight equal to and above 8,500 pounds were classified under the emission label of heavy duty engine (1). This grouping encompassed a wide range of vehicles and engine sizes, with a broad spectrum of applications. However, the city bus received special notice under the proposed 1991 emission standards when this class of vehicle was singled out for a reduced particulate standard of 0. 1 grams per brake horsepower hour (g/bh-hr), compared to the 0. 25 g/bh-hr level for all other vehicles/engines in this category. The proposed regulation would require the trucks to reach the 0. 1 standard by 1994.

Although the 1990 Clean Air Act in the U. S. delayed the bus specific standard until 1993, (all engines will be required to be at the 0. 1 level by 1994), the proposed legislation had already initiated or encouraged efforts by the engine manufacturers to develop advanced electronic engine control technologies and/or alternatively fueled engines, to meet the lower standard.

Since emissions certification for this class of vehicle are done on an engine dynamometer and the emission rates are determined in terms of grams per brake specific horsepower (g/hp-hr), the translation into emission factors for on-road applications is questionable. The EPA Recommended Practice (2) for determining the exhaust emissions from heavy duty vehicles, and the applied heavy duty chassis transient cycle, provides the basis for obtaining emission rates from this type of vehicle under transient conditions in grams per mile. It also creates an opportunity to compare those emission rates to those obtained from the engine test procedure.

Heavy duty chassis tests were performed in the early 1980's in order to create a database of emissions from heavy duty vehicles and as an extension of the project, to investigate the relationship between engine and chassis emissions testing [3,4]. Since this work, there have been very few reported studies which have investigated the emissions from urban buses or the relationship between the engine and chassis testing procedure.

The shortfall of information in this area is largely due to the lack of facilities with the necessary instrumentation for the testing and characterization of the emissions from both the vehicle and the engine. In this project, the opportunity for comparison was created when two independent events occurred. First, the engines which were to be installed into the ORION buses were certified at the Southwest Research Institute and second, the Mobile Source Emissions Division (MSED) had installed and commissioned a heavy duty chassis dynamometer with complete emissions characterization instrumentation at the Environment Canada facility in Ottawa.

The purpose of this project was to obtain a better understanding of the relationship between the two types of testing and to create a baseline of chassis emission rates for future tests on other buses built by Ontario Bus Industries. In addition to the main objective, testing was performed over other driving cycles to investigate the effect of duty cycle on the emission rates and at three inertia weight settings to investigate the effect of vehicle weight on those emission rates. Finally, one bus was tested under two engine horsepower calibrations to investigate its effect on the emissions from the vehicle.

3.0 DESCRIPTION OF EVALUATION

This section describes the vehicles, the fuels, the test cycles, and the test procedures used in the chassis emissions program. A description of the dynamometer, the sampling system and the analytical procedures for the test program is also provided. Emission measurements were performed using the exhaust emission analysis procedures as found in the Canadian Motor Vehicle Safety Act (CMVSA).

The engine testing at Southwest Research Institute was performed according to the procedures specified in the US Code of Federal Regulations, Schedule 40. They will not be described in this report.

3.1 Test Plan

The test program required the measurement of regulated emissions and aldehydes, while the vehicles were operated over the following chassis dynamometer cycles:

- Heavy Duty Chassis Transient Cycle
- Central Business District
- New York Bus Cycle
- New York Bus Composite Cycle

The regulated emissions included total hydrocarbons, carbon monoxide, oxides of nitrogen and particulate, while carbon dioxide was also measured in order to determine fuel consumption by the carbon balance method (5). The test procedure required that each vehicle be tested at least twice in each selected combination of fuel, inertia weight and engine horsepower calibration.

With the exception of the cold start phase of the Heavy Duty Transient Cycle, all tests were performed on a well warmed engine. It was felt that this was appropriate since the other cycles were selected to represent in-use emissions from a transit vehicle. The sequence and timing of the soak periods between tests were maintained as consistently as possible from test day to test day. This was imperative in order to develop a database of comparable information. *Table 1.* lists the test sequence and timetable which was followed each test day.

Full testing on the first bus was conducted with the engine calibration at 270 horsepower and then repeated following the replacement of the engine's injection pump, which reduced the engines available horsepower to 240. Testing on the second bus was conducted at the 270 horsepower setting only.

