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Performance and Durability Evaluation of Continuously Regenerating Particulate Filters on Diesel Powered Urban Buses at NY City Transit

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ABSTRACT

Particulate emission from diesel engines is one of the most important pollutants in urban areas. As a result, particulate emission control from urban bus diesel engines using particle filter technology is being evaluated at several locations in the US. A project entitled “Clean Diesel Demonstration Program” has been initiated by NY City Transit under the supervision of NY State DEC and with active participation from several industrial partners.

Under this program, several NY City transit buses with DDC Series 50 engines have been equipped with continuously regenerating diesel particulate filter system and are operating with ultra low sulfur diesel (< 30 ppm S) in transit service in Manhattan since February 2000. These buses are being evaluated over a 8-9 month period for operations, maintainability and durability of the particulate filter. In addition, an extensive emissions testing program is being carried out under transient cycles on a chassis dyno to evaluate the emissions reductions obtained with the particle filter.

The on-road operational data over eight months showed stable exhaust back pressure with the particle filters, indicating successful filter regeneration. No adverse operational or maintenance issues were observed which can be attributed to the filter system. The emissions results from the first phase of testing exhibited >90% reductions in CO, HC and PM with the particulate filter. In addition, >99% reductions in Carbonyls and up to 80% PAH and 94% NO_2-PAH destructions were also achieved.

In this paper, the operational and emissions testing data from the NY City Clean Diesel Demonstration Program are discussed in detail.

INTRODUCTION

The New York State Department of Environmental Conservation (NYSDEC), as authorized by Title 6, Section 56-0607 of the 1996 Clean Water/Clean Air Bond Act, sought project proposals from municipalities, public benefit corporations or authorities, to demonstrate technologies that will have the potential of reducing emissions of air pollutants from diesel-powered vehicles.

Although alternative fueled vehicles utilizing compressed natural gas, hybrid electric drives and other technologies are playing an increasingly important role in reducing the pollution caused by vehicles utilized by public entities in New York State, it is clear that these vehicles are not available to many public entities. Obstacles such as exceedingly high incremental costs, complex and costly refueling infrastructures, and the unavailability of many types of vehicles, make it certain that that diesel-powered vehicles will remain an important part of the public fleet for some time to come. Therefore, since increasing evidence indicates that emissions from diesel vehicles may be harmful to human health and overall air quality, NYSDEC has determined that it is critical to establish a program to demonstrate that these vehicles can be operated in a manner more protective of the environment. Of particular interest to NYSDEC is the accelerated deployment of advanced or innovative technologies allowing for the reduction of the harmful emissions created by the operation of these diesel-powered vehicles throughout New York State.

Particulate filter systems are proving to be a very effective technology for reduction of diesel engine PM emissions. One such system is the patented continuously regenerating diesel particulate filter technology which utilizes NO_2 to combust soot collected in a particulate filter [1]. An oxidation catalyst upstream of the filter oxidizes a portion of the NO present in the exhaust, which is then used to combust the soot. With NO_2, the combustion of soot occurs at about 300°C lower and in the temperature range that is typical of diesel engine exhaust systems. Therefore the regeneration of the filter is continuous, requiring no external heating. Thus the continuously regenerating diesel particulate filter (CRDPF) system is completely passive. In previous studies [2, 3, 4], the CRDPF technology has been found to produce >90% reductions in PM, HC and CO. The CRDPF does not cause any significant NOx reduction.

The performance of CRDPFs is impacted by the sulfur level of the fuel [2, 5, 6]. During tests with various levels of sulfur it has been shown that as the sulfur level in fuel increases, the amount of sulfates generated by catalytic emission control systems also increases. In addition, the increased sulfur in the fuel reduces the catalyst efficiency for NO to NO_2 oxidation. This reduces soot combustion and hence filter regeneration is affected. In order to ensure maximum performance and durability of the CRDPF it is recommended to use fuel with <50 ppm sulfur. CRDPFs have been in operation in several European countries with ultra low sulfur diesel fuel since the mid-1990s [2]. The lack of such fuels has limited the use of CRDPFs in North America until recently. The recent (1999-2000) introduction of ultra low sulfur diesel (ULSD) fuel with less than 30 ppm sulfur in North America has enabled the CRDPF application in the US.

Switching existing diesel powered vehicles to ultra low sulfur diesel fuels and retrofitting them with CRDPFs is a possible way to achieve a significant impact on New York's air quality. Therefore, a one-year test program is currently underway using buses in New York City to demonstrate the viability of this retrofit approach.

The project objectives are:

- Evaluate the particulate emissions reductions achievable on existing urban bus engines, using continuously regenerating diesel particulate filters (CRDPF) in conjunction with ultra low sulfur diesel fuel (<30 ppm S)
- Evaluate the maintainability and durability of such particulate filters in rigorous NY City transit service
- Evaluate fuel parameters that enable the application of diesel particulate filter technology on urban buses

CRDPFs have been installed on 25 of the same model buses operating in normal transit service from the same depot. Extensive emission testing is being performed on two of these demonstration vehicles under transient operation. The emissions test will document the effect of a CRDPF on vehicle out emissions including regulated emissions, toxics emissions and particle size distribution. A separate fuel matrix test will explore the effects of different ULSD fuel property parameters on engine and CRDPF emission levels. The emission testing will be repeated after about 9 months of durability testing to determine the effects of operation on the performance of the CRDPF.

The test program started in February 2000. This paper discusses the results of the initial emission test and the first 8 months of field durability testing.

EXPERIMENTAL

The details about the test vehicles, the CRDPF and the emissions test program are discussed in this section.

Test Vehicle Engine Description	
Model	1999 DDC Series 50
Displacement	8.5L
Type	4-Stroke
Power (hp)	275 @ 2110 rpm
Configuration/ No. Cyl	Turbocharged Inline 4 cyl
Controls	DDEC IV
Certified emissions for 1999 Series 50 engine	
NOx (g/bhp-hr)	3.956
HC (g/bhp-hr)	0.76
CO (g/bhp-hr)	0.75
PM (g/bhp-hr)	0.042

Table 1: DDC Series 50 Engine Description

TEST VEHICLES

The diesel buses used for the demonstration program were chosen from the existing fleet at Mother Clara Hale depot in Manhattan. All of the test vehicles were 1999 40 foot Orion model V transit buses. The buses have Detroit Diesel Series 50 engines equipped with an oxidation catalyst as standard equipment. A description of the engine and its certified emissions are provided in Table 1.

FUEL

The ultra low sulfur diesel fuel for the demonstration project was produced by Equilon Enterprises in their Delaware refinery. The sulfur content of the Equilon fuel was fixed at less than 30 ppm and the entire quantity of the ULSD fuel was produced in one single batch. Table 2 provides the properties of the New York standard DF #1 fuel and the Equilon ULSD. Both of these fuels were used for emissions testing. Rad Energy facilitated the fuel supply to NY City Transit.

Analysis	**Unit**	**Base DF#1**	**ULSD**
Total Sulfur	ppm wt	247	27
API Gravity	Deg API	42.6	39.6
Flash Point	Deg F	120	160
Cetane Index		42.3	45
Cetane Number		46.7	47.5
Distillation	Deg F		
IBP			383
50%		412	445
90%		486	508
EP		583	562
Cloud Point	Deg F	-64	-40
Pour Point	Deg F	-75	-45
Viscosity @40	cst	1.36	1.79
Aromatics	Wt%	23.1	24.1
Poly Aromatics	Wt%	3.9	2.5

Table 2: Test fuel properties

CRDPF DESIGN – The diesel particulate filter used in this study is commercially known as Continuously Regenerating Technology or CRT™ and is manufactured by Johnson Matthey. The device is made up of two chambers where the oxidation step in the inlet is followed by the soot collection/combustion process. The first chamber contains an oxidation catalyst consisting of a ceramic honeycomb substrate coated with a proprietary highly active Pt group metal. Aside from oxidizing a portion of the NO for soot combustion, the catalyst also oxidizes CO, HC and SOF portion of the PM. In the second chamber, the exhaust flows through a bare ceramic wall-flow filter. The filter is also a honeycomb design with alternate channels blocked at each end forcing exhaust to flow through the walls of the filter where gaseous components pass through whereas soot is trapped. The trapped soot is then combusted by the NO_2 generated by the catalyst. A diagram of a typical CRDPF is provided in figure 1.

