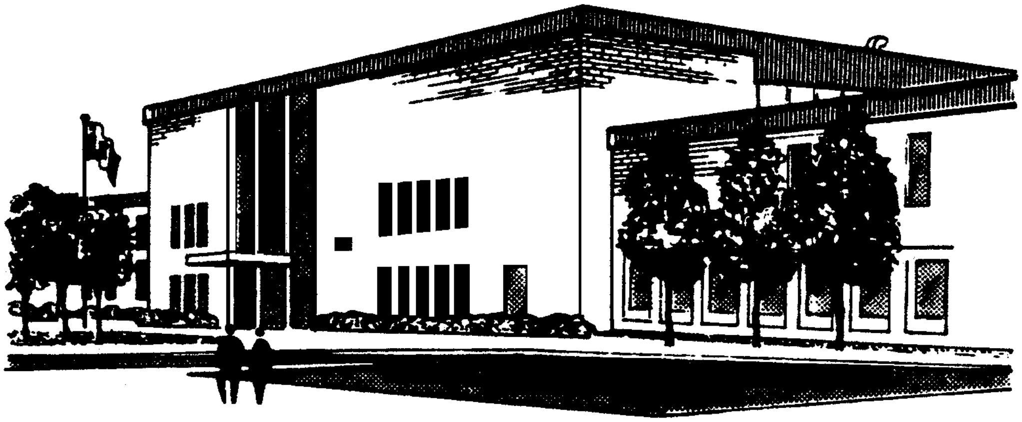
Diesel Particulate Filter (DPF) Demonstration



ERMD REPORT # 02-17

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Executive Summary

Public awareness with regard to harmful emissions arising from transportation in urban centers is increasing; as a result governments and industry are under growing pressure to curb the rise of vehicle emissions. In January 2003, a pilot project was initiated in Edmonton, Alberta to investigate ways of improving urban air quality by reducing emissions from urban transit buses. Under this project, two diesel buses were retrofitted with a diesel particulate filter (DPF) system developed by Johnson Matthey and operated on a Shell diesel fuel containing less than 50 ppm sulphur.

The Emissions Research and Measurement Division (ERMD) of Environment Canada undertook exhaust emission measurements of the two Edmonton Transit 40' New Flyer buses in their original configurations (OEM), and with Johnson Matthey's Continuously Regenerating Technology (CRT®). In most programs, these types of measurements are undertaken in a laboratory under tightly controlled conditions. However, the purpose of this field study was to evaluate the emission reductions that a CRT would have on these vehicles driven on road, in local environmental conditions.

The two buses were each fitted with a CRT on January 10, 2003 and had been operating in revenue service until ERMD began the emissions testing on February 3, 2003. The buses, which had been running on an ultra low sulfur diesel fuel (< 50ppm sulfur), were tested over the road using ERMD's Dynamic Dilution On/Off-road Emissions Sampling System (DOES2). The route taken by the bus while undergoing testing was in real city traffic with various stops and idles in order to simulate real world driving conditions. Dilute exhaust samples were analyzed for carbon monoxide, carbon dioxide, oxides of nitrogen, total hydrocarbons, and total particulate mass.

Each bus was tested over a minimum of three repeats with the CRT installed, followed by testing with it's original muffler. The results showed that there were significant reductions in the total hydrocarbon (THC), carbon monoxide (CO), and total particulate matter (TPM) emissions while the buses were operated with a CRT. One of the buses exhibited an increase in NOx emissions while the other did not. This result warrants further investigation.

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1.0 Introduction

Public awareness with regard to harmful emissions is increasing. Governments and industry are under growing pressure to curb the rise of vehicle emissions. Urban transit buses operated on diesel fuel contribute significantly to ambient air pollutants. These emissions include Oxides of Nitrogen (NOx), Carbon Monoxide (CO), Carbon Dioxide (CO_2), unburned hydrocarbons (THC), and particulate matter. These emissions are of concern for a number of reasons including, detrimental effects to human health[1], and to the environment, where they contribute to smog, acid rain, and global warming. In particular relevance to this project, the emissions of NOx and particulates are strongly associated with diesel combustion. Diesel fuelled vehicle emissions are a significant source of particulate matter less than 10 microns (PM10) which was declared toxic as defined under the Canadian Environmental Protection Act (CEPA) 1999.

In order to meet stringent new emissions standards, which will be phased in 2007-2010 (NOx limits are set to decrease from the 2004 standard of 2.4 g/bhp-hr to 0.2 g/bhp-hr; while particulate limits will decrease to 0.01 g/bhp-hr from 0.05 g/bhp-hr [2]), manufacturers have been working on various in-cylinder controls and exhaust after-treatment systems. One potential emission control system is the continuously regenerating diesel particulate filter (CRDPF). The CRDPF used in this study was the Johnson Matthey's CRT™. This system had been evaluated by the Emissions Research and Measurement Division (ERMD), under laboratory testing conditions, in conjunction with a large-scale demonstration project in New York City[3].

The objective of this study was to evaluate the exhaust emissions of two diesel powered urban transit buses retrofitted with CRDPFs in the field under real world conditions. In particular the project partners wanted to investigate the effects that Edmonton's frigid winter would have on the performance of the CRDPF. Unfortunately, the temperature range (4°C to –6 °C) during testing was less than mean temperatures for that time period[4].

Staff from the ERMD of Environment Canada traveled to Edmonton, along with a mobile sampling unit and analyzer bench, in order to collect and analyze exhaust emission samples from the buses operating under real world conditions. The project was based at Edmonton Transit's Mitchell Station, and field testing was completed within a one week time frame.

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[1] US Environmental Protection Agency. Office of Mobile Sources. Regulatory Announcement "New Emission Standards from Heavy Duty Diesel Engines Used in Trucks and Buses." EPA 420-F-97-016. 1997

[2] US-EPA Code of Federal Regulations, Schedule 40, Part 86, July 1st, 2001.