TABLE 1. - ORION Bus Daily Test Sequence

Test Description	Emissions Sampled	Test Duration (seconds)
HD Transient Test Cold Start Phase	THC, CO, NO_x, CO_2, PM Aldehydes, Methane, VOC	1060
SOAK		1200
HD Transient Test Hot Start Phase	THC, CO, NO_x, CO_2, PM Aldehydes, Methane, VOC	1060
SOAK		900
Central Business District	THC, CO, NO_x, CO_2, PM Aldehydes, Methane, VOC	600
SOAK		600
New York Bus Cycle	THC, CO, NO_x, CO_2, PM Aldehydes, Methane, VOC	600
SOAK		600
New York Composite Cycle	THC, CO, NO_x, CO_2, PM Aldehydes, Methane, VOC	1029

3.2 Vehicle Description

Table 2., lists the specifications of the two urban transit buses and their respective engines which were tested for this study. The buses were supplied to the MSED by Ontario Bus Industries (on loan from Mississauga Transit). Both were received in good condition as they were new vehicles with very little mileage accumulation. Both of the engines had been tested at the Southwest Research Institute for the Cummins Engine Company exhaust emissions inspection program and then installed into the chassis by OBI.

TABLE 2. Vehicle Description

MSED Number	91-103	91-104
OBI Number	30295	30293
Vehicle	ORION 45 Passenger Bus	ORION 45 Passenger Bus
Date of Manufacture	1990	1990
Curb Weight (pounds)	26000	26000
Vehicle Mileage (Km)	747	626
Engine Manufacturer	Cummins	Cummins
Engine Displacement (l)	10	10
Number of Cylinders	6	6
Air Intake	Turbocharged	Turbocharged
Engine Fuel Type	Diesel	Diesel

When conducting the exhaust emissions tests, the vehicles were placed on the chassis dynamometer, with the vehicle drive wheels cradled between the chassis dynamometer rolls. Fans were placed in front of, and behind the tires in order to keep them cool during the transient testing. Safety precautions included chain restraints on the rear frame assembly and wheel chocks in front of the front tires.

During an early test run some difficulty was experienced with the bus tires. It appeared as if the tread rubber was separating from the tire body due to excessive heat build up. The original tires on the vehicles were then replaced with bald tires and no further problems were encountered.

3.3 Fuel

Previous studies have shown that the broad range of properties inherent to diesel fuel can have have a significant effect on the exhaust emission rates and vehicle drivability (6). For that reason many transit properties specify their fuel directly with a supplier, but usually the fuels are Number 1 or Number 2 commercial diesel or a blend of both types.

For this project most of the tests were performed using a Number 2 diesel emission reference fuel, which has the same specifications as the fuel used at SwRI for the engine testing. Some tests were performed with the fuel which was on board the vehicles when they arrived at the MSED. A sample of the commercial fuel was analyzed by the Alberta Research Council. The results of that analysis, and the fuel properties of the emissions reference fuel are listed in *Table 3.*

TABLE 3 - Diesel Fuel Specifications

Item	Commercial Diesel Fuel	Reference Diesel Fuel
Cetane Number	43.6	45. 0
Distillation Range:		
IBP, °F	348.8	364
10%, °F	384.8	430
50%, °F	445.1	506
90%, °F	533.3	581
EP, °F	592.7	626
Gravity, API	35.3	34. 5
Total Sulfur, %	0.14	0. 297
Hydrocarbon Composition:		
Aromatics, %	25.6	38. 8
Paraffins, Olefins	74.4	61. 2
Napthalenes		
Flash Point, °F	131	176

3.4 Chassis Dynamometer Testing and Test Cycles

The chassis dynamometer testing procedures followed in this project program were specified by the US Environmental Protection Agency report entitled "*Recommended Practice for Determining Exhaust Emissions from Heavy Duty Vehicles Under Transient Conditions*" (2). The sampling and test procedures are very similar to those described for light duty vehicle emissions certification testing. As with the light duty testing, the various driving cycles implemented for the project provide a speed versus time profile which the driver of the vehicle attempts to match with the vehicle on the dynamometer rolls.

The dynamometer used for this project was a single axle Clayton heavy duty chassis dynamometer. The system has twin rolls (split) 8.65 inches in diameter, 120 inches in length, and 20 inches between roll centres. Inertia simulation is provided by the connection of inertia wheels to the driven roll of the dynamometer. The MSED dynamometer is capable of simulating inertia weights from 10,000 to 45,000 pounds. Road power, or Road Load Horsepower, is simulated by an electric DC reversible machine rated for 300 horsepower. The electronic programming feature of the dynamometer controller allows the operator to develop a speed-power curve for the test vehicle. In order to calculate the this curve the following equation is used:

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

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 EPA recommended procedure, the inertia setting for bus testing is equal to the sum of the empty bus weight, plus half passenger load and the driver (at 150 pounds per person) and the equivalent weight of the non-rotating wheel assemblies [6]. For these buses the inertia simulation as calculated from above was 29,600 pounds. Ontario Bus Industries requested that the bus be tested to simulate full load, empty load and at a much lower weight to match testing performed at another facility. *Table 4*, lists the test inertia weights and their corresponding Road Load Horsepower at 50 miles per hour.