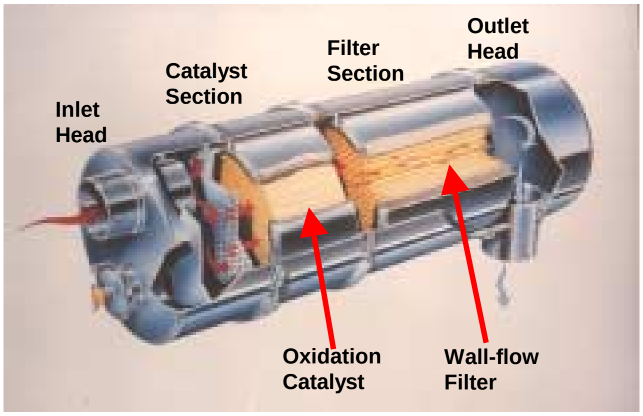


Figure 1: Schematic of the continuously regenerating diesel particulate filter system

The CRDPF unit used in this application was 11 in. in diameter and 31.5 in. in length. This contained an oxidation catalyst with about 4.2 L volume and a wall-flow filter with 12.5 L volume. The size requirement is determined based on the engine power and emissions. Normally, the CRDPF is designed to replace the existing OE muffler and thus fit in the existing space and mate with the OE exhaust pipes. The substrate for the oxidation catalyst and the particulate filter were manufactured by Corning Inc. The CRDPF is a modular unit with separate inlet head, outlet head, catalyst and filter sections. Figure 2 shows a unit that has been disassembled. All the modules are built with stainless steel and connected by V-clamps. The modular design provides easy access for filter maintenance at prescribed intervals. Figure 3 is a picture of the CRDPF installed in one of the test buses.

Figure 2: Disassembled CRDPF

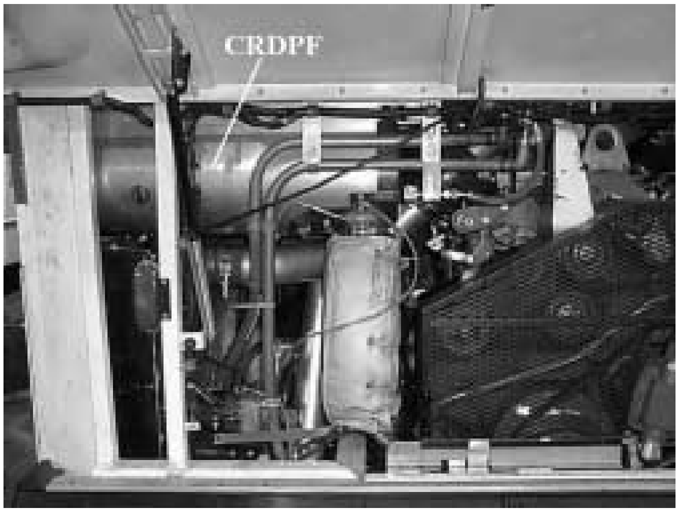


Figure 3: Bus with CRDPF

EMISSIONS TEST PROGRAM

Two vehicles chosen at random from the test group underwent emissions testing at the Environment Canada -Environmental Technology Centre in Ottawa, Ontario. The objectives of the emissions tests are listed below:

- Evaluate the difference in emissions between ultra low sulfur diesel and the standard DF #1 diesel fuel currently used by New York City Transit.
- Evaluate the reduction of regulated and toxic emissions resulting from the use of a CRDPF with ULSD.
- Document the effects on particle number count and particle size resulting from the installation of a CRDPF on the diesel engine.

Emissions test procedures – As can be seen in Table 3 the buses were tested in three configurations and on two different test cycles. The baseline emissions were gathered with the bus in its original configuration operating on New York Standard DF #1 fuel. Data were also collected with the bus running on the Equilon ULSD fuel with the original catalytic muffler and again with the CRDPF.

The two cycles used for testing were the Central Business District (CBD) and the New York Bus (NYB) Cycle. Both are time-based cycles operating for approximately 10 minutes each. The CBD (Figure 4) consists of 14 repetitions of acceleration from 0 to 20 mph, cruising at 20 mph and a deceleration back to 0. The CBD cycle covers 2 miles for an average speed of 6 mph. The NYB (Figure 5) cycle is more representative of actual operation in New York City. It is made up of 65% idle time and 13% acceleration with no time spent cruising [7]. The cycle covers 0.5 miles for an average speed of 1.5 mph. According to NYC transit the average speed of their buses is 3.5 mph.

	OE Muffler*		OE Muffler*	CRDPF	
Fuel	NY DF #1		Equilon ULSD	Equilon ULSD	
S50 Bus 1 NYCTA Bus #6019	CBD	NYB	CBD	CBD	NYB
S50 Bus 2 NYCTA Bus #6065	CBD		CBD	CBD	

* OE Muffler included an oxidation catalyst

Table 3: Emissions Test Matrix for NY City Buses

Before beginning any test cycles the buses were warmed up until the engine operational temperatures reached normal levels. For each test eight cycles were run with a 3-minute soak between cycles. Samples were collected on cycles 2, 3, 4, 6, 7 and 8. The first and fifth cycles were used to condition the equipment and the driver, by simulating the complete cycle but not collecting any data.

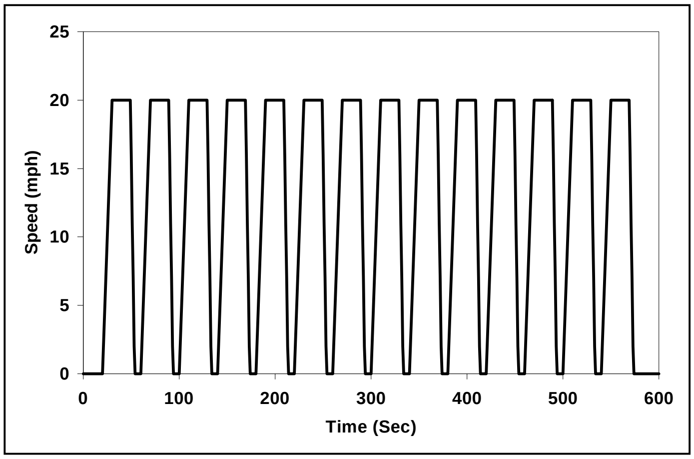


Figure 4: Central Business District Cycle

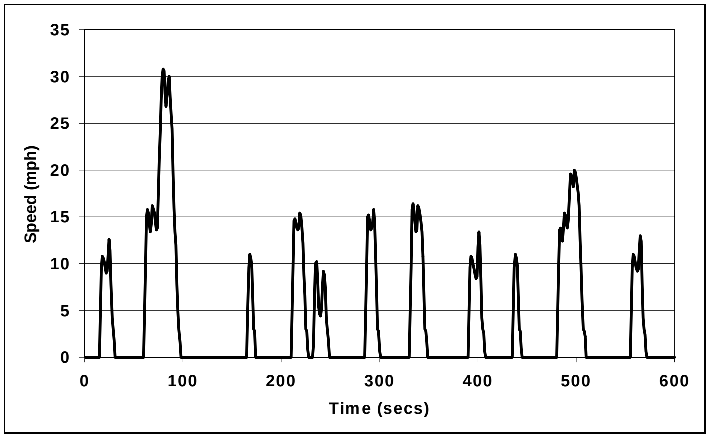


Figure 5: New York Bus Cycle

The test procedures that were followed and the exhaust emission rate and fuel economy calculations for the testing of these buses were outlined by the US-EPA [8]. The sample collection and analysis methods used for the various emissions are listed in Table 4.

