DSNY and Cummins Inc.: A Collaboration Towards Cleaner Air

A Demonstration of Diesel Particulate Filter Emission Control Technologies on Refuse Collection Trucks

and Deployment of Natural Gas Powered Street Sweepers

Project Summary Report

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Submitted to

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By

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About Cummins Inc.

Cummins Inc., headquartered in Columbus, Indiana, is a global power leader, a multinational fortune 500 corporation of complementary business units with more than 24,000 employees worldwide. Cummins designs, manufactures, distributes and services engines and related technologies, including fuel systems, controls, exhaust, air handling, filtration, emission solutions and electrical power generation systems.

Cummins is committed to providing its customers with the best available products for their needs. To fulfill this commitment, Cummins continues to develop the best available technology to reduce emissions and noise from their products while maintaining high standards for fuel economy and reliability valued by fleet customers. In addition, as part of their environmental mission, Cummins is committed to demonstrating a commercially viable product that emits zero particulate matter while meeting all other emission and fuel economy requirements by 2010.

About DSNY

DSNY began life in 1881 as the Department of Street Cleaning and has grown to provide much more than street cleaning. Backed by a strong environmental stewardship at the highest levels within the Department, DSNY continues to strive towards making New York City neighborhoods cleaner. Over the past decade, DSNY has increased their commitment to providing cleaner air to local communities through cooperative research and deployment programs. Many of these initiatives are focused on reducing air emissions from diesel-powered trucks within the fleet. To date, DSNY has undertaken initiatives to deploy clean-fueled technologies and after treatment devices as well as cleaner fuels and remains one of the most progressive municipal fleets for reducing their impact locally.

DSNY is continuously exploring ways to operate a cleaner vehicle fleet and recent milestones include:

- DSNY began deploying diesel particulate reducing technologies in the early 1990s
- In 2004 became the first city mayoral agency to fuel exclusively with Ultra-Low Sulfur Diesel fuel
- First fleet on the East coast to deploy ultra-low-sulfur-diesel fuel and diesel particulate filters in combination
- First fleet to deploy SCR on a collection truck fleet in the U.S (2003)
- 240 light duty cars and trucks in the DSNY fleet are fueled with natural gas
- 26 collection trucks fueled with natural gas
- 9 street sweepers fueled with natural gas
- 125 collection trucks have diesel particulate filter technology installed
- Began introducing ethanol-powered vehicles to the fleet in 2000 and more than 400 are in service today
- First city agency to begin dispensing Ethanol-85 fuel

About NESCAUM

NESCAUM is a nonprofit association of air quality control divisions representing the states of Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont. NESCAUM's purpose is to exchange technical information, and to promote cooperation and coordination of technical and policy issues regarding air quality control among the member states. To accomplish this, NESCAUM sponsors air quality training programs, participates in national debates, assists in exchange of information, and conducts research.

NESCAUM staff focus on a variety of air quality relevant issues, including the control of mobile sources of air pollution. NESCAUM's Mobile Sources Group works on programs to reduce criteria, toxic, and greenhouse gas (GHG) pollution from motor vehicles. The team consists of automotive, and diesel powertrain engineers, as well as policy and public health experts having a blend of professional experience in government, industry, and public advocacy. The Mobile Source Group continually gains direct experience in emerging emission control trends through the management of projects researching and implementing controls. The Mobile Source Group also provides policy guidance and expert technical support to our member states on issues related to motor vehicle pollution control. The Group works with federal regulators, local community groups, legislators, and environmental nonprofit organizations to develop options to assist the member states in the development of regulatory programs to control motor vehicle pollution.

About M.J. Bradley & Associates, Inc.

M.J. Bradley & Associates, Inc. (MJB&A) is an environmental consulting firm headquartered in Concord, Massachusetts with a national reputation for helping clients balance environmental goals with business objectives as well as demonstrating clean emission technologies. By providing clients with high-quality information and services, and facilitating collaboration, MJB&A assists private and public sector clients in meeting the challenges posed by changes in environmental and energy law and policy, energy markets, technology and business climate. The technical and transportation services group is located separately in Manchester, New Hampshire.

The technical and transportation services group participates in a variety of project areas with a concentration in advanced vehicle and combustion technologies. MJB&A has leveraged project facilitation, independent testing and analyses and documentation and reporting experiences gained across a wide range of vehicle applications to further the development and deployment of advanced emission control programs for both on- and off-road vehicles. MJB&A continues to be at the forefront in deploying advanced transportation vehicles and emission control technologies, with a proven track record of successful emissions technology projects. Projects include implementation of proof of concept demonstrations, large-scale retrofit deployments, and emission testing programs. Many of these projects have been used to develop a road map for future efforts to reduce on- and off-road emissions.

The diversity of the MJB&A team both within and outside the technical and transportation services group provides clients with expertise in technical, policy, legal, economic and regulatory issues. MJB&A also consults in the fields of energy and environmental policy, electric generating technologies, greenhouse gas policy and stakeholder groups.

About Fleetguard Emission Solutions

Fleetguard Emission Solutions is a member of the Fleetguard family of companies. Fleetguard is a wholly-owned business unit of Cummins Inc. and the world's leading designer and manufacturer of heavy-duty air, fuel, hydraulic and lube filtration, chemicals, and exhaust system technology products for diesel and gas powered equipment. Fleetguard Emission Solutions was established in 2003 to research, develop and commercialized systems and products for use in mobile and stationary applications. The company focuses on retrofitting the existing engine population with emissions control devices and the development of new emissions system solutions and products for new engines and original equipment manufacturer products. Fleetguard Emission Solutions is committed to developing superior products that meet or surpass emission regulations. Supported by the Cummins North American distributor network and Fleetguard worldwide, Fleetguard Emission Solutions systems bring value to customers, from installation to support after the sale.

Acknowledgements

Undertaking a project of this magnitude relies on the valued contribution of many participants. In early 2000, Tom Balon of M.J. Bradley & Associates, Inc. (MJB&A) began laying the groundwork for developing and implementing this retrofit project. Two underlying goals led to the concept of retrofitting refuse collection trucks with emission controls: (1) reducing urban air pollution impacts, and (2) pushing the envelope with respect to retrofits on borderline (i.e., low exhaust temperature) applications.

Paul J. Moynihan, MJB&A project manager, and lead author would like to thank Cummins Inc. (Cummins) and New York City Department of Sanitation (DSNY) for their funding and support of this project. The level of support provided by DSNY in terms of hours spent during the design, installation, and tracking phases of the project was a key element in the project's success. In particular, MJB&A would like to recognize Spiro Kattan at DSNY for his thoroughness and dedication to seeing this project succeed. In addition, several retired, and active employees of DSNY should be recognized for their support of this project, including Bob Martin, Tim Harte, Vinny Pellegrino, Sandeep Mehta, and Andrew Juhasz.

Fleetguard Emission Solutions (FES) was instrumental in design and implementation phases, providing engineering analysis and hands-on support to ensure that the deployment occurred as quickly as possible while ensuring durability of the emission controls. Both Marty Chiaramonte and Michael Prostakov from FES were instrumental in the planning, design and implementation phases of the project and provided valuable insight based on their wide experience in diesel engine operation and design and previous experience with retrofit projects.

MJB&A would also like to recognize the efforts of Dave Park at NESCAUM, the overall project manager and regulatory agency liaison for keeping the project on track both internally and with the Environmental Protection Agency (EPA) and the New York State Department of Conservation (NYS DEC).

One partner, without whom a significant portion of the project would not have been possible, is Johnston Sweeper Company. Mr. Walter Pusic was responsible for engaging Johnston Sweeper in this project and was instrumental in spearheading the development of natural gas sweepers internally at Johnston Sweeper.

Mr. Ed Hall of Cummins Metropower played an important role in the project, ensuring that all servicing of the trucks and emission control devices occurred smoothly and with minimal impact to daily DSNY operations.

Finally, putting together a project of this size, supporting the data logging, design and installation, as well as documenting it through meeting minutes and this report took the effort of a number of MJB&A staff, including Dana Lowell, Steve Piper, Lauren Wilensky, Chris Hamel, Amy Stillings, Lydia Garrant, and Matt Solomon.

This project was undertaken pursuant to an agreement with the United States in connection with settlement of disputed claims in an enforcement action under the Clean Air Act.

Executive Summary

The New York City Department of Sanitation (DSNY) in collaboration with Cummins Inc. initiated a project to reduce the amount of hazardous air pollutants generated by the DSNY fleet of refuse collection trucks and street sweepers. This project served to realize this goal by facilitating the installation of diesel particulate filters (DPFs) on a number of refuse collection trucks. Independently, DSNY switched their entire fleet from standard No. 2 diesel fuel to ultra-low sulfur diesel (ULSD).

The primary goal of the project was to reduce particulate matter (PM) emissions generated by the Cummins heavy-duty diesel engines that are used in the fleet's refuse collection trucks and street sweepers, though reductions in hydrocarbons (HC) and carbon monoxide (CO) were also expected. Several advanced emission control options were considered, though ultimately the use of DPFs and ULSD fuel were found to be practical for use on DSNY refuse trucks, and could feasibly be implemented within the budget of this project. Furthermore, this project was used as an opportunity for DSNY to design, purchase and deploy four new compressed natural gas (CNG) street sweepers, which have significantly lower PM emissions than their diesel-fueled counterparts.

Significant pre-installation data logging was performed in order to determine whether or not the refuse trucks maintained the required exhaust backpressure and temperature levels required for DPF regeneration. It was expected that typical duty cycles may differ significantly between boroughs, and therefore, separate data logging occurred for both trucks based out of Manhattan versus the Bronx. Ultimately, analysis indicated that the Manhattan duty cycles were clearly able to support DPF installation, whereas it was questionable whether or not the standard filters would be effective on the Bronx-based trucks. Because data logging proved to be inconclusive, two Bronx-based trucks were retrofit with filters to test whether or not the filters would regenerate. It was found that, even under the most adverse conditions the filters functioned properly, and retrofits were installed on trucks in both Manhattan and the Bronx.

Two different DPF manufacturers participated in the project. During the pilot phase of the program, Engelhard, Inc. supplied a DPX™ catalytic particulate filter and Johnson-Matthey a CRT®. Further into the project, two Johnson-Matthey CCRT® particulate filters were also deployed. Both manufacturers supplied DPFs that are verified by the EPA under the voluntary retrofit program as filters that are capable of attaining the same emissions reductions. Each of the filters also requires the use of ULSD for proper operation.

Performance testing was performed on several of the trucks to determine overall effectiveness of the DPFs. Each filter deployed during this project is verified to achieve a minimum of 60% reduction in PM, and test results on a New York City-based emission test cycle indicates near 90% reductions in PM. In addition, significant reductions in CO and HC emissions were realized, while changes in nitrogen oxides (NOx) and carbon

dioxide (CO_2) emissions were found to be statistically insignificant. Fuel economy, was expected to decrease slightly because of the energy differences between ULSD and standard on-road diesel and a slight decrease (less than 1 percent) was shown.

The parallel PM emission reduction strategy alongside the DPF installations was deploying CNG street sweepers. Johnston Sweeper Company, the main sweeper provider for the New York City fleet, designed, manufactured, and delivered four CNG sweepers within an eight-month timeframe. At the same time as the testing program for the DPFs, the street sweepers were tested, showing that the CNG sweepers with oxidation catalysts realized substantial reductions of particulate matter and CO emissions over the diesel-fueled models.

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API	American Petroleum Institute
ASTM	American Society for Testing and Materials
Btu	British Thermal Unit
^{o}C	Celsius
CAA	Clean Air Act
CARB	California Air Resources Board
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COV	Coefficient of Variability
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DSNY	New York City Department of Sanitation
ECD	Emission Control Device
EPA	Environmental Protection Agency
^{o}F	Fahrenheit
FTF	Flow Through Filter
g/gal	gram per gallon
g/s	gram per second
H_2O	water
HC	Hydrocarbon
HFRR	High Frequency Reciprocating Wear Rig
hp	Horsepower
ISO	International Organization for Standardization
JSC	Johnston Sweeper Company
L	liter
MJB&A	M.J. Bradley & Associates, Inc.
mm	millimeter
MTA	Metropolitan Transportation Authority
NAAQS	National Ambient Air Quality Standards
NESCAUM	Northeast States for Coordinated Air Use Management
NJDEP	New Jersey Department of Environmental Protection

NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxides
NYS DEC	New York State Department of Environmental Conservation
O_2	Oxygen
O_3	Ozone
OEM	Original Equipment Manufacture
PAH	Polyaromatic Hydrocarbon
Pb	Lead
PEMS	Portable Emission Monitoring System
PM	Particulate Matter
ppm	Parts Per Million
rpm	revolutions per minute
SBOCLE	Ball on Cylinder Lubricity Evaluator
SCR	Selective Catalytic Reduction
SO_2	Sulfur Dioxide
SO_3	Sulfur Trioxide
SOF	Soluble Organic Fraction
THC	Total Hydrocarbon
ULEV	Ultra Low Emission Vehicle
ULSD	Ultra Low Sulfur Diesel
VOC	Volatile Organic Compound

1.0 Introduction

Over the past thirty years, a shift has occurred from gasoline to diesel fuel for use in heavy-duty trucks and buses with diesel engines dominating the market today. Today, nearly 90 percent of the fuel used on an energy basis in heavy-duty vehicles is diesel. Figures 1 and 2 illustrate the growth trend of heavy-duty vehicles over the last 20 years with respect to both heavy-duty vehicle population and miles traveled.[1] With these engines lasting for many years and several hundreds of thousands of miles, their environmental impact is significant. For the most recent year data is available, heavy-duty diesel vehicles contributed nearly 24 percent of all particulate matter (PM) from the transportation sector as illustrated in Figure 3.[2,3]

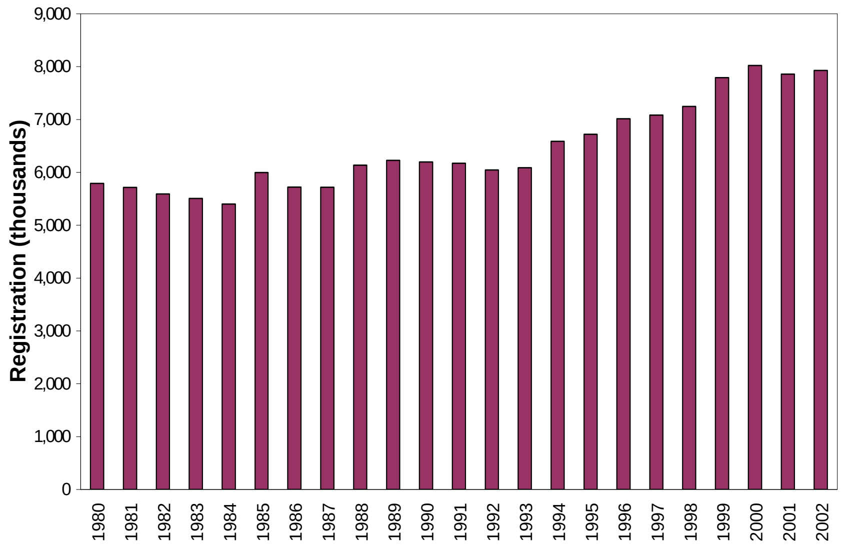

Figure 1: Historical Heavy-Duty Vehicle Registrations

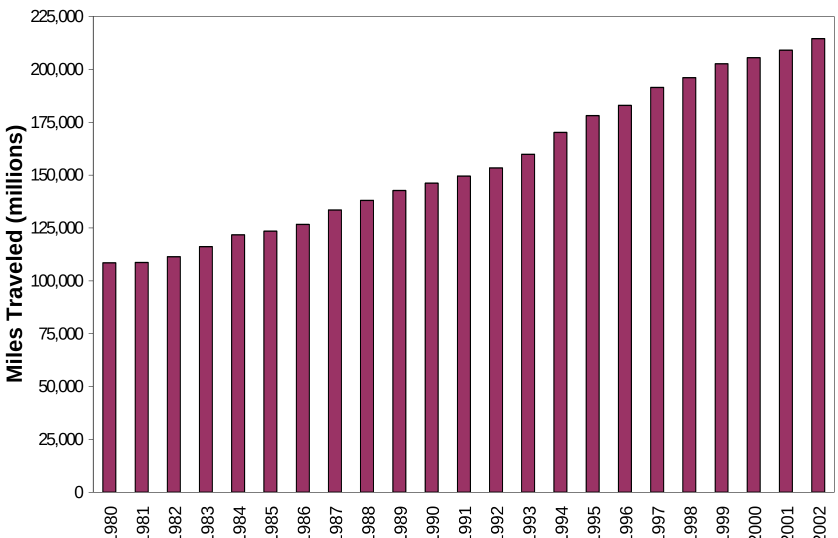

Figure 2: Historical Heavy-Duty Vehicle Miles Traveled

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[1] Source: Davis, S.C., Diegel, S.W., "Transportation Energy Data Book, Edition 24", U.S. Department of Energy Oak Ridge National Laboratory, December 2004.