[3] Performance and Durability Evaluation of Continuously Regenerating Particulate Filters on Diesel Powered Urban Buses at NY City Transit Part 1 & 2, SAE Reports 2001-01-0511 & 2002-01-0430

[4] *Edmonton's Weather*. URL: http://www.gov.edmonton.ab.ca/transportation_streets/streets_engineering/snow_and_ice_control/edmontons_weather.html [March 24, 2003].

2.0 Vehicles

The test vehicles were New Flyer 40’ low floor buses. Details on the test vehicles are provided in Table 1.

Table 1. Test Bus Specifications

Bus #	4267	4215
Bus Model	D40LF	D40LF
Year	2001	2000
Engine Make	Cummins	Cummins
Engine serial #	46085548	46016939
Engine Mileage	99255	126303 (122485 @ install)
Power (hp)	280 @ 2200rpm	280 @ 2200rpm
Displacement	8.3L	8.3L
Number of Cylinders	6	6
Electronic controls	ECM	ECM
Emission control device	Dual substrate catalyst	Dual substrate catalyst

3.0 Test Fuels

The test fuel used for this test program was an ultra low sulfur diesel fuel (ULSD) supplied by Shell Canada. The fuel used during the testing of the buses was from the batch delivered to Edmonton Transit December 20, 2003. Samples of the fuel were taken at the Sherwood Marketing Terminal and the analysis was done by Shell Canada at the Scotford Refinery Laboratory. These fuel properties can be found in Table 2.

Table 2: Test Fuel Properties

Fuel Property	**ULSD**
Density (kg/m^3)	822.6
Carbon Fuel Fraction	0.857
Sulphur	18.7 ppm

4.0 Sampling System

The sampling set-up consisted of the DOES2 system and the following analyzers: a total hydrocarbon (THC) flame ionization detector (FID), a chemiluminescence NOx analyzer, and a non-dispersive infrared carbon monoxide analyzer (CO) and a non-dispersive infrared carbon dioxide (CO_2) analyzer.

4.1 Dynamic Dilution On/Off-road Emission Sampling (DOES2) System

The primary function of the DOES2 is to collect a known quantity of raw exhaust (partial flow) from the exhaust system of an engine and mix this with a known quantity of ambient dilution air. Diluting the raw exhaust with ambient air, while maintaining a constant temperature and flow velocity, conditions the sample and minimizes condensation, a major obstacle to particulate matter collection in the field.

To collect the raw exhaust, a probe is inserted into the exhaust pipe of the engine. The probe exit is connected to a dilution tunnel by a heated sample line which is maintained at a temperature of 375 ± 20 degrees Fahrenheit. There are two large vacuum pumps (main and dilution air supply) contained within the vacuum pump enclosure that are used for the DOES2. The main pump is connected to the exit of the dilution tunnel and it draws a continuous quantity of sample through the dilution tunnel. The dilution pump draws air through a pre-filter in order to remove any ambient particle material and then through a variable flow solenoid valve to control the flow rate of the dilution air. The air then goes through the dilution pump and into a plenum located in the DOES2, and eventually through the dilution air Laminar Flow Element (LFE) to measure the flow rate. The dilution air is introduced into the dilution tunnel at a point approximately 3 inches from the raw exhaust inlet. Both streams then pass through a mixing orifice and are thoroughly mixed as they travel approximately 10 tunnel diameters where they reach a sample probe. The volume of diluted exhaust sample is drawn using small vacuum pumps and is set and maintained by mass flow controllers. The diluted sample is collected at the end of the sample line in a Cali-5-Bond™ (5-layer) sampling bag, and is drawn through a particulate filter. This technique is used in order to determine average weighted emission rates over defined periods of operation. Figure 1 represents a schematic flow diagram of the raw sample once it enters the DOES2.

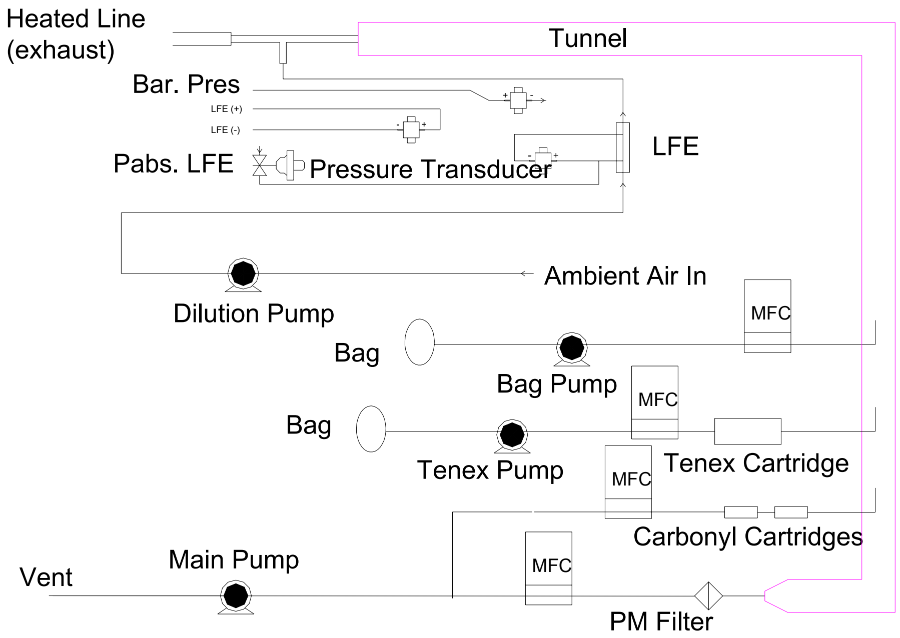

Figure 1. Schematic Flow Diagram of the DOES2

During operation, the engine functions under various speed and load conditions. As a result, the volume of exhaust varies, as does the concentration of the pollutants. In order to accurately measure the emissions under transient conditions, proportional sampling is employed. This is accomplished by varying the flow rate of the dilution air, inversely proportional with the volumetric engine inlet airflow. The instantaneous volume of dilution air is determined from the ratio of the engine inlet air mass at any given instant over the engine inlet air mass at idle. This ratio, multiplied by the exhaust sample flow at idle, is subtracted from the total mass flow rate through the tunnel (which is held constant).

$$\text{Qdil}\ (t_n) = \text{Qtotal} - \frac{[\text{engine inlet air}\ (t_n)]}{[\text{engine inlet air}\ (t_{idle})]} \times \text{Qexhaust}\ (t_{idle})$$

During testing, the engine air intake flow rates were measured using a 1000 SCFM LFE connected to the engine air inlet. The airflow is determined on a per second time basis. Prior to commencing the actual test sequence the engine inlet air volume is measured with the engine at idle.