COMPOUND	Analysis Method	Sample Collection
Carbon Monoxide (OEM)	Non-Dispersive Infrared Detection (NDIR)	Continuous Collection
Carbon Monoxide (CRDPF)	Gas chromatography (GC)	Tedlar™ Bag
Carbon Dioxide	Non-Dispersive Infrared Detection (NDIR)	Continuous Collection
Oxides of Nitrogen	Heated Chemiluminescence Detection	Continuous Collection
Nitric Oxide	Heated Chemiluminescence Detection	Continuous Collection
Nitrogen Dioxide	Calculated	
Total Hydrocarbons	Heated Flame Ionization Detection (FID)	Continuous Collection
Particulate Matter	Gravimetric Procedure	70mm Pallflex T60A20 Filters
Soluble Organic Fraction	Dichloromethane Soxhlet Extraction	47 mm Pallflex T60A20 Filters
Organic Carbon /Elemental Carbon	Thermal/Optical Transmittance (TOT)	Quartz coated T60A20 Filters Filters
SO4/SO2	Ion Chromotography	Carbonate Coated T60A20 Filters Filters
Carbonyl Compounds	High Performance Liquid Chromatography	2,4-DNPH coated-Silica Gel Cartridges
Volatile Organic Compounds	GC-FID	Tedlar ™ Bag
Methane and Light Hydroarbon Compounds	GC	Tedlar ™ Bag
Polycyclic Aromatic Hydrocarbons	HRGC/HRMS High resolution gas Chromatography/ mass spectrometry	Polyurethane Foam

Table 4: Summary of sample collection and analysis

The buses were driven on a single roll chassis dynamometer system with a 0.61m (24 inch) diameter roll. The inertia weight and road loads were simulated during testing using a 400 Hp direct current motor. The buses were tested at an inertia weight of 31500 lb and a road load of 45.8 Hp.

The total exhaust stream produced by the buses was collected and diluted using a constant volume sampling (CVS) dilution system with a total dilute exhaust volume of 2000 scfm. The dilution air was taken from the test cell and was conditioned by HEPA filtration for removal of particulate matter. The total volume of raw exhaust was transferred from the buses to the CVS through a 6 inch diameter flexible, stainless steel pipe that was insulated. The raw exhaust was then diluted with laboratory air and the mixture directed through a critical flow venturi. During the exhaust emissions test continuously proportioned samples of the dilute exhaust mixture and the dilution air were collected and stored in sample bags for analysis.

Regulated Emissions - Gaseous samples were analyzed for the concentrations of total hydrocarbons (THC), oxides of nitrogen (NO_X), and carbon monoxide (CO) and carbon dioxide (CO_2). Concentrations of nitrogen dioxide (NO_2) were determined by subtracting nitric oxide (NO) measurements from NO_X, assuming the sum of NO_X was NO plus NO_2. For the tests with the CRDPF, the concentrations of CO were below the NDIR detection limits and therefore these samples were analyzed by GC.

A particulate sampling system directed the exhaust through 70 mm diameter Pallflex filters (Teflon coated glass fiber) which were used to collect particulate mass from the sample stream. A gravimetric method was used to determine the particulate mass. In order to ensure adequate sample loading on the filters while testing with the CRDPF in place, the filter was sampled over 6 repeats of the drive cycles. A dilution tunnel blank was collected over a 60 minute time period and these results were factored into the calculation of total particulate mass**.**

Carbonyl Analysis - During sampling, dilute exhaust was drawn through silica gel Sep-Pak cartridges coated with 2,4-DNPH. The carbonyl compounds selectively react with the 2,4-DNPH forming hydrazones that are retained on the cartridge. The hydrazones are removed from the cartridge using a solvent and the liquid sample that results is analysed by high performance liquid chromatography (HPLC). For the emissions tests with the OE muffler in place the carbonyl cartridges were collected for each individual test cycle. With the CRDPF in place the carbonyl compounds were collected over three repeats of the test cycles in order to ensure an adequate sample that is required for detection. A total of 23 carbonyl compounds were analyzed.

Detailed HC Analysis – Gaseous samples were collected for analyses of methane and non-methane hydrocarbons (NMHC). 161 volatile organic compounds (non-methane hydrocarbons) were determined by high-resolution gas chromatography with a flame ionization detector following cryogenic pre-concentration. The lighter hydrocarbon compounds were determined by GC.

PAH and NO_2PAH - The analyses for polycyclic aromatic hydrocarbons and nitrated polycyclic aromatic hydrocarbons were performed using a pre-extracted Soxlhlet apparatus and the extraction was analyzed by high resolution GC/MSD. The 70 mm filter and polyurethane foam were treated as one sample. Over 45 PAH/NO_2PAH compounds were analyzed.

Soluble Organic Fraction of Particulate Matter - 47 mm diameter Pallflex filters were collected for particulate mass determination and were Soxhlet extracted with - dichloromethane. The mass lost on extraction was expressed as a percentage of total particulate mass.

Total Organic and Elemental Carbon -The two quartz filters (one primary particulate matter filter and one secondary adsorbed carbon filter) were submitted for analysis of total organic and elemental carbon using NIOSH Method 5040 Thermal/Optical Transmittance (TOT) method.

As with the particulate sample collection, all of the above mentioned unregulated compounds were collected over multiple test cycles, with the CRDPF in place, in order to ensure adequate sample required for detection.

Before being installed on the buses the CRDPFs used for emissions testing were de-greened so that the emissions data is representative of actual in use values. The units were installed on a DDC series 50 engine on a 500 hp DC dynamometer and run for 20 hours. The cycle used for de-greening was the CTA (Chicago Transit Authority) cycle that has a relatively high average exhaust temperature that works well for conditioning a catalyst.

Particle sizing test procedures and equipment – Diesel particulate matter typically exhibits a bimodal mass-weighted size distribution, with a nucleii mode between 0.01 and 0.05 micron, and an accumulation mode between 0.1 and 1.0 micron. A third mode is sometimes observed at 7-8 microns. The number-weighted size distribution is characterized by a single mode between 0.007 and 0.05 micron. The fractional alveolar deposition, as a function of aerodynamic diameter, increases greatly for sizes below 0.5 micron, so it is felt that these ultra-fine particles are of the greatest importance when considering human health effects [9].

The sampling train for the particle size measurements was different from that used for the other regulated and unregulated emissions. Kittleson, Khalek and others have found that the measured particle size distribution is a strong function of the sampling and dilution methods [10]. A constant volume sampling (CVS) system, with its variable dilution factor during transient cycles and long residence time, is unsuitable for making representative size distribution measurements. Instead, sampling was carried out directly from the vehicle exhaust pipe and a mini dilution tunnel was used for dilution purposes. In addition, an attempt was made to skew the dilution parameters towards ‘real world’ values for temperature, humidity, residence time, and dilution factor.

A 3/8th inch probe mounted in the transfer line sampled raw vehicle exhaust at the end of the OEM exhaust system. A constant volume displacement pump drew 1 lpm raw exhaust into the diluter, where it was thoroughly mixed with 100 lpm of filtered dilution air. The temperature in the minidiluter, while not directly regulated, typically was around 25 C, and the humidity varied from 20 – 30%. The transit time of the complete system from probe to instruments was less than 0.1 second. These parameters were chosen as a compromise between the competing factors influencing particle growth and formation and the actual values that might be encountered as the exhaust leaves the vehicle and mixes with the ambient air.

Particle size distribution measurements were made during the emissions testing using two distinct instruments and methods. The Scanning Mobility Particle Sizer (SMPS), TSI model #3934, measures mobility diameter through the range 0.005- 1 micron. This instrument can scan through one of three preset size ranges, which takes approximately 5 minutes to produce a complete size distribution, or can measure one pre-selected size in real time. The SMPS was used to measure particle sizes under both transient and steady state conditions. During the transient test cycles (CBD and NYB), the SMPS was set to measure the concentration of 10nm or 100nm particles in real time, with three 10-minute cycles repeated for each size. To effectively address the issues of potential production of ultra-fine particles and related health effects, it was felt that the SMPS must also be run using the scanning size distribution method. Therefore, three 10-minute steady-state cycles were run (at idle, 15 and 30 mph), while the SMPS completed two 5-minute size distribution scans from 5 – 250 nm.

The second instrument used was the Electrical Low Pressure Impactor (ELPI), from Dekati Ltd. Finland, which measures aerodynamic diameter using an impactor. It has twelve stages, each covering a subset of the size range between 0.035-10 micron. The impaction method allows for the accumulation of particulate in each size bin and the generation of composite data for mass or number, while the real time readout capability enables the storage and 'playback' of this accumulation process during the sampling/testing time frame. One caveat that must be appreciated is that because of the low pressures in the impactor, the measurement of the smallest size particles are subject to a large degree of error due to a variable loss of volatiles. This limits the practical range of this instrument to ~ 0.06-10 micron.