TABLE 4. Inertia Weight and Road Load Horsepower Settings

Vehicle Configuration	Inertia Weight Pounds	Road Load Horsepower @ 50 mph
Fully Loaded	33000	81.2
Empty	26000	72.4
†Selected	19500	38.2†

† *At this setting the above calculation was not followed as it was an attempt to match another testing facility which does not calculate road load in this manner.*

Four driving cycles, or tests, were implemented for this project. The first test was the Heavy Duty Chassis Transient Cycle (HDTC) which was derived from the same on-road vehicle data as was used to develop the engine transient test cycle (7). This test consisted of two driving cycles during which the exhaust was sampled and a soak period between the cycles when the vehicle was shut off and no sampling performed. The two driving cycles are identical and are composed of three driving patterns arranged in the order listed below.

TABLE 5. Heavy Duty Chassis Transient Cycle

Segment	Duration (seconds)	Average Speed mph	Total Distance miles
New York Non-Freeway	254	7.56	0.53
Los Angeles Non-Freeway	285	14.55	1.15
Los Angeles Freeway	267	44.94	3.33
New York Non-Freeway	254	7.56	0.53
TOTAL	1060	18.55	5.54

The second test which was performed each day used the Central Business District (CBD) driving cycle which was 600 seconds in length and consisted of 15 segments which are repeated through the test. Each segment contains an acceleration up to 20 mph, followed by a steady state at 20 mph for 20 seconds and then a deceleration to idle. The cycle is based upon the specifications for assessing bus performance, the Advanced Design Bus cycle.

The third test which was performed each test day used the New York Bus Cycle which simulates non-freeway driving in New York City. This cycle is 600 seconds in duration with an average speed of 3. 89 mph (6. 26 Km/hr) and a total distance of 0.65 miles (1. 04 Km).

The final test was performed over the New York Bus Composite Cycle, which was derived from a study of buses during in use service in New York City. The driving trace consists of both non-freeway and freeway operation with an average speed of 8. 77 mph (14. 12 Km/hr) and total distance of 2. 51 miles (4. 04 Km).

3.5 Emission Measurement Methodology

The regulated gaseous emission measurements of total hydrocarbons, carbon monoxide, oxides of nitrogen, particulate and carbon monoxide were performed in accordance with the EPA recommended practice for heavy duty chassis testing where possible and applicable. Additional sampling was performed for the determination of the emissions rates of 11 aldehyde/ketone compounds.

The gaseous and particulate emissions were obtained using a large single dilution constant volume sampler (CVS). The CVS is composed of a stainless steel dilution tunnel ten inches in diameter and one hundred inches in effective length, coupled to a secondary dilution tunnel for particulate collection in accordance with accepted procedures. The main system incorporates the principle of critical flow with a venturi, to provide a constant mass flow and to enable the determination of instantaneous and cumulative volumetric flow of the dilute exhaust. During this test a flow rate of 1,050 standard cubic feet was selected.

This flow rate ensured that sufficient dilution air was introduced into the tunnel, that when combined with the in-line heat exchanger, the temperatures at both the gaseous sample probe and the heated hydrocarbon probe, were within the accepted limits for heavy duty vehicle testing. The gaseous sampling zone contained two proportional sampling probes. One sample flow was drawn from the probe to tedlar bags for temporary storage until analysis could be performed. The other sample probe provided a gaseous sample which was drawn through dintrophenyl hydrazine coated silica gel cartridges for aldehyde collection.

The bagged samples were analyzed for carbon monoxide and carbon dioxide using non-dispersive infrared detectors and oxides of nitrogen using a chemiluminesence detector. A heated NOx instrument and sampling train is preferred for this type of testing but was not available for the project. A study at SwRI demonstrated that the bag NOx was normally 7% lower than the result when measured continuously using the heated system. Total hydrocarbon measurements were performed on a continuous basis using a heated probe, filter and sample line, coupled to a heated flame ionization detector. Aldehyde measurements were performed using a liquid chromatograph.

The particulate was collected on 70 mm Pallflex T60A20 filters using the double dilution technique. The particulate sampling system consisted of: one inch diameter, polished stainless steel probe, through which a sample of the dilute exhaust from the main tunnel was directed into the secondary dilution tunnel. Dilution air was introduced into the front of the second tunnel at a controlled rate, while a sample was drawn through a sample probe at the end of the tunnel and through a 70 mm teflon coated glass fiber filter. The volume of the dilution air and the volume of the sample which had been drawn through the filter, were measured and displayed by mass flow meters and digital displays. Temperatures at the main tunnel sample probe and the secondary tunnel sample probe were monitored to ensure compliance with accepted test guidelines.

4.0 RESULTS

4.1 Emission Measurements

Two urban buses were tested over four driving cycles, under three simulated vehicle loading conditions. In addition the first bus was tested with an engine which was calibrated to produce 270 horsepower and then modified to reduce the available horsepower to 240. The second bus was tested at the 270 horsepower state only. Both buses were tested at full load using commercial fuel and emissions certification fuel.

