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Kevin F. Brown
Engine Control Systems Ltd.

Greg R. Rideout
Environment Canada

Jeffery E. Turner
Ontario Ministry of Transportation

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Kevin F. Brown
Engine Control Systems Ltd.

Greg R. Rideout
Mobile Source Emissions Division
Environment Canada

Jeffery E. Turner
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ABSTRACT

This updated paper presents chassis dynamometer emissions testing of various heavy duty vehicles with and without retrofitted diesel oxidation catalyst technology. Analysis is provided into both the vehicle emissions baselines and emissions with retrofitted catalyst technology over the New York Composite and Central Business District cycles. The vehicles studied include four urban buses, two school buses and four heavy duty trucks. Some of these vehicles in this study have been followed for up to two years. The paper will discuss in-use heavy duty vehicle emissions issues and the use of diesel oxidation catalyst technologies.

INTRODUCTION

This study presents in-use emissions test results for various typical heavy duty diesel vehicles. The vehicles are being tracked over time to assess their in-use emissions patterns. The first years results were reported in a previous paper [1].

There are a myriad of in-use factors that effect heavy duty vehicle emissions. Some of these factors are related to the mechanical condition of the engine or vehicle while others are related to driving patterns. Some factors appear to have a temporary effect while others may be due to cumulative mechanical wear.

What is certainly lacking is an understanding of how heavy duty vehicle emissions fluctuate with driving patterns and/or deteriorate with engine condition.

The retrofitting of heavy duty diesel engines with oxidation catalyst technologies has been commonplace for many years on off-road vehicles used in mining, materials handling and other industrial markets. In these applications the driving force has been worker health and safety, and ultimately employee state of mind and productivity.

In the urban environment, health concerns regarding diesel particulates have resulted in thousands of buses being retrofitted with oxidation catalyst or particulate filter technologies. Even natural gas buses commonly employ oxidation catalysts to maintain low particulate, carbon monoxide and hydrocarbon emissions.

In the United States, the implementation of the urban bus rebuild / retrofit requirements [2] has increased interest in the potential emissions reductions that may be attained in the in-use heavy duty diesel vehicle fleet from the introduction of emissions reductions technologies.

The vehicles tracked in this study operate exclusively under urban in-use conditions. Their duty cycle operation is characterized by a majority of time spent in low speed operation, excessive periods of idle and hard accelerations. This type of operation is felt to induce the greatest challenge to proper and efficient diesel engine operation. In addition, these conditions pose the greatest challenge to proper catalyst operation.

The results presented in this paper are part of an extensive investigation which has been under way for several years in Ottawa, Canada, in which diesel exhaust aftertreatment systems have been installed, demonstrated in service and tested. Heavy duty vehicles such as trucks, school buses and transit buses are being tracked over time in an effort to also gain further understanding of the in-use factors that may affect vehicle emissions.

The trucks in the current program are operated by Canada Post and Brewer's Retail and the school buses by the Stock Transportation Group. All the trucks operate in the metropolitan Ottawa area.

The transit buses are owned and operated by the Ottawa-Carleton Regional Transit Commission (OC Transpo). OC

Transpo operates a fleet of about 800 conventional and articulated buses providing transit service throughout the city of Ottawa (population 314,000) and surrounding suburbs (metropolitan population 678,000). Since all of its buses are diesel powered and because of their significant presence in the downtown area, OC Transpo is very sensitive to public perception of the cleanliness of these vehicles.

The two test cycles employed in this study, the New York Composite (NY Comp) and Central Business District (CBD) cycles are felt to reflect "worst case" urban driving conditions. These cycles have been used in a number of emission studies to characterize the emissions reduction potential of alternate fueled buses and other emissions related technologies [3, 4, 5].

EXPERIMENTAL

CATALYST, CONVERTER AND CONVERTER MUFFLER DESCRIPTIONS - The AZ diesel oxidation catalyst coating used in these experiments is specifically designed for the effective reduction of the soluble organic fraction contributing to the particulate mass. The catalyst has a loading of Platinum on a molecular sieve containing washcoat which is stabilized against deterioration at elevated temperatures.

The converters used in this study on the International school buses utilize 62.0 cells/cm2, 7L large frontal area (LFA) substrates and were installed in front of the original vehicle mufflers.

The converter mufflers used in this study on the Mack and International trucks utilize 46.5 cells/cm2, 5.1L and 7L LFA substrates respectively. The test units were installed in the location of the original vehicle muffler.

The converter mufflers used in this study on the coach engines and urban buses utilize multiple 46.5 cells/cm2 LFA substrates to provide catalyst volumes of up to 15.3 L. The converter muffler designs used in this study were installed in the location of the original vehicle mufflers. The converter mufflers afford comparable backpressure and sound attenuation to the original vehicle mufflers.

THE FUEL used in these tests was typically commercially available fuel " as received" by the vehicle operator. In Canada, diesel fuel available at retail outlets contains a maximum of 0.05 weight percent sulfur. The implementation of this maximum sulfur content is by agreement between the Canadian government and fuel producers. Fuel which is purchased in bulk by fleet operators may surpass the 0.05 weight percent sulfur level.

The fuel used in emissions of the urban bus tests in late 1995 was 0.05 weight percent sulfur certification fuel.

During 1996, on eight separate dates, fuel samples were taken from the urban buses and sent for analysis to the Cleveland Technical Center for sulfur analysis by a D-4294 test method. Table 1 below shows the analysis results.

The results in Table 1 indicate a possible seasonal variation in fuel sulfur content. Sulfur content reaches an apparent low in summer at approximately 0.05 weight percent but then increases in late summer to an apparent winter value of 0.15 weight percent.

Fuel sulfur content is of interest due to the use of exhaust oxidation catalysts. It was intended that the amount of sulfation produced should be related back to the sulfur content of the fuel to help explain variances in test to test sulfate levels.

Table 1. Urban Bus Fuel Sulfur Measurements

Sample Date	Sulfur Level
March 26, 1996	0.1420%
April 17, 1996	0.0887%
April 22, 1996	0.0905%
June 3, 1996	0.0580%
August 1, 1996	0.0515%
August 14, 1996	0.0691%
August 19, 1996	0.0640%
September 17, 1996	0.1440%

H.D. CHASSIS DYNAMOMETER TESTS - The test equipment used to determine the exhaust emission rates of various compounds is described in the following paragraphs. All tests were conducted in accordance with the procedures outlined in "Recommended Practice for Determining Exhaust Emissions from Heavy Duty Vehicles Under Transient Conditions" [6] and the US-EPA Code of Federal Regulations.

Gaseous emission measurements were obtained using a total dilution constant volume sampling (CVS) system. The total volume of raw exhaust was transferred from the vehicle to the CVS through a 10 cm diameter flexible stainless steel pipe. The raw exhaust was then diluted with laboratory air and the mixture directed through a dilution tunnel 25.4 cm in diameter and 254 cm in effective length, a heat exchanger, and a critical flow venturi calibrated to maintain the dilute exhaust flow rate at 42.48 m3/min.

The gaseous sampling zone of the dilution system was equipped with several probes. One sample probe was used to draw samples of the dilute exhaust from the tunnel to tedlar bags for analysis of carbon monoxide and carbon dioxide. The second probe directed a sample of the dilute exhaust through silica gel cartridges which had been treated with 2,4 dinitrophenylhydrazine (DNPH) solution for carbonyl collection and measurement. A dedicated heated probe, line and filter system upstream of this zone was used for continuous collection of dilute exhaust samples for total hydrocarbon and oxides of nitrogen measurement by heated flame ionization detector and chemiluminescence. A second probe in the same area as the heated probe was used to direct a sample from the main tunnel to a secondary dilution tunnel, where a the sample drawn through 70mm teflon coated glass filters for particulate collection.

The stored gaseous samples were analyzed for the concentrations of nitrogen oxides (NOx) and hydrocarbons as a back up to the continuous samples, while carbon monoxide (CO) and carbon dioxide (CO_2) were quantified through the use of a non-dispersive infrared detectors. The dilute exhaust concentrations were then corrected for the dilution air levels and the exhaust emission rates in grams per mile (gpm) were calculated. The carbonyls were characterized and quantified through the use of liquid chromatography and will be reported in a separate report. The particulate samples were characterized for the soluble organic (SOF) content using soxhlet extraction. The SOF analyses are being compared with a second extraction method which involves polar and non-polar extractions. These analyses are referred to as Total Organic Extractables (TOE).