The ELPI was used to record particle size distributions during the transient driving cycles (CBD and NYB), and during steady state vehicle operation noted above (idle, 15 and 30 mph). The ELPI, while effective at capturing the real-time changes in particle size distributions, is limited to particles larger than ~60 nm, and only resolves the distribution into twelve relatively wide size bins. It should also be understood that mobility and aerodynamic diameter can in principle be related through equations involving the shape and density of the measured particles. To the extent that these parameters remain unknown, one may make the assumption of spherical shape and unit density, and so relate the different size metrics only approximately.

FIELD EVALUATION

Buses from Mother Clara Hale depot in NY City were used for the durability study. This depot operates 141 total buses, 66 of which are the 1999 Orion model V. The fuel supply for the entire depot was switched over from standard DF#1 to the ULSD fuel for this demonstration project. This enabled the CRDPF operation and also eliminated the possibility of mis-fuelling with high sulfur fuel. A total of 25 of the 1999 Orion V buses with DDC S50 engines were retrofitted with the CRDPFs. The CRDPF retrofit started in February 2000. The durability testing will continue for 9 months and is expected to end in November 2000.

Of the 25 buses with CRDPFs, 3 were equipped with data loggers that continuously monitor exhaust back pressure and temperature, upstream of the CRDPF. The data loggers were installed in the wheel chair ramp access space on the driver's side of the bus as shown in Figure 6. This location is protected from weather and is not regularly accessed for maintenance. Two of the data logger equipped buses were the same ones used for emissions testing (6065 & 6019).

Exhaust back pressure measured upstream of the CRDPF can be used to evaluate the proper operation of the CRDPF. Generally, this back pressure data is obtained under a specific test condition such as Full Load Full Throttle on a chassis dyno and a trend is developed over time. This trend plot indicates if the CRDPF system is working satisfactorily. An unusual increase in back pressure is indicative of insufficient filter regeneration or of an engine problem that is causing excessive soot generation. However, access to a chassis dyno for such testing is very limited. Therefore, this test can be modified by using peak exhaust back pressure data from on-road operations and a back pressure trend can be developed. This is what is used in the present application.

Exhaust temperature provides information on the driving cycle and how effectively the filter is regenerating. Typically, the CRDPF requires at least 40% operation at or above 275°C for effective filter regeneration. By monitoring the engine exhaust temperature, it can be determined if there will be any potential problem with filter regeneration. Sudden or unusual changes in exhaust temperature can also indicate engine related problems.

A thin-film strain-gage based pressure sensor and a 1/8th. in. K-type thermocouple are used for pressure and temperature monitoring, respectively. Both the exhaust back pressure and the temperature are measured at the CRDPF inlet, within the inlet section (Figure 1), approximately 6 inches prior to the catalyst. The thermocouple protrudes halfway inside the inlet chamber, within the gas flow. Pressure and temperature are measured continuously while the vehicle is operating on-road under its typical driving cycle and collected in the data logger on PCMCIA memory cards. This is real-time data and the peak back pressure and temperature represent that obtained under actual driving conditions of these vehicles. Such data is collected on a regular basis from the time the CRDPF is installed on the vehicle. This data is utilized to develop time versus peak back pressure trends as well as histograms.

Figure 6: Data logger installation

In addition to data logging, the group of 25 buses equipped with CRDPFs is continuously compared to a control group of 41 buses without CRDPFs, to compare operational and maintenance parameters. This is to identify any operational and maintenance issues that are related to CRDPF installation. The metrics used to compare the two groups are:

- Fuel economy in miles per gallon
- Number of exhaust system related road calls
- Mean distance between failures in miles, where a failure is defined as an unplanned maintenance action.

These parameters are monitored on a weekly basis.

RESULTS AND DISCUSSIONS

Since the project is still continuing, only the results from the initial emissions testing and first 8 months of durability testing are presented here.

PROTOTYPE TESTING

Prior to the start-up of the actual project, a prototype CRDPF was tested for fit, form and function on one of the representative Orion V buses at NYCTA. Besides, finalizing any mechanical issues, this unit was operated on-road for about a month to evaluate any operational issues. Using a data logger, the exhaust temperature and the back pressure were monitored during on-road operation. Figure 7 is a histogram of the on-road exhaust temperature data. Each one of the bars represents the total number of data points collected within each temperature interval. The data is analyzed in 25°C intervals between 100 and 450°C. For this vehicle, the maximum frequency occurred between 300 and 324° C, which is represented by the bin labeled 325. The line represents the percent of operating time that the exhaust was above a certain temperature. For this bus the exhaust temperature was above 275^{o}C for 50% of the operating time. This temperature profile is very favorable for successful regeneration of the CRDPF and the results indicated that the CRDPF would satisfactorily operate on these Orion V buses with DDC S50 engines.

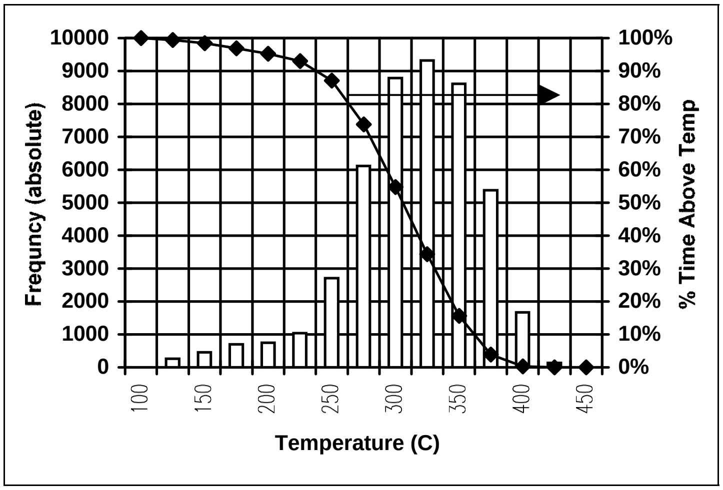


Figure 7: On-road Exhaust temperature profile for 1999 Series 50 bus in New York City w/ Prototype CRDPF

EMISSION TESTS - PHASE I

Bus #6019 and #6065 were the two 1999 Orion V buses with DDC S50 engines that were emissions tested at Environment Canada. Bus 6019 was tested over both the CBD and NYB cycles. Bus 6065 was only tested on the CBD cycle. Under the CBD cycle, both buses were tested for effects of fuel change from LSD to ULSD with the OE muffler. The results from regulated emissions testing and calculated fuel economy (FE) are presented in Table 5. A selection of the toxics and PM filter analysis from these tests are presented in Table 6.

Results from Table 5 are also presented in graphical form in Figures 8 and 9. The emissions data for the two buses under CBD cycle are averaged and reported in Figure 8. On the CBD cycle, comparing the emissions due to fuel change from baseline LSD (NY DF#1) to the Equilon ULSD, results showed 76% reduction in THC, 29% in CO and 23% in PM. One of the key reasons for this PM reduction was the reduced sulfur in the Equilon fuel. As can be seen from Table 6, the fuel change caused >90% reduction in SO_2 emission and sulfate formation with the Equilon fuel.

Bus ID	Test Cycle	Configuration	Fuel	FE	CO_2	NO_X	THC	CO	PM
				mpg	g/mile	g/mile	g/mile	g/mile	g/mile
NYCTA #6019	CBD	OEM	LSD	3.3	2942	25.6	0.18	1.8	0.22
NYCTA #6019	CBD	OEM	ULSD	3.4	2948	25.6	0.06	1.2	0.19
NYCTA #6019	CBD	CRDPF	ULSD	3.1	3236	26.4	0.03	0.16	0.04

% Reduction baseline to ULSD					-0.2	0.0	66.7	34.7	15
% Reduction Baseline to ULSD & CRDPF					-10.0	-3.1	83.3	91.4	82
Bus ID	**Test Cycle**	**Configuration**	**Fuel**	**FE**	**CO_2**	**NO_X**	**THC**	**CO**	**PM**
				mpg	**g/mile**	**g/mile**	**g/mile**	**g/mile**	**g/mile**
NYCTA #6019	NYBUS	OEM	LSD	1.5	6483	70.3	0.91	13	0.65
NYCTA #6019	NYBUS	CRDPF	ULSD	1.4	7177	70.3	0.06	0.23	0.04
% Reduction Baseline to ULSD & CRDPF					-10.7	-4.3	93.4	98.3	95.4
Bus ID	**Test Cycle**	**Configuration**	**Fuel**	**FE**	**CO_2**	**NO_X**	**THC**	**CO**	**PM**
				mpg	**g/mile**	**g/mile**	**g/mile**	**g/mile**	**g/mile**
NYCTA #6065	CBD	OEM	LSD	3.3	2897	23.3	0.26	2.1	0.21
NYCTA #6065	CBD	OEM	ULSD	3.5	2884	25.1	0.04	1.6	0.14
NYCTA #6065	CBD	CRDPF	ULSD	3.7	2679	23.8	0	0.09	0.01
% Reduction Baseline to ULSD					0.5	-7.6	85.7	23.9	31
% Reduction Baseline to ULSD & CRDPF					7.5	-2.1	100.0	95.9	95