4.2 Analyzers

The emission analyzers and associated reference calibration gases were set up in one of Edmonton transit's maintenance bays see Figure 2. The temperature of the room was maintained between 15 and 25°C.

The manually operated analysis bench, consisting of the following instruments, was used to analyze the gaseous emissions of the diluted samples:

1. Heated Flame ionization detector (HFID) for THC: the analyzer is fitted with a constant temperature oven housing the detector and sample-handling components. The detector, oven and sample-handling components must be suitable for temperatures of up to 395^{o}F maintained by the detector. H_2/He fuel is necessary for the burner operation.
2. Non-dispersive infrared detectors (NDIR) for CO and CO_2: the maximum CO_2 interference measured from the minimum water ratio must be 1000:1 for CO analyzers and 100:1 for CO_2 analyzers, whereas the maximum CO_2 interference determined from the minimum CO_2 rejection ratio for CO analyzers shall be 5000:1.
3. Chemiluminescence (CL) for NOx: the NO_2 to NO converter efficiency must be at least 90% and the CO_2 quench interference less than 3%. Since the CL is not a high vacuum analyzer, the sample must be heated to a range of 140 to 446^{o}F.

For each of the above analyzers, zero and span gases with the appropriate regulators were required at the test location for calibration. Each range of each analyzer required a span gas for this purpose.

Figure 2. Analyzers and Gas Cylinders in Edmonton Transit's Maintenance Bay

4.3 Data Acquisition

A portable industrial grade computer controls the DOES2. The computer was connected to the DOES2 at the appropriate location with the supplied cables. The computer was used to read and record the signals from the various sensors, calculate the dilution air requirement, control the variable flow solenoid valve and calculate the emission rates for each of the regulated exhaust emissions. The computer was placed inside the bus and connected to the DOES2 by two 20-pin connectors and a 9-pin serial port connector. A line from the generator through a UPS powered the computer.

The engine signals that were recorded include:

- Exhaust temperature: thermocouple located in the exhaust pipe
- Engine speed: Hall Effect sensor with magnet attached to flywheel

5.0 Vehicle Instrumentation

The bus was instrumented with various sensors to monitor the engine as it performed its duty cycle. The sensors included an engine speed sensor, an exhaust temperature probe, and a laminar flow element (lfe) for measuring air intake.

5.1 Engine Speed

The engine speed is normally measured using a rare earth magnet and a Hall effect sensor. The magnet is epoxied onto the crankshaft pulley and the Hall effect sensor is itself epoxied into a 4" long piece of stainless tubing. The pulse train from the sensor is fed into a frequency to voltage converter chip and the computer reads the corresponding voltage. Speed data, like exhaust temperature, is recorded primarily to verify the repeatability of the test cycle.

5.2 Exhaust Temperature

The exhaust temperature was measured using a K-type thermocouple installed in the exhaust manifold using an NPT to Swagelock™ fitting. The thermocouple was connected to the box using K-type extension wire connected to a high gain amplification board. The cold junction reference temperature was measured at the board.

5.3 Air Intake

The engine air intake was measured using a 1000 SCFM Laminar Flow Element (LFE). The vehicle's air filter was removed and the LFE was placed over the intake pipe using rubber air intake boots and metal adapters. The LFE was secured to the vehicle, to prevent it from moving as the vehicle completed its duty cycle, by means of ratchet straps and bungee cords. The placement of the LFE was such that the rear compartment door was unable to shut completely. This hatch was tied down to prevent damage to the bus and LFE. To measure the air intake, the pressure drop across the flow element was recorded using a differential pressure transducer mounted in the DOES2. As well, the inlet air density to the element was determined by measuring the absolute pressure and the temperature. The absolute pressure was measured using the barometric pressure for the day. The inlet temperature to the LFE was measured using a thermometer and recorded at the beginning testing. The data from the LFE was converted to a flow rate by the computer, each second.

6.0 Sampling Set up

The set up involved mounting the DOES2 and the generator on the vehicle, installing the LFE, mounting the various sensors, installing the exhaust probe and heated line, running all the lines to the DOES2 and mounting the computer on the vehicle. Figure 3. shows the DOES2 and on board computer, while Figure 4. shows the LFE mounted to the engine air intake of the test vehicle.

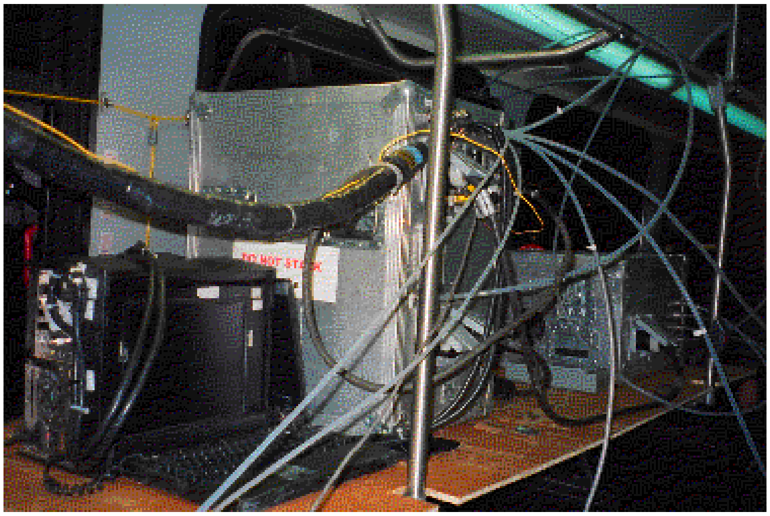

Figure 3. DOES2 and On Board Computer Fastened to Bus

Figure 4. LFE plumbed to Engine Air Intake

6.1 Mounting of DOES2 and Generator

The Honda generator was mounted to the front of the bus on an Edmonton Transit bike rack as pictured in Figure 5. The DOES2, pump box, and computer were kept in the interior of the bus. The exhaust lines from the DOES2 and pump box were diverted out a side window and strapped to the side of the bus along the extension cords to the generator.