The chassis dynamometer which was used to simulate the vehicle loads which are present during actual operation of the vehicle on the road was a Clayton heavy duty chassis dynamometer system which uses a 22371 kW DC motor as a power absorption unit for road load simulation and mechanical flywheels for inertia simulation. The rolls on which the vehicle was driven were 22 cm in diameter, 305 cm in length with 50.8 cm between roll centers.

The dynamometer loadings were determined according to SAE 840349 for the test vehicles. These values are listed in Table 2 below.

Table 2. Dynamometer Loadings for Chassis Tests

Vehicles	Road Load (kW) @ 80 km/hr	Inertia Weight (Kg)
MCI and GMC 12.2m urban buses	57.9	12818
‘92 International school buses	50.8	9208
‘92 Mack MS250P trucks	53.4	7485
‘94 International Series 4900 truck	64.5	10818

VEHICLE DESCRIPTIONS - All vehicles used in these tests were in-use heavy duty fleet vehicles. Table 3 gives a full description of the vehicles.

Table 3. Vehicle Descriptions

1989 MCI Classic (12.2m) urban bus: 3 vehicles DDC 6V92TA DDEC II (9.05L two stroke: 189 kW)
1984/5 GMC Classic (12.2m) urban bus: 2 vehicles DDC 6V71N (7L two stroke: 135 kW)
1992 International School Bus, Model 3800: two vehicles Navistar DT466 (7.63L four stroke: 145 kW)
1992 Mack MS250P Heavy Duty Truck: 2 vehicles Renault RV3-E3-180 (6.1L four stroke: 134 kW)
1994 International Series 4900 Heavy Duty Truck Navistar DT466- mechanical (7.63L four stroke: 145 kW)

TEST DESCRIPTIONS - The driving cycles used for exhaust emissions testing for this paper include the New York Composite (NY Comp) and Central Business District (CBD) cycles. Typically, three repeats of each test cycle were conducted with and without the diesel oxidation converter or converter muffler installed. A three minute “soak” period was introduced between repeats of the tests. Table 4 provides some details of the test cycles. Reference [4] gives a full description and comparison of the test cycles used in this study.

Reference parameters are also given for the US HDTC engine test cycle for comparison to the chassis cycles used in this study. There are two main differences between the US HDTC and the NY Comp and CBD. The first is that as chassis cycles the entire vehicle will be tested with vehicle specific load factors as opposed to just an engine with a standard “prescribed” load. The average cycle speed is also greatly reduced for the CBD and NY Comp to levels 34% and 53% lower than the HDTC. This reduction in average speed reflects a greater emphasis on urban driving conditions typical of buses and trucks.

Table 4. Test Cycle Parameters

Cycle	Duration (seconds)	Distance (km)	Average Speed (kph)
HDTC (each phase)	1060.0	8.88	30.25
CBD	600.0	3.31	19.85
NY Composite	1030.0	4.03	14.08

The New York Composite test cycle is an actual driving cycle, consisting of variable speed and acceleration maneuvers which are typical of actual in-use heavy duty vehicles.

The New York Composite Cycle has the highest percentage of time spent accelerating (34.11%) and decelerating (28.96%). The cycle spends only 7.7% of time cruising and 29.15% of time spent idling [3]. This cycle is felt by the authors to be fairly representative of bus and truck urban driving patterns.

Figure 1 illustrates the catalytic converter inlet and outlet exhaust temperatures over the New York Composite Cycle as observed for a 1992 International school bus with a DT466 (7.63L four stroke turbocharged) engine. The first third of the NY Composite is largely spent at or near engine idle, resulting in a characteristic converter inlet and outlet temperature of approximately 150 ^{o}C (see Figure 1). The next two thirds of the cycle consists of heavy accelerations with consistently higher average vehicle speeds. At any given time, the outlet exhaust temperature can be seen to be approximately 50-70 ^{o}C cooler than the inlet. With respect to time, in this part of the cycle, the converter outlet exhaust temperature maxima lag behind the corresponding inlet exhaust temperature maxima by as much as 50 seconds. These exhaust temperature features result in catalyst performance effects.

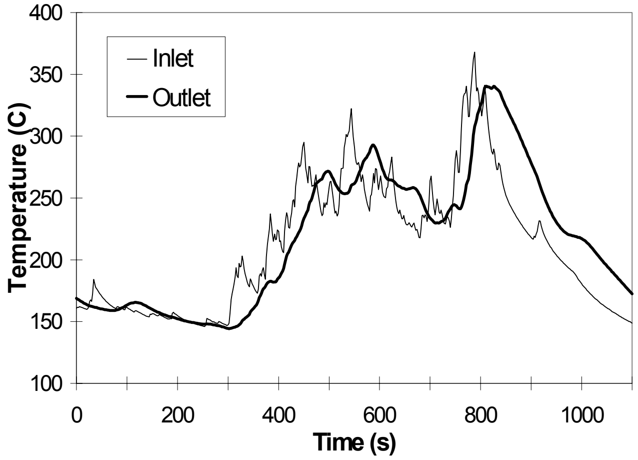

Figure 1. Exhaust Temperature Trace for School Bus over the NY Composite Cycle

In addition, different vehicles will produce different exhaust temperatures and flows over the same test cycle for a wide variety of reasons. Thus, the same test cycle often produces different environments for exhaust aftertreatment.

Figure 2 illustrates the observed exhaust temperatures for a 1989 MCI urban bus equipped with a DDC 6V92TA DDECII and oxidation converter muffler. This electronically controlled two stroke engine produces an observed maximum inlet exhaust temperature at least 50^{o}C cooler than the school bus over the NY Composite cycle. Further, as this urban bus utilizes a converter muffler which results in greater exhaust gas expansion than a converter, the maximum outlet temperature is observed to be approximately 90^{o}C cooler than that observed for the school bus. Thus, the effective catalyst volume in the converter muffler of the 6V92TA DDECII equipped bus is exposed to very different temperature conditions than the catalyst in the converter of the DT466 equipped school bus shown in Figure 1.

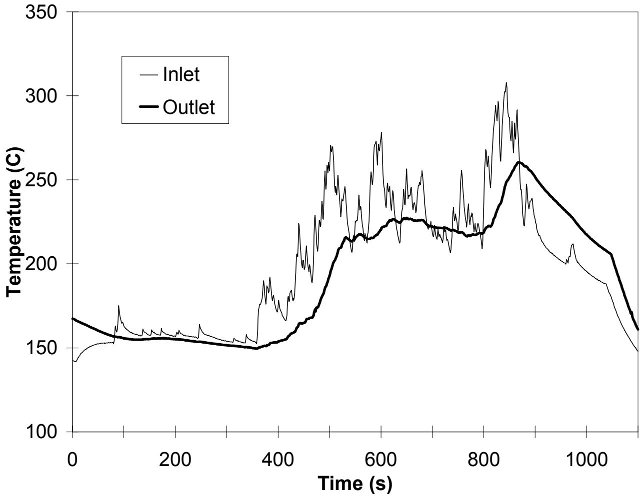

Figure 2. Exhaust Temperature Trace for MCI urban bus equipped with DDC6V92TA DDECII over the NY Composite Cycle

The CBD, part of the advanced design bus (ADB) cycle, is a synthesized sawtooth cycle. It consists of idle, acceleration up to 32.18 km/ hour, cruise, and deceleration modes repeated 14 times over 600 seconds. Synthesized cycles are often criticized as consisting of accelerations which cannot be met by all vehicles and as being biased towards a single steady state speed [5]. Furthermore, constant acceleration, speed, and deceleration driving patterns rarely occur in actual urban driving. Due to acceleration discontinuities introduced at modal transitions, synthesized cycles have been reported as likely to have reduced repeatability.

Figure 3 illustrates the exhaust temperature trace for the school bus over the CBD. In the trace, the 14 repetitions of the "sawtooth" pattern over 600 seconds are very evident Further, it can be seen in Figure 3 that the inlet and outlet converter temperatures track very closely with little evidence of any temperature lag as was the case with the NY Composite cycle (see Figure 1). This is an important difference between the CBD and the NY Comp cycle. As a result, it can be expected that gaseous and particulate reduction performance would be favored over this cycle.