Table 5: Regulated Emission Test Results for DDC S50 Powered NYCTA Buses 6019 and 6065

Bus ID	**Test Cycle**	**Configuration**	**Fuel**	**Carbonyl**	**PAH**	**NO2PAH**	**SO4**	**SO2**	**SOF**	**OC**	**EC**	**TC**
				mg/mile	**ug/mile**	**ug/mile**	**mg/mile**	**mg/mile**	**%**	**mg/mile**	**mg/mile**	**mg/mile**
#6019	CBD	OEM	LSD	73	62	5.0	62	270	59	29	90	119
#6019	CBD	OEM	ULSD	66	49	3.4	2.8	21	n/r	33	111	145
#6019	CBD	CRDPF	ULSD	bdl	14	1.5	13	7.0	bdl	6.6	1.5	8.1
% Reduction baseline LSD to ULSD				10	22	32	95	92		-14	-23	-22
% Reduction baseline LSD to ULSD with CRDPF				>99	78	70	79	97	>99	77	98	93
Bus ID	**Test Cycle**	**Configuration**	**Fuel**	**Carbonyl**	**PAH**	**NO2PAH**	**SO4**	**SO2**	**SOF**	**OC**	**EC**	**TC**
				mg/mile	**ug/mile**	**ug/mile**	**mg/mile**	**mg/mile**	**%**	**mg/mile**	**mg/mile**	**mg/mile**
#6019	NYB	OEM	LSD	294	201	23	37	620	54	109	403	512
#6019	NYB	CRDPF	ULSD	bdl	42	1.3	1.3	14.5	bdl	bdl	bdl	bdl
% Reduction baseline LSD to ULSD with CRDPF					79	94	96	98	>99	>99	>99	>99
Bus ID	**Test Cycle**	**Configuration**	**Fuel**	**Carbonyl**	**PAH**	**NO2PAH**	**SO4**	**SO2**	**SOF**	**OC**	**EC**	**TC**
				mg/mile	**ug/mile**	**ug/mile**	**mg/mile**	**mg/mile**	**%**	**mg/mile**	**mg/mile**	**mg/mile**
#6065	CBD	OEM	LSD	77	66	3.8	37	316	65	42	90	133
#6065	CBD	OEM	ULSD	70	63	2.6	3.9	31	68	26	82	110
#6065	CBD	CRDPF	ULSD	0.9	15	0.5	2.6 *	7.4	bdl	bdl	bdl	bdl
% Reduction baseline LSD to ULSD				9	5	32	89	90	-5	38	9	17
% Reduction baseline LSD to ULSD with CRDPF				99	78	87	93	98	>99	>99	>99	>99

OC = Organic Carbon	* = large amount of error associated with this value analysis
EC = Elemental Carbon	bdl = below detection limit
n/r = Not reportable	SOF = Soluble Organic Fraction

Table 6: Non-regulated and Toxics Emissions Test Results for DDC S50 Powered Buses 6019 and 6065

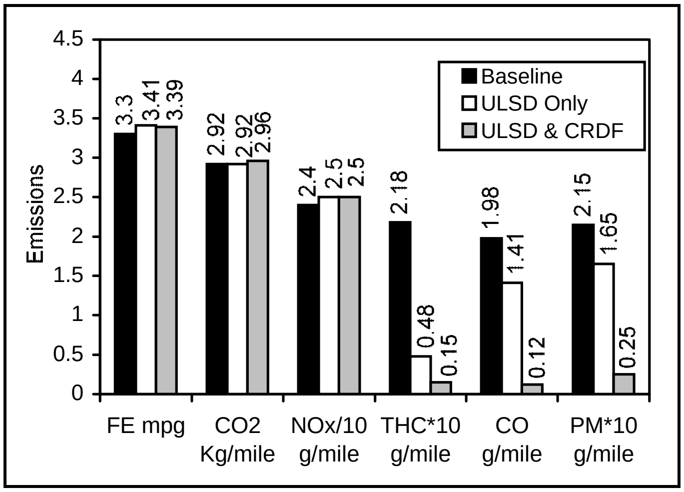


Figure 8: Average DDC S50 emissions results CBD Cycle

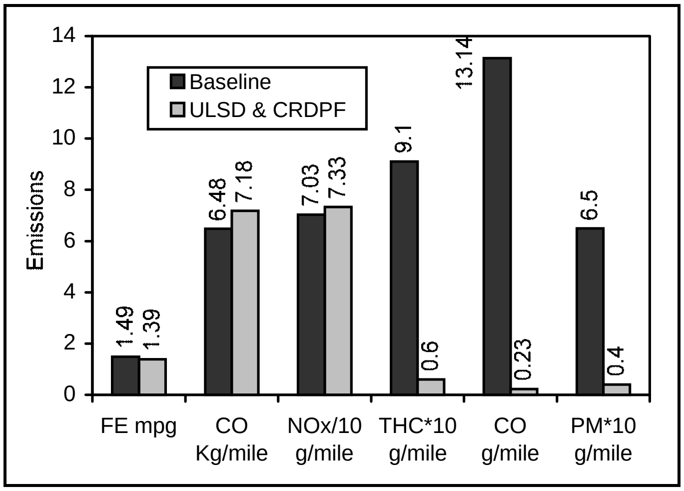


Figure 9: Average DDC S50 emissions results NYB Cycle

The carbonyl, PAH/NO_2PAH values presented in Table 6 represent the sum of numerous compounds. It should be noted that not all of the compounds analysed were detected in the above tests. As stated earlier, tests with the CRDPF, required sample collection over several repeat test cycles, therefore the CRDPF results presented in Table 6 are the average of two repeats only. As there was such a small mass on the particulate sample filters, the SOF, OC, EC analysis resulted in several values below detection limits and other values reported with a high level of error associated with them.

With CRDPF retrofit and ULSD, the average emissions were reduced by 92% for THC, 94% for CO and 88% for PM under the CBD cycle. There was no noticeable change in NOx emissions from baseline. In addition, there was >99% reduction in toxic carbonyls and 78% in PAH. The nitro-PAHs were also reduced by an average of 79%. PM filter analysis for CRDPF tests showed >99% reduction in SOF, >95% reduction in soot (both in elemental and organic carbon forms) and 86% reduction in sulfate. The calculated fuel economy results exhibited only about 3% variation with CRDPF equipped vehicles. This was well under experimental accuracy and essentially indicated no significant change in the observed fuel economy with the CRDPF. However, this is better analyzed later in the durability section with real operational records.

For the NYB cycle tests (Figure 9), the CRDPF showed even higher – 93-98% reductions in THC, CO and PM, compared to the emissions with the LSD and the OE muffler. Again, the NOx results remained essentially unchanged while the Carbonyl and the PAH emissions dropped by >99% and 79%, respectively. The nitro-PAHs were reduced by 94%. The PM filter analysis exhibited 96-99% reduced sulfate, SOF and total carbon (soot) emissions. The extremely high efficiency of the CRDPF system was clearly evidenced in comparing the PM and total carbon values between the CBD and the NY Bus cycle tests. NY Bus cycle is a much more rigorous (55% lower fuel economy) and high emission cycle than the CBD, which caused about 3 times higher PM and about 4 times higher total carbon emission in the PM, with the OE muffler and LSD. However, with the CRDPF, the PM emission in bus 6019 remained the same at 0.04 g/mile under both CBD and NYB cycles. In addition, the total carbon on the PM measurement filter (Pallflex) collected during CRDPF tests, remained undetectable even under the NY bus cycle. Please note that as per the test plan in Table 3, only one bus was tested under the NYB cycle.