This section describes the results of the emissions measurements which were performed during this project.

4.1.1 Regulated Emissions

The emission rates of carbon monoxide, carbon dioxide, oxides of nitrogen, total hydrocarbons, particulate mass, formaldehyde and total aldehydes are presented in *Tables 6 through 10*, for bus number 30295. These tests were performed using emissions certification diesel fuel.

The emission rates of carbon monoxide, carbon dioxide, oxides of nitrogen, total hydrocarbons and particulate mass are presented in *Tables 11 to 12* for bus number 30293. These tests were performed with the engine calibrated at 270 horsepower, using commercial diesel fuel.

Fuel consumption (L/100km) is also presented and may be converted to mpg by dividing the L/100km into 282.5.

TABLE 6. Emission Rates of OBI Bus 30295

Test Cycle: Heavy Duty Transient Cycle - Cold Start

A. Engine Calibration 270 HP

Emissions (g/mi)	Vehicle Loading (%GVWR)		
	84	66	50
THC	1.25	1.00	1.23
CO	10.81	10.95	8.74
NO_X	19.33	15.72	11.97
CO_2	2359.15	1970.80	1776.80
PM	1.93	1.71	1.59
FC (L/100KM)	76.67	64.14	57.80
Formaldehyde (mg/mile)	51.04	70.09	10.97
Total Aldehydes (mg/mile)	154.77	156.66	86.06

B. Engine Calibration 240 HP

Emissions (g/mi)	Vehicle Loading (%GVWR)		
	84	66	50
THC	1.24	1.07	1.01
CO	15.11	11.26	11.05
NO_X	18.43	13.99	12.21
CO_2	2334.30	1948.52	1783.92
PM	2.59	1.95	1.97
FC (L/100KM)	76.08	63.44	58.07
Formaldehyde (mg/mile)	74.27	84.62	94.18
Total Aldehydes (mg/mile)	173.54	189.42	200.53

TABLE 7. Emission Rates of OBI Bus 30295

Test Cycle: Heavy Duty Transient Cycle: Hot Start

A. Engine Calibration 270 HP

Emissions (g/mi)	Vehicle Loading (%GVWR)		
	84	66	50
THC	1.13	1.02	1.20
CO	12.84	11.98	9.41
NO_X	19.94	15.59	12.06
CO_2	2159.10	1843.15	1578.85
PM	1.475	1.49	1.23
FC (L/100KM)	70.32	60.08	51.46
Formaldehyde (mg/mile)	47.99	61.28	30.12
Total Aldehydes (mg/mile)	116.09	142.20	116.86

B. Engine Calibration 240 HP

Emissions (g/mi)	Vehicle Loading (%GVWR)		
	84	66	50
THC	1.09	1.01	0.99
CO	20.20	11.03	11.74
NO_X	18.70	13.84	12.43
CO_2	2127.63	1750.53	1636.44
PM	2.36	1.58	1.50
FC (L/100KM)	69.68	57.85	53.41
Formaldehyde (mg/mile)	77.74	79.13	84.66
Total Aldehydes (mg/mile)	166.79	170.34	183.67

TABLE 8. Emission Rates of OBI Bus 30295

Test Cycle: Central Business District

A. Engine Calibration: 270 HP

Emissions (g/mi)	Vehicle Loading (%GVWR)		
	84	66	50
THC	1.36	1.69	1.88
CO	26.80	21.97	17.35
NO_X	27.59	20.32	16.03
CO_2	2950.80	2497.65	2166.10
PM	3.075	2.52	2.05
FC (L/100KM)	96.55	81.74	70.85
Formaldehyde (mg/mile)	114.47	145.26	148.32
Total Aldehydes (mg/mile)	237.23	276.89	267.27

B. Engine Calibration: 240 HP

Emissions (g/mi)	Vehicle Loading (%GVWR)		
	84	66	50
THC	1.63	1.67	1.19
CO	48.09	21.55	23.12
NO_X	25.96	17.61	16.76
CO_2	3069.97	2254.78	2214.13
PM	4.76	2.34	2.76
FC (L/100KM)	101.49	73.89	72.61
Formaldehyde (mg/mile)	132.73	136.87	132.95
Total Aldehydes (mg/mile)	260.98	248.88	250.20

TABLE 9. Emission Rates of OBI Bus 30295

Test Cycle: New York Bus Cycle

A. Engine Calibration: 270 HP

Emissions (g/mi)	Vehicle Loading (%GVWR)		
	84	66	50
THC	3.67	2.90	3.33
CO	76.08	76.81	53.20
NO_X	37.16	36.06	27.54
CO_2	5360.05	4946.00	4035.35
PM	8.83	8.31	6.36
FC (L/100KM)	176.88	163.50	133.02
Formaldehyde (mg/mile)	332.23	341.09	356.57
Total Aldehydes (mg/mile)	597.15	666.63	643.72