Figure 5. Generator Mounted to Front of Transit Bus

6.2 Heated Line and Exhaust Probe

A 25’ long length of heated line connected the exhaust probe to the DOES2. The line was fed out to the exhaust pipe, from the DOES2, via the roof hatch. The exhaust probe was a piece of ½” stainless steel tubing which was bent in such a way as to fit at least 4” down inside the end of the exhaust pipe while being parallel to the flow and lying at the centre of the exhaust cross section. The probe was connected to the heated line with a Swagelock ™ fitting**.**

7.0 Test Cycle

The bus model used for testing was a low floor model New Flyer transit bus with the potential to be in use for many hours a day. Care was taken to choose a route that would simulate the normal operating conditions for a typical city bus. This operation included numerous stops and starts, traveling at various speeds depending on routes taken, and idling periods. Another goal in developing an on road test trace was to make it as repeatable as possible. One way to mitigate fluctuations in the test trace was to test at off peak hours (at night and in the afternoon). Driver error can also be a factor in test repeatability and this was buffered by having the same operator for each set of tests on each bus. The doors of the bus were opened at each stop to simulate the time to load passengers and to keep a consistent pattern. The length of the test route was 6.7 kms (4.16 miles), taken from a meter mounted in the bus wheel well, and took, on average, just under 18 minutes to complete. The route driven was a modified version of Edmonton transit's route #122, West Edmonton Mall/Westmount as seen in Figure 6. The following is a step-by-step guide to the route taken:

1. *START @ stop # 5928 154 st and 118 ave*
2. *#5368*
3. *#5806*
4. *Lights at 149 st*
5. *# 5099*
6. *Lights or #5244*
7. *#5387*
8. *#5573*
9. *#5472*
10. *#5178*
11. *#5464*
12. *#5248*
13. *#5051*
14. *#5207*
15. *#5466*
16. *#5322*
17. *#5066*
18. *#5366*
19. *#5429*
20. *#5256*
21. *Travel non stop (except for traffic signals which were red on occasion) back to Mitchell station obtaining speeds up to 60 km/h*
22. *END @ 1st garage door entrance at Mitchell Station*

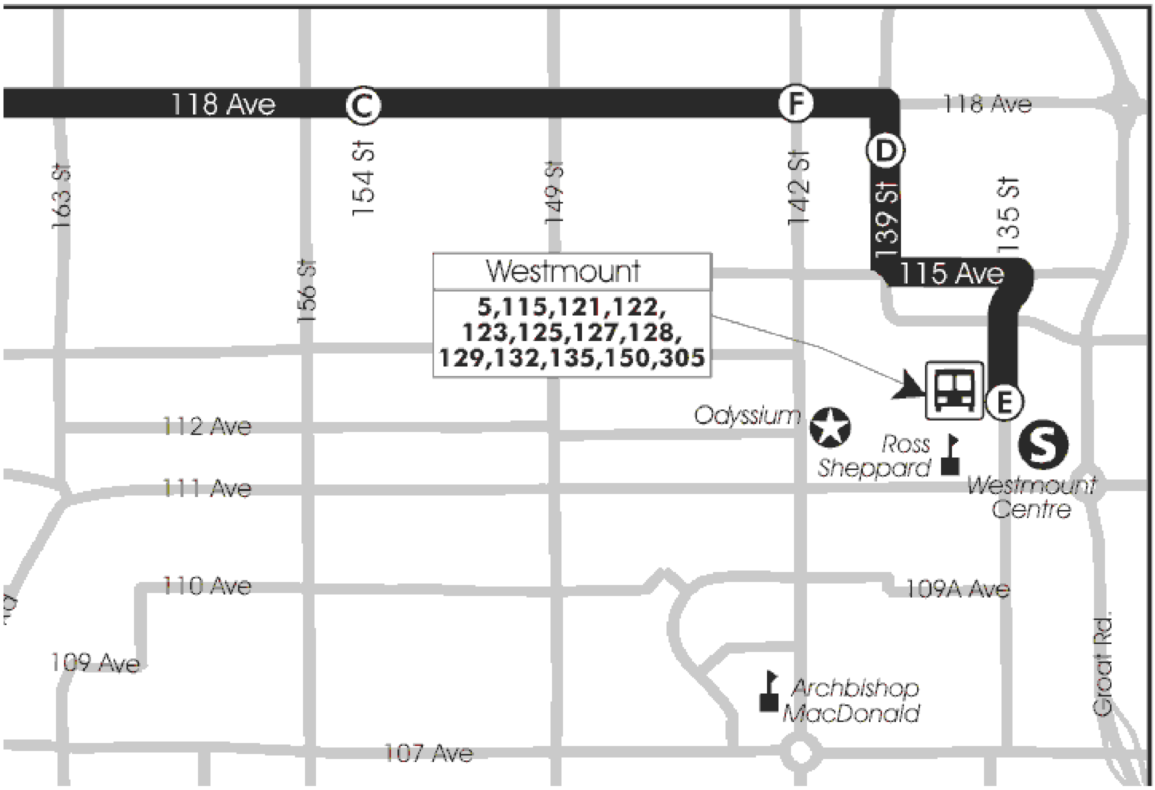

Figure 6. Section of Route #122 Used for Emissions Testing (with permission of Edmonton Transit System)

The repeatability of this test cycle is demonstrated in Figures 7. and 8. Figure 7. shows the exhaust temperatures obtained from the four tests comprising one set (February 5, 2003 bus #4215 with CRT). Figure 8. represents the engine speed (rpm) for two consecutive OEM runs for bus #4267 on February 4. As time passes, traffic, driver error, and road signals contribute to variances in the trace.