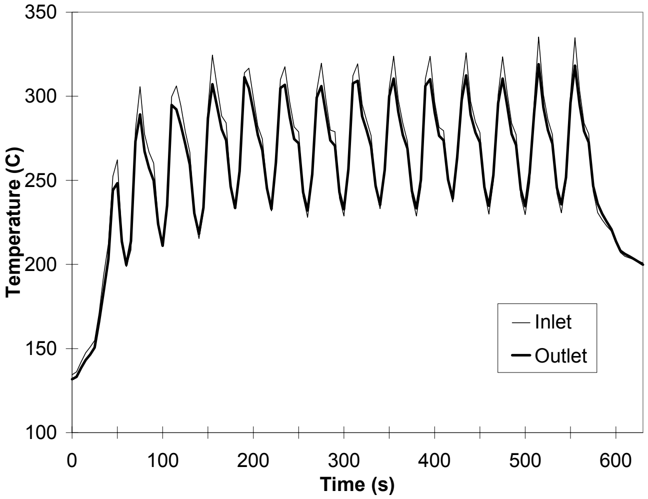

Figure 3. Exhaust Temperature Trace for International School Bus equipped with DT466 engine over the CBD cycle

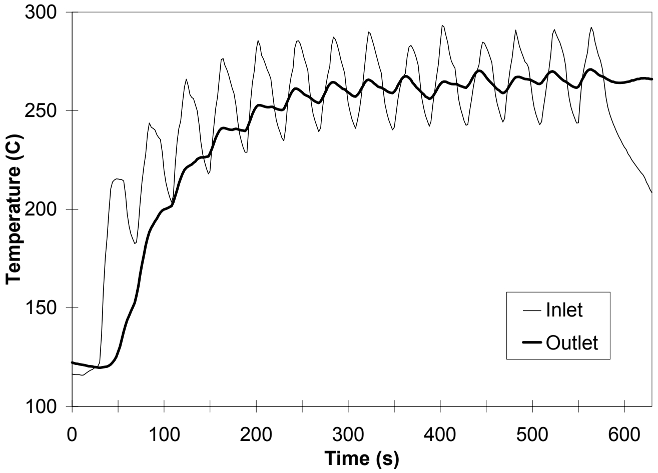

Figure 4. Exhaust Temperature Trace for MCI urban bus equipped with DDC6V92TA DDECII over the CBD Cycle

Figure 4 illustrates the exhaust temperature trace for the MCI urban bus equipped with the 6V92TA DDECII and converter muffler. Figure 4 shows the maximum inlet exhaust temperature to be 290 ^{o}C, approximately 30 ^{o}C cooler than was observed for the DT466 equipped school bus over the CBD cycle as shown in Figure 3. Further, whereas the school bus converter inlet and outlet exhaust temperatures tracked closely as shown in Figure 3, this was not the case for the MCI urban bus. Figure 4 shows that the gas expansion which occurs in the converter muffler results in a very consistent outlet exhaust temperature which is approximately 25 ^{o}C cooler than the inlet.

Figures 2 and 4 also illustrate a major difference for the MCI urban bus over the two different chassis test cycles. The repetitious CBD "sawtooth" cycle shown in Figure 4 results in a fairly consistent average outlet exhaust temperature of 265 ^{o}C, whereas the same vehicle over the NY Composite cycle (see Figure 2) never attains this outlet exhaust temperature.

These simplistic comparisons illustrate that the CBD cycle should yield more consistent and higher PM and gaseous reduction performances.

RESULTS AND DISCUSSION

APPLICABILITY OF THE TEST CYCLES- The urban buses in this study were equipped with dataloggers to record typical in-use exhaust temperatures. This data is useful as an aid to determine whether the oxidation catalyst will operate properly in-use and to examine the appropriateness of the test cycles.

Figure 5 displays a typical example of in-use muffler inlet exhaust temperatures observed for one of the DDC 6V71N equipped urban buses in-use. These vehicles are typically operated during "rush hour" commuting periods of the day and at other high demand periods of the year.

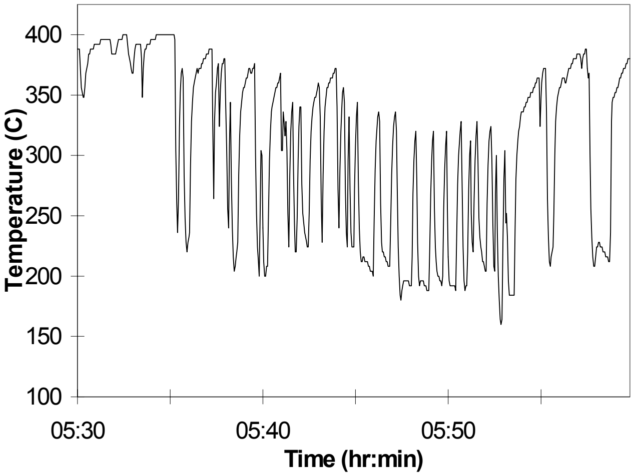

Figure 5. Typical in-use exhaust temperature trace for a DDC 6V71N equipped urban bus.

This mechanical normally aspirated two stroke engine produces exhaust gas temperatures above 200 ^{o}C for over 71% of its in-use operation and above 300 ^{o}C for over 39% of its in-use operation. As previously mentioned, these high exhaust temperatures promote higher efficiencies for the oxidation of CO, HC's and particulate. The exhaust temperature pattern of the 6V71N's indicate that catalyst performance should not be hindered by cool exhaust temperatures or by excessive carbon build-up.

Figure 6 displays an example of the insulated muffler exhaust temperatures observed for one of the DDC 6V92TA DDECII equipped urban buses in-use. These buses are operated all day in Ottawa. Figure 6 shows that the typical inlet and outlet exhaust temperature range is greatly reduced for the 6V92TA DDECII equipped buses compared to the 6V71N equipped buses. For this particular temperature trace, the inlet exhaust temperature was between 200-300 ^{o}C approximately 70% of the time. In addition, the outlet exhaust temperature is seen to be consistently in the 220-270 ^{o}C range.

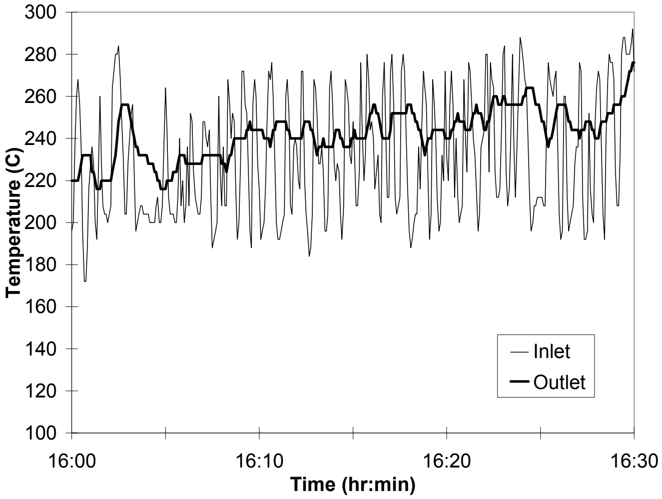

Figure 6. Typical in-use exhaust temperature trace for a DDC 6V92TA DDECII equipped urban bus.

The US HDTC is an extremely valuable standardized engine test which allows the emissions of different engines to be compared. However, it is impossible for any single standardized test to accurately predict the absolute emissions of any in-use vehicle. There are a myriad of different chassis configurations, vehicle weights, loads, drivetrains, etc., and vehicle uses which greatly effect any individual in-use vehicle.

The NY Composite and CBD cycles have been used in this study for emissions evaluation as they are felt to reflect urban driving patterns characteristic of heavy duty vehicles. In terms of measuring catalyst performance and relating this to in-use aftertreatment system performance, the most important variable to examine is exhaust temperature.