Figure 10 is a comparison of hydrocarbon speciation of the gas phase sample collected during NY Bus cycle testing on bus 6019, with and without the CRDPF. Only a selection of the compound names are presented on the x-axis. As can be seen, the hydrocarbons are significantly reduced across the whole range, with the use of a CRDPF and ULSD. Figure 11 compares some of the individual PAH component emissions between the baseline engine and the CRDPF over the NYB cycle. Phenanthrene appears to be the most dominant PAH among the components. The CRDPF produced about 79% reduction in Phenanthrene.

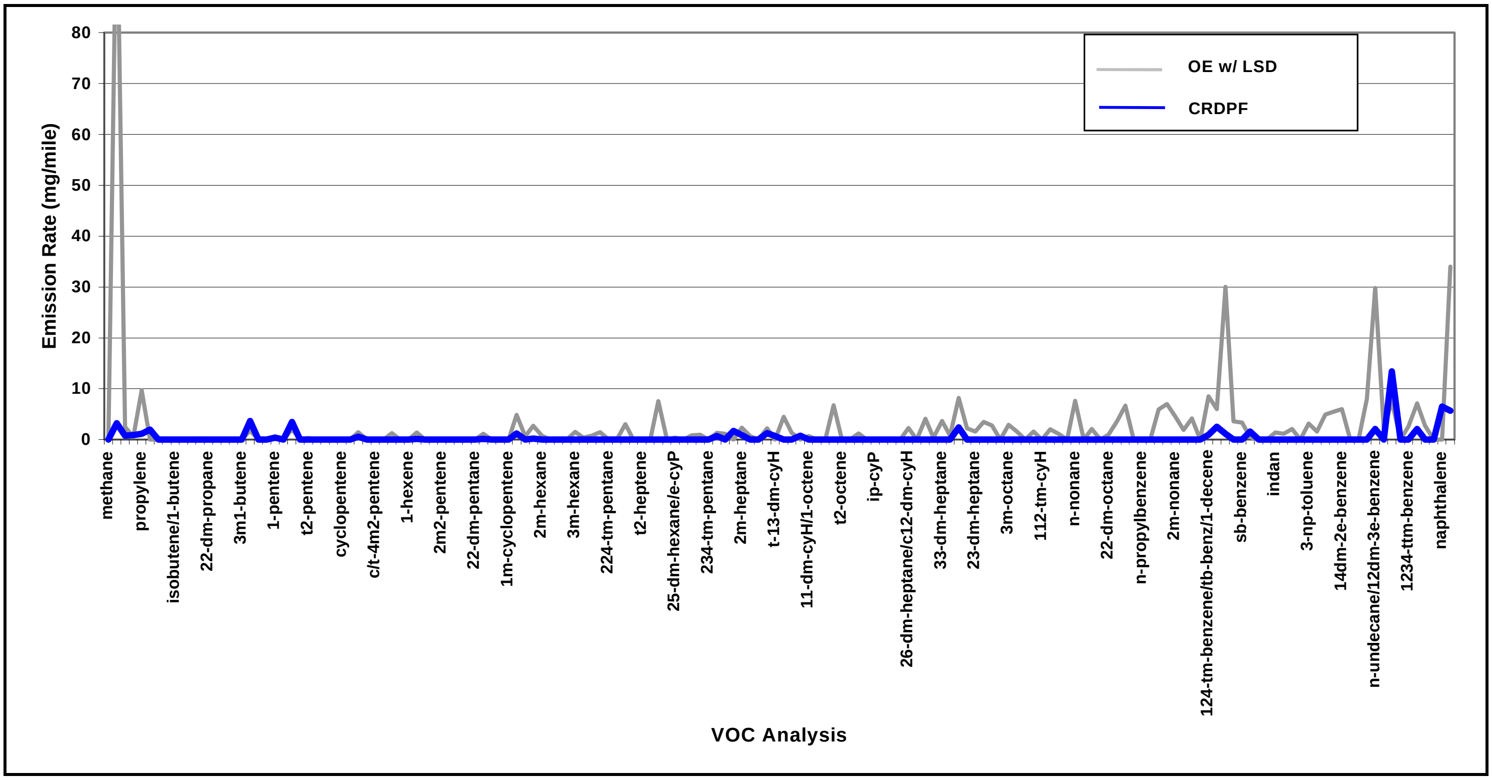


Figure 10: VOC and Methane analysis from Bus 6019 under NY Bus cycle, with and without CRDPF

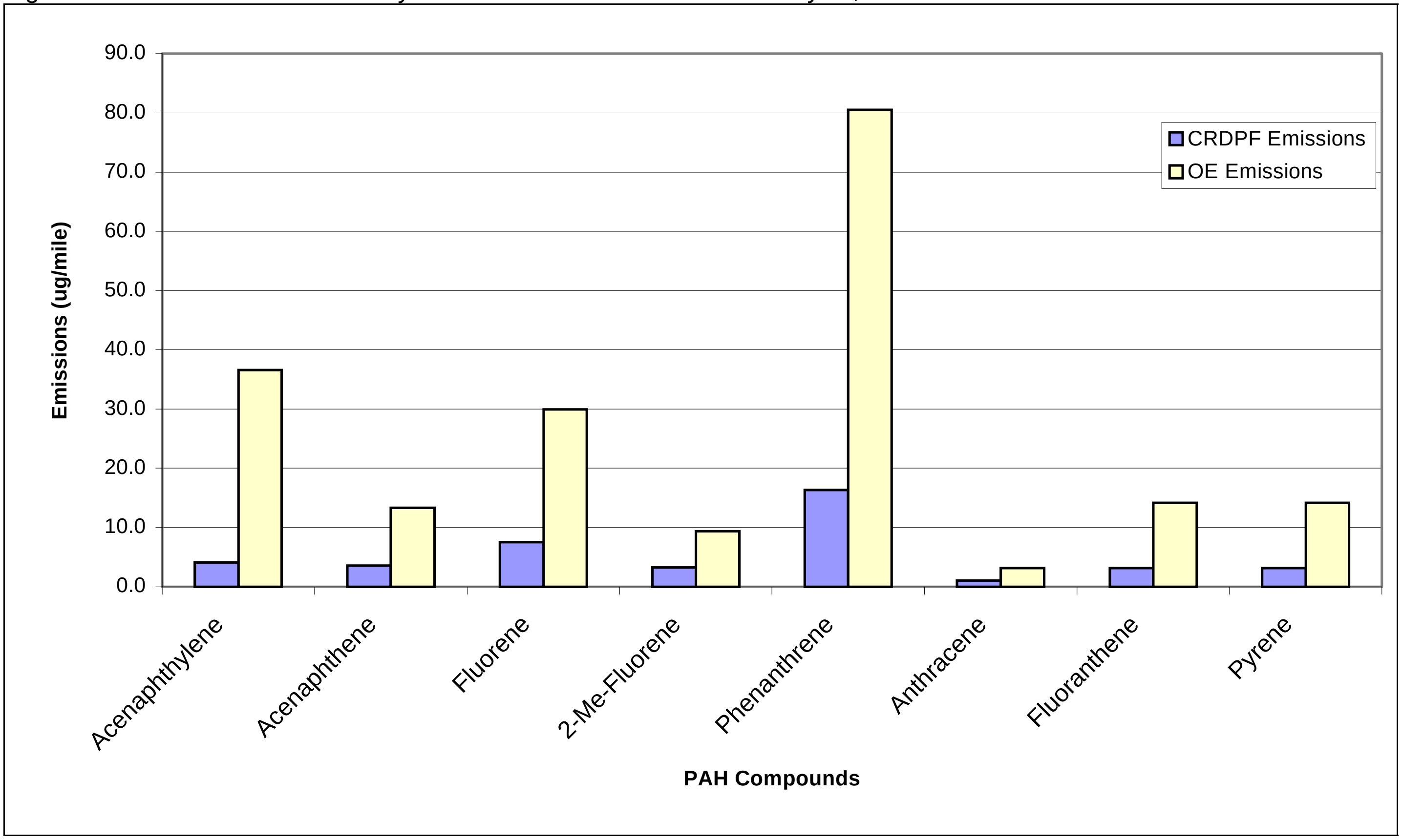


Figure 11: PAH Emissions from Bus 6019 under NY Bus cycle, with and without CRDPF

Particle Sizing – An example of an ELPI particle size distribution for bus 6065 is presented in Figure 12. The graph represents the average data taken during the CBD testing. In the figure, the average particle concentration over the six test cycles is given for each size bin, so that comparison among the different fuel and after-treatment changes can be seen. Switching from 300-ppm sulfur fuel to ULSD 30-ppm sulfur fuel appears to have little effect on the particle size distribution, while the CRDPF reduces the number of particles by at least 99% across the entire size range. Figures 13 and 14 show SMPS mobility diameter size distributions from bus 6065 for 15 and 30 mph ten-minute steady state cycles. There is some reduction in numbers of particles smaller than 30 nm as a function of lowering fuel sulfur level. The CRT reduces the particle number significantly across the entire mobility size range of 5-250 nm.