[2] Ibid.

[3] Particulate matter is classified into two categories, PM-10 and PM-2.5. PM-10 represents all particulate matter sized at or below 10 microns and PM-2.5 is all PM less than 2.5 microns in size.

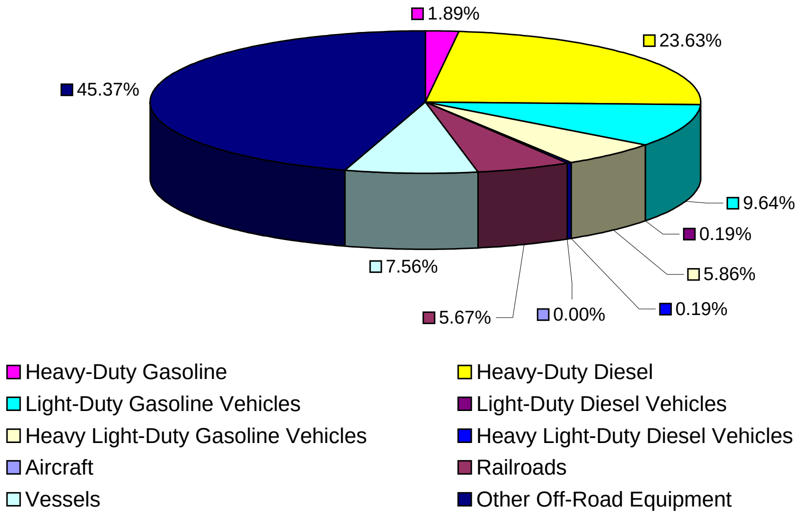

Figure 3: 2001 PM-10 Emissions from Transportation Sources

1.1 The Diesel Engine and Air Quality Regulation

As early as 1970, the United States Environmental Protection Agency (EPA) acknowledged that reducing emissions from heavy-duty vehicles would provide a noticeable benefit to air quality. EPA first enacted opacity-based standards followed by standards for hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), and PM. Recently EPA has focused more closely on reducing PM and NOx (as a precursor to ozone) emissions from heavy-duty vehicles. During the eight-year period after passage of the Clean Air Act Amendments of 1990, EPA lowered PM and NOx emission standards for heavy-duty vehicles by 83 percent and 37 percent, respectively. In addition, starting in 2007, the emission standards will be lowered even more as shown in Table 1.

To meet the 2007 standards, diesel engines will most likely have to be certified with exhaust after treatment technologies. Because control technologies such as diesel particulate filters (DPF) are sensitive to the level of sulfur in fuel, they will require the use of ultra-low sulfur diesel (ULSD) fuel. EPA has issued separate fuel regulations that require fuel sold in 2006 and beyond to have a maximum sulfur content of 15 parts per million (ppm).

Additionally manufacturers will be able to attain the PM exhaust standards by using alternative fuels such as compressed natural gas (CNG). However, the NOx standard will require engine system modifications even in CNG applications so some development is necessary for both types of engines on the part of the engine manufacturers.

Table 1: EPA Emission Standards for Heavy-Duty Engines (g/bhp-hr) [a]

	NOx	NMHC [b]	PM	
Year	Heavy-Duty & Urban Bus Engines		Heavy-Duty Engines	Urban Bus Engines
1991	5.0	1.3	0.25	0.1
1994	5.0	1.3	0.1	0.07
1998	4.0	1.3	0.1	0.05
2004	2.4 [c]		0.1	0.05
2007+	0.2	0.14	0.01	0.01

a – gram per brake horsepower-hour (g/bhp-hr)

b – Non-Methane Hydrocarbons

c – Manufacturers also have the option of meeting a combined 2.5 g/bhp-hr for NOx plus NMHC provided NMHC does not exceed 0.5 g/bhp-hr.

Over the last ten to fifteen years, manufacturers have made strides in producing cleaner diesel engines relying on internal engine modifications such as high-pressure injectors, pre-injection techniques, and exhaust gas recirculation. Diesel oxidation catalysts (DOCs) have also been used, but are typically only required on urban buses. Many internal engine modifications were designed and tested thoroughly in a laboratory environment prior to being introduced into the marketplace. With the manufacturers now relying on exhaust after treatment devices more than just laboratory testing is required. Performance in real-world applications where the devices are subject to factors that influence performance such as ambient temperature and duty cycle is a must.

Manufacturers have also increased the availability and reliability of CNG engines to provide fleets with a choice of fuels. One of the major hurdles to increased CNG market penetration has been fueling infrastructure. Many large municipal fleets have invested in CNG fueling infrastructure over the last decade with the goal of increasing the number of CNG vehicles on the road. In the New York City area, there are currently 10 publicly accessible CNG fueling stations with several additional stations available to government agencies or fleets exclusively.

1.2 Background

In 1998, Cummins Inc. (Cummins) entered into an agreement with EPA to promote the design and deployment of advanced emission controls on heavy-duty diesel vehicles. Additionally, Cummins used this opportunity to further the penetration of CNG vehicles in the marketplace.

Equipping or retrofitting heavy-duty diesel engines with DPFs can realize PM reductions of approximately 90 percent. DPFs are also capable of reducing HC and CO by 50 percent or more. While over 1 million DOCs have been installed on diesel trucks as original equipment by manufacturers to comply with the 1994 PM standard, installation of DPFs is currently occurring only as a retrofit, and chiefly on a voluntary basis. EPA estimates that 60,000 vehicles have been committed for retrofit with DPFs under the Voluntary Diesel Retrofit Program since it began in 1999.

Cummins undertook a supplemental environmental project (SEP) in New York City to retrofit a significant number of Cummins engine heavy-duty sanitation vehicles with emission control devices (ECD) within the five boroughs of New York City as part of their strategy to reduce PM, HC, CO and potentially NOx emissions from heavy-duty engines. This project originally was designed to retrofit approximately 260 trucks with DPFs. Additionally, Cummins proposed to put four compressed natural gas (CNG) street sweepers into service. Although PM reduction is the primary focus of this project, HC reduction is also of significant value. No NOx reduction benefit is expected from DPFs.

Specific goals of the project were:

- Reduce PM, HC, and CO emissions from in-use heavy-duty diesel engines in local urban neighborhoods;
- Provide implementation experience that is necessary to facilitate the successful retrofit of refuse collection trucks as well as their long-term maintenance;
- Assess the effectiveness of emission control device (ECD) technologies in reducing pollution over long periods of time;
- Quantify the emissions reductions achieved from the retrofit program and from each emission control device; and
- Purchase and deploy 4 CNG street sweepers, and document emission reductions achieved from the fuel switch.

Cummins chose to focus on refuse collection trucks for this project for two reasons 1) they are used throughout the country, and 2) pose a challenging duty cycle. In addition, these trucks are highly visible sources of PM air pollution.

To date, the most progress with retrofitting diesel engines with DPFs has been made by transit agencies. A number of transit fleets have led successful programs attributable to several factors; among them are centralized fueling and maintenance and a favorable duty cycle. Centralized fueling has been critical to the pioneering fleets because ULSD is not widely available throughout the country.

A typical refuse collection truck duty cycle consists of frequent starts and stops, as the truck collects municipal solid waste curbside, with low overall average speed. The challenge posed by this type of application is that the low average speed translates into low overall exhaust temperatures, whereas DPFs require relatively high exhaust temperatures for consistent regeneration.

1.3 Project Description

At the onset, Cummins brought together a variety of interested parties to participate in the project. Cummins primary partner in this project is the Department of Sanitation New York City (DSNY) who provided the trucks for retrofit and integrated the CNG vehicles into their fleet. The Northeast States for Coordinated Air Use Management (NESCAUM) and M.J. Bradley & Associates, Inc. (MJB&A) provided assistance with management and retrofit oversight. Engelhard Corporation and Johnson Matthey Corporation were identified as the suppliers of the DPFs, Fleetguard Emission Solutions (formerly Fleetguard-Nelson) was responsible for manufacturing the final DPF retrofit package, and Cummins Metropower (a local Cummins dealership) was brought in to assist in streamlining the installation while minimizing the personnel burden on DSNY.

Retrofitting refuse collection trucks powered by Cummins diesel engines with DPFs will provide the DPF manufacturers the experience they need to facilitate the widespread implementation of this technology in a low average speed duty cycle application.

When this project was conceived, the vision was to have DSNY be the primary participating fleet, with consideration given to other fleets if time and budget allowed. DSNY was chosen for two reasons: 1) they are an existing Cummins customer, and 2) they operate a vocational application (i.e., refuse collection trucks) which provides an excellent opportunity for evaluating DPFs in a low average speed, low exhaust temperature application. The decision to choose a fleet that is a current Cummins customer is an obvious one -- it allows project managers to use existing relationships with DSNY to access vehicles and contact staff. In addition, project managers are able to take advantage of existing relationships with the local Cummins dealer for fleet technical support on installation, maintenance, and repair issues.

The focus on DSNY refuse collection trucks stemmed from a desire to reduce PM, HC, and CO emissions from in-use heavy-duty diesel engines in local urban, ozone and PM non-attainment area neighborhoods. The most important goal of the project was to achieve the maximum amount of emission reductions in these localized urban areas within the non-attainment area of New York City.

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2.0 Advanced Emission Control Options for Heavy-Duty Diesel Vehicles

Emission control alternatives are available for heavy-duty diesel vehicles with differing results depending upon what pollutants are of greatest interest. The focus of this project was PM reduction, with reductions of other pollutants beneficial, but not required. PM reductions can be achieved using both fuel-based and after treatment options. Available options for reducing PM are described below, with a listing of current EPA- and California Air Resources Board (CARB) verified technologies provided in Appendix A.

EPA, under it's voluntary retrofit program, maintains a clearinghouse of information on different after treatment and fuel formulations that have passed their rigorous testing requirements and have proven diesel emission reductions. EPA administers this program under the Environmental Technology Verification program, whose goal is "to objectively evaluate the ability of emission control devices to reduce pollutants, and to provide performance data to fleet owners and air quality planners."[4]

Similarly to EPA, CARB also maintains a database of information on different emission reduction strategies for diesel vehicles. CARB and EPA have agreed to honor the other's verification processes and emission reduction claims to reduce the need for manufacturers to go through two separate verification procedures.

2.1 Diesel Oxidation Catalyst (DOC)

A DOC can be used across a range of exhaust temperatures and is an efficient method of reducing PM in low exhaust temperature applications. They can be used with on-road diesel fuel; however, ULSD fuel increases the effectiveness of the DOC. A typical lifespan for a DOC ranges from 7-15 years and 100,000 – 150,000 miles.

A DOC is a virtually maintenance-free retrofit device that works by providing a chemically reactive substrate over which the exhaust gas passes. The substrate is typically of honeycomb shape and allows the exhaust gas to flow through it, similar to a standard muffler. The substrate is usually metal or ceramic and is coated with precious metals that, in the presence of the exhaust gas and sufficient temperature, oxidize the pollutants as illustrated in Figure 4. Diesel PM is made up of several components, carbon, hydrocarbons, polyaromatic hydrocarbons (PAHs), metals, sulfate and water (H_2O). The liquid HCs

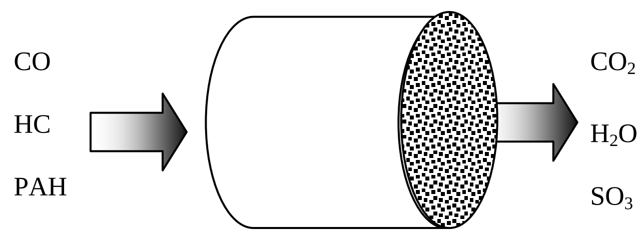

Figure 4: Diesel Oxidation Catalyst Schematic

[4] http://www.epa.gov/otaq/retrofit/over_nescaumreport.htm

adsorbed onto the carbon molecule are typically referred to as the soluble organic fraction (SOF) of PM. The precious metals facilitate the oxidation of the SOF portion of the PM. In addition, during the process of oxidizing HC and CO to carbon dioxide (CO_2) and water, a DOC also oxidizes sulfur dioxide (SO_2) to undesirable sulfur byproducts (SO_3).

Reducing PM is the primary target of a DOC; however, reductions in CO and HC emissions are also seen. The fuel used influences the amount of PM reduced. Switching from on-road diesel to ULSD[5] diesel and utilizing a DOC, PM emission reductions on the order of 40 percent are typical. The increased performance is primarily a result of the ULSD producing a lower sulfate portion of PM, which also enhances DOC performance, combined with the DOC's ability to reduce the SOF, or "wet" portion of the PM.

Typical emission reductions using a DOC are shown in Table 2. Options for employing a DOC using both on-road and ULSD fuel are shown.

Table 2: DOC Emission Reductions (approximate)

	Pollutant		
Fuel	**PM**	**CO**	**HC**
On-Road Diesel	25%	80%	80%
ULSD	40%	80%	80%

2.2 Flow through Filter (High Performance Diesel Oxidation Catalyst)

Flow through filters are relatively new to the market and have recently received verification as a Level 2 device from the California Air Resources Board (CARB). These are also referred to as a high performance or PM-targeted DOCs and are able to provide higher PM reductions, in the 50 percent range. The greater performance of the flow through filter is achieved in part by forcing the exhaust to traverse a more tortuous path, resulting in increased contact with the oxidizing catalyst.

2.3 Alternative Diesel Fuel options

The most commonly used alternative diesel fuel used in the New York City area currently is ULSD. There are other alternative diesel fuel formulations available, which have beneficial results for reducing emissions. All of these diesel fuel formulations are based on mixing base diesel fuel with a small quantity of another substance. In some US markets, these alternative formulations are marketed using standard on-road diesel fuel as the base blending stock. By using ULSD as the base blending stock, even greater emission reductions can be achieved. Below, ULSD and the four most readily available diesel alternatives are described, including: biodiesel, emulsified diesel, oxygenated diesel, and diesel with a fuel-borne catalyst. This project used ULSD for two reasons: 1) the fuel is readily available in the New York City area, and 2) it will be required, at a

[5] On-road highway diesel is allowed to have up to 500-ppm sulfur content. Typical sulfur contents for on-highway diesel and ULSD found in the New York City area are 350 ppm and typically around 15 ppm, respectively.

minimum, beginning in 2006. For this second reason, both Cummins and DSNY were interested in gaining early experience with the fuel.

2.3.1 Ultra-Low Sulfur Diesel Fuel

Switching a fleet from standard fuel to ULSD offers meaningful PM reductions with no detrimental impact on the vehicle, provided manufacturer fuel requirements are met (e.g., lubricity). PM reductions in the 20 percent range are typical. Maintaining lubricity is a concern because sulfur in diesel fuel acts as a lubricity agent and engine components such as the fuel pump are designed with minimum fuel lubricity requirements. When sulfur is removed, the lubricity requirement is achieved through fuel additives. Additional detail about the differences between ULSD and on-road diesel as well as a comparison of ULSD versus manufacturer fuel requirement is provided in Chapter 5.