B. Engine Calibration: 240 HP

Emissions (g/mi)	Vehicle Loading (%GVWR)		
	84	66	50
THC	2.95	3.72	3.42
CO	148.26	54.50	103.81
NO_X	50.45	33.67	35.40
CO_2	6470.13	4508.09	5000.42
PM	1.42	6.94	1.15
FC (L/100KM)	216.22	148.35	166.67
Formaldehyde (mg/mile)	401.78	420.70	346.71
Total Aldehydes (mg/mile)	736.07	786.96	639.13

TABLE 10. Emission Rates of OBI Bus 30295

Test Cycle: New York Composite Cycle

A. Engine Calibration: 270 HP

Emissions (g/mi)	Vehicle Loading (%GVWR)		
	84	66	50
THC	1.40	1.55	1.32
CO	39.21	31.30	25.54
NO_X	22.95	17.48	14.94
CO_2	2756.2	2395.30	2132.85
PM	5.57	3.69	3.06
FC (L/100KM)	90.91	78.90	70.13
Formaldehyde (mg/mile)	44.90	45.39	44.0
Total Aldehydes (mg/mile)	81.00	89.20	90.59

B. Engine Calibration: 240 HP

Emissions (g/mi)	Vehicle Loading (%GVWR)		
	84	66	50
THC	1.72	2.32	1.82
CO	56.41	19.00	37.88
NO_X	22.13	17.80	15.73
CO_2	2895.00	2220.93	2188.68
PM	5.85	2.65	4.39
FC (L/100KM)	96.28	72.74	72.60
Formaldehyde (mg/mile)	45.37	45.61	43.33
Total Aldehydes (mg/mile)	83.81	83.02	81.99

TABLE 11. Emission Rates of OBI Bus 30293

Test Cycle: Heavy Duty Transient Cold Start

A. Engine Calibration: 270 HP

Emissions (g/mi)	Vehicle Loading (%GVWR)	
	84	**66**
THC	1.09	1.05
CO	12.25	9.10
NO_X	16.14	10.55
CO_2	2133.81	1674.59
PM	2.11	1.65
FC(L/100KM)	69.42	54.51
Formaldehyde (mg/mile)	97.54	108.78
Total Aldehydes (mg/mile)	206.27	223.87

Test Cycle: Heavy Duty Transient Hot Start

B. Engine Calibration: 270 HP

Emissions (g/mi)	Vehicle Loading (%GVWR)	
	84	**66**
THC	1.00	0.97
CO	13.74	8.69
NO_X	16.62	9.69
CO_2	1954.99	1453.64
PM	1.69	1.15
FC(L/100KM)	63.74	47.36
Formaldehyde (mg/mile)	108.38	113.82
Total Aldehydes (mg/mile)	214.16	221.13

TABLE 12 - Emission Rates of OBI Bus 30293

Central Business District A. Engine Calibration 270 HP			New York Bus Composite Cycle A. Engine Calibration 270 HP			New York Bus Cycle B. Engine Calibration 270 HP		
Emissions (g/mi)	Vehicle Loading (% GVWR)		Emissions (g/mi)	Vehicle Loading (% GVWR)		Emissions (g/mi)	Vehicle Loading (% GVWR)	
	84	66		84	66		84	66
THC	1.49	1.48	THC	2.14	1.53	THC	3.81	3.06
CO	27.86	17.37	CO	36.87	21.58	CO	81.95	49.11
NO_x	20.25	11.91	NO_x	18.31	12.20	NO_x	35.00	24.10
CO_2	2586.74	1772.71	CO_2	2468.28	1814.98	CO_2	5054.99	3687.34
PM	2.97	1.85	PM	3.47	2.61	PM	8.49	5.92
FC (L/100KM)	84.83	58.13	FC (L/100KM)	81.52	59.71	FC (L/100KM)	167.23	121.57
Formaldehyde (mg/mile)	230.73	200.91	Formaldehyde (mg/mile)	45.56	44.87	Formaldehyde (mg/mile)	545.69	498.28
Total Aldehydes (mg/mile)	363.40	351.61	Total Aldehydes (mg/mile)	81.39	78.92	Total Aldehydes (mg/mile)	933.13	883.74

5.0 DISCUSSION

5.1 Chassis versus Engine Dynamometer Results

Engine dynamometer testing yields emission rates in grams per horsepower hour. Translation of these results into grams per mile can be calculated based upon an assumed equivalent vehicle distance of 6.396 miles for the engine transient cycle. *Tables 13 and 14* list the emission results of both buses and the corresponding engine test results converted to grams per mile (using 6.396 miles). The chassis test results for each of the inertia weight settings used in the study, are presented in order to determine which condition yielded the closest agreement to the engine tests.