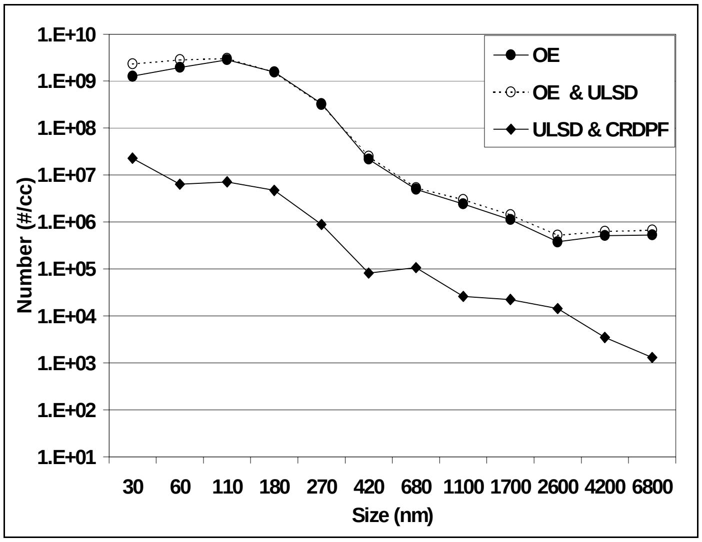


Figure 12: ELPI Particle size distribution over the CBD cycle

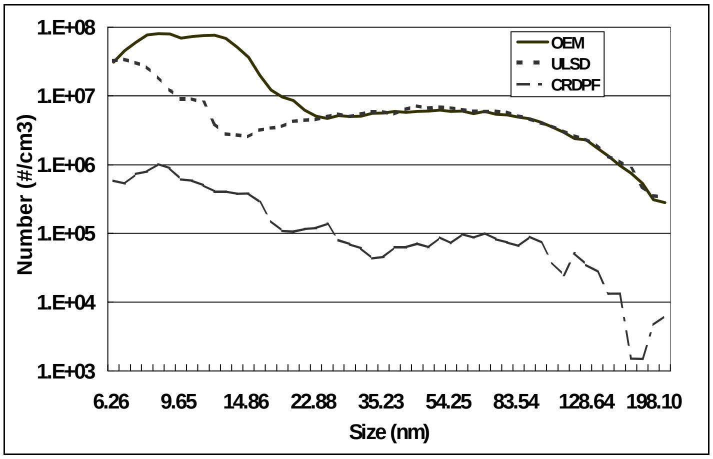


Figure 13: SMPS Mobility size distribution for 15mph steady state Cycle

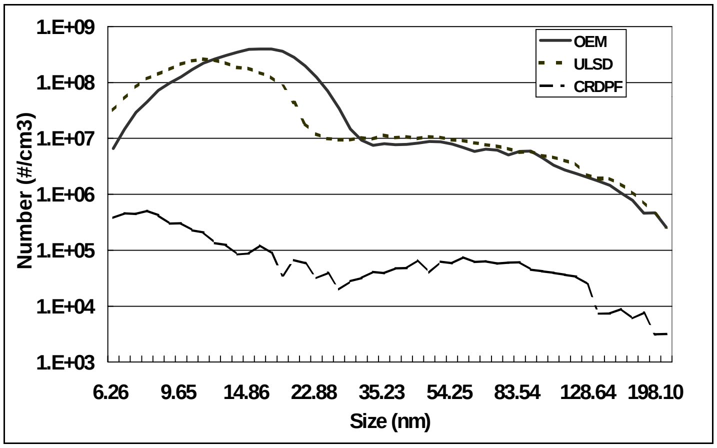
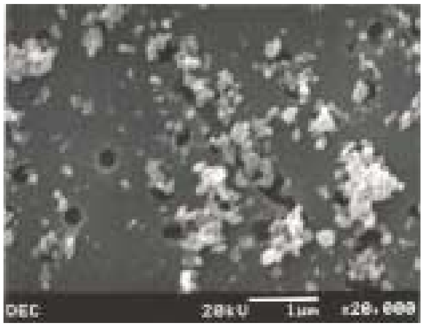


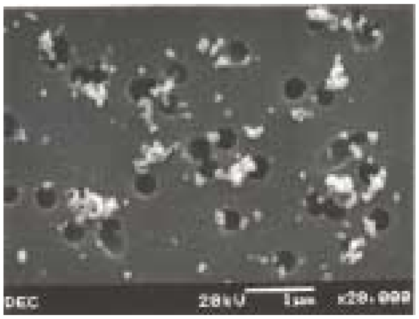
Figure 14: SMPS Mobility size distribution for 30mph steady state Cycle

A JEOL 5800 LV Scanning Electron Microscope was used to produce the micrographs shown in Figure 15. All samples were gold coated and photographed at a magnification of 20,000 using an SEI detector. The samples were collected by drawing a slipsteam from the CVS dilution tunnel through a 47mm polycarbonate filter. The filter media had a pore size of 0.4 microns. These pores appear as the uniform but randomly distributed dark circles in the figure. The samples were collected from bus 6019 for 30 minutes (3 CBD cycles), except for the case with the CRDPF, where it was necessary to sample for 60 minutes (6 CBD cycles), in order to obtain enough filter loading to adequately analyze the sample. In fact, even after doubling the sampling time, it was necessary to carefully search the CRDPF sample to find any particles. As such, these micrographs of a particular area on the filter should not be considered a quantitative measure of particle emissions. On the other hand, the figures do show representative changes in the average shape and size of the emitted particles. The OE 300 ppm case contains what appears to be mature soot composed of 30-80nm soot monomers and aggregates of these monomers, as well as ~300nm sulfate particles.

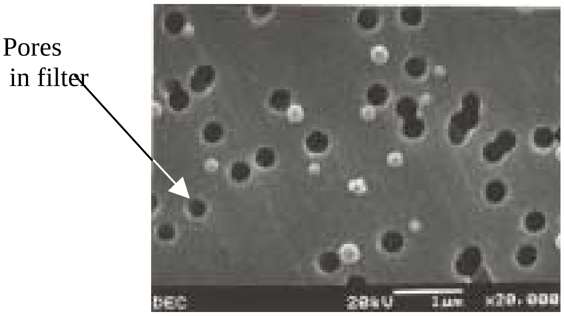
The OE 30 ppm case shows fewer sulfate particles and generally fewer and smaller soot agglomerates. The CRT case is conspicuous in the nearly total absence of any fractal aggregates and the presence of relatively large spherules, as well as probably some sulfate particles.



a) OE configuration with 300 ppm sulfur fuel



b) OE configuration with 30 ppm sulfur fuel



c) With CRDPF and 30 ppm sulfur fuel

Figure 15: Visual comparison of particle deposits from bus 6019 over CBD Cycles

Frenklach [11] has performed Monte Carlo simulations of particle growth both with and without simultaneous surface growth. The simulations demonstrate that aggregation with sufficiently small spherical particles in the presence of surface growth leads to a spheroidal shape, attributed to rapid surface growth and intense particle nucleation. It is presumed that the formation of spherules precedes that of aggregates. The CRDPF case contains almost no carbon particles for the liquid and gas-phase material present to adsorb onto or coalesce around. Therefore, the average particle diameter remains small, resulting in the formation of only the sphere-shaped collector particles as seen in the micrograph. No further aggregate formation is observed.

DURABILITY

The installation of the CRDPFs on the 25 test vehicles was accomplished between January and March 2000. The two buses used for emissions testing were put into service in mid-April. NY City Transit is carefully monitoring the operational and maintenance issues related to the CRDPF equipped buses by comparing them to a control fleet of 41 similar buses without CRDPF. Some of the parameters being monitored include the vehicle fuel economy, road calls related to CRDPF and Mean Distance Between Failure (MDBF). In the case of MDBF, a failure is defined as an unplanned maintenance action.