2.3.2 Emulsified Diesel:

Emulsified fuel is base blending stock diesel fuel blended with up to 20 percent water and proprietary additives in such a way that the combination creates a stable emulsion that will not separate, and the water molecules are completely enclosed by fuel molecules. This prevents the water from coming into contact with engine and fuel system components to prevent corrosion and maintain lubricity. Emulsified fuel can result in PM reductions from 16 to 25 percent, while also significantly reducing NOx emissions.

2.3.3 Biodiesel:

Biodiesel is a renewable low-sulfur fuel with high oxygen content and low sulfur content that is derived from vegetable oils or animal fat. Biodiesel can be used neat (B100), but it is typically blended with petroleum diesel. PM reductions of nearly 50% are possible, depending upon the blend ratio. It is generally recommended that biodiesel be mixed in at 20% of the total fuel mix because this B20 blend achieves much of the potential PM reduction benefit while minimizing potential NOx emission increases associated with moderately higher combustion temperatures.

2.3.4 Oxygenated Diesel:

Oxygenated diesel is a blend of standard petroleum diesel fuel with a small amount of an alcohol (up to 10%), either ethanol or methanol, and proprietary additives that keep the alcohol from separating out of the diesel. Oxygenated diesel fuel provides similar PM reductions as biodiesel, typically around 20 percent, and also exhibits the potential for an increase in NOx emissions.

2.3.5 Fuel-Borne Catalysts:

Fuel-borne catalysts are capable of reducing emissions of both NOx and PM, with little to no capital investment. Proprietary catalyst packages, which may include small amounts of platinum, cerium, other precious metals, or iron compounds, are marketed by a number of companies. PM reductions of up to 15% are possible, depending upon the fuel/catalyst ratio. Some catalyst metals could potentially be considered hazardous when emitted to the atmosphere and as a result certain catalysts such as Cerium are recommended only when used with a diesel particulate filter that prevents their emission to the atmosphere.

Table 3 provides an overview of alternative fuels and their impact on emissions of NOx and PM as compared to on-road diesel fuel.

Table 3: Emission Reduction Benefits of Alternative Diesel Fuels

	Pollutant	
Fuel Type	**NOx**	**PM**
ULSD	No Impact	20 %
Emulsified Fuel [a]	9 % to 20 %	17 % to 25 %
Biodiesel (1 – 100 % blend) [a]	0 % to -10 %	0 % to 47 %
Oxygenated Diesel [b]	-10 %	20 %
Catalyzed Fuel [a]	0 % to 5 %	0 % to 15 %

a – Source: EPA listing of verified technologies, http://www.epa.gov/OMS/retrofit/retroverifiedist.htm.
b – Source: Clean Alternative Fuels: Ethanol, EPA420-F-00-035

2.4 Diesel Particulate Filter

A Diesel Particulate Filter physically captures diesel carbon particulates and oxidizes them to CO_2, preventing soot discharge from the tailpipe. The design of the substrate is honeycomb, similar to a DOC, but the DPF technology works by physically blocking every other cell of the filter as shown in Figure 5. Exhaust gas enters the DPF and then must pass through the cell wall, leaving a deposit of particulate matter behind. Over time, this particulate will build up and must be oxidized (i.e., regenerated). This oxidation of the collected soot is achieved by including a precious metal catalyst similar to those used in a DOC. The catalyst can either be applied directly to the filter substrate, or

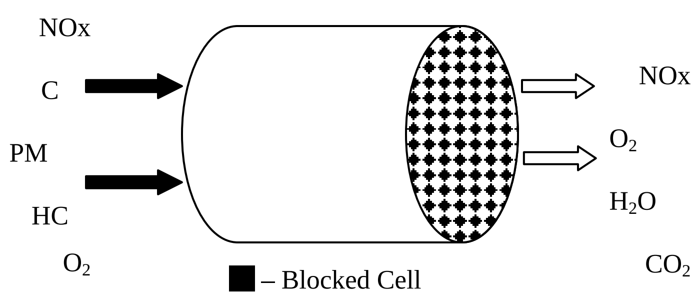

Figure 5: Diesel Particulate Filter Schematic

can be applied to a separate flow through substrate ahead of the filter. Ordinarily, oxidation of carbon soot requires temperatures above 600 ^{o}C, but the catalyst promotes oxidation at lower temperatures. DPF technology can provide reductions of PM, HC and CO of 80 percent or more, with the possibility of reductions in other pollutants.

Filters require relatively high exhaust temperatures for consistent regeneration and this can pose a challenge given the widely varying duty cycles of heavy-duty trucks. This is especially true of sanitation trucks where the average speed is very low resulting in low overall exhaust temperatures. Long idle periods and light-load operation present a situation where the DPF collects PM, but cannot regenerate. Typically consistent filter regeneration requires exhaust temperatures above 260 ^{o}C for at least 30 percent of the time the engine is operating. During periods of high engine load, these temperatures are easily achieved, but at lower loading points exhaust temperature can fall below 250 ^{o}C. Although DPFs offer high potential PM reduction, the risks of plugging and/or failure indicate that caution must be taken to understand these issues prior to widespread implementation. Because sulfur interferes with the activity of the DPF catalyst, a DPF cannot operate successfully with standard diesel fuel. In general, fuel sulfur must be less than 50 parts per million (ppm) for successful DPF operation and therefore, ULSD is commonly used in conjunction with a DPF.

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3.0 DSNY Fleet Analysis

At the start of the project DSNY had nearly 600 vehicles equipped with diesel-powered Cummins engines available for retrofit. The two largest groups of trucks were refuse collection trucks and street sweepers, including 281 and 315 vehicles, respectively. The project was initially conceived with the goal of retrofitting refuse collection trucks to assist in developing a PM reduction solution for a low average speed and low exhaust temperature application. However, throughout the project it was necessary to consider other applications beyond refuse collection trucks.

3.1 Vehicles Considered

The available refuse collection trucks spanned each of the five boroughs of New York City and were all Crane Carrier bodies. Table 4 shows the breakdown of trucks equipped with Cummins engines by borough.

Table 4: Refuse Trucks by Borough

Borough	No. of Trucks
Bronx	32
Brooklyn	91
Manhattan	63
Queens	65
Staten Island	29

One vocational truck application also considered during the project was diesel street sweepers. DSNY currently has a fleet of over 400 diesel street sweepers with a number of them available for DPF retrofits. While the original goal was to retrofit up to 260 refuse collection trucks, the sweepers were being considered in the latter half of the project for two reasons: 1) some exhaust temperature monitoring performed during May 2002 has indicated that certain DSNY refuse collection truck duty cycles may not allow for adequate exhaust temperature to trigger regeneration (discussed further in chapter 4), and 2) the refuse collection trucks at DSNY have only a seven-year life span before retirement.

The vehicle life issue leads to two disadvantages: 1) only late model vehicles will be retrofit (1997 or later) to allow for the maximum amount of in-service time for the DPFs, and 2) that based on the current contract awards the latest round of vehicle acquisitions will not be equipped with Cummins engines. Therefore, of the approximately 280 refuse collection trucks equipped with Cummins engines, a majority will be retired starting in 2004 with the remainder anticipated to be retired in 2005. Table 5 shows several typical trucks along with their in-service dates and expected retirement dates.

However, because DSNY's refuse collection trucks accumulate almost twice the mileage on an annual basis as compared to the street sweepers (an approximate average of 10,000 miles per year versus 5,200) deploying DPFs on the refuse collection trucks offered the opportunity to maximize PM emission reductions. In addition, discussions with EPA indicated that EPA preferred the refuse collection truck application to the sweepers.

Table 5: Truck In-Service Example Information

Truck ID	In-Service Date	End of Warranty	Program End *
25CF-01	8/14/97	8/03	8/04
25CF-100	10/8/97	10/03	10/04
25CF-200	12/31/97	12/03	12/04
25CF-281	2/27/98	2/04	2/05

* – Program end corresponds to the truck expected end of useful life. These dates roughly correspond to the end of this completed project.

3.2 Vehicle Early Retirement Hurdle

Midway through the project the City of New York began a program to implement citywide fleet reductions and budget saving measures. As part of this, a portion of the DSNY refuse collection truck fleet was targeted for early retirement. Unfortunately, a significant number of the Cummins engine trucks identified as candidates for DPF installation were among the trucks to be retired early. Because the end of useful life for these trucks roughly corresponded with the end of the project (i.e., in service for two years), by retiring them early, installing DPFs on these trucks would not achieve the project goals.

The original schedule for 260 retrofits called for phasing installations over three calendar years (2001-2003); however, because a number of trucks were included in the early retirement pool, the number of trucks available was reduced to 70. This resulted in a reprogramming of the consent decree project to include other fleets, including school and transit bus fleets. A complete list of the trucks retrofit including installation date and mileage accumulated is provided in Appendix B.

4.0 Data Logging

Data logging was necessary to establish the duty cycle and performance profiles of the candidate vehicles so that the DPF manufacturer and integrator could verify that the trucks achieve proper temperatures for regeneration. Not every truck that was identified as a candidate for retrofit was data logged; rather, representative trucks from select depots were data logged.

Additionally, continuous in-use performance monitoring of the DPF was tracked to help prevent in-use operational failures and to establish a baseline performance level for future comparison. Identifying situations that could cause performance problems, both with the DPF and the truck, before a problem occurs, allows for more effective preventative maintenance and fewer road calls.

The continuous performance monitoring consisted of backpressure and exhaust temperature in-use as well as periodic visual inspection of the DPF substrate. The data used for comparing performance before and after the installation of the DPF were backpressure, exhaust temperature, vehicle speed and ambient temperature.

4.1 Pre-Installation Data logging

Since this project represented some of the first fleet-scale refuse collection truck applications for passively regenerating DPF technology, significant data was collected during the development phase. The suitability of the application to the filter technology was verified and documented using exhaust temperature as the key parameter.

4.1.1 Exhaust Temperature Requirements

Several operating characteristics were quantified in order to verify that the refuse collection trucks were an appropriate application for the DPF technology. The particulate filters installed for this project utilize passive regeneration i.e., there is no supplemental heat source to trigger the regeneration event. Instead, the filter's catalyst relies on heat transferred from the exhaust gas to initiate regeneration. The exhaust gas must therefore reach a minimum temperature with sufficient frequency to allow the filter to operate properly. The temperature and frequency requirements are filter-specific, and are to some extent specified by each manufacturer according to the criteria included in their verification letter from EPA or CARB. As a condition for allowing this retrofit project under its consent decree with the engine manufacturer, EPA required that the vehicles meet the operational requirements specified by the filter manufacturers.

Refuse collection trucks are an especially difficult application in terms of meeting the filter manufacturer's temperature requirements, for several reasons. The vehicle tends to operate at low speeds, with frequent stops. This combination of low average speed and significant idling results in a lower average exhaust temperature than that of vehicles that operate for extended periods of time or at high speeds. While refuse trucks are heavy in and of themselves, they may carry widely varying loads, depending on the volume and composition of the refuse they are carrying at any given time. This makes it difficult to accurately predict the temperature profile of an entire fleet based on data collected from a small number of vehicles. The low ambient temperatures typical in New York during winter months provide an added impediment to reaching the required exhaust temperature needed for regeneration.

4.1.2 Pre-Installation Data logging Procedures

Since the failure of a DPF to regenerate can result in engine damage due to excessive backpressure and/or catastrophic meltdown of the filter itself, it was essential to verify the suitability of the retrofit vehicles prior to filter installation. This was accomplished by monitoring the exhaust temperature of several typical candidate vehicles during actual in-use operation. Initial exhaust temperature data logging was performed during the winter of 2000-2001.

The exhaust temperature data logging procedure consisted of installing a thermocouple in the muffler inlet pipe, and connecting the thermocouple output to a data logger mounted on the vehicle. The truck was then operated on its normal daily route. This process was repeated over several days, and the resulting temperature-time data was statistically analyzed to determine the daily averages and to ensure that minimum operating temperature criteria were met. A snapshot of in-use exhaust temperature from a single truck is provided in Figure 6.

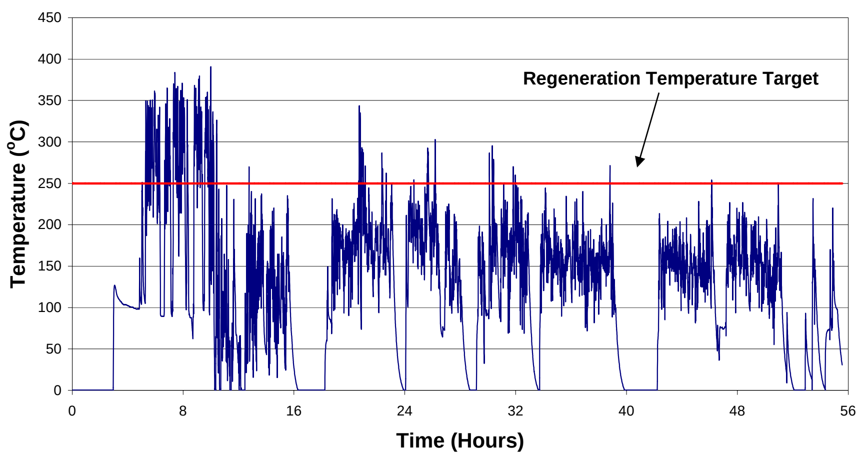

Figure 6: Pre-Installation Exhaust Temperature Profile

4.1.3 Pre-Installation Engineering Assessment

Fleetguard Emission Solutions along with the DPF suppliers performed a detailed engineering analysis on the exhaust temperature data and determined that the trucks operating out of Manhattan depots had suitable duty cycles to support regeneration of the DPF. Figure 7 graphically shows results of the data logging analysis for one of the trucks, which indicates marginal acceptability for a DPF. To improve the potential for more consistent regeneration, the decision was made to install insulation along the exhaust pipe between the engine and muffler.

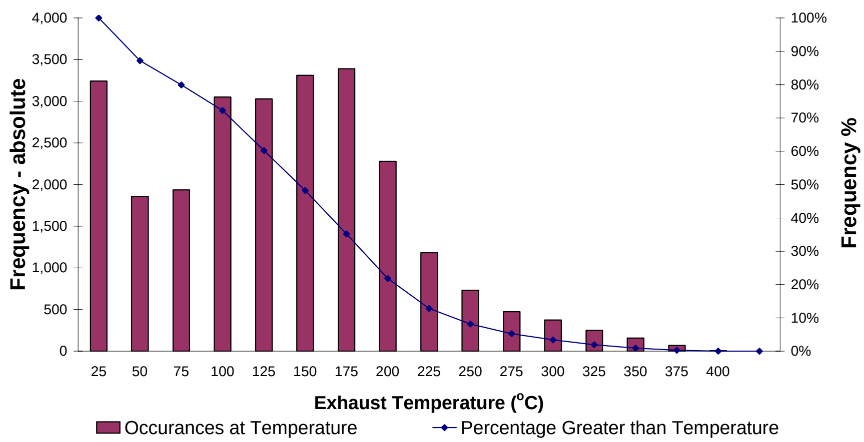

Figure 7: Pre-Installation Data Logging Analysis

Midway through the project, data logging was performed on several additional trucks operating in the Bronx to determine whether the different duty cycle was acceptable. The Bronx duty cycle is a local-only cycle characterized by frequent starts and stops like the Manhattan duty cycle, but with an end-of-day tipping at a transfer station in the Bronx. Unlike the Manhattan trucks, the Bronx trucks do not travel at high speeds on a highway en route to a transfer station. This led to some concern that exhaust temperatures would not reach adequate temperature for regeneration, frequently enough to prevent failure.

Fleetguard Emission Solutions determined through data logging that the application was borderline acceptable for a first generation DPF, and would meet the minimum requirements for a second generation DPF. Further discussion about the difference between first and second generation DPFs is provided in Chapter 6.