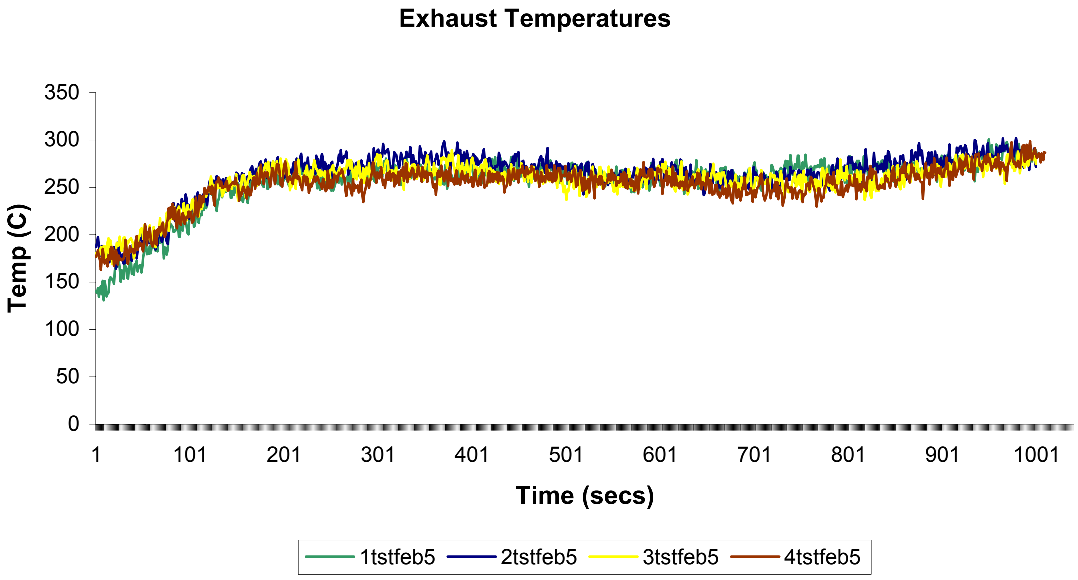

Figure 7. Engine Exhaust Temperature Over Four Tests

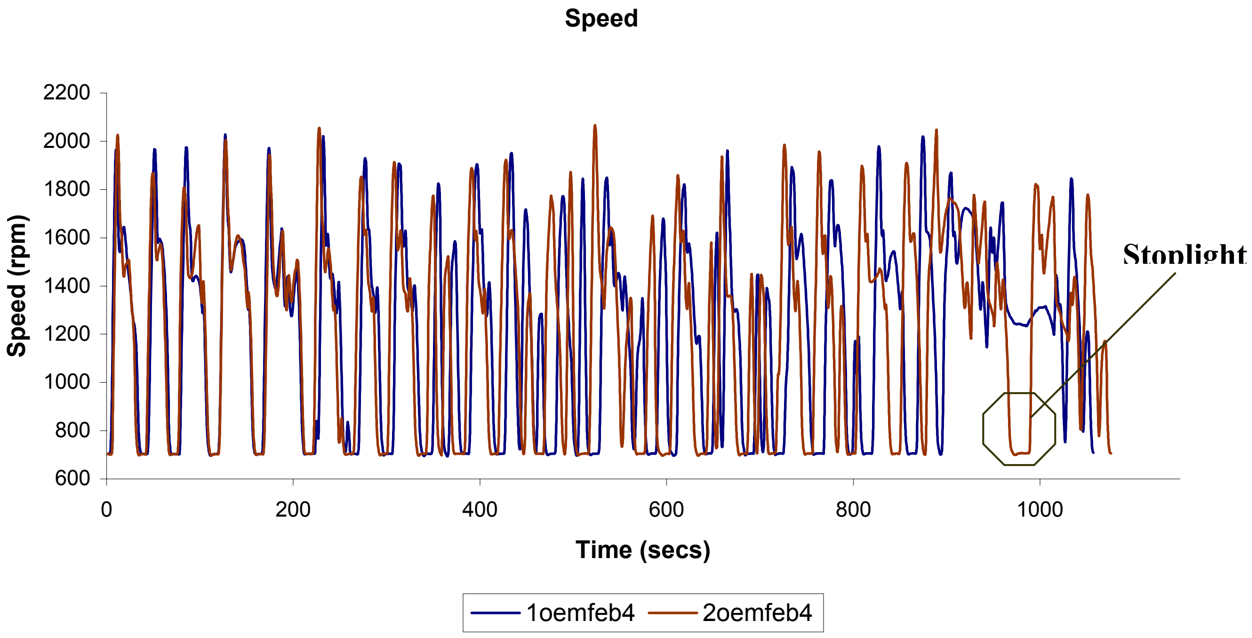

Figure 8. Engine Speed over Two Consecutive Runs

Note that while the curves may not indicate an exact repeat of the driving pattern, the trends are the same, as are the average results for the different parameters as seen in Table 3.

Table 3. Operating Parameter Averages for Each Set of Tests

	Total Flow (Qtot) lpm	Engine air intake (Qeng) scfm	Dilution air flow (Qdil) lpm	Exhaust flow (Qexh) lpm	Main flow (Qmain) lpm
Bus # 4267 w/ CRT	32.35	279.55	22.50	9.86	30.54
Bus # 4267 w/ OEM	32.28	287.63	22.01	10.27	30.48
Bus # 4215 w/ CRT	32.35	312.15	21.92	10.43	30.67
Bus # 4215 w/OEM	32.24	306.19	21.79	10.45	30.56

8.0 Test Procedures

Testing commenced once the DOES2 system and sensors were installed, allowed to warm up, and verified to be functioning correctly as read on the computer. New filters were installed in each of the filter holders and an evacuated Tedlar™ or Cali-5-Bond™ (5-layer) sampling bag was connected to the DOES2 sample line. The vehicle was then driven to the official start point and waited for the test to be initiated. Once at the start point after all the pumps were started, the sampling was initiated.