Figure 7 compares the percentage of time of specific exhaust temperature ranges observed at the muffler inlet for a 6V92TA DDECII powered bus over the CBD and NY Composite cycles to observed muffler inlet exhaust temperatures in-use. The histograms of the observed in-use exhaust temperatures were constructed from several hours of recorded data on two different occasions.

From comparison of the percentage of times spent in specific exhaust temperature ranges, some simplistic discussion points can be presented. With respect to exhaust temperature, the CBD cycle results in higher percentages of time spent in low exhaust temperature ranges of 0-150 ^{o}C (idle) and high exhaust temperature ranges 250-300 ^{o}C. The

NY Composite cycle results in higher percentages of time spent at mid range exhaust temperatures of 151-250 °C. In terms of observed exhaust temperatures, In-use exhaust temperature trace (1) compares very favorably to the NY Composite (see Figure 7). In-use exhaust temperature trace (2) compares to mixture of NY Composite and CBD exhaust temperature ranges. This data supports the applicability of these test cycles to in-use transit bus operation.

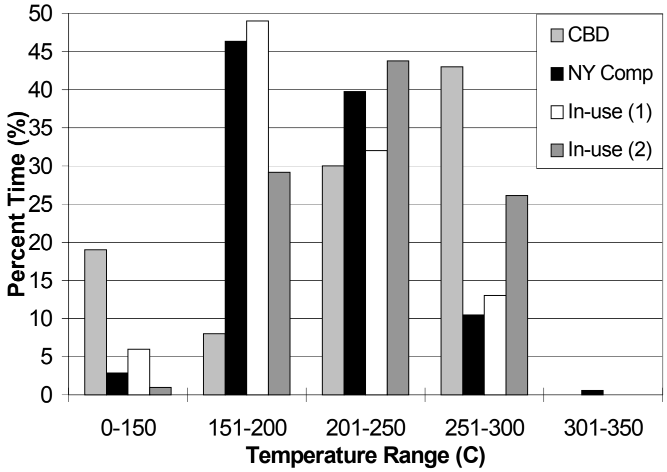

Figure 7. Comparison of Exhaust Temperatures

In terms of catalyst performance, this data suggests that in-use performance should be similar to results obtained over the NY Composite cycle or an average of the performance observed over the NY Composite and CBD cycles.

TRANSIT BUS EMISSIONS TESTS RESULTS- Table 5 summarizes the overall average performance of the oxidation converter mufflers for Total Hydrocarbons (THC), Carbon Monoxide (CO), Total Particulate (TPM), Soluble Organic Fraction (SOF), Insoluble Particulates (Insol.) and Oxides of Nitrogen (NOx), in terms of the percentage of each emittant reduced.

Table 6 lists the results of all emissions tests to date for the five oxidation converter muffler equipped 12.2m urban buses that have been in the study.

Fuel efficiency test results are included in Table 6. As indicated, in all but one test, fuel efficiency improved with the installation of the oxidation converter mufflers, even though it is known that exhaust system backpressure was slightly increased by the installation of the converter muffler.

The following charts, Figures 8, 9 and 10 show the measured exhaust emissions for OC Transpo 12.2 m buses powered by 6V92TA DDECII and 6V71N engines. The figures compare emissions levels of the bus with original mufflers and with the oxidation converter mufflers. Two of the test cycles were CBD (indicated beneath bus number), while the remainder were NY Composite test cycles.

Table 5. Average Reduction of Transit Bus Exhaust Emissions by Converter Mufflers

Emission	**6V92TA DDECII NY Comp**	**6V92TA DDECII CBD**	**6V71N NY Comp**	**6V71N CBD**
TPM	**19%**	**26%**	**34%**	**44%**
SOF	**43%**	**57%**	**58%**	**na**
Insol.	**17%**	**19%**	**11%**	**na**
THC	**49%**	**63%**	**71%**	**83%**
CO	**45%**	**66%**	**74%**	**92%**
NOx	**1%**	**31%**	**4%**	**18%**

There are two characteristic testing differences between the 6V92TA DDECII and 6V71N engines. From Table 6, it can be seen that the two engines yield very similar TPM emissions but the 6V71N engines produce on average higher NOx and CO emission levels. From Table 5, it can be seen that the second difference is that converter muffler performance on the 6V71N engines is better than on the 6V92TA DDECII engines. This is a result of the higher SOF and exhaust temperature levels of the 6V71N engine.

This study was intended to have identical pairs of experimental buses. There have been three 6V92TA DDECII buses tested under the study. Originally, Buses 8930 and 8922 were paired. After the first round of testing in Nov/95 (8922) and Dec/95 (8930), it was readily apparent that the two buses yielded very different emissions results. After re-examining the maintenance and rebuild records of both buses, it was discovered that the two engines had undergone different levels of rebuild; 8930 an in-frame rebuild (top end only) and 8922 an out-of-chassis rebuild (entire engine). Although both buses were rebuilt as 189kW engines, the out-of-chassis rebuilds result in the use of a different camshaft and ECM software. This is common practice for many transit authorities who will choose to upgrade bus engines at the time of rebuild.

It was decided to remove the converter muffler from bus 8930 and install it on bus 8910 which had an identical rebuild to bus 8922. However, subsequent emissions testing of these vehicles has indicated that bus 8922 still differs in PM composition to bus 8910 (equipped with the identical engine) and bus 8930 (equipped with different camshaft and ECM software). As these are real world "in-use" vehicles with emissions testing at different times and with the vehicles/engines tested "as-received", it is unlikely that any two "in-use" vehicles should yield emissions levels any better than "similar" to eachother.

Particulate Matter- TPM emissions levels for all transit bus tests are displayed in Figure 8. TPM emissions levels from the two engines equipped with mufflers, on both cycles were indistinguishable from each other, with all values falling into a range from 1.4 to 2.0 g/km (see Table 6).

For the 6V92TA DDECII engines, TPM was reduced on average by 19% over the NY Composite cycle and by 26% on the CBD cycle with use of the converter muffler. Given that the NY Composite and CBD test cycle average vehicle speeds are approximately 50% and 33% lower than the US HDTC, these results are felt to be reasonable.

Table 6. NY Composite and CBD Emissions Data for 12.2m urban buses

Emissions (grams/kilometer)	Mileage (km)	PM	HC	CO	NOx	Fuel Use (km/L)	SOF	TOE	SO4
MCI Classics: DDC 6V92TA DDECII									
Bus 8930: Catalyst Instal.	543,205								
Bus 8930: 5-Dec-96	561,705								
NY Comp: Baseline		1.41	1.91	3.47	11.46	1.49	na	na	na
NY Comp: Catalyst		1.00	1.31	2.30	12.04	1.49	na	na	na
Bus 8922: Catalyst Instal.	576,658								
Bus 8922: 22-Nov-96	591,680								
NY Comp: Baseline		1.50	2.30	8.07	16.08	1.42	0.32	0.33	0.01
NY Comp: Catalyst		1.53	0.91	4.75	12.00	1.57	0.15	0.17	0.02
Bus 8922: 22-Nov-96	591,680								
CBD: Baseline		1.63	1.15	6.37	17.61	1.41	0.30	na	na
CBD: Catalyst		1.20	0.43	2.20	12.14	1.61	0.13	na	na
Bus 8922: 10-Jan-96	602,900								
NY Comp: Baseline		1.54	2.29	6.50	12.32	1.47	0.24	na	na
NY Comp: Catalyst		1.20	1.47	4.99	11.85	1.57	0.14	na	na
Bus 8922: 11-Jun-96									
With Insulation	631,379								
NY Comp: Baseline		2.00	1.75	13.91	15.38	1.45	na	0.68	na
NY Comp: Catalyst		1.77	0.69	7.89	15.13	1.53	na	0.29	na
Bus 8910: Catalyst Instal.*	518,785*								
Bus 8910: 29-Feb-96	522,800								
NY Comp: Baseline		1.39	1.89	6.30	10.47	1.56	0.42	0.42	0.07
NY Comp: Catalyst		1.20	1.00	3.60	10.42	1.61	0.25	0.30	0.00
Bus 8910: 30-May-96									
With Insulation	542,500								
NY Comp: Baseline		1.71	2.58	8.78	9.83	1.39	0.57	0.49	na
NY Comp: Catalyst		1.16	1.10	2.37	9.99	1.58	0.36	0.30	na
GMC Classics: DDC 6V71N									
Bus 8423: Catalyst Instal.	772,508								
Bus 8423: 9-Dec-95	775,554								
NY Comp: Baseline		1.53	3.00	22.72	16.54	1.51	0.68	0.73	0.01
NY Comp: Catalyst		0.96	0.91	4.23	15.87	1.61	0.30	0.38	0.01
Bus 8423: 9-Dec-95	775,554								
CBD: Baseline		1.83	2.02	26.73	19.83	1.23	na	na	na
CBD: Catalyst		1.02	0.35	2.15	16.25	1.42	na	na	na
Bus 8548: Catalyst Instal.	811,413								
Bus 8548: 4-Jan-96	819,899								
NY Comp: Baseline		1.34	2.35	24.24	18.97	1.67	0.68	0.71	0.01
NY Comp: Catalyst		0.94	0.65	8.14	18.30	1.59	0.27	0.32	0.01

*Converter Muffler from bus 8930 was removed on February 7, 1996 after 30,000 km and installed on bus 8910.