4.2 Continuous Data logging

Each truck equipped with a Johnson-Matthey DPF was also equipped with a continuous backpressure monitoring/data logging system. This system continuously monitors and records exhaust backpressure data from a point in the exhaust just before the DPF. The system was equipped with enough memory to store 270 days of data sampled at one-second intervals, averaged every ten minutes. Periodic analysis of the data was useful in establishing operational trends and to help define appropriate maintenance procedures for each truck. Generally, all trucks from the same depot were assumed to have very similar operating characteristics. Therefore, analysis of the backpressure data from each individual truck was not necessary. However, looking at the data from trucks across different depots could assist in determining and revising the maintenance schedule on a borough-by-borough and possibly even a depot-by-depot basis.

In addition to being used in determining maintenance schedules, the continuous backpressure monitoring data was useful for spotting trends related to other systems on the truck. One example of this was truck 25CF235, which experienced a backpressure alarm, indicating that the DPF was experiencing a high level of soot loading. After DSNY and Cummins Metropower performed a thorough query of the truck's diagnostic codes, it was determined that the root cause of the malfunction was a fan clutch solenoid. The solenoid was locked in the 'on' position, resulting in continuous operation of the cooling fan. As a result, exhaust temperature was lowered to the point of impeding DPF regeneration. This required the DPF to be removed, thoroughly cleaned and reinstalled.

5.0 ULSD Deployment

One of the impediments to citywide deployment of DPFs on the refuse collection trucks was the availability of ULSD. Both types of DPFs utilized during this project require ULSD. At the start of the project, New York City Metropolitan Transit Agency (MTA) was the only large-scale purchaser of ULSD in the city, and availability was limited. In addition, funding from this SEP was not allocated for offsetting the ULSD price premium, instead focusing on putting technology on the road. DSNY agreed to deploy ULSD, however, financially and logistically was constrained to only supplying it in two boroughs, Bronx and Manhattan.

The two different filters that were considered for deployment both require the use of ULSD to avoid potential catalyst fouling. The target sulfur concentration for this application was less than 30 parts per million (ppm). Sulfur in diesel fuel acts as a lubricant and the engine is designed with minimum fuel lubricity requirements. When sulfur is removed, the lubricity requirement is achieved through additives. Additionally, other properties of the fuel may change slightly and care must be taken that all manufacturer requirements are followed. Table 6 provides Cummins' recommendations for fuel properties along with a comparison of the fuel being supplied to DSNY.

Table 6: Select Cummins Recommended Fuel Properties vs. DSNY As-Supplied

Fuel Property	Cummins Specification	DSNY As-Supplied Average
Sulfur	500 ppm maximum (on-road)	16.5 ppm
Carbon Residue on 10% Bottom	0.35 % by wt., max	0.015%
Water	500 ppm max water & sediment	< 500 ppm
Sediment > 1μm		
Ash	0.02 %, by wt., max	< 0.01%
Cloud Point	10 ^{o}F below lowest expected ambient	-14 ^{o}F
Kinematic Viscosity @ 40^{o}C	1.3 / 5.84 cSt, min/max	1.74 cSt
Cetane Number	45 minimum	43.2 (Cetane Index)
Lubricity	0.45 mm max	0.35 mm
Density @ 15^{o}C	0.816 – 0.876 g/cc	0.821 g/cc

When this project began, DSNY was fueling all diesel vehicles with commercially available on-road diesel, which is allowed to have up to 500-ppm sulfur content. Therefore, a number of hurdles were overcome to introduce ULSD to the DSNY fleet.

The first hurdle faced involved securing a supplier for the fuel. Fortunately, several other agencies in New York (e.g., DOT, MTA) were implementing ULSD purchases, which provided DSNY with some leverage. This also confirmed that there was significant demand in New York City such that the cost penalty of purchasing ULSD was minimized. At the time, the cost premium for a gallon of ULSD versus a gallon of on-road diesel was approximately $0.15. This cost premium was attributable to two factors, the additional refining processes required to remove the sulfur and add in lubricity agents, and the need for dedicated storage and delivery systems. The supplier usually achieves the latter by thoroughly cleaning both tanks and trucks and making them unavailable to other fuel products.

The second and larger hurdle was to begin penetrating the DSNY fleet with ULSD. One major concern that DSNY had was whether or not they wanted to commit to switching their entire fleet, or only select locations as necessary. To begin, DSNY committed to switching one storage tank at the Manhattan-11 depot to ULSD.

By midsummer 2001 all of the groundwork had been laid to begin implementing ULSD in the Manhattan-11 depot; however, before any DPFs could be installed, it was necessary to verify that the sulfur level in both the depot storage tank as well as the vehicles was below 30 ppm. To do this, a plan was developed to begin receiving deliveries of ULSD after the standard diesel in the storage tank was drawn down as much as feasible. It was estimated that it would take several deliveries before the sulfur content of the diesel in the tank was acceptable. DSNY and Cummins gathered fuel samples after each delivery and had them analyzed under a standard ASTM test to determine overall properties in addition to sulfur content. After five deliveries, the sulfur content in the depot storage and truck tanks was acceptable, and the DPF retrofits began.

One final step was required before DSNY began implementing DPFs. To prevent misfueling, DSNY installed signage on each DPF-equipped refuse collection truck instructing that only ULSD was to be used in the truck, and installed locks on the fuel filler cap. While it was expected that the signage was sufficient, the locks were installed as a backup to prevent accidental misfueling. Because the DPFs are so sensitive to fuel sulfur content, these steps were taken to minimize the potential of contaminating any of the DPFs.

A major concern with switching a fleet from on-road diesel to ULSD was maintaining the sulfur level below specification. The most comprehensive method of verifying this was to test each delivery; however, this was determined to be cumbersome and impractical. The solution for this project was to have it written in the supplier’s contract that all ULSD must be stored and transported in dedicated tanks and trucks, respectively. This will minimize the potential for contamination of the ULSD with a higher sulfur product. In addition, DSNY performed periodic spot analyses from random deliveries.

During July of 2004, DSNY switched all depots citywide over to ULSD. This has allowed for much simpler fuel tracking and has opened the ability for DSNY to move trucks between depots without having to worry about fuel issues.

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6.0 DPF Technology

During the initial planning phase of the project, DSNY provided valuable input regarding their past experiences with and knowledge of DPFs. In addition, DSNY made clear that with respect to their fleet operation, they had two overriding objectives: (1) that the deployment of DPFs minimally affect the day-to-day operations and responsibilities, and (2) that the project provide an opportunity for different technologies to be implemented, so that a balanced decision on how to retrofit their fleet could be made. The first of these objectives was very simple, but paramount for the success of any retrofit project. If the retrofit equipment has an adverse impact on the ability of the truck to perform it's job, then it is unlikely that further retrofits will be embraced. The DPFs deployed during this project were made up of a series of individual parts, integrated into a final DPF package, which was designed to replace the original muffler as closely as possible. Usually when a manufacturer is referred to regarding a DPF, it is really the manufacturer of the honeycomb substrate that is being referenced as opposed to the final integrator. For this project, two different DPF substrate manufacturers supplied products: Engelhard, Inc. and Johnson Matthey. Fleetguard Emission Solutions packaged and integrated the final product for both of them.

6.1 DPF product descriptions

6.1.1 Engelhard

The Engelhard DPX™ catalytic particulate filter is verified under the EPA's NESCAUM Third Party Verification Process and until was also verified under CARB's Diesel Risk Reduction Rule. A summary of the minimum verified performance of the system is shown in Table 7. The DPX™ is a patented emission control technology that contains a single module catalyzed particulate filter. It is a completely passive emission control system, which does not require the use of supplemental heat. In certain applications, the DPX™ does not require the introduction of ULSD; however, due to the low speed and exhaust temperature profile of the DSNY refuse collection truck fleet, the implementation of ULSD was necessary. EPA's verification process and approval requires the use of ULSD with the DPX™ to guarantee the emission reductions shown in Table 7.

Engelhard's DPX™ catalytic particulate filter traps particulates and then uses a patented catalytic technology to essentially continuously burn them at normal diesel operating exhaust temperatures. Because the removal mechanism is filtration, particulate removal is continuous; however, regeneration is periodic. Reductions of CO and HC are achieved during reaction with the catalyst that converts them to CO_2 and H_2O.

6.1.2 Johnson-Matthey

6.1.2.1 CRT®

The Johnson Matthey CRT® particulate filter, referred to during this project as their first generation DPF, is a verified technology under the EPA's NESCAUM Third Party Verification Process as well as the California Air Resources Board (ARB)'s Diesel Risk Reduction Rule. Johnson Matthey has also developed a second generation DPF, the CCRT®, designed for low exhaust temperature applications, which has been verified by both EPA and CARB. A summary of the minimum verified performance of the Johnson Matthey products is shown in Table 7. The CRT® is a patented emission control technology that contains an oxidation catalyst and a particulate filter. It is a completely passive emission control system, which does not require the use of supplemental heat, and has a modular design. The CRT® particulate filter requires low sulfur fuel for proper operation. Differing levels of PM reduction can be achieved depending upon the sulfur content of the fuel. Johnson Matthey recommends ULSD with 15-ppm sulfur for maximum PM reduction, although reliable regeneration can occur using 30 ppm or 50 ppm sulfur fuel. The CRT® filter can operate at sulfur levels up to 500 ppm but such operation requires significantly higher exhaust temperatures. EPA's verification process and approval requires the use of ULSD with the CRT® to guarantee the emission reductions shown in Table 7.

Table 7: DPF Operating Criteria and Verified Performance

Technology	Exhaust Temperature Requirements [a]	Maximum Fuel Sulfur Content	Verified Emission Reductions (EPA/CARB)			
			PM	CO	NOx	HC
Engelhard DPX ™	≥ 250 °C for ≥ 30% of duty cycle	30 ppm	60% / 85%	60% / n/a	n/a	60% / n/a
Johnson Matthey CRT® [b]	≥ 240 °C for ~ 40% of duty cycle	30 ppm	60% / 85%	60% / n/a	n/a	60% / n/a
Johnson Matthey CCRT® [b]	≥ 200 °C for ~ 40% of duty cycle	30 ppm	60% / 85%	60% / n/a	n/a	60% / n/a

a – Published EPA/CARB verification information as of July 2005.

b – Johnson Matthey guidelines for proper regeneration are 240 °C for 40% of the duty cycle for the CRT® and 200 °C for 40% of the duty cycle for the CCRT®. Data in the table represent thresholds and limits set by the EPA and CARB, rather than the actual emission reduction potential of the various technologies, as experienced in operation.

The CRT® particulate filter takes advantage of the fact that soot will oxidize at a lower temperature in the presence of NO_2 versus oxygen. This lower temperature is compatible with the typical exhaust temperature from diesel engines and is even more critical given the low exhaust temperature from refuse collection trucks.

6.1.2.2 CCRT®

Johnson Matthey also manufactures a CCRT® particulate filter that was deployed on two trucks operating in the Bronx. The CCRT® is designed in much the same manner as the CRT®, however, is engineered to operate with lower exhaust temperatures. Both the CRT® and CCRT® are verified to provide the same reductions of HC, CO, and PM.

6.2 DPF Installation

The DPF installation process was relatively simple. The process involved replacing the OEM muffler and exhaust pipe with the DPF unit, which was similar in size to the original parts, and the installation and wiring of a monitoring system. At the beginning of the project, the first few installations took from four to eight hours to complete. However, after the first few, the installation time was cut in half to approximately two to four hours each.

Initially, the OEM exhaust pipe and heat shield were removed, followed by installation of the monitoring system. The monitoring system consisted of a Johnson Matthey CRTdm mounted to the exhaust support structure in a weatherproof enclosure (Figures 8 and 9). The monitoring device includes thermocouples and pressure sensors to measure exhaust temperature and backpressure between the turbocharger outlet and the DPF. In addition warning lamps were installed in the cabin to alert the operator if the system required maintenance (Figure 10). The two alarm lights are yellow and red, and were set up to illuminate when the backpressure reaches predetermined levels. The system was programmed so that the yellow and red warning lamps will illuminate when the backpressure reaches and/or exceeds 7” Hg and 9” Hg, respectively for a period of five percent of any 60-minute interval. When the yellow light comes on, the engine will derate and allow the truck to ‘limp’ back to the depot for maintenance. When the red light comes on, the operator is to shut down the truck immediately and have the truck towed back to the depot.

Figure 8: Johnson Matthey Monitoring Device

Figure 9: Backpressure Monitor

Figure 10: Alarm Indicator Lights

To complete installation, the lower exhaust pipe was insulated using a flexible woven insulating material that was provided with the DPF (Figure 11). Because the DPF operates better when exhaust temperature is maintained, the insulation was installed to maximize the exhaust temperature at the DPF. After the lower exhaust pipe was reinstalled, the DPF, heat shield and upper exhaust pipe followed, to complete the installation.

Figure 11: Insulated Lower Exhaust Pipe

6.3 DPF maintenance

Cleaning and maintenance was an important consideration for a successful DPF application, especially low average speed and low exhaust temperature applications such as refuse collection trucks. Routine maintenance was required on the DPFs, and Cummins and Fleetguard Emission Solutions along with Engelhard and Johnson Matthey developed a set of recommendations for DPF cleaning. These cleaning procedures are provided in Appendix C.

Maintenance and cleaning was application-specific and significant consideration was given to establishing a cleaning interval for the DSNY trucks. Over the road trucks that reach consistently high exhaust temperatures and undergo regeneration more often than a low exhaust temperature application may require less frequent cleaning, on the order of every 50,000 to 100,000 miles. The DSNY trucks were expected to require more frequent cleaning, on the order of every 10,000 miles, or approximately once per year. Under this project, DSNY required that all trucks undergo a DPF cleaning at least once prior to the end of 2004. In addition, close monitoring of the backpressure alarm systems was used to assist in determining whether cleaning was required more frequently.

Cummins Metropower, the local Cummins distributor, performed the cleaning for DSNY under this project. Prior to the conclusion of the project, DSNY and Cummins Metropower determined a course of action for future cleaning of the DPFs. Cummins Metropower is equipped with a specially designed cleaning system that is capable of performing cleaning of different types of DPFs. In order to properly clean the DPF, the filter module must first be removed from the truck. The cleaning machine operates by forcing compressed air through the DPF, which dislodges the accumulated soot and ash and deposits it into a container.

The resulting ash must be disposed of properly. The New York State Department of Environmental Conservation (NYS DEC) was solicited as to whether this ash is classified as a hazardous waste. NYS DEC ruled that in accordance with 6 NYCRR 371.1, the residues from burning of fossil fuels are not considered to be hazardous waste, and that in accordance with 6NYCRR Part 364, the transportation of the ash, in limited quantities (<500 pounds), can occur with regular solid waste. A copy of the NYS DEC ruling is provided in Appendix D.

6.4 Backpressure monitoring

One of the concerns about using DPF technology is plugging of the DPF, which could lead to excessive engine backpressure. Plugging could occur for several reasons; the DPF never reaches sufficient temperature for regeneration and PM builds up in the filter, misfueling contaminates the DPF, or engine malfunction such as a bad turbo or fuel injector. If backpressure remains unchecked, it can increase to levels that may severely reduce engine performance. This was a major concern for both DSNY and Cummins.

For this reason, Cummins required that each DPF provider also integrate an exhaust backpressure alarm that alerts the driver if the backpressure is rising too much. Both Engelhard and Johnson Matthey provided visual and audible alarms, mounted on the dashboard. These backpressure alarms light up if a predetermined backpressure is exceeded for more than a set interval. There was a great deal of discussion regarding what these set points should be to help ensure that catastrophic failures would not occur. In addition, Johnson Matthey's system also logs backpressure so that periodically, the information can be retrieved and analyzed to look for backpressure trends that may be indicative of potential problems.

To determine whether any changes in backpressure had occurred, and as a method of verifying that the DPFs were regenerating with enough frequency, DSNY periodically checked the backpressure with a handheld gauge on each of the retrofit trucks as well as ambient temperature and odometer readings. At convenient intervals DSNY recorded a backpressure reading for each truck at idle and stall conditions. Figure 12 shows an historical record of backpressure as periodically measured at stall condition on two trucks operating with DPFs.