Upon completion of the test cycle, the loaded PM filter was removed from the filter holder and placed in a petri dish that was sealed with paraffin tape before transport back to the ERMD lab. Particulate mass was determined gravimetrically by weighing the filter on a Sartorius model M5P-000V001 balance upon its return to the ERMD. Before the final filter weight was taken the filters were conditioned at 40% ± 10% RH, and 20 to 25 degrees Celsius for a minimum of 8 hours.

The bag of gaseous sample was removed from the DOES2 and brought to the maintenance bay where it was read on the analyzers, which had all been zeroed and calibrated using standard reference gases. After the sample bag was analysed, it was evacuated, flushed with nitrogen, and then evacuated again. After each test, the data from the computer was downloaded onto a diskette and analyzed on a separate laptop in the lab room which provided emission results in grams per minute and fuel consumption in litres, based on a carbon mass balance.

The heated sample line was disconnected from the DOES2 for the initial run of each configuration. This initial run ensured that the equipment was warmed up prior to conducting a test, and also served as a measurement of the ambient air levels of these exhaust components. The concentrations of the emissions found in the sample bag represented the level of the ambient air pollutants found at the site. These ambient values were used in the mass emission calculations.

8.1 System Verification and Repeatability

After every test, the DOES2 operation was verified by ensuring that expected trend lines were observed for various flow rates. Plots of the engine air intake (Qeng), dilution air (Qdil), raw exhaust (Qexh) and the main flow through the dilution tunnel (Qmain) were created after each test. The plots provided an easy tool to verify that Qmain remained constant throughout the run, and that Qeng and Qexh varied proportionally while the Qdil curve varied inversely to Qeng (or Qexh). Should Qdil have reached low constant values of approximately 5 L/min, the test parameters would have been adjusted since the DOES2 cannot restrict the dilution flow to less than 5 L/min. The dilution flow in the DOES2 was verified, as it should remain between approximately 10 L/min and 35 L/min.

To ensure repeatability from test to test, the following parameters were compared: exhaust temperature, air intake, and system average flow rates. The thermocouples and pressure transducers were also verified, as they are expected to give ambient (verifiable) values. For example, the dilution air temperature (Tdil) should be close to the ambient air temperature. Figure 9. shows a typical plot examined between tests to verify that the DOES 2 system was performing as expected.

The emission rates for a test configuration were averaged and a coefficient of variation was calculated. A minimum of three tests were conducted per test configuration but more tests were repeated as required.

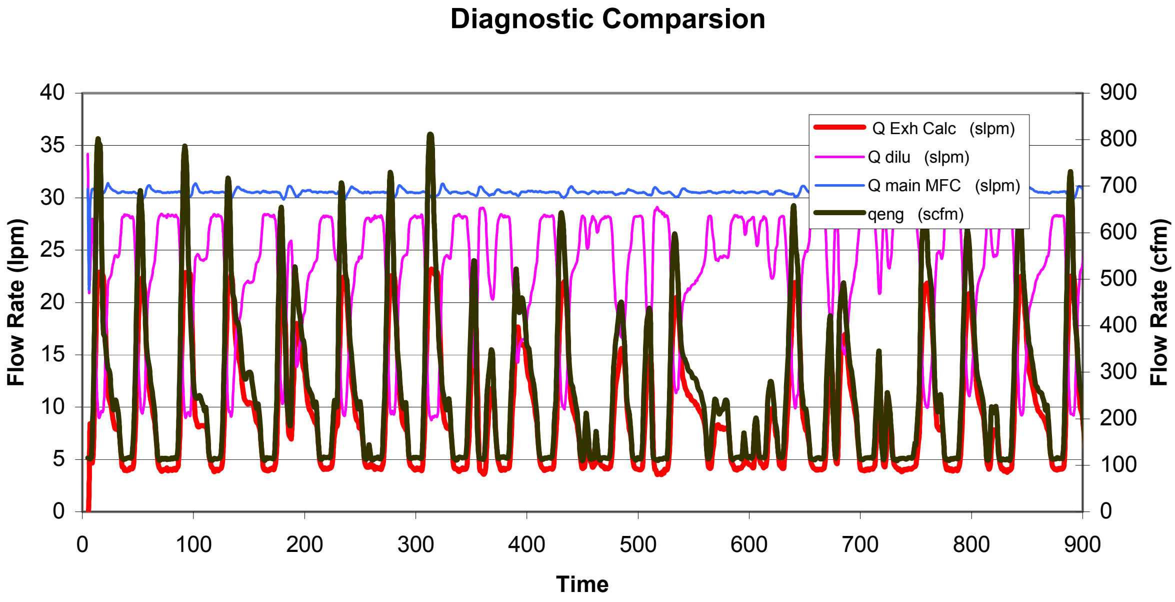

Figure 9. DOES2 System Verification Diagnostic Chart

9.0 Results and Discussions

The CRT works on the principal that exhaust first passes through an oxidation catalyst that oxidizes a portion of NO in the exhaust stream into NO_2 [3]. This catalyst section also oxidizes CO, THC, and the SOF portion of PM. The second part of the CRT is a ceramic filter that traps the soot. The soot accumulates in the filter until the system is regenerated. The CRT system utilizes the highly oxidizing NO_2 generated in the catalyst section to oxidize the soot. A limiting factor in the use of CRDPFs is the sulfur content in diesel fuel, as high sulfur levels 'poison' the catalyst section of the CRDPF and inhibit the reaction of NO to NO_2[5]. This problem will be eased however due to the implementation of new sulfur content limits in diesel fuel (<15ppm sulfur content). This regulation takes effect June 1, 2006[6].

In order for the CRDPFs to properly regenerate it is important for the exhaust temperature to reach and maintain an adequate level. While it takes temperatures of up to 650 degrees Celsius for regeneration with no precious metal catalyst present, the CRTs tested contained platinum and therefore were capable of regeneration at temperatures of

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[5] Heavy Duty Standards / Diesel Fuel RIA. Chapter III – Emissions Standards Feasibility. December 2000. EPA420-R-00-026.