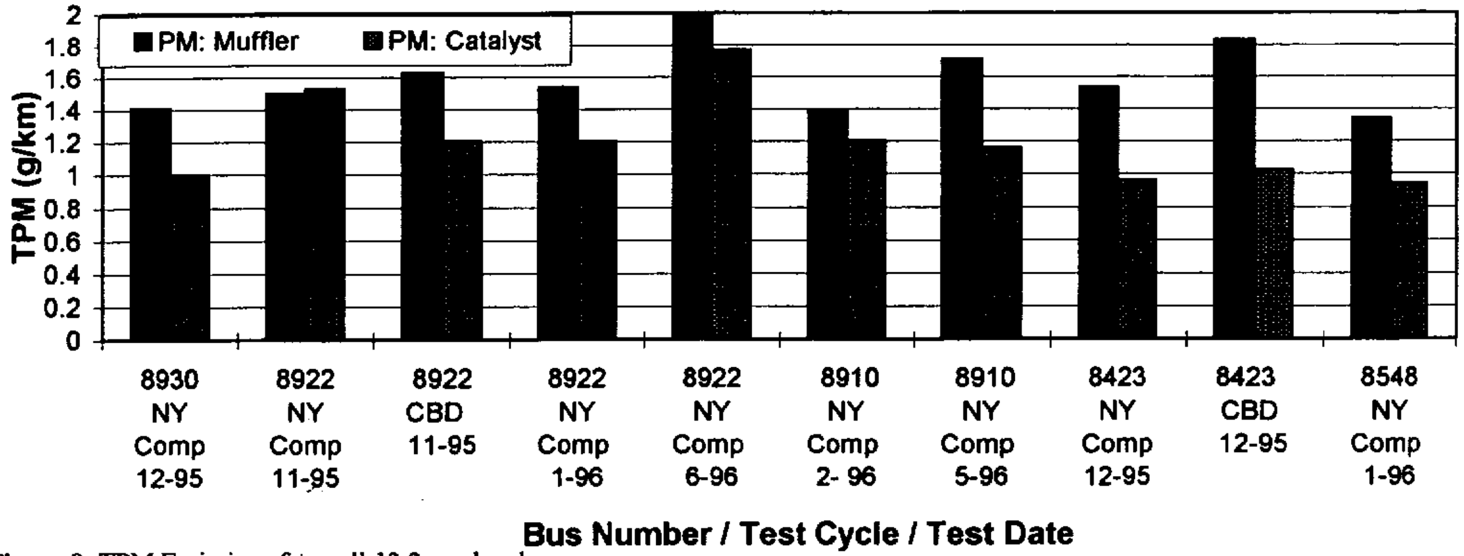

Figure 8. TPM Emissions from all 12.2m urban busses

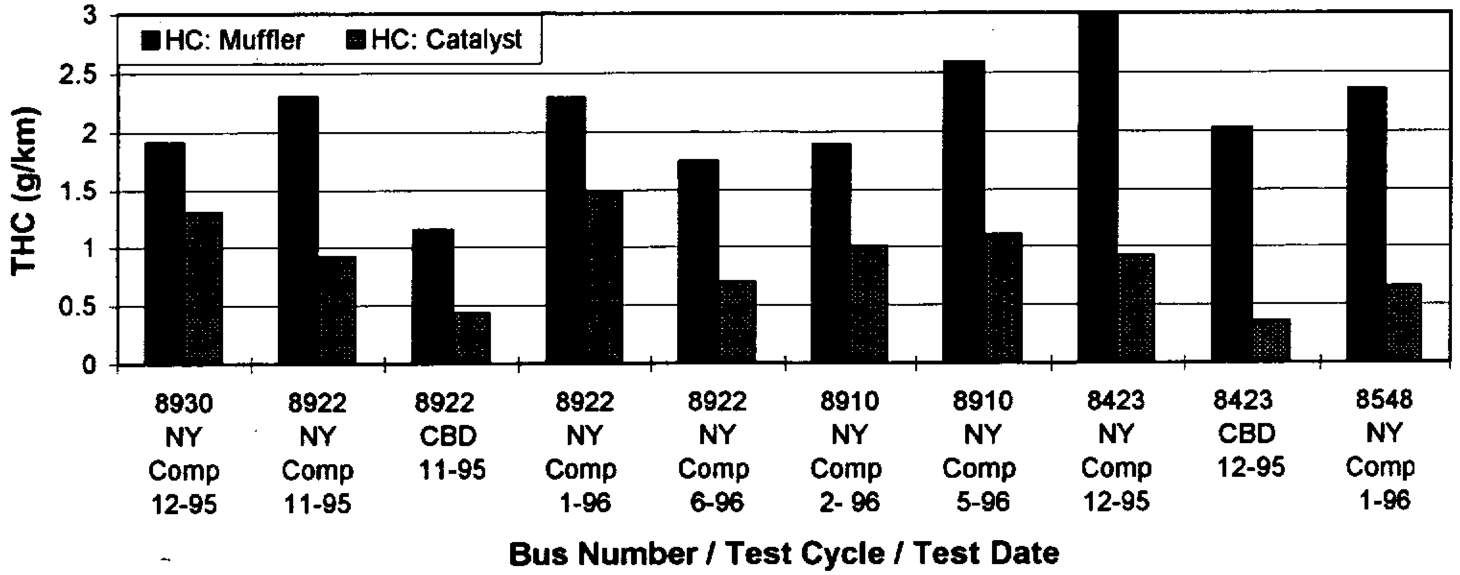

Figure 9. THC Emissions from all 12.2m urban busses

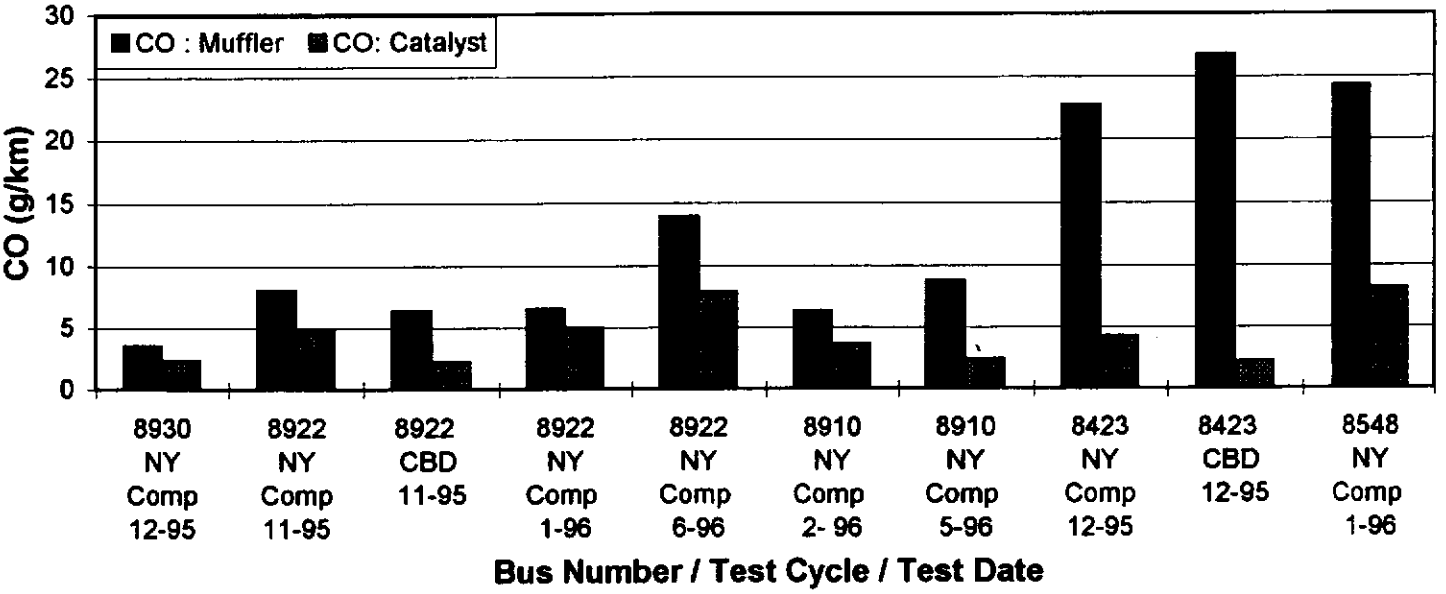

Figure 10. CO Emissions from all 12.2m urban busses

For the 6V71N engines, the converter mufflers resulted in a TPM reduction of 34% over the NY Composite cycle and 44% over the CBD cycle.

Sulfation due to the conversion of sulfur dioxide to sulfur trioxide by diesel oxidation catalysts is known to offset TPM reductions. In this study to date, sulfate production due to the use of the converter mufflers has not been a significant issue even for tests performed on buses with the higher sulfur fuels (fuel sulfur levels: low- 0.05 wt.%, high- 0.144 wt%).

SOF / Insoluble Carbon- The soluble organic fraction is composed of high molecular weight organics that are fuel or lube oil based. In this study, the SOF content has been found to vary for the same vehicles on different test dates. Also, there appears to be marked differences in SOF levels between vehicles with identical engines. The SOF level also varies significantly with the driving cycle of the vehicle. Given the complex issues that are related to SOF content, the following points can be presented.

The 6V71N engine has a characteristically higher percentage of SOF than the 6V92TA DDECII. Engine out SOF levels of 44-51% are characteristic for the 6V71N engines in this study. The converter muffler SOF conversion efficiency over the NY Composite cycle was found to be 58%.

The 6V92TA DDECII buses in this study show variable engine out SOF contents of approximately 18% for bus 8922 and 32% for bus 8910. These vehicles are identical and have identical engines with very similar mileages since rebuild. With reference to emissions tests, bus 8930 which was removed from the study due to camshaft and ECM differences can be estimated to have a SOF content in the 30-35% range, which would be similar to bus 8910. In a previous paper the Volatile Organic Fraction (VOF: thermal desorption GC technique) for a 1991 6V92TA DDECII (207kW) was reported to be 34% [1].

TPM measurements for Bus 8922 when tested over the NY Composite in November of 1995 indicated no TPM conversion but an SOF conversion of 53%. The CBD cycle tested at the same time yielded a 26% reduction in TPM. This discrepancy lead to bus 8922 being recalled for additional NY Composite testing in January 1996. These tests showed a 22% reduction in TPM. The November 1995 NY Composite test cycle result remains unexplained.

SOF conversion efficiency (using the muffler equipped emissions tests as a reference baseline) for the 6V92TA DDECII's was on average 43% over the NY Composite and 57% over the CBD cycle.

Table 5 also indicates the converter mufflers resulted in an apparent 11 to 19% reduction in the insoluble content of the TPM. All diesel oxidation catalysts must have some activity to oxidize carbon to prevent the surface from becoming excessively fouled. However, this study indicates that the even subtle backpressure differences on these engines can result in significant shifts in the ratio of SOF/Insolubles in favor of SOF. Thus, SOF and insoluble content measurements made using the muffler equipped emissions tests as a baseline reference do not give an accurate measure of the SOF and insoluble content reduction made by the converter muffler. In reality, the SOF reduction is likely higher and the insolubles reduction is likely lower.

Total Hydrocarbons (THC)- As indicated in Figure 9, the oxidation converter muffler was responsible for significant reductions in THC emissions. With reference to Table 5, the buses powered by 6V92TA DDECII's operating over the NY Composite cycle averaged a 49% reduction and a 63% reduction over the CBD cycle. The buses powered by 6V71N's performed even better with a 71% average reduction over the NY Composite cycle and 83% over the CBD cycle.