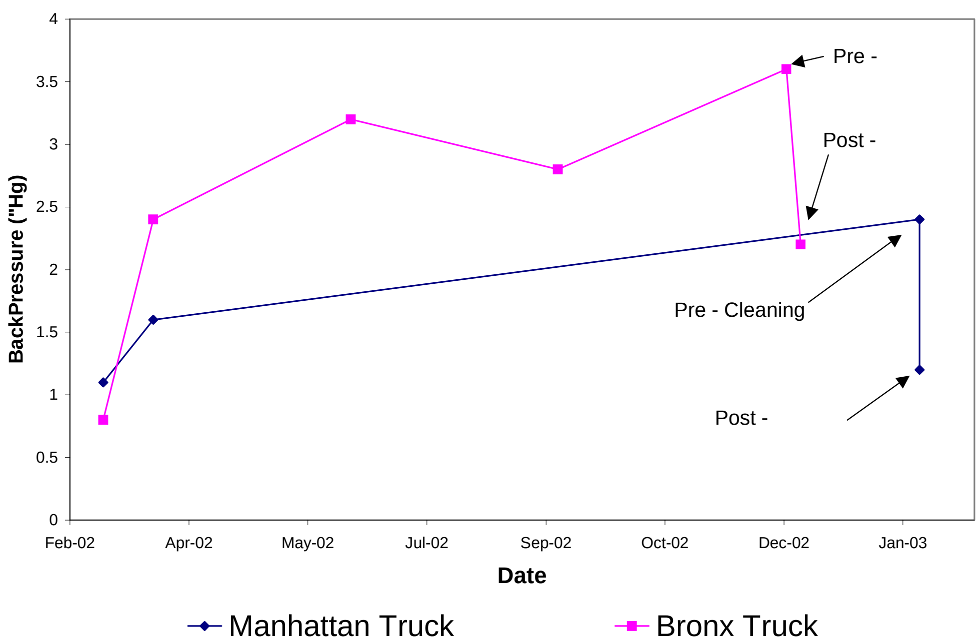

Figure 12: Historical Backpressure Readings for Select Trucks

7.0 DPF Deployment

The deployment of DPFs throughout the DSNY fleet was broken down into two phases. The first, a pilot phase, was intended to verify what the engineering analysis had concluded, that DPFs would be viable in a refuse collection truck application. The second phase involved full-scale installation of the remaining DPFs. Prior to each of these phases warranty concerns were sorted out.

7.1 Warranty Issues

In addition to the vehicle length of service issue, a strong concern raised by DSNY at the outset of the project was to ensure that there would be an absolute minimum of failures on the street – preferably none. This concern was a valid one because while the trucks have an anticipated useful life of seven years, with some able to last up to 10, the engine warranty was only five years. DSNY did not want the DPFs to cause an out-of-warranty failure since the DPFs will be on the vehicles through the end of their useful life.

To resolve the warranty issue, the DPF manufacturers provided a warranty on the DPFs that covers failures of the DPF, with Cummins Metropower administering the warranties. In the case of an engine failure due to a problem not related to the DPF, the engine warranty shall prevail.

7.2 Pilot Phase Deployment

The pilot program began with installation on four trucks, all operating out of the Manhattan-11 depot. During the pilot phase, products from both DPF suppliers were utilized. Two of the four were equipped with Engelhard DPX™ technology and two with Johnson Matthey CRT® technology. These first four were installed in late August of 2001. The timing of the installation was advantageous because it allowed for several months of operation during warmer weather before entering winter. This was important to determine that the DPFs were operating correctly under the best possible conditions, and provide an in-use baseline that winter operation could be compared to. Winter operation was a concern because the trucks already have a low exhaust temperature profile, and lower ambient temperatures will lower the exhaust temperature even further. These four trucks, identified in Table 8, were closely monitored to see if any adverse backpressure trends could be identified. If backpressure steadily and/or rapidly increased, it would be an indication that the DPF was not regenerating, and that too much soot and PM was accumulating. Figure 13 provides backpressure detail for one of the four pilot phase trucks during the first year of operation.

Table 8: Pilot Phase Trucks

Truck ID	Depot	DPF Technology	Date Installed
25CF-042	Manhattan-11	Johnson Matthey CRT®	8/29/2001
25CF-043	Manhattan-11	Johnson Matthey CRT®	8/29/2001
25CF-044	Manhattan-11	Engelhard DPX™	8/30/2001
25CF-045	Manhattan-11	Engelhard DPX™	8/30/2001

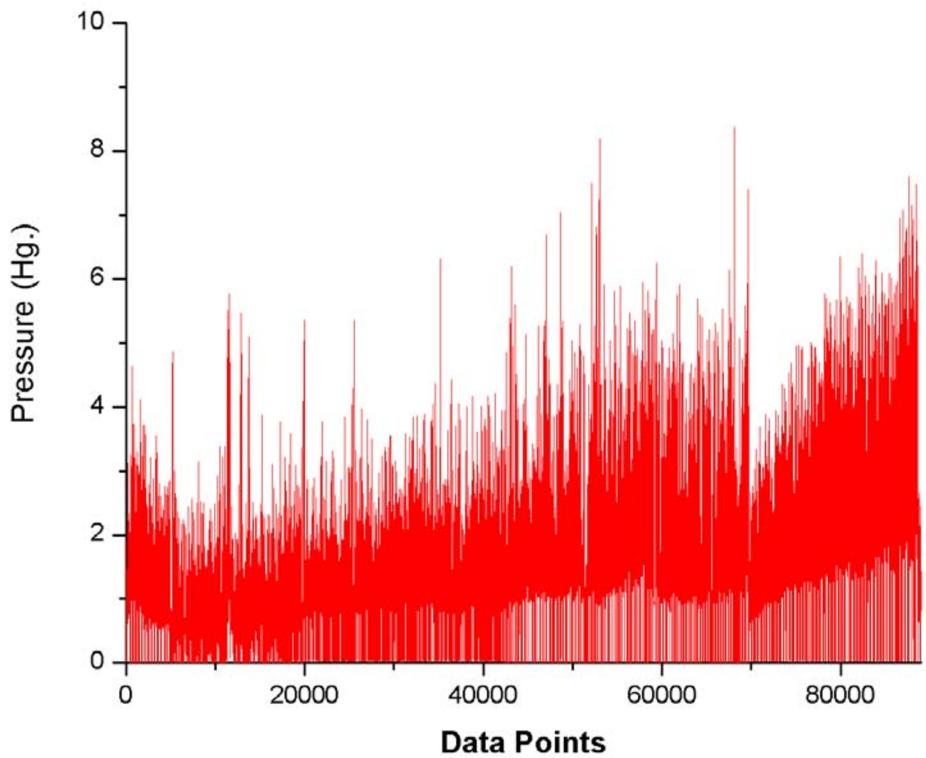

Figure 13: Backpressure Readings for a Single Pilot Phase Truck During the First Year of Operation

Figure 14: DPF Prior to Teardown

Prior to full-scale implementation of the second phase, two of the original four pilot DPFs underwent a complete teardown and visual inspection. The two remaining units remained in service as-is, to assist in better establishing a cleaning/maintenance schedule. This occurred approximately one year after installation. Figures 14 through 16 show the units as they were being disassembled. The visual inspection was performed to determine whether there were any visible signs that the DPFs were not operating correctly.

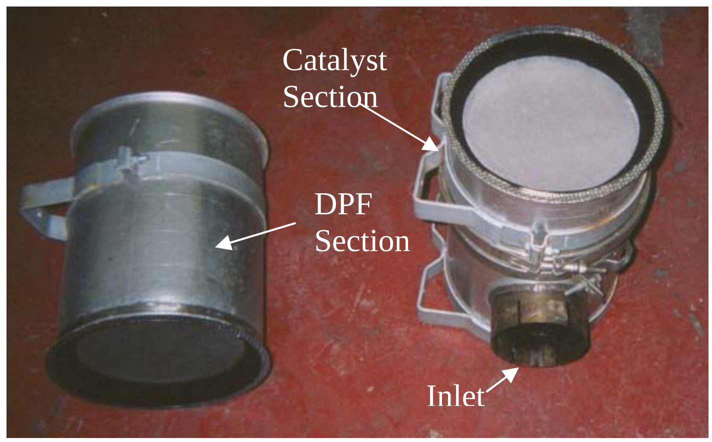

Figure 15: DPF Inlet and Outlet Sections

Prior to the teardown, DSNY measured backpressure at both high idle, and at stall, consistent with how they have been tracking the backpressure of the four pilot trucks since installation. In addition, the data collected by the Johnson Matthey CRTdm was downloaded and analyzed to determine whether there had been any high backpressure events just prior to the teardown. A review of the data indicates that there were no high backpressure readings.

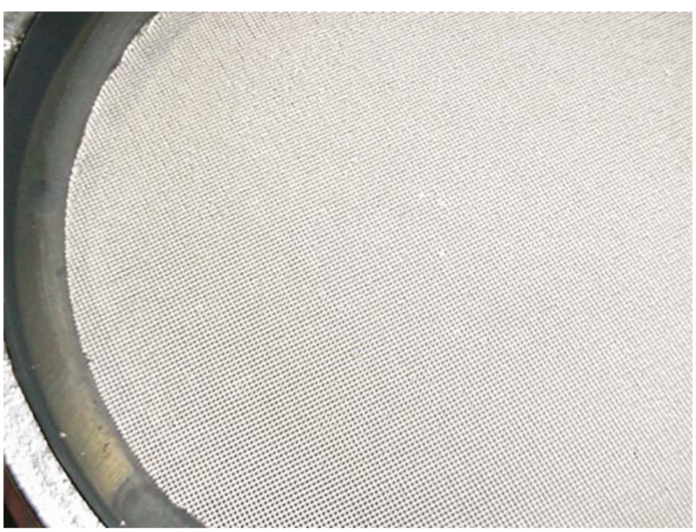

Figure 16: DPF Outlet Face

The teardown involved removing the DPF from the truck and performing a visual inspection of the filter and a cleaning. The visual inspections for both DPFs indicated no problems with the filters, and the outlet of each filter was noted to be very clean. Cleaning was performed in accordance with the instructions established earlier during the pilot phase, and as provided in Appendix C.

After each filter was cleaned, the filter was reversed and reassembled; and a backpressure reading was taken to compare against the pre-cleaning value. The backpressure dropped by a factor of approximately two or three, back to the level seen at original installation. In addition, upon startup, there was no visible ‘puff’ of black soot as might be expected after reversing the filter if the cleaning procedure was not complete and thorough.

7.3 Full-Scale Deployment

At approximately the six-month mark, in the spring of 2002, additional installations commenced as part of the second phase. Appendix B provides a complete listing of the trucks that were retrofit, including date of retrofit and technology used.

One major change between the pilot phase and full-scale deployments was that in going to full-scale deployment, only one DPF technology was used. One primary reason for limiting participation to only one technology was the desire of DSNY to have essentially a standard DPF product deployed on its Cummins refuse collection trucks. After evaluating both technologies against six essential criteria, the Johnson Matthey product was chosen for the remainder of the DPFs. The Engelhard DPX™ product was nearly equivalent to the Johnson Matthey CRT®, except that the Engelhard backpressure monitor did not include the ability to data log the information, whereas the Johnson Matthey CRT® DM can store up to approximately three months of backpressure data. Having the ability to download historical backpressure data and track it for performance trends was very important to DSNY, and therefore, this one criterion was critical in deciding with which vendor to continue the project.

The full-scale deployment of DPFs includes trucks from Manhattan and the Bronx. Because the Bronx trucks do not have as advantageous a duty cycle as the Manhattan trucks (because there is no high-speed highway travel), there was concern about whether the standard DPF would be able to perform. To investigate this, the project deployed two second-generation Johnson Matthey DPFs, or CCRT®s. The CCRT® has the ability to regenerate at even lower exhaust temperatures than a CRT®; however, there is a cost penalty. To date, after approximately two years of operation, the Bronx trucks equipped with CRT® technology have not experienced any problems attributable to the operation of the DPF.

This trend was especially encouraging considering the particularly cold winters experienced by the New York City area during the first few years of the project. Figure 17 shows the average winter monthly temperature trends during the project. The first winter that the pilot trucks were on the road, the average temperatures were much higher than normal, approximately seven degrees above normal. During the winter of 2002/2003, temperatures were on average colder than normal, and the winter of

2003/2004 was one of the coldest in many years. Having the DPFs operate during a colder than normal winter was significant, because the lower the ambient temperature, the lower the exhaust temperature. While it is not a linear relationship, the ambient temperature still impacts exhaust temperature because the intake air is colder and there is possibility for heat loss through the exhaust system. By having the DPFs operate successfully during the past two winters, DSNY felt able to proceed with confidence beyond the end of this project.

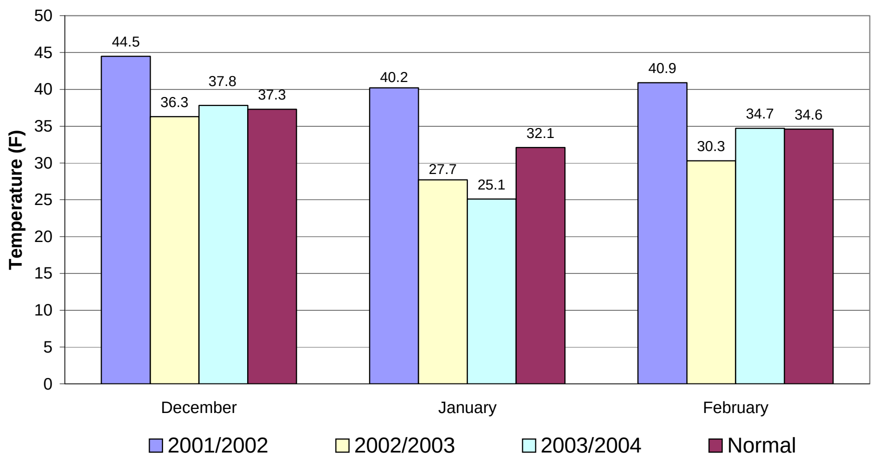

Figure 17: New York City Average Monthly Temperatures

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8.0 CNG Street Sweeper Deployment

8.1 Overview

One important component of this consent decree project was the deployment of four CNG street sweepers. Historically, DSNY has limited sweeper acquisitions exclusively to diesel-powered vehicles. At the start of the project, DSNY had approximately 450 street sweepers, only five of which were fueled by CNG. DSNY's preferred sweeper provider is Johnston Sweeper Company (JSC) located in Chino, California.

Johnston Sweeper Company, a subsidiary of Johnston Group PLC, manufactures road sweepers, airport runway clearance vehicles, municipal and contractor cleansing machines and road construction and maintenance vehicles. Founded in England in 1903, JSC employs over 1,000 people in eight facilities worldwide. Their main US office and factory, located in Chino, California, markets their products throughout North and South America.

The most recent contract for providing street sweepers to DSNY at the outset of the project had been awarded to JSC, however, did not have provision for supplying CNG sweepers. Over a period of several months, DSNY and Johnston revised the existing contract to allow the final four sweepers scheduled for delivery to be CNG instead of diesel. Funding from this project was used to offset the differential cost between CNG and diesel sweepers.

It may seem simple in concept to deploy the CNG street sweepers; however, JSC was not producing a CNG sweeper at the time, and a number of steps were required before they could be delivered. As lengthy as the process was to go from concept to commissioning, remarkably, Johnston Sweeper was able to accomplish it all within eight months.