[6] "Sulphur in Diesel Fuel Regulations", Canada Gazette Part II, Vol. 136, No. 16 SOR/DORS/2002-254

250-300 degrees Celsius [7]. The manufacturer has set a guideline of a minimum temperature of 260 degrees Celsius during 40% of the time spent running. Figure 10. shows the average exhaust temperatures of bus #4267 with and without a CRT. Note that Bus# 4215 showed a similar pattern.

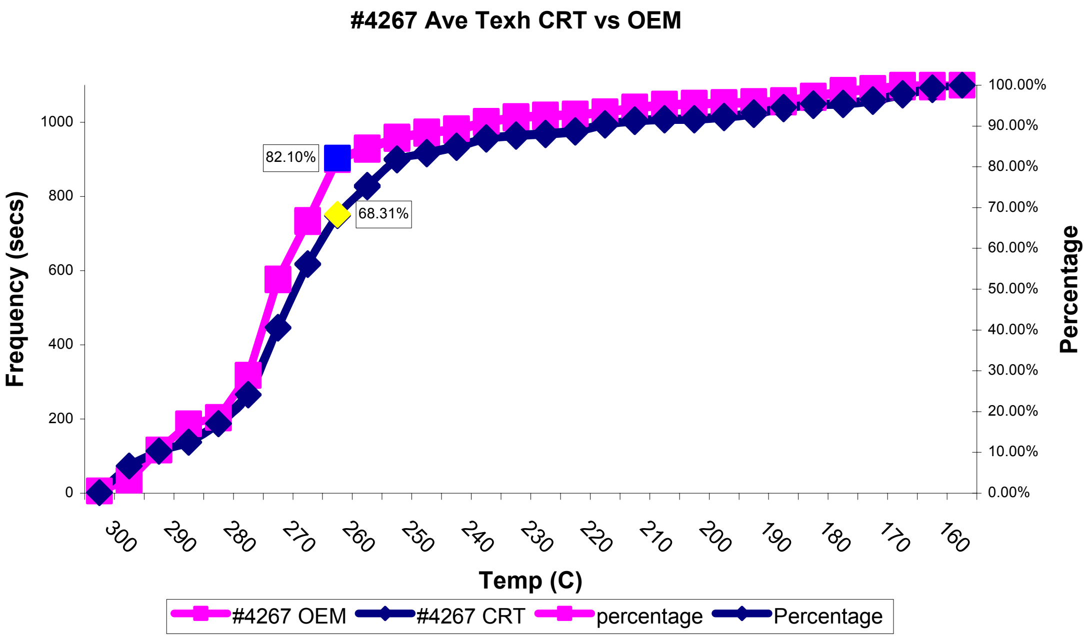

Figure 10. Average Exhaust Temperature for Bus #4267 with CRT and with OEM

The DOES2 system enables the measurement of certain parameters (such as the measured concentrations of gaseous emissions, total flow through the tunnel, engine air intake, dilution air flow, etc.), which in turn provide for the calculation of the mass emission rates (in grams of pollutant / mile). The total exhaust flow rate was obtained from a mass balance on the air intake of the engine. A carbon mass balance calculation was used to determine the amount of fuel used for each run.

The mass of each pollutant was determined based on the following equations:

Hydrocarbon mass:

$HC\ mass = Vmix * Density\ HC * (Sample\ HC\ (ppm) - (Ambient\ HC\ (ppm) * (1 - 1/DF)))/10^6$

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[7] Heavy Duty Standards / Diesel Fuel RIA. Chapter III – Emissions Standards Feasibility. December 2000. EPA420-R-00-026.

Oxides of nitrogen mass:

$$NO_X\ mass = Vmix * Density\ NO_x * (Sample\ NO_X\ (ppm) - (Ambient\ NO_X\ (ppm) * (1-1/DF)))/10^6$$

Carbon monoxide mass:

$$CO\ mass = Vmix * Density\ CO * (Sample\ CO\ (ppm) - (Ambient\ CO\ (ppm) * (1-1/DF)))/10^6$$

Carbon Dioxide mass:

$$CO_2\ mass = Vmix * Density\ CO_2 * (Sample\ CO_2\ (ppm) - (Ambient\ CO_2\ (ppm) * (1-1/DF)))/10^2$$

Where:

Vmix = total dilute exhaust volume in ft^3 per test.
DF = dilution factor
Density CO: 32.97 g/ft^3
Density CO_2: 51381 g/ft^3
Density THC: 16.33 g/ft^3
Density NO_2: 54.16 g/ft^3

NOTE: Mass NOx emissions have not been corrected for humidity.

In order to complete the carbon balance on the engine, it was assumed that carbon entered or left the engine through only three different paths: the air intake, the exhaust, and the fuel flow. The total mass of carbon in the air intake was known using the air intake rates and the concentrations of CO_2, CO and THC as measured during the ambient runs. Similarly, the total mass of carbon in the exhaust was known from the raw concentrations of CO_2, CO and THC. The carbon content of the particulate matter was considered to be insignificant in comparison to the gaseous carbon. The carbon entering the engine via the fuel therefore must make up the difference in the mass of carbon between these two streams. The carbon fuel fraction (CFF) and specific gravity for each fuel used in the mass balance calculations are shown in Table 2.

Emissions data from the testing of the buses with a CRT in place and in their original configuration are listed in Tables 4 and 5. These tables show the mass emission rates of CO, CO_2, NOx, THC, and Particulate Matter (PM) on a distance basis for each test. The fuel consumption (FC) calculated from the carbon mass balance is shown in miles per imperial gallon, and in litres per 100 kilometres. The average value used to evaluate the percent change in emissions from each configuration is also shown with the percent coefficient of variation (COV %), which indicates how much the results from each run deviated from the average.