TABLE 13. Comparison of Emissions from Chassis and Engine Dynamometer Tests
Heavy Duty Transient Cycle - Emission Rates (g/mile)

Inertia Weight	Test Phase	THC		CO		NOx		PM	
		Chassis	Engine	Chassis	Engine	Chassis	Engine	Chassis	Engine
BUS #30295									
33,000	CS HS	1.25 113	2.08 1.93	10.81 12.84	8.99 9.60	19.33 19.94	14.10 15.76	1.93 1.48	1.44 1.39
26,000	CS HS	1.00 1.02	2.08 1.93	10.95 11.98	8.99 9.60	15.72 15.59	14.10 15.76	1.71 1.49	1.44 1.39
19,500	CS HS	1.23 1.20	2.08 1.43	8.74 9.41	8.99 9.60	11.97 12.06	14.10 15.76	1.59 1.23	1.44 1.39
BUS #30293									
33,000	CS HS	1.07 1.00	2.75 2.11	12.25 13.74	8.27 9.16	16.14 16.62	14.31 15.75	2.11 1.41	1.65 1.44
19,500	CS HS	1.05 0.97	2.75 2.11	9.10 8.69	8.27 9.16	10.55 9.69	14.31 15.75	1.65 1.15	1.65 1.44

TABLE 14. Comparison of Engine and Chassis Emission Rate Difference (based on gram/mile) Percentage Difference Between Chassis and Engine Emission Rate

Inertia Weight	Test Phase	THC	CO	NO_X	PM
OBI Bus #30295					
33,000	CS HS	-40 -41	20 34	37 26	34 6
26,000	CS HS	-52 -47	22 25	11 -1	19 7
19,500	CS HS	-41 -38	-3 -2	-15 -24	10 -12
OBI Bus #30293					
33,000	CS HS	-61 -53	48 50	13 6	28 -2
19,500	CS HS	-62 -54	10 -5	-27 -38	0 20

In general, the chassis HC emission rates were significantly lower than the engine HC rate and showed the least amount of agreement of any of the compared emissions.

The chassis CO emission rate for Bus 30295 was usually higher, but showed good agreement at the 19,500 pound setting and reasonable agreement at the other inertia weights. Agreement was especially poor for Bus #30293 at the 33,000 pound setting.

The chassis NO_X emission rate was greater than the engine result at the highest inertia setting and lower at the lowest inertia tests. Best agreement was observed at the 26,000 pound setting for Bus #30295, which could be expected due to the indicated relationships between NO_X chassis emissions and inertia weight setting.

Particulate emission rates were usually greater for the chassis tests, but showed good agreement for the hot start phase of the 26,000 pound and 33,000 pound tests.

Overall, with the exception of hydrocarbons, the chassis transient tests yielded higher emission rates than the engine tests. This may be attributed to the assigned equivalent vehicle distance (6.693 miles) of the engine test cycle, which may be a high estimate thus producing lower emission rates.

Another method which has been used to compare chassis to engine dynamometer test results, calculates the emissions per kilogram of fuel consumed. This technique avoids the unsureness associated with using an equivalent distance. The results of this calculation are presented in *Table 15* and compared in terms of percentage difference between chassis and engine results in *Table 16* . The results of the g/mile determination are also presented in *Table 16* to illustrate any improvement through the fuel specific emission rate.

On the basis of fuel specific emission rates, it appears that the chassis testing yields lower emission rates in all cases and produces a lesser amount of agreement between the two test methods, (with a few exceptions).

TABLE 15. Comparison of Emissions from Chassis & Engine Dynamometer Tests - OBI Bus #30295 Heavy Duty Transient Cycle (g/kg fuel)

	Test Phase	THC	CO	NO_X	PM
33,000 IW Chassis	CS HS	3.54 3.45	15.25 17.15	23.93 28.15	2.445 2.48
26,000 IW Chassis	CS HS	1.22 1.33	10.54 13.62	18.84 21.15	1.881 1.565
19,500 IW Chassis	CS HS	1.16 1.27	12.74 14.87	18.29 19.35	1.990 1.850
Engine Result	CS HS	1.59 1.74	11.29 13.66	15.46 17.51	2.054 1.785

TABLE 16 - Comparison of Engine and Chassis Emission Rate Differences based on g/kg fuel and g/mile - Percentage Difference Between Chassis and Engine Emission Rate
OBI Bus #30295 - Heavy Duty Transient Cycle

Inertia Weight	Test Phase	THC		CO		NO_x		PM	
		g/kg	g/mile	g/kg	g/mile	g/kg	g/mile	g/kg	g/mile
33,000	CS	-66	-40	-31	20	-21	37	-23	34
	HS	-62	-41	-21	34	-25	26	-37	6
26,000	CS	-67	-52	-16	22	-23	11	-19	19
	HS	-63	-47	-13	35	-31	-1	-25	7
19,500	CS	-55	-41	-28	-3	-35	-15	-16	10
	HS	-49	-38	-20	-2	-38	-24	-28	-12

In conclusion, chassis transient testing produces emission results which do not show good agreement with the engine transient testing. A previous study (4) observed the same results and suggested that this may be largely due to the effect of the automatic transmission on the chassis results.