One primary reason for introducing CNG street sweepers into the DSNY fleet was to bring about technologies that will lower the amount of PM generated in urban neighborhood settings. Most street sweepers are classified as heavy-duty vehicles, and as such are subject to EPA's heavy-duty engine emission standards. Table 9 contains an abbreviated list of heavy-duty

Table 9: EPA Emission Standards vs. Cummins Certification for 2002 Model Year (g/bhp-hr)

	NOx	HC	PM
EPA Standard	4.0	1.3	0.10
Cummins Engine Certification			
Diesel	4.0	1.3	0.10
CNG	2.7 NOx + NMHC		0.08
ULEV CNG	1.8 NOx + NMHC		0.02

ULEV – Ultra Low Emission Vehicle

engine emission standards for PM, NOx and HC applicable to 2002 model year heavy-duty vehicles compared with the Cummins CNG and diesel engine certification.

8.2 Design & Manufacturing

The standard sweeper on order from DSNY is the Johnston 4000-series model. The CNG model purchased under this project used the architecture of the diesel 4000-series as the basis; however, when considering switching fuels significant design changes were necessary to accommodate the fuel delivery system and storage tanks.

The CNG sweepers are four-wheel, two axle type with a gross vehicle weight (GVW) of 27,000 pounds. In addition, the JSC 4000CNG models, as shown in Figure 18, are equipped with 2002 model year Cummins 5.9B-230G engines and Fleetguard-Nelson oxidation catalysts. Table 10 provides a comparison of specifications between the diesel and CNG models.

Figure 18: JSC4000 CNG Model Sweeper

Table 10: CNG and Diesel Sweeper Specifications

	JSC 4000	JSC 4000CNG
Engine Manufacturer	Cummins	Cummins
Engine Model	ISB 190 6	B5.9-230G
Fuel	Diesel	CNG
Rated Horsepower	190	230
Wheelbase (in.)	130	130
Overall Length (in.)	210	235

Gaseous fuels have very different storage and delivery properties than liquid fuels, and, therefore, require different hardware for safe and reliable use. Liquid fuels, such as gasoline or diesel fuel, are stored at atmospheric pressure and pumped to the engine at a rate determined by the engine's fuel consumption requirements. In contrast, gaseous fuels such as CNG are stored under pressure – therefore, their tendency is to continuously flow to the engine, and their flow must be restricted by an amount corresponding to the needs of the engine.


Figure 19: CNG Storage Tanks

To accommodate CNG fueling, the sweepers were fitted with new, high-pressure storage tanks, as shown in Figure 19, and a completely new, custom-built fuel delivery system including high-pressure fuel lines and pressure regulators. Because high-pressure storage vessels require substantially more structural material per unit of fuel than liquid tanks, and gas occupies more volume than liquid on an energy basis, the fuel tanks for the CNG sweepers are substantially larger than their diesel counterparts. This presented the JSC engineers with a challenge in that the CNG fuel tanks cannot be placed in the same location as a diesel fuel tank on the vehicle. To accommodate the larger-sized tanks JSC extended the overall length of the vehicle. This was accomplished by moving the cab forward of the front wheels by 26 inches, to allow for a vertical "stack" of storage cylinders located between the cab and the elevator (see Figures 20 and 21 for a schematic comparison of the CNG and diesel sweepers).

Some of the more noticeable changes that will affect the driver involve general drivability. Drivability was positively affected by moving the cab forward. While the CNG and diesel sweepers have the same wheelbase dimension, the increased front wheel overhang and driver position appears to increase the maneuverability of the sweeper. Switching from the diesel to CNG engine also positively affected drivability because the CNG engine has a rated horsepower of 230 compared to 190 for the diesel.

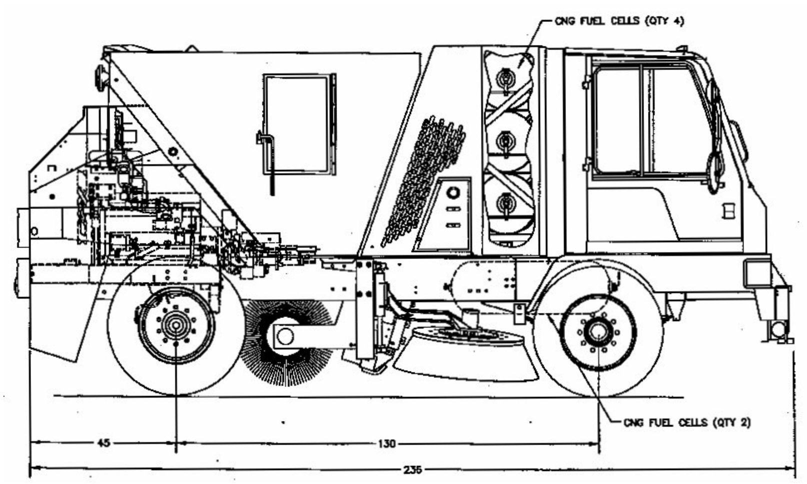

Figure 20: CNG Sweeper Schematic

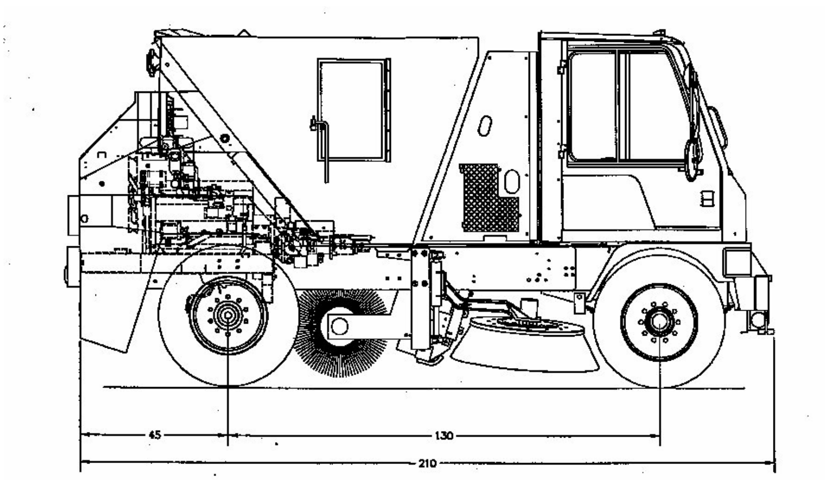

Figure 21: Diesel Sweeper Schematic

8.2.1 CNG Infrastructure

One of the drawbacks to widespread deployment of CNG vehicles in general is location of refueling stations, or infrastructure. Many times, fleet operators are faced with a chicken and egg situation – if there is no infrastructure, then CNG-fueled vehicles cannot be deployed, but investments in CNG infrastructure are limited without proven demand. Fortunately for this project sufficient infrastructure was available. DSNY utilizes centralized fueling locations for all CNG vehicles in their fleet. Suppliers with existing infrastructure are KeySpan Energy and ConEdison. At the start of this project significant upgrades in local fueling infrastructure were beginning with one DSNY and six NYC DOT CNG fueling stations in either in the planning process or under construction in the New York City area. Appendix E provides a listing of all CNG stations within a 25-mile radius of New York City.

8.2.2 Safety and Special Training

Switching to CNG sweepers often raises concerns about safety and special training required for operators and mechanics related to general operation of the sweepers. Natural gas by itself is a relatively harmless fuel; however, when compressed, it poses different safety and training requirements than diesel fuel. CNG safety issues are both depot and vehicle specific. Depending upon the design of the depot, upgrades to the ventilation system may be required to provide adequate ventilation in the event of a leak. In addition, fueling infrastructure must be protected to minimize the possibility of a tank or line rupture as a result of accident. The DSNY facilities where the sweepers were deployed are already equipped to handle natural gas vehicles and did not require any special modifications. With respect to vehicle safety issues, CNG vehicles have been in operation throughout the US for the better part of the last quarter century. Some of the vehicle safety design elements are covered previously in section 8.2. DSNY follows manufacturer guidelines for operation, maintenance and safety concerns.

8.2.3 In-Service Operation

DSNY operates all four CNG sweepers in regular service on various routes in Queens and Manhattan. These routes tend to have a short travel time where the sweeper can reach speeds of 40 mph while transporting to the sweeping area. Typically, sweeping is done at 6 to 8 mph and on average the sweepers accumulate approximately 20 miles per day. Since their introduction, the sweepers have logged significant in-service operation time and mileage accumulating a combined 25,090 miles.

8.2.4 Service and Maintenance

DSNY operates with an aggressive maintenance schedule for both diesel and CNG vehicles in their fleet and has seen no impact on service intervals from the CNG sweepers. As mentioned earlier, DSNY operates according to manufacturer operating and maintenance procedures and manuals.

8.3 Emission Testing

One of the goals of the project was to document the benefit of introducing CNG street sweepers into the DSNY fleet. The method chosen for determining the emission benefits was chassis dynamometer testing. Further discussion about the dynamometer testing is provided later in this chapter.

Street sweepers present several challenges in terms of achieving and quantifying emissions reductions. While they share many of the characteristics of refuse collection trucks that make them a worthy target for advanced emission controls, such as continuous low-speed operation in congested urban neighborhoods, their specialized auxiliary equipment and wide variability of service routes make it difficult to develop accurate and broadly applicable test cycles and performance standards.

In addition, their unique chassis and drivetrain (hydrostatic drive) design complicates chassis-based emission testing, since most dynamometers are designed for conventional vehicles. Since there has been little chassis-based emission testing of street sweepers to date, this project represented many "firsts" in the area. In addition to generating baseline emission data, many lessons can be shared to facilitate future street sweeper emission testing events.

8.3.1 Duty Cycle

In order for a chassis dynamometer test to accurately reflect real-world operation of a test vehicle, that vehicle must be operated in a manner similar to, or at least representative of, its typical operation under real-world conditions. Prior to this project, there was no standardized testing method specifically for street sweepers. Whereas other categories of heavy vehicles, such as urban buses and garbage collection trucks have pre-determined test cycles based on empirical data and statistical methods, no such cycles had been developed for sweepers. There also exist general test cycles, such as the CBD (central business district) cycle, which is often used in cases such as this where there is no predetermined protocol. Advantages to this approach include consistency for comparing various vehicles' emission performance and repeatability, as the cycle is quite simple in its design and typically results in relatively little deviation from one lab or test driver to another. However, this cycle, while an improvement over older steady-state tests, is not representative of the real-world acceleration and deceleration patterns particular to street-sweeping operation.

This project therefore presented a unique opportunity to set a standard for comprehensive and scientifically meaningful emission testing of this class of heavy-duty urban vehicles. The process of developing a unique test cycle consisted of two main tasks: determining the actual in-use behavior of the vehicles, and then using this information to formulate a succinct, repeatable test cycle.

To determine the in-use operating behavior, a speed-time trace was generated for two vehicles during normal service. The speed data was collected by connecting a data logging device (in this case a laptop computer equipped with data acquisition hardware and software) to the vehicle's speed sensor. The result of this effort was two speed-time data sets, each reflecting one full day of street sweeper operation. Figure 22 shows an excerpt of the sweeper speed-time data as collected.

The next step was to convert this data, representing approximately 14 hours of sweeper operation, into a 30-minute cycle that accurately reflects the relevant characteristics of the sweeper's in-use drive cycle. Engineers at West Virginia University (WVU) accomplished this with computer software they developed specifically for this purpose. This program works by examining the entire set of in-use data, and breaking it up into "microtrips," each microtrip consisting of an acceleration from and deceleration to zero, with any length of drive time in between. The computer then selects and concatenates a random grouping of these microtrips with a total length of thirty minutes, an average speed equal to that of the whole-day average, and a portion of idle time equal in percentage to that of the entire data set. A speed-time representation of the final cycle, referred to as the NY Sweeper Cycle, is shown in Figure 23. Further discussion regarding the raw data and development of the cycle is provided in Appendix F.

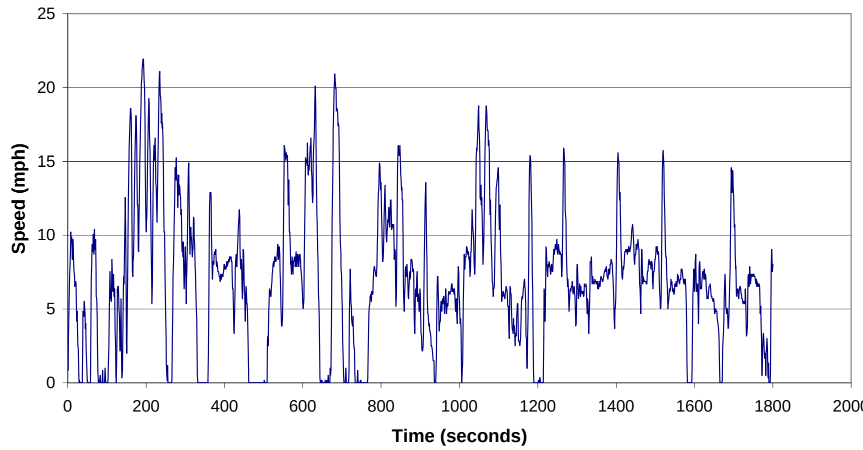

Figure 22: Snapshot of Sweeper In-Use Operation

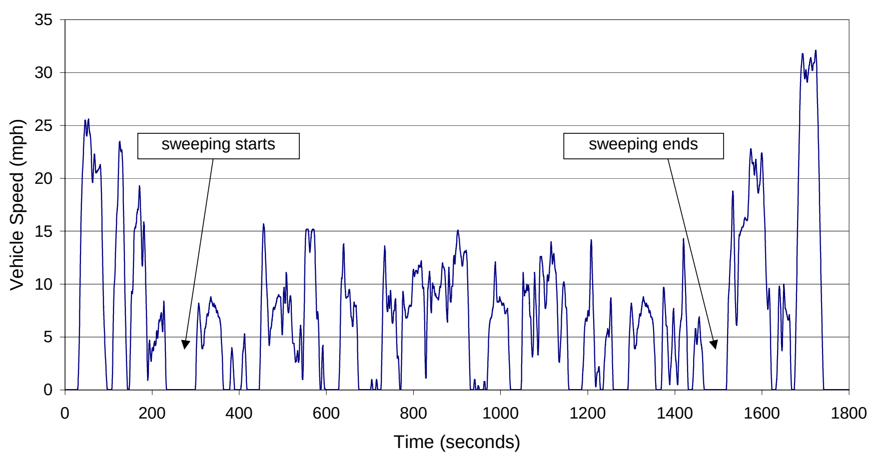

Figure 23: NY Sweeper Cycle

8.3.2 Physical Configuration

The sweepers also presented issues with respect to physically mounting them onto the chassis dynamometer. The JSC 4000 series, like most commercial sweepers, is equipped with a single-rear-wheel type rear axle. Typical heavy-duty vehicles, for which the dynamometer was designed, feature a dual-rear-wheel configuration, which allows for the removal and replacement of the outer wheels with special hub adapters designed for connection to the dynamometer. For vehicles without dual rear wheels, removal of the wheel was not an option. Therefore, special “add-on” hub adapters were fabricated specifically for the sweeper, as seen in Figure 24.

8.3.3 Operation on Rear-Wheel Dynamometer

Figure 24: Custom-Made Hub Adapter

Effectively testing the sweepers on the WVU dynamometer involved special attention to the operating parameters of the vehicle's hydrostatic drive system. The 4000-series sweepers are equipped with a solenoid-controlled hydraulic motor, which allows for the vehicle to be "locked" in low gear, or to switch between low and high gear in a manner similar to a traditional automatic transmission. The settings are based on the drive mode selected by the operator, "sweep" or "travel". In "sweep" mode, the vehicle is restricted to low gear, while "travel" mode allows for the vehicle to automatically shift into high gear when the vehicle speed reaches 14 mph. As mentioned above, the vehicle speed sensor is located at the right front wheel of the vehicle. During dynamometer testing the front wheels do not rotate, the vehicle was not receiving any speed data, and thus was not able to "shift" at the required points in the drive cycle.