The reduction of THC emissions demonstrates the very attractive added benefit of effective oxidation catalyst technology. While the total amount of HC produced over the CBD cycle was lower for both engine types than those of the NY Composite cycle, greater reductions were also observed with the converter mufflers over the CBD cycle due to the hotter average catalyst temperatures (see Figures 2 and 4).

As previously discussed, the 6V71N powered buses experienced better converter muffler conversion efficiencies than the 6V92TA DDECII powered buses because of its characteristic hotter exhaust temperatures (see Figure 5).

Carbon Monoxide (CO) -Transit bus CO emissions are shown in Figure 10 and Table 6. The 6V71N's powered buses produced about three times as much CO per kilometer as the 6V92TA DDECII powered buses. Again, a high level of conversion efficiency is indicated for the oxidation converter mufflers, especially for the hotter running 6V71N powered buses.

Insulation of the 6V92TA DDECII converter mufflers has been demonstrated by US HDTC tests to ensure adequate catalyst activity and improve gaseous emissions reduction performance. In-use, added insulation was shown to greatly improved both HC and CO conversion efficiencies over the NY Composite cycle (see Table 6).

Heavy Duty Truck Results

Tables 7, 8 and 9 present the full results of all emissions tests for the heavy duty trucks in this study. It is felt by the authors that these vehicles are typical of urban truck fleets which accumulate low annual mileages. Two of the vehicles have accumulated annual mileages less than 20,000 km/yr., two vehicles less than 35,000 km/yr. and one vehicle accumulated just under 60,000 km/yr. Assuming a 250 workday/year calendar, the average daily mileage ranges from 80 to 240 km/day.

TPM emissions levels for all vehicles were found to vary substantially in the 0.3 to 0.8 g/km range over the NY Composite and CBD test cycles (see Tables 7,8 and 9). With respect to individual vehicles, the highest TPM emissions level produced was typically at least 70% higher than the lowest TPM emissions level found for the same vehicle. Both Insoluble fraction and SOF levels varied substantially for all vehicles between test dates. THC emissions were equally as variable.

Tables 7 and 8 illustrate one unique characteristic of the school buses. These vehicles are poorly utilized in the summer months. Emissions tests during the July and August summer months indicate that TPM levels peak in this time.This result is believed to be due to temporary fuel injector fouling. In any case, once the school year begins the TPM emissions decrease, thus, this is an example of a temporary effect which induces greater emissions variability.

Fuel use for each vehicle was found to vary by as much as 24% between the lowest and highest values over the same test cycle. This is a significant finding as it supports that tremendous cost and emissions reductions which could be attained in the in-use fleet merely by improved fuel use management and /or optimized vehicle maintenance.

Fuel use measurements for the trucks with aftertreatment were between 0 to 1.7% higher when compared to the baseline values. In comparison, the fuel use for the urban buses equipped with converter mufflers was lower than with standard mufflers. Overall, it is felt that any differences in fuel use are within acceptable levels or within the margin or error of measurement.

Thus, variability has been found to be the norm for these vehicles. There are many reasons for the variability in the emissions tests. First, with the exception of a tire inspection, each vehicle was tested "as received". No attempt was made to assess the mechanical condition of the vehicle or fuel quality. The authors feel that these vehicles represent average or above average vehicle maintenance.

Tables 10 and 11 summarize the overall average emissions results for the two, 1992 International school buses over the NY Composite cycle and CBD cycles respectively. The vehicles were retrofitted with oxidation converters installed ahead of the original vehicle mufflers. Emissions testing was conducted five times over a two year period.