Table 4. Bus #4267 Emissions Rates (g/mile) with CRT and OEM

Run	HC (g/mile)	NOx (g/mile)	CO (g/mile)	CO_2 (g/mile)	PM (g/mile)	Fuel (L/100kms)	Fuel (Mpg) imperial
CRT							
1tstfeb3	0.174	36.26	0.599	3281	0.228	79.0	3.58
2tstfeb3	0.143	34.04	0.633	3404	0.237	81.9	3.45
1tstfeb4	0.156	33.40	0.707	3375	0.189	81.2	3.48
2tstfeb4	0.149	33.88	0.515	3512	0.177	84.5	3.34
3tstfeb4	0.133	32.85	0.454	3240	0.146	78.0	3.62
Average	**0.151**	**34.09**	**0.582**	**3362**	**0.195**	**80.9**	**3.49**
COV (%)	10.31	3.82	17.05	3.19	19.17	3.19	3.17
OEM							
1oemfeb4	0.301	33.0	1.763	3078	0.471	74.2	3.81
2oemfeb4	0.326	31.5	1.771	3042	0.511	73.3	3.85
3oemfeb4	0.300	32.8	1.884	3210	0.547	77.3	3.65
4oemfeb4	0.307	35.1	1.783	3343	0.442	80.5	3.51
Average	**0.309**	**33.1**	**1.800**	**3168**	**0.493**	**76.3**	**3.71**
COV (%)	3.97	4.42	3.14	4.32	9.29	4.31	4.25

Table 5. Bus #4215 Emissions Rates (g/mile) with CRT and OEM

Run	HC (g/mile)	NOx (g/mile)	CO (g/mile)	CO_2 (g/mile)	PM (g/mile)	Fuel (L/100kms)	Fuel (Mpg) imperial
CRT							
1tstfeb5	0.197	46.4	0.622	3749	0.158	90.2	3.13
2tstfeb5	0.189	44.7	0.808	3716	0.159	89.5	3.16
3tstfeb5	0.184	45.7	0.771	3422	0.137	82.4	3.43
4tstfeb5	0.168	46.9	0.631	3469	0.119	83.5	3.38
Average	**0.184**	**45.9**	**0.708**	**3589**	**0.143**	**86.4**	**3.28**
COV (%)	6.71	2.11	13.48	4.66	13.22	4.66	4.67
OEM							
1oemfeb6	0.382	39.6	3.554	3544	0.530	85.4	3.31
2oemfeb6	0.423	43.1	3.251	3794	0.559	91.4	3.09
3oemfeb6	0.420	44.2	3.091	3721	0.473	89.7	3.15
4oemfeb6	0.423	40.8	3.733	3687	0.569	88.9	3.18
5oemfeb6	0.439	42.2	3.792	3581	0.473	86.3	3.27
Average	**0.417**	**42.0**	**3.484**	**3665**	**0.521**	**88.4**	**3.20**
COV (%)	5.08	4.36	8.73	2.79	8.82	2.78	2.78

Testing for the different configurations took place on four different days: day 1 bus #4267 with CRT (only two runs); day 2 bus #4267 with CRT followed by OEM testing; day 3 bus #4215 with CRT; day 4 bus #4215 with OEM. Replacement of the CRT with the OEM muffler took place at the local Cummins dealer. A tunnel blank was taken in between the testing of buses #4267 and #4215 to guard against the possibility of 'hang up' in the tunnel.

The difference in emission rates between the CRT and OEM are shown in Table 6. The percent reduction values are based on the average emission rates in g/mile calculated from the following equation:

$$\% \text{ Change} = \frac{\text{(Emission Rate [g/mile]}_{\text{OEM}} - \text{Emission Rate [g/mile]}_{\text{CRT}}}{\text{Emission Rate [g/mile]}_{\text{OEM}}}$$

Statistical analysis in the form of a student's t-distribution test was performed to verify that comparing two sets of emission data, which contained a certain degree of variability, was statistically significant. The shaded cells in the tables represent values that do not have statistical significance since the "t" distribution was less than the 99% confidence level. This implies that the calculated percent change is lower than the error expected based on the standard deviation of the test sets that were compared. A single factor ANOVA test was also performed to confirm the statistical significance of the results. The ANOVA analysis confirmed the findings of the student's t-distribution with the exception of the CO_2 result for Bus # 4267, which proved to be just within the significant threshold.

Table 6. Percent Difference in Emissions (g/mile) and Fuel Consumption (L/100kms) Between the Baseline Fuel and the Ethanol-diesel Fuel Average Results

Bus id:		**THC**	**NOx**	**CO**	**CO_2**	**PM**	**FC**
BUS # 4267	**% reduction due to CRT**	51.1	-3.0	67.7	-6.1	60.4	-6.0
BUS # 4215	**% reduction due to CRT**	55.8	-9.5	79.7	2.1	72.51	2.2

Note: a negative value indicates an increase in emissions with the CRT.

The Fuel Consumption (FC) reduction was determined on a per volume basis and determined as follows:

$$\% \text{ Reduction} = \frac{\text{Fuel Consumption } [\textit{unit}]_{\text{OEM}} - \text{Fuel Consumption } [\textit{unit}]_{\text{CRT}}}{\text{Fuel Consumption } [\textit{unit}]_{\text{OEM}}}$$

These results show that emissions of THC, CO, and PM were significantly lower when the buses were operated with a CRT compared to being operated in the OEM state. The hydrocarbons decreased over 50%, carbon monoxide decreased up to 80%, and the total particulate matter decreased between 60 and 73 %. The amount of fuel consumed, based on the carbon mass balance, was found to have not changed significantly. There was a statistical difference in NOx emissions for bus #4215 (higher emissions with a CRT) but no substantial change for bus # 4267. The other measured pollutant, CO2, did not show a significant difference for either bus.

10.0 Conclusions

The testing undertaken in this study concluded that both buses showed significant decreases in THC (51-60%), CO (68-80%), and PM (60-73%) emissions with the CRT in use. There was a significant increase in NOx emissions with the use of a CRT for Bus #4215 while Bus #4267 showed no statistical difference in NOx emissions. The lack of a significant change in fuel consumption boads well for potential fleet retrofits where an increase of fuel consumption could be very costly, and a potential deterrent to the implementation of new emission control devices.

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