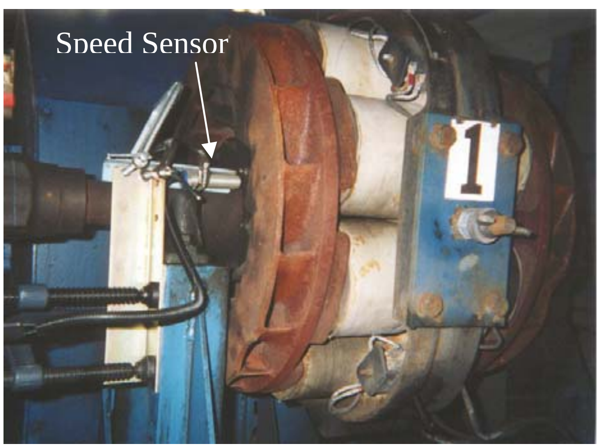

Figure 25: Additional Speed Sensor Installed on Power Absorber

Further complicating the problem, the 4000CNG speed control system is configured differently than for the diesel-powered model. For the CNG sweepers, the problem was solved by installing an extra speed sensor on one of the dynamometer's power absorbers (Figure 25) and connecting its output wires to the appropriate circuit on the sweeper's ECM panel (Figure 26). This approach was effective in allowing the vehicle to switch gears at its natural shift points, and to accelerate to the required top speeds of the test cycle. Unfortunately, following the exact same procedure did not produce the same effect when applied to the diesel-powered vehicles. For these sweepers it was necessary to manually enable and disable the solenoid. The nature of the test cycle allowed this manual switching to be accomplished while ensuring repeatability and accurate following of the cycle's speed trace. This was due to the fact that the cycle was designed with distinct pauses between the two "travel" modes, at the beginning and end, and the "sweep" mode in the middle of the cycle. The cycle was designed

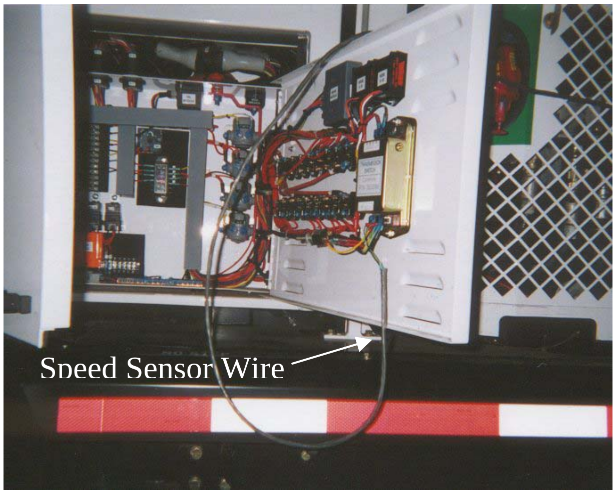

Figure 26: Speed Sensor Connection at ECM

specifically to allow for the driver to switch modes using the dashboard control panel. Because the vehicle must idle for a period of 10 to 15 seconds during each of the "switch" events, and the switch has no effect on the engine's behavior at idle, there was a sufficient cushion of time to allow for variability in operator's response without affecting the results of the test.

8.3.4 Emission sampling (CNG)

In addition to the procedural changes necessary to physically prepare the street sweepers for testing, the CNG-fueled vehicles required changes to the dynamometer laboratory gas sampling systems. While CNG engines are generally as clean or cleaner than diesels for many pollutants, they tend to emit much higher levels of HC, specifically methane (unburned fuel). The HC analyzers, therefore, had to be recalibrated with a higher-concentration span gas (~1000-ppm propane) than was used for the diesel emission testing (300-ppm).

8.3.5 Test Conditions

One of the first steps in setting up a vehicle on the dynamometer is determining the appropriate simulated test weight. Simulated weight allows for test conditions to more closely reflect real-world operation. Vehicles are normally installed on a dynamometer empty, i.e., there is no material in the sweeper hopper. However, it is prudent to add weight to the vehicle to have test conditions that are more representative of typical in-use sweeper operation. In order to accurately add the same amount of weight to each sweeper to provide consistency between tests, the weight is added via a set of selectable flywheels, consisting of a series of discs that allow simulation of an inertial load equivalent to the gross vehicle weight.

The simulated test weight (i.e., gross vehicle weight) is determined by the following equation:

$$GVW = CurbWeight + (GVW_{Tire} - CurbWeight)x0.7 \qquad \text{Equation 8.1}$$

Where: CurbWeight = the combined curb weight from front and rear as indicated on the vehicle plate;

GVW_{Tire} = the gross vehicle weight as determined by the physical limits of the tires; and

0.7 is a 70% load/capacity factor.

After the appropriate test weight is determined, the flywheels on the dynamometer are set to equal the calculated weight as closely as possible. The diesel and CNG street sweepers were tested with simulated weights of 25,320 and 26,886 pounds, respectively. The CNG sweeper had a higher test weight because it had a higher curb weight.

8.3.6 Street Sweeper Emission-Testing Results

To evaluate the emissions benefit of the CNG sweepers, a comparison of the emissions associated with CNG and diesel sweepers was conducted. Table 11 provides a summary of how each type of sweeper was configured. The US EPA and the California Air Resources Board certify the 5.9B-230G engines to ULEV standards under EPA Certificate of Conformity 493E and CARB Executive Order 493E, respectively.

Table 11: Sweeper Engine/After Treatment Summary

	Johnston Sweeper Model	
	4000-CNG	4000
Engine	5.9B-230G	ISB-190
Fuel	CNG	Diesel
Horsepower	230 @ 2800 rpm	190 @ 2600 rpm
Torque (ft-lb)	500 @ 1600 rpm	520 @ 1400 rpm
After Treatment	Oxidation Catalyst	Oxidation Catalyst

The sweepers were tested on the duty cycle developed under this program over a period of five days. Table 12 provides a summary of the sweepers tested. Depending upon the test parameter, distinct differences were seen as the fuels were varied.

Table 12: Sweeper Test Information Summary

	CNG	Diesel
Sweeper Model Year	2001	2001
Gross Vehicle Weight (lb) *	27,000	27,000
Test Weight (lb)	26,886	25,320
Engine Type	5.9B-230G	ISB-190
Fuel	CNG	ULSD & No. 2 Diesel

* – GVW corresponds to that taken from the vehicle plate, not as calculated based on the tire capacity.

At the beginning of this project, DSNY was using Federal No. 2 diesel fuel throughout their depots, and gradually phased in ULSD with all depots operating on ULSD as of July 2004. As a result of the changing fuel profile, the diesel sweepers were tested on both No. 2 diesel and ULSD. Significant PM reductions of 28.6 and 88.1 percent were achieved when switching fuels to ULSD and CNG, respectively. The CNG street sweepers exhibited an overall reduction in energy efficiency (on an equivalent gallon basis) compared to a diesel sweeper. Table 13 provides a summary of the sweeper test results.

Table 13: Street Sweeper Test Results *

	PM		NOx		CO		CO_2		Fuel Economy	
Fuel	**(g/mi)**	**% Reduction**	**(g/mi)**	**% Reduction**	**(g/mi)**	**% Reduction**	**(g/mi)**	**% Reduction**	**(mpg)**	**% Change**
No.2 Diesel	0.42	---	33.5	---	17.7	---	4924	---	2.05	---
ULSD	0.30	28.6 %	32.7	2.4 %	20.1	- 11.9 %	4747	3.6 %	2.12	3.4 %
CNG	0.05	88.1 %	23.4	30.1 %	0.56	96.8 %	4079	17.2 %	1.68	- 18.0 %

* – Results represent a CNG vehicle equipped with a DOC, while the diesel sweepers were not equipped with after treatment.

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9.0 Refuse Collection Truck Emission Testing Protocol

9.1 Transportable Heavy Duty Vehicle Chassis Dynamometer Testing

The WVU Transportable Heavy Duty Vehicle Emissions Testing Laboratory measures emissions from heavy-duty diesel and alternatively fueled vehicles across North America. The main objective of the research performed is to contribute information to a database that can be used to ascertain emissions performance and fuel efficiency of heavy-duty vehicles. In addition, the laboratories have performed extensive work to support the development of heavy duty driving cycles and to assess emissions from new engine and fuel technologies. West Virginia University (WVU) designed, constructed and now operates two Transportable Heavy Duty Vehicle Emissions Testing Laboratories. These laboratories travel to transit agencies and trucking facilities, where they are set up to measure emissions generated by both diesel and alternatively fueled vehicles.

The transportable laboratory consists of a dynamometer test bed, instrumentation trailer and support trailer. The test bed is transported to the test site by a tractor truck where it is lowered to the ground. On vehicles with a dual drive-wheel setup, the vehicle is prepared by removing the outer rear drive wheels and replacing them with special hub adapters. If the vehicle has a single rear wheel setup, the drive wheels are removed and replaced with different rims and tires that are equipped with an adapter to allow for connection to the dynamometer. The subject vehicle is then driven onto the test bed where it is supported with jacks and secured with chains. The hub adapters are then attached to provide a connection between the drive axle of the vehicle and the inertial flywheels and power absorbers of the dynamometer. Speed-increasing gearboxes transmit drive axle power to flywheel sets. The flywheel sets consist of a series of selectable discs used to simulate vehicle inertia. During the test cycle, torque cells and speed transducers at the vehicle hubs monitor axle torque and speed.

The instrumentation trailer holds both the emissions measurement system for the laboratory and the data acquisition and control hardware necessary for the operation of the test bed. Exhaust from the vehicle is routed into a 45-cm dilution tunnel at the instrumentation trailer. The tunnel mixes the exhaust with ambient air, which both cools and dilutes the exhaust. Dilution tunnel flow is controlled using a critical flow venturi system (CVS). A two-stage blower system maintains critical flow through the venturi throat restrictions to maintain a known and nearly constant mass flow of dilute exhaust during testing. The flow can be varied from 500 to 3,000 scfm by adjusting the CVS.

Dilute exhaust samples are drawn, using heated sampling probes and sample lines, from a sample plane located 15 feet from the mouth of the dilution tunnel. Levels of CO_2, CO, NOx and HC are measured continuously then integrated over the complete test time. A sample of the ambient (dilution) air is continuously collected throughout the test in a Tedlar bag and analyzed at the end of each test to establish background. These background measurements are then subtracted from the continuous measurements. Details of the analyzers used by the transportable lab are given in Table 14.

Table 14: Summary of Analyzers Used for Emissions Measurement

Emission Parameter	Measurement Method	Equipment Specification
Hydrocarbons	Flame Ionization Detector	Rosemount Analytical Model 402
Carbon Monoxide	Non-Dispersive Infrared	Rosemount Analytical Model 880A
Carbon Dioxide	Non-Dispersive Infrared	Rosemount Analytical Model 880A
Nitrogen Oxides	Chemiluminescent	Rosemount Analytical Model 955
Non-methane HC	Gas Chromatograph	Varian 3600
Particulate Matter	Gravimetric	70-mm Fiberglass Filter

In addition to continuous, integrated and background samples, additional exhaust samples are drawn from the dilution tunnel and collected in 3 liter Tedlar bags for test runs on vehicles powered by CNG. Background samples are also collected in Tedlar bags to correlate with CNG vehicle testing. These samples are then sent to the WVU speciation laboratory to determine non-methane hydrocarbon (NMHC), methane and formaldehyde concentrations using gas chromatography (GC) analysis. These concentrations will then be converted to a gram per mile (g/mi) basis consistent with other pollutant emission rates.

A gravimetric measurement of particulate matter (PM) is obtained using 70-mm fiberglass filters. The filters are conditioned for temperature and humidity in an environmental chamber before each weighing to reduce error due to variation in water content per CFR 40, Part 86, Subpart N. Similar to collection of background samples for gaseous emissions, a background particulate sample is taken either before or after the test. To collect the background, ambient air is drawn through the sampling line through a separate conditioned filter. One problem that can occur with this method is ambient contamination by an intermittent source. For example, during a ten-minute test if a street sweeper passes by during the middle, the engine inlet air and dilution air could have heavy particulate loading. If the sweeper is not operating when the background sample is taken, the vehicle particulate emission rate can be overstated. Similarly, if a sweeper passes by during background sampling, but not during testing, background particulate levels can be higher than that from the vehicle exhaust. To eliminate these possibilities, the dilution tunnel inlet air is filtered to prevent ambient particulate from entering the sampling train.

Additional information about specific test procedures, including dynamometer and vehicle set up and information on measurement methods are provided in Appendix G.

9.2 Test Cycles

Chassis tests are differentiated into cycles and routes; cycles are defined as a speed-time relationship whereas a route is defined as a distance -time relationship. The difference lies in that for the cycles, not all vehicles (ones with unsynchronized manual transmissions) can match the required speed-time relationship. Each of the refuse collection trucks were tested on one of two test cycles, either the New York Garbage Truck Cycle or Orange County Refuse Collection Truck Cycle. It was expected, however, that running a single test cycle on each of the sanitation trucks that were equipped with DPFs would result in particulate levels below the detection limits of the test equipment. To guard against this, triple or double cycles were run, consistent with the procedure developed under SAE J2711. For consistency of comparisons, triple or double cycles were also run on trucks that were not equipped with DPFs.

Prior to performing a test sequence (which is made up of at least 3 repeatable tests), the vehicle was operated on the dynamometer through a complete test cycle to bring the vehicle's engine and transmission as well as associated dynamometer equipment up to operating temperature in addition to allowing the operator to become familiar with the drive cycle. This procedure helps to ensure that losses associated with vehicle and dynamometer drivetrain components were consistent from test to test. At the completion of this pre-conditioning test, the engine idles for 30 seconds, and was then shut down and allowed to soak for a period of 20 minutes. The engine was then started one minute prior to the beginning of the test.

Test to test variation was monitored to assure quality of the research conclusions. Testing was considered to be complete when a minimum of three complete tests were performed and the test to test variation shows acceptable repeatability. This typically occurred when all readings were within five percent.

9.2.1 New York Garbage Truck Cycle

The New York Garbage Truck Cycle (NYGTC) was developed by WVU several years prior to this project to specifically test sanitation collection trucks that operate in New York City. The cycle features a series of accelerations to speed, a very short cruise at speed and then deceleration to idle. The cycle is characterized by a significant portion of idle time. Figure 27 illustrates a triple New York Garbage Truck Cycle.

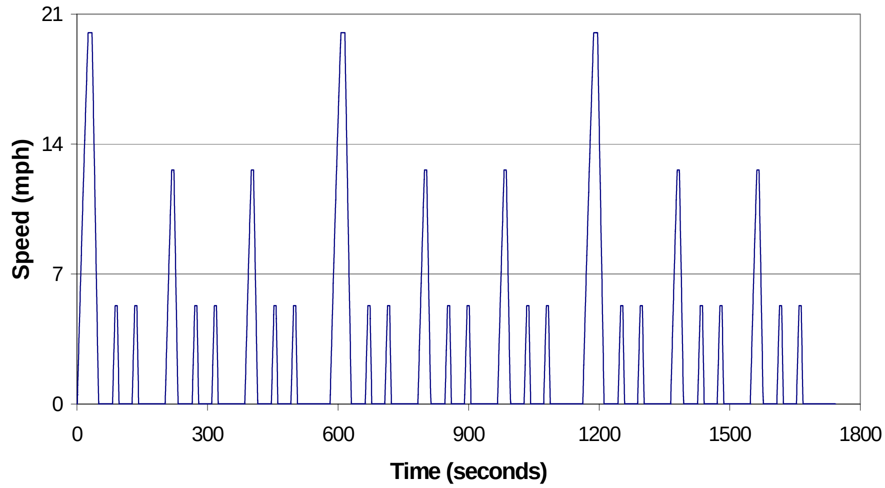

Figure 27: Triple New York Garbage Truck Cycle

9.2.2 Orange County Garbage Truck Cycle

The Orange County Refuse Truck Cycle (OCRTC) was developed by WVU to specifically test sanitation collection trucks that operate in Orange County California. The cycle is similar to the NYGTC, however, is characterized by less idle time. Running a single OCRTC on a truck with a DPF could lead to the same potential PM accuracy issues that may occur when running a single NYGTC. Therefore, the vehicles were operated on double OCRTCs during the testing, as illustrated in Figure 28.