Table 7. NY Composite Test Results for International School Buses and Series 4900 Truck with DT466 Engines

Test Date / Test I.D.	Mileage (km)	PM (g/km)	HC (g/km)	CO (g/km)	NOx (g/km)	Fuel Use (km/L)	SOF (g/km)
1992 Int. School Bus;	Vehicle 94-53						
Jul-94: Baseline	40963	0.68	1.06	3.04	10.36	2.19	0.17
Oct-94: Baseline	45444	0.35	1.28	1.95	9.04	2.64	0.12
Oct-94: Catalyst		0.30	0.29	0.60	10.35	2.65	0.04
Mar-95: Baseline	53296	0.42	1.57	2.30	8.36	2.65	0.19
Mar-95: Catalyst		0.27	0.30	0.92	8.92	2.64	0.07
Aug-95: Baseline	5001*	0.60	1.19	2.17	9.70	2.60	0.15
Aug-95: Catalyst		0.52	0.27	0.76	11.18	2.70	0.10
Apr-96: Baseline	18230	0.37	1.06	2.12	8.58	2.55	0.12
Apr-96: Catalyst		0.28	0.18	0.63	9.75	2.49	0.06
Jul-96: Baseline	24548	0.47	1.41	2.77	10.14	2.56	0.16
Jul-96: Catalyst		0.46	0.29	1.23	10.19	2.51	0.14
1992 Int. School Bus;	Vehicle 94-54						
Jul-94: Baseline	65361	0.57	1.30	2.61	9.85	2.38	0.12
Dec-94: Baseline	76111	0.38	0.63	1.80	7.66	2.35	0.14
Dec-94: Catalyst		0.34	0.08	0.36	8.09	2.36	0.08
Mar-95: Baseline	82450	0.59	1.82	2.10	8.25	2.41	0.24
Mar-95: Catalyst		0.37	0.18	0.32	8.53	2.35	0.12
Aug-95: Baseline	95386	0.82	1.47	2.36	8.31	2.48	0.41
Aug-95: Catalyst		0.41	0.26	0.72	8.85	2.45	0.03
Apr-96: Baseline	118454	0.37	0.73	1.90	8.20	2.55	0.41
Apr-96: Catalyst		0.34	0.19	0.56	8.39	2.48	0.03
Oct-96: Baseline	131884	0.58	0.81	3.24	8.99	2.62	0.15
Oct-96: Catalyst		0.50	0.27	1.23	8.76	2.59	0.12
1994 Int. Series 4900	Vehicle 95-109						
Nov-95: Baseline	17613	0.52	0.45	2.28	8.56	3.31	0.15
Nov-95: Catalyst		0.26	0.26	1.41	9.03	3.32	0.03
Nov-96: Baseline	33002	0.36	0.97	2.67	9.14	2.68	0.15
Nov-96: Catalyst		0.34	0.65	1.56	9.85	2.63	0.11

* new odometer installed

Table 8. CBD Test Results for International School Buses with DT466 Engines

Test Date / Test I.D.	Mileage (km)	PM (g/km)	HC (g/km)	CO (g/km)	NOx (g/km)	Fuel Use (km/L)	SOF (g/km)
1992 Int. School Bus;	Vehicle 94-53						
Jul-94: Baseline	40963	0.38	1.00	2.05	8.22	2.30	0.14
Oct-94: Baseline	45444	0.33	1.46	2.06	7.74	2.47	0.15
Oct-94: Catalyst		0.21	0.12	0.11	8.30	2.47	0.07
Mar-95: Baseline	53296	0.29	1.54	2.31	7.94	2.46	0.19
Mar-95: Catalyst		0.20	0.26	0.18	7.97	2.50	0.07
Aug-95: Baseline	5001*	0.55	1.16	2.03	8.22	2.53	0.15
Aug-95: Catalyst		0.32	0.24	0.19	4.83	2.45	0.06
Apr-96: Baseline	18230	0.32	0.97	1.82	7.86	2.43	0.12
Apr-96: Catalyst		0.23	0.12	0.09	8.94	2.32	0.12
Jul-96: Baseline	24548	0.38	1.24	2.60	9.22	2.43	na
Jul-96: Catalyst		0.29	0.29	0.20	9.75	2.38	na
1992 Int. School Bus;	Vehicle 94-54						
Jul-94: Baseline	65361	0.37	1.22	2.18	7.89	2.53	0.10
Dec-94: Baseline	76111	0.37	1.44	1.83	7.97	2.19	0.10
Dec-94: Catalyst		0.30	0.01	0.01	8.26	2.27	0.07
Mar-95: Baseline	82450	0.42	1.67	2.06	7.62	2.20	0.20
Mar-95: Catalyst		0.30	0.06	0.03	8.48	2.10	0.12
Aug-95: Baseline	95386	0.55	1.15	2.35	8.29	2.25	0.26
Aug-95: Catalyst		0.33	0.14	0.13	9.27	2.24	na
Apr-96: Baseline	118454	0.32	0.75	1.88	7.39	2.32	0.10
Apr-96: Catalyst		0.29	0.13	0.10	7.64	2.28	0.09
Oct-96: Baseline	131884	0.44	0.81	2.36	8.19	2.40	0.16
Oct-96: Catalyst		0.34	0.16	0.45	8.50	2.35	0.11

* new odometer installed

Table 9. New York Composite Test Results for Mack MS250P Trucks

Test Date / Test I.D.	Mileage (km)	PM (g/km)	HC (g/km)	CO (g/km)	NOx (g/km)	Fuel Use (km/L)	SOF (g/km)
1992 Mack MS250P;	Vehicle 95-67						
May-95: Baseline	38900	0.39	0.65	2.67	10.90	2.70	0.17
May-95:Catalyst		0.26	0.14	0.93	11.80	2.75	0.15
Aug-95: Baseline	46956	0.45	0.30	2.85	10.89	2.99	0.15
Aug-95: Catalyst		0.27	0.12	1.09	13.09	2.92	0.07
Apr-96: Baseline	66630	0.57	0.72	3.73	11.35	3.10	0.35
Apr-96: Catalyst		0.40	0.37	2.30	11.95	2.92	0.21
Oct-96: Baseline	80070	0.63	0.83	4.31	12.31	3.26	0.35
Oct-96: Catalyst		0.43	0.75	3.51	12.72	3.23	0.14
1992 Mack MS250P;	Vehicle 95-69						
May-95: Baseline	195282	0.39	0.41	2.18	11.41	3.09	0.28
May-95: Catalyst		0.34	0.09	1.42	11.18	3.00	0.13
Aug-95: Baseline	209016	0.42	0.49	2.06	11.98	3.11	0.15
Aug-95: Catalyst		0.37	0.11	1.41	11.63	3.08	0.09
Aug-96: Baseline	266395	0.68	0.75	4.05	12.90	2.69	0.29
Aug-96: Catalyst		0.52	0.56	2.30	14.15	2.59	0.23

Table 10. NY Composite Average Results Summary for International School Buses

	Baseline (g/km)	With Converter (g/km)	Percent Reduction
TPM	0.50	0.38	24%
THC	1.19	0.23	81%
CO	2.27	0.73	68%
Fuel Use (km/L)	2.60	2.60	0%

Table 11. CBD Average Results Summary for International School Buses

	Baseline (g/km)	With Converter (g/km)	Percent Reduction
TPM	0.40	0.28	30%
THC	1.22	0.15	88%
CO	2.13	0.15	93%
Fuel Use (km/L)	2.37	2.34	+1.3%

Although the CBD test cycle yielded 20% lower overall average TPM emissions compared to the NY Composite cycle, both THC and CO emissions were similar. The oxidation converter yielded higher percentage reductions for TPM, THC and CO over the CBD cycle due to the higher average exhaust temperatures of this cycle as previously discussed (see Figure 3). However, the TPM reduction on a mass basis was 0.12 g/km for both the CBD and NY Composite cycles.

Table 12 summarizes the overall average emissions results for the Series 4900 International truck over the NY Composite cycle. Although a 1994 model year vehicle, the engine was apparently a 1993 (145kW) production model. Thus, the emissions are very similar to the 1992 International school buses, yet it is difficult to draw comparisons given the limited emissions data for this vehicle.

Baseline and converter muffler TPM emissions were lower for this truck compared to the similar school buses. Converter muffler average TPM reduction performance was also higher for this truck compared to the buses but gaseous performance was considerably less. The reasons for these differences are unclear.