5.2 *Inertia Weight Effect on Exhaust Emissions*

As described earlier, inertia simulation, during chassis testing of transit buses, is normally set at; the sum of the empty vehicle weight plus half passenger load (plus the driver) at 150 pound per person, plus the equivalent inertia weight of the non-rotating vehicle wheel assembles. After selecting the *Loaded Vehicle Weight (Inertial Setting)*, the *Road Load Power* in horsepower is then calculated.

In this study, the test sequence was repeated at three inertia settings to determine the effect of vehicle loading on the emission rates from the transit buses. The three setting selected were 33,000, 26,000 and 19,500 pounds, or 84%, 66% and 50% of the rated *Gross Vehicle Weight*. The 84% and 66% settings were thought to be representative of the fully loaded and empty vehicle conditions.

The tests at the lowest selected inertia setting, 19,500 pounds, were performed to provide comparison data to previous emissions tests at another test facility. The following paragraphs compare the results at the highest two settings, since the 19,500 load is not representative of on-road conditions.

Vehicle: OBI Bus #30295 (See Tables 6-10)

Since testing was performed on this vehicle at two different engine horsepowers, the results are discussed for each of the settings on each of the driving cycles. Observations are made with respect to the decrease on load.

With the engine operating at 270 horsepower over the HDTC, inertia had little effect upon the emission rates of THC and CO, but differences were observed for NO_X, particulate and fuel consumption as these results decreased with reduced load. At the lower engine horsepower setting (240), the emission rates of THC, CO, NO_X and particulates all decreased with the lower inertia setting.

Over the CBD, both engine calibrations demonstrated a decrease in CO, NO_X and particulates while the THC increased for the 270 HP engine and was unchanged for the 240 HP tests.

On the NYBC, the 270 HP emission rates of THC were lowered with decreased load, while the other emissions were unchanged. The 240 HP tests showed an increase in THC and particulate and a decrease in CO and NO_X, between the 84% and 66% GVW tests.

On the New York Composite Cycle, the 270 HP tests showed a slight increase in THC and a decrease in CO, NO_X and particulate, with reduced load. At the 240 HP setting THC again increased, while CO, NO_X and particulate emission rates were significantly decreased.

Over each of the duty cycles and at both engine calibrations, fuel consumption was seen to decrease with reduced load.

Vehicle: OBI Bus #30293 - Engine Horsepower: 270 (See tables 11-12)

Over the HDTC, the decreased load resulted in reduced CO, NO_X and particulate, while THC seemed unchanged.

Results over the CBD cycle were similar to the previous bus, with reduced CO, NO_X and particulate rates. However the THC was not changed by the load reduction, when for the other vehicle it increased.

The NYBC demonstrated a slight reduction in THC and significant reductions in CO, NO_X and particulate emission rates.

The New York Composite Cycle had lower emission rates of THC, CO, NO_X and particulate, with reduced load. This was also observed for Bus #30295 with the exception of THC which increased slightly.

As expected, fuel consumption was lowered for each of the driving cycles with reduced vehicle loading.

5.3 Engine Horsepower Effect

The initial bus was tested with the engine in the same configuration as it was when tested on the engine dynamometer. At that time the engine had a rated horsepower of 270. Once the test program was completed, the fuel delivery pump was replaced, which reduced the available horsepower to 240. The test program was then repeated to determine the effect of the reduced power on the exhaust emissions.

Table 17. lists the observed percentage difference of the 270 and 240 engine horsepower calibrations.

Table 17. Comparison of Emission Rates 240 HP VS 270 HP Engine Powers
Percentage Difference

	HDTC (CS)	HDTC (HS)	CBD	NYBC	NYCC
THC	-0.8	-4	20	-20	22
CO	40	57	79	95	44
NO_X	-5	-6	-6	36	-4
CO_2	-1	-1	4	21	5
PM	34	60	55	-84	5
FC	-0.8	-0.9	5	22	6

Over the HDTC, the emission rates of THC and NO_X and the fuel consumption, were similar, but obvious increases in CO and particulate were observed for the reduced HP engine. These results were also observed during the test over the Central Business District Cycle. There was however, a greater difference in THC, which increased by 20% with the decreased engine power.

Results over the New York Composite Cycle followed some of the patterns of the CBD results, with a 22% increase in THC and increased CO, while NO_X and fuel consumption were similar for both engine settings. Particulate did not follow the trend as it was apparently only sightly affected by reducing engine horsepower, (5% increase).