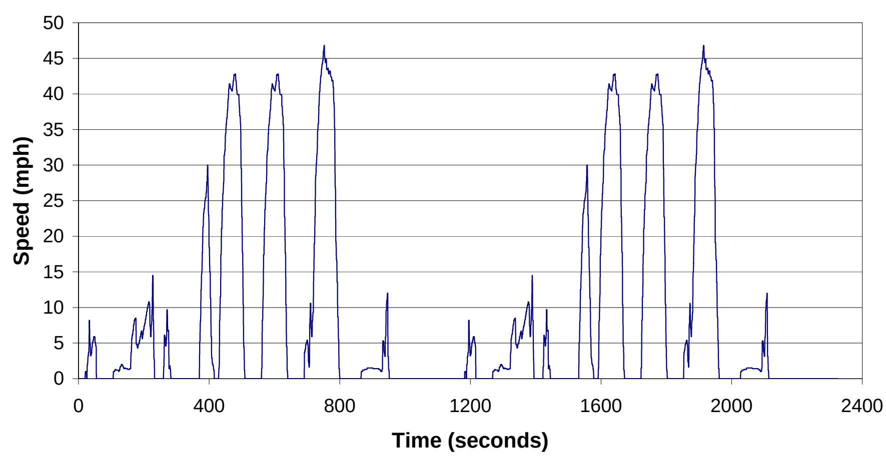

Figure 28: Double Orange County Refuse Truck Cycle

10.0 Emission Testing Results

The DPF performance testing occurred after several months of in-service operation. At the time of publication, the durability testing was ongoing at the Environment Canada laboratory facilities. The initial performance testing occurred using the WVU transportable vehicle dynamometer, as described in section 9. Durability testing consisted of removing the DPF from the vehicle and exercising the DPF through a test on an engine dynamometer using the test procedures outlined in the US EPA Heavy-Duty Transient Test Cycle for On-Road Engines protocols.

The initial performance testing occurred during January 2002 on the first four of the refuse collection trucks in the pilot study. To evaluate the performance of the DPFs, the same truck was tested with the DPF and again with the original muffler. This established a direct comparison of results of the same truck, allowing a simple evaluation of the effectiveness of the DPF. Table 15 provides a summary of the trucks tested, after treatment, and test cycles that they were exercised through.

Table 15: Truck/Test Cycle Summary

Truck ID	After Treatment	Test Cycles
25CF-042	CRT®	NYGTC
25CF-043	CRT®	OCRTC
25CF-044	DPX™	OCRTC
25CF-045	DPX™	NYGTC

Although the primary focus of this project was the reduction of PM, the emission testing allowed for comparisons between other pollutants as well as fuel economy. Overall, testing was performed to determine PM, NOx, HC, CO, and CO_2 emissions as well as fuel economy. Emission testing results for each of these parameters is presented below.

10.1 Particulate Matter Emissions

10.1.1 Overview

Combusting fuel in an external combustion unit such as a boiler results in relatively long combustion residence times and relatively complete combustion. In an internal combustion engine, fuel has a limited duration in which to burn and is also combusted in a relatively small space resulting in high peak flame temperatures. As a result, some level of incomplete combustion occurs with internal combustion engines, although typically less than one percent. Incomplete combustion products such as CO and volatile organic compounds (VOC) are typically controlled in an oxidation catalyst, which oxidizes these compounds to CO_2 and water.

Particulate Matter (PM) from internal combustion engines is caused by incomplete combustion, and has two main components, carbon particles and sulfates. In addition, the

PM contains some metals from the fuel, lubricating oil, and byproducts of engine wear. The carbon particles are generally less than 2.5 microns in diameter (greater than 90 percent, by mass, are typically less than 1 micron), on the surface of which organic hydrocarbon compounds are adsorbed.

Testing for particulate emissions in diesel exhaust has presented a problem for researchers for some time. Smoke opacity and integrated dilute particulate filtration are two methods that have been used in the past. Smoke opacity works well for an engine that produces substantial amounts of visible smoke. For example, smoke opacity measurements would be applicable to an older diesel-powered truck that exhibits puff or full load visible smoke. However, it is unlikely that conventional opacity meters can detect the ultra fine particulate matter exhausted by modern diesel and CNG engines.

Integrated dilute particulate filtration (used by WVU) is achieved by passing a diluted amount of exhaust gas across a filter and then measuring the change in filter mass after the test is completed. Filters are conditioned with respect to temperature and humidity before both pre- and post-test weighing in accordance with standardized EPA test protocols.

10.1.2 PM Results

Significant PM emission reductions were documented during the initial performance testing as a result of implementing ULSD in conjunction with a DPF. Both the Engelhard DPX™ and Johnson Matthey CRT® are verified under EPA and CARB programs to provide a minimum of 60 percent reduction in PM, and provided much greater reductions over the two test cycles. The Engelhard DPX™ realized from nearly 85 percent up to almost 98 percent PM reductions depending upon the test cycle run. The Johnson Matthey CRT® realized reductions of 82 percent and approximately 87 percent depending upon the test cycle. Although the different DPF technologies showed a range of emission reductions, on average, implementing DPFs provided an 88 percent reduction in PM versus using ULSD alone. Table 16 and Figure 29 provide a summary of the test results by DPF technology and test cycle.

Table 16: PM Emission Test Results

Test Cycle	Fuel	After Treatment	Engelhard DPX™		Johnson Matthey CRT®	
			(g/mi)	% Reduction	(g/mi)	% Reduction
NYGTC	ULSD	None	3.04	---	3.56	---
NYGTC	ULSD	DPF	0.076	97.5 %	0.64	82.0 %
OCRTC	ULSD	None	0.73	---	0.95	---
OCRTC	ULSD	DPF	0.11	84.9 %	0.12	87.4 %
Average			***88 % Reduction***			

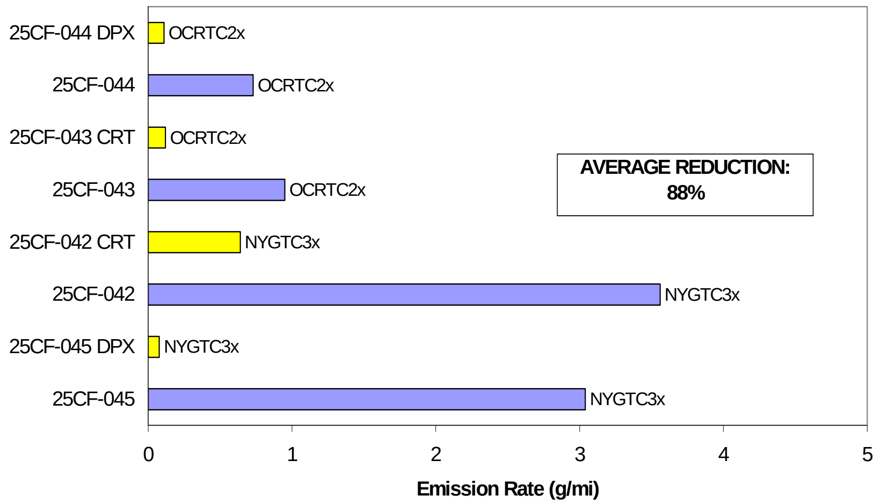

Figure 29: PM Emission Test Results

The emission test results show an obvious improvement in PM emissions with the deployment of DPFs. There are visual cues to the PM reductions when looking at both the truck exhaust and the DPF sections. Figure 30 shows the exhaust outlet pipe from one of the trucks after it had been in service for over four months. In addition, during testing, one of the DPFs was disassembled for inspection. Figure 31 shows the disassembled DPF, with the inlet face on the left and the outlet face on the right. The inlet face is covered with diesel soot, as expected, and the outlet face is not, indicating that the DPF is removing a significant amount of the PM from the exhaust.

Figure 30: Exhaust Outlet Pipe

Figure 31: DPF Inlet and Outlet Faces

Caution must be exercised in drawing any conclusions when comparing the DPX™ and CRT® because emission testing on each cycle was performed on only one truck for each DPF. The primary limitation of this is statistical robustness. Given this qualification, what the data does show is that both technologies achieved similar emission reductions in excess of their verified levels.

10.2 Carbon Monoxide Emissions

10.2.1 Overview

Carbon monoxide (CO) is a colorless and odorless, poisonous gas that is a byproduct of burning carbon-based fuels. It is generally a local emission issue with the impact typically occurring in low-lying areas such as urban canyons. CO affects the ability of blood to carry oxygen and results in impaired cardiovascular, pulmonary and nervous systems. Excess CO emissions are usually associated with cold engine startup and once the engine has warmed to operating temperature the oxidation catalyst is usually sufficient to complete at least partial combustion of excess CO into CO_2. Until 2002, the Northern New Jersey-New York-Long Island area was classified as non-attainment for CO. Both NYS DEC and NJ DEP submitted request to EPA to have their respective portions of the non-attainment area reclassified as in attainment. These requests were approved and the states must continue to maintain compliance.

10.2.2 CO Results

Significant CO emission reductions were demonstrated after installing the DPFs. Both manufacturers have received EPA verification for a minimum of 60 percent CO reductions, and on average greater than 83 percent were observed during testing.
Table 17 and Figure 32 provide a summary of the test results by DPF technology and test cycle.

Table 17: CO Emission Test Results

Test Cycle	Fuel	After Treatment	Engelhard DPX™		Johnson Matthey CRT®	
			(g/mi)	% Reduction	(g/mi)	% Reduction
NYGTC	ULSD	None	12.2	---	11.7	---
NYGTC	ULSD	DPF	2.34	80.8 %	1.34	88.5 %
OCRTC	ULSD	None	4.91	---	5.25	---
OCRTC	ULSD	DPF	0.79	83.9 %	1.09	79.2 %
Average			***83.1 % Reduction***			

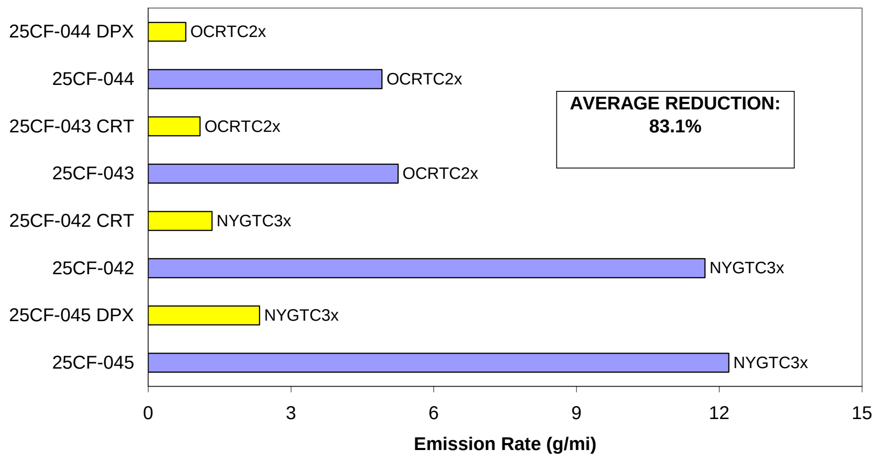

Figure 32: CO Emission Test Results

10.2.3 CO Time Series Data

The oxidation catalyst portion of the DPF is able to complete the oxidation of CO into CO_2. Figure 33 provides second-by-second data for one of the tests and shows that the DPF provides outstanding CO reduction over normal engine operation, and practically eliminates CO emissions during times of light engine load.

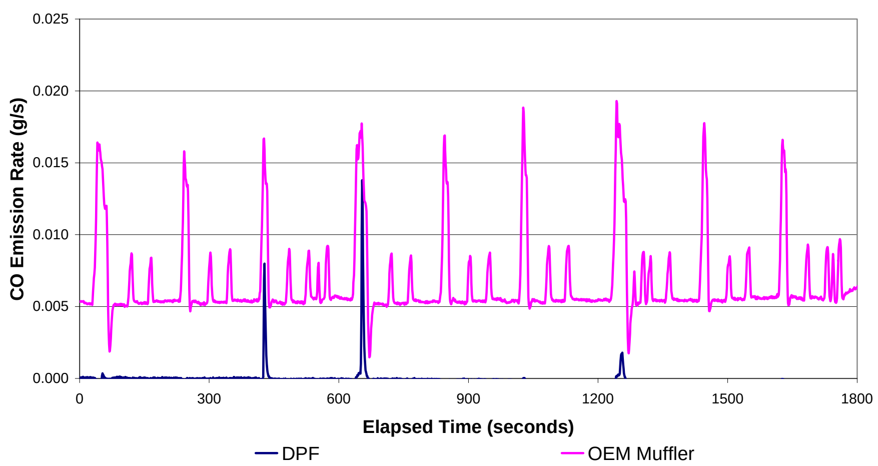

Figure 33: Real-Time CO Emissions: NYGTC Example

10.3 Hydrocarbon Emissions

10.3.1 Overview

Diesel fuel consists primarily of hydrocarbon compounds, or organic compounds made up of solely carbon and hydrogen. When diesel fuel is burned, the organic portion of the exhaust is primarily hydrocarbon (HC), and generally, the entire organic portion of diesel exhaust is referred to as HC. In some cases, HC is also referred to as VOC, although the definitions of VOC and HC only partially overlap. VOCs fit into the larger picture of non-attainment as a precursor for ozone, for which a NAAQS has been established. The entire Northeast United States is in the ozone transport region and the New York City area is in non-attainment for ozone.

10.3.2 HC Results

The installation of a DPF realized significant overall reductions in HC emissions. Similar to CO, both manufacturers' DPFs are verified for a minimum of 60 percent HC reductions, and on average nearly 85 percent were observed during testing. Table 18 and Figure 34 provide a summary of the test results by DPF technology and test cycle.

Table 18: HC Emission Test Results

Test Cycle	Fuel	After Treatment	Engelhard DPX™		Johnson Matthey CRT®	
			(g/mi)	% Reduction	(g/mi)	% Reduction
NYGTC	ULSD	None	7.61	---	8.29	---
NYGTC	ULSD	DPF	1.4	81.6 %	1.23	85.2 %
OCRTC	ULSD	None	3.12	---	3.29	---
OCRTC	ULSD	DPF	No Data	N/A	0.43	86.9 %
Average			***84.6 % Reduction***			

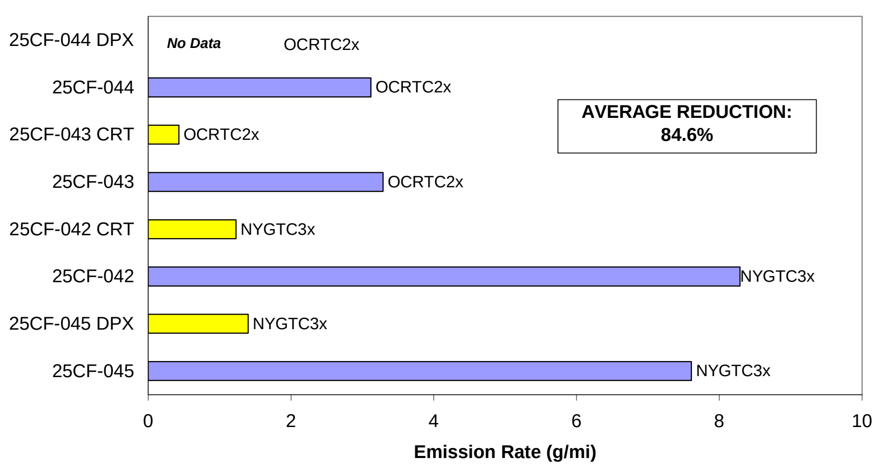

Figure 34: HC Emission Test Results

10.3.3 HC Time Series Data

In addition to oxidizing CO, the oxidation catalyst portion of the DPF is able to complete the oxidation of HC into CO_2. Figure 35 provides second-by-second data for one of the tests and shows that the DPF provides outstanding HC reduction over normal engine operation. The gradual rise in HC emissions may indicate catalyst cooling over time due to significant idle/low speed operation and the temporary spikes at high engine load may in part be attributable to reduced exhaust residence time in the catalyst.