Table 12. New York Composite Average Results Summary for Series 4900 Truck

	Baseline (g/km)	With Converter Muffler (g/km)	Percent Reduction
TPM	0.44	0.30	32%
THC	0.71	0.46	35%
CO	2.48	1.49	44%
Fuel Use (km/L)	3.00	2.98	+0.7%

Table 13 presents the overall emissions summary for the two Mack MS250P trucks over the NY Composite cycle. The overall average TPM emissions for both vehicles equipped with standard mufflers were very similar to the school buses with a baseline TPM emission of 0.50 g/km. The average converter muffler TPM reduction was 26% over the NY Composite cycle, however, the two vehicles showed marked differences in the individual vehicle converter muffler TPM reductions. One vehicle showed TPM reductions in the 30% to 40% range while the second vehicle showed TPM reductions in the 12% to 24% range.

As can be seen in Table 9, baseline emissions tests of both Mack trucks indicate a steady increase in all emissions from May, 1995 to October 1996. Baseline TPM emissions for vehicles 95-67 and 95-69 increased by 61% and 74% respectively. THC emissions increased by 27% for Vehicle 95-67 and by 82% for vehicle 95-69. Carbon monoxide increased by over 60% and NOx by at least 15% for both vehicles.

Emissions tests for the vehicles with the converter mufflers installed showed higher TPM mass reductions but a decline in gaseous reductions as baseline TPM emissions increased during this time period. The reason for the decline in converter muffler gaseous performance is believed to be excessive idling of these vehicles. Excessive idling of diesel engines can cause fuel injector fouling and significant lube oil consumption. These conditions compounded by the excessive periods of cooler exhaust temperatures can lead to the fouling of the catalyst surface. Surface fouling blocks off the precious metal sites thus preventing the coordination of gaseous emissions. The surface carbon does not necessarily effect the reduction of TPM as the SOF partitions onto the catalyst surface in the liquidous phase and the deposited carbon can actually serve as an adsorbent allowing more SOF to partition to the catalyst surface.

Table 13. New York Composite Average Results Summary for Mack MS250P Trucks

	Baseline (g/km)	With Converter (g/km)	Percent Reduction
TPM	0.50	0.37	26%
THC	0.59	0.31	47%
CO	3.12	1.85	41%
Fuel Use (km/L)	2.99	2.94	+1.7%

OVERALL AVERAGE NOx EMISSIONS FOR TRUCKS AND BUSES- The overall average NOx emissions level for all trucks and buses in their baseline configurations to date is 11.99 g/km. The overall average NOx emissions level for all vehicles in their catalyst retrofitted configuration is 11.95 g/km. Thus, the overall difference between the baseline and catalyst equipped values is negligible. This overall result is fairly consistent with US HDTC engine tests which have shown NOx emissions with this particular diesel oxidation catalyst to be on par or slightly below baseline engine out NOx emissions levels.

However, in this study of heavy duty vehicle emissions, NOx emissions have proven to be highly variable between baseline emissions tests and tests conducted with oxidation converters and converter mufflers. Even for the same vehicle, there have been considerable variations in NOx emissions between individual test dates in both baseline and catalyst equipped tests.

Figure 11 illustrates the NOx emissions results of all vehicle tests to date in order of decreasing NOx emissions levels. Figure 11 also contains data of New York Bus Cycle tests that were conducted on the 1992 International School Buses in 1994 and 1995 as previously reported [1]. As the baseline NOx emissions levels were organized in order, a fairly consistent graph line results.

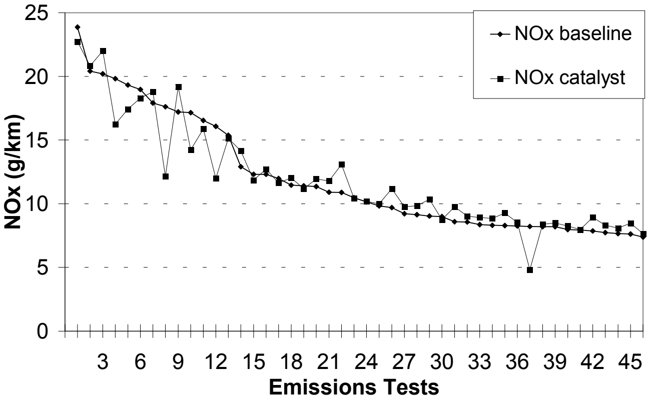

Figure 11. NOx emissions from all vehicle tests.

Figure 11 illustrates many tests where NOx emissions are on par between the baseline and catalyst equipped tests. However, numerous tests also show significant variations in NOx emissions. As this work represents a study of uncontrolled test vehicles it is not possible to positively identify the differences between testing, mechanical influences and influences of the retrofitted catalyst technology.

However, Figure 11 does show two apparent trends. As was reported previously [1], there is a trend towards 3-5% elevated NOx levels in vehicle / emissions cycles tests which yield lower than 11 g/km of NOx. For vehicle / emissions cycle tests which yield higher than 11 g/km there is a trend towards NOx levels which are 5-10% lower than baseline. Some individual tests show NOx emissions decreases of 20-30%. Again, the exact reasons for these variations in NOx emissions are impossible to separate from other potential influences. Overall, when the NOx emissions are considered from all chassis cycle tests, the overall average emissions level for both baseline and catalyst equipped vehicle is on par.

SUMMARY AND CONCLUSIONS

Diesel oxidation catalysts were found provide TPM reductions between 19% and 50% for transit buses and trucks.

The average TPM emission for transit buses without exhaust aftertreatment was 1.58 g/km. The average TPM emissions found for transit buses equipped with diesel catalyst technology was 1.20 g/km. This correlates to an average TPM mass reduction of 0.39 g/km. The Canadian Urban Transit Association reports that in 1995 the Canadian transit bus fleet numbering 10,230 vehicles traveled a total of 783,420,049 kilometers [7]. Based on extrapolated results in this study, the Canadian transit fleet would have produced approximately 1246 metric tonnes of TPM. In this study to date, diesel oxidation catalysts have indicated the potential to reduce these annual emissions by an average of 305 metric tonnes.

Major CO reductions of 45-93% and THC reductions of 50-90% were observed for both trucks and buses equipped with diesel oxidation converters and converter mufflers in this in-use study. On a mass basis, the THC and CO reductions found would extrapolate to Canadian transit fleet emissions reductions of over 1100 metric tonnes / year and 6900 metric tonnes / year. The reductions for the North American truck fleet would be vast.

SOF levels were reduced by 43-58% on transit bus tests. The older 6V71N engines demonstrated higher levels of SOF and higher exhaust temperatures than the 6V92TA DDECII's which was responsible for the greater observed TPM conversion levels observed on those buses.

Fuel sulfur levels as high as 0.15 wt% were found, however, these higher fuel sulphur levels did not lead to a significant level of sulphation.

No adverse impact on fuel economy was experienced. In fact, transit bus test results indicate that fuel mileage actually improved slightly, even though it was known that the converter mufflers imposed slightly higher backpressures on the engines.

While on average NOx emissions are not affected by the presence of the catalyst, a number of individual test results indicated significant deviations from baseline. The reason for these deviations is not known. US HDTC tests conducted with this catalyst have shown slight decreases of 1.5 to 5%.

Overall, cycle-to-cycle and vehicle-to-vehicle fluctuations in chassis emissions tests have proven to be the norm in this study. This highlights the need for careful monitoring of vehicle maintenance practices and records, pre-test screening and careful test and pre-conditioning practices to ensure that test data variability is kept to a minimum.

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NOMENCLATURE

NY Comp.: New York Composite Cycle
CBD: Central Business District Cycle
HDTC: Heavy Duty Transient Cycle
TPM or PM: Total Particulate Matter
THC or HC: Total Hydrocarbons
CO: Carbon Monoxide
NOx: Nitrogen Oxides
SOF: Soluble Organic Fraction
TOE: Total Organic Extractables
SO4: Sulpahte
C or ^{o}C: Degrees Celsius
kph: Kilometers / Hour
g/km: Grams / Kilometer
Kg: Kilogram
kW: Kilowatts
km/L: Kilometers / Liter
km: Kilometers