The New York Bus Cycle maintained the trend towards higher CO with decreased power. However, THC and particulate decreased while NO_X and fuel consumption increased, each of which was opposite to the results on the other cycles. This cycle, which is 600 seconds in duration and has an average speed of 3.39 mph, was designed to simulate congested urban district operation of city buses. It combines a large amount of idle with rigorous acceleration and deceleration and very little steady state operation. The replacement of the fuel pump (reduced HP) has resulted in significant decreases in particulate and THC but at a cost of increasing the emission rates of CO, NO_X and the fuel consumption. This may be representative of the classic trade off between NO_X and THC/PM emission rates.

Over the other test cycles; HDTC, CBD and NYCC, the following list summarizes the overall average effect of decreasing the engine horsepower.

Emission	*Average Percent Change*	*Standard Deviation*
NO_X	-5.09	1.05
CO	55.0	15.5
Particulate	38.5	22.0
*THC	9.6	11.8
*Fuel Consumption	2.3	3.2

5.4 Duty Cycle Effect Upon Emissions

The effect of the driving cycle has been evident in each of the previous discussion sections, where results for each exhaust emission may have differed from one cycle to another. An example of this is the engine horsepower effect on the particulate emission rate. During testing over the HDTC, CBD and NYCC, the particulate increased, while for the NYBC it was significantly decreased. Therefore, it may be said that the loading or duty cycle differed in such a way as to cause this result. *Table 18.* looks at the results of the testing of Bus #30295 at the 270 HP engine calibration and the averaged emission rates under the 33,000 and 26,000 pound loading.

TABLE 18. Averaged Emissions Rates for Bus 30295 at 33,000 and 26,000 Pound Inertia Weights 270 HP Engine

	HDTC (CS) (g/mile)	HDTC (HS) (g/mile)	CBD (g/mile)	NYBC (g/mile)	NYCC (g/mile)
THC	1.13	1.08	1.53	3.29	1.48
CO	10.88	12.41	24.39	76.45	35.25
NO_X	17.53	17.77	23.96	36.61	20.22
PM	1.82	1.49	2.80	8.57	4.63
FC (L/100 km)	70.4	65.2	89.1	170.2	84.9

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From *Table 18*, the following observations can be made:

The emission rates of the above components differ significantly from the HDTC, to the other three cycles, with the HDTC emission rates being lower in all cases.

The New York Bus Cycle yields the highest emission rates of each of these components.

The CBD and NYCC emission rates are similar for THC and NO_X, but show a difference in CO and particulate which are reduced on the CBD cycle.

Fuel consumption is lowest over the HDTC and greatest over the NYBC. Similar fuel consumption rates were observed over the CBD and NYCC. This was also observed in the emission rates of THC and NO_X.

5.5 Chassis Emission Tests Comparison

Chassis emissions testing on transient buses has been ongoing at the New York City's Mobile Systems Laboratory. The information generated by this testing is useful in pollution modeling, emission inventory studies and other programs undertaken by the department, or the New York City Transit Authority.

This study has attempted to duplicate the loading conditions of the NY dynamometer to compare the results from the two facilities. In order to duplicate the testing, the MSED performed testing at 19,500 pounds inertia weight and attempted to generate a power curve to match that of the NY city laboratory. The following tables compare the results of the two labs over the New York Bus and New York Composite Cycles.

TABLE 19. Comparison of Emission Rates (g/mile) - Environment Canada VS New York City Lab

Component	New York Bus Cycle			New York Composite Cycle		
	MSED 270 HP	MSED 240 HP	NY City	MSED 270 HP	MSED 240 HP	NY City
THC	3.33	3.42	7.18	1.32	1.82	4.52
CO	53.20	103.81	35.04	25.54	37.88	22.97
NO_X	27.54	35.40	48.01	14.94	15.73	41.55
PM	6.36	1.15	4.39	3.06	4.39	1.67

Agreement between the facilities appears very poor. Contributing to this is the difference between the equipment and procedures, as well as the vehicles tested. It should be noted that the New York lab results were for 122 buses.

Emission rates ranged a great deal for this testing, ie: CO on the NY Bus Cycle had an average of 35.04 but a standard deviation of 36.06, with a maximum value of 192 g/mile.

Real correlation between facilities can only be performed under strictly controlled conditions. The above comparison does not reflect on either facility since the comparison was not strictly defined.

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8.0 APPENDICES

A.1 *Emission Results of Bus 30295 with the engine at 270 horsepower*

A.2 *Emission Results of Bus 30295 with the engine at 240 horsepower*

A.3 *Emission Results of Bus 30293 with the engine at 270 horsepower*

A.4 *Aldehyde Emission Results - All tests*

A.5 *Driving Cycle Traces*