Table 7 shows the parametric data from the a monthly fleet-report from NY City Transit. As of October 31, 2000, the 25 CRDPF equipped vehicles had accumulated a total of 557,918 miles (an average of 22,317 miles per vehicle). Comparison of the 25 retrofit buses to the control group of 41 buses (without CRDPF) in the Mother Clara Hale (MCH) depot shows that the retrofit buses have similar fuel economy and MDBF. The fuel economy for the retrofitted vehicles is 2.09 mpg compared to a fleet average of 2.10 mpg for the control group. To date there have been no CRDPF related failures in the test group. For the month of September (last data) MDBF for the test group was 3,847 miles compared to 3,230 miles for the control group. These results indicate that the installation of the CRDPFs has had no adverse effect on the fuel economy, maintenance or availability of the buses. Please note that the road call was for a DDEC ECM exhaust temperature sensor failure on a CRDPF equipped bus. The sensor was damaged and provided high exhaust temperature warning which resulted in engine shut down. There was no CRDPF performance issue.

Total Accum. CRDPF Fleet Miles	**557,918**
Average Miles/Bus	**22,317**
Total CRDPFs Installed	**25**
Total Related Road Calls	**1**
Fuel Economy	**2.09**
Remaining MCH Fleet Economy	**2.10**
MDBF September 00	**3,847**
MDBF remaining MCH Fleet	**3,230**

Table 7: Field Test Fleet report

As mentioned earlier, on-road operational data in the form of exhaust temperature and back pressure are being collected to monitor the CRDPF operation on selected buses. The on-road exhaust temperature for the three monitored buses ranges between 100 and 400 °C. Figure 16 is a histogram of the on-road temperature for bus 6065 operating in August. The exhaust temperature is above 275°C for 60% of the operating time. This is well within the temperature range for optimum regeneration of the CRDPF.

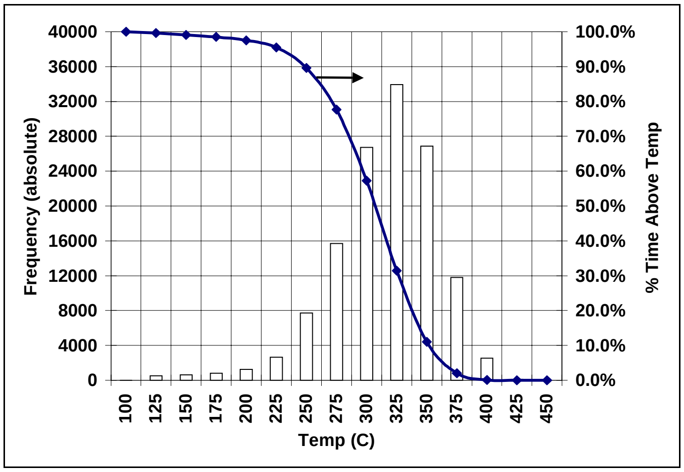


Figure 16: On road temperature histogram for bus 6065

Examples of the exhaust back pressure data measured on the vehicles is shown in figures 17 & 18. It should be noted that only the peak or maximum back pressures observed during the road tests over a fixed period of time is plotted here. This allows the trend to be observed and analyzed for the operation of the CRDPF.

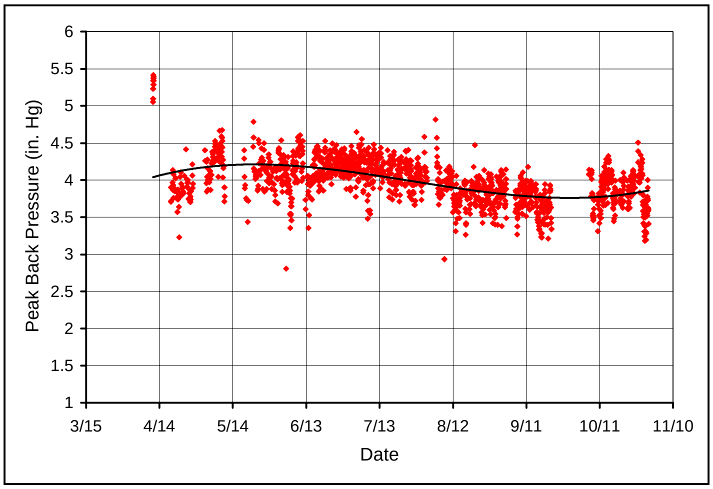


Figure 17: On-road peak exhaust back pressure for bus 6065

The peak back pressure on these buses varies between 4.0 and 4.5 in Hg. Overall, the pressure is steady on all three monitored vehicles indicating stable operation and regeneration of the CRDPFs.

The back pressure histogram for bus 6065 operating in July and August is shown in figure 19. The analysis indicates that the bus is operating with a back pressure at or below 3.0 in Hg for 90% of the time.

The initial high back pressure observed on both cases appear to be real, since it was noticed in a third data logged bus and also during the prototype testing. At this time, it is not clear why the filter system goes through this initial high pressure for a very short time. This will be further investigated.

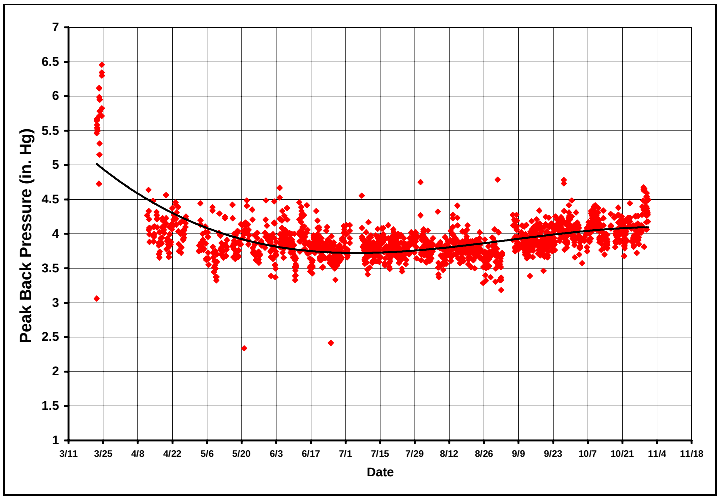


Figure 18: On-road peak exhaust back pressure for bus 6019

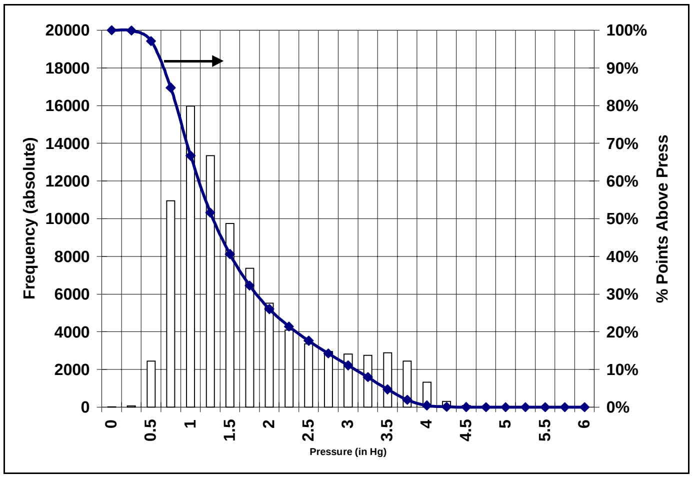


Figure 19: On-road back pressure histogram for bus 6019

CONCLUSION

In the NYCTA demonstration program, the results of initial chassis emission testing and eight months of operation with the CRDPF indicate the following:

- Greater than 90% reductions in PM, CO and THC are possible by retrofitting existing diesel powered buses with ULSD fuel and CRDPFs.
- Greater than 99% reduction in Carbonyls and up to 80% reduction on PAH and >90% on NO_2-PAH emissions are possible by retrofitting a 1999 model DDC series 50 powered bus with CRDPF technology.
- Greater than 99% reductions in particle counts for all size ranges are possible with a CRDPF retrofit.
- The stable back pressure and high exhaust temperature observed on the CRDPF equipped buses indicate successful regeneration and satisfactory operation of the particle filter system on these DDC S50 engines under NY transit operation.
- 8 months of operation on 25 buses without a failure or any significant increase in fuel economy indicates that the CRDPF has no adverse effect on the operation, reliability or maintainability of the vehicles thus retrofitted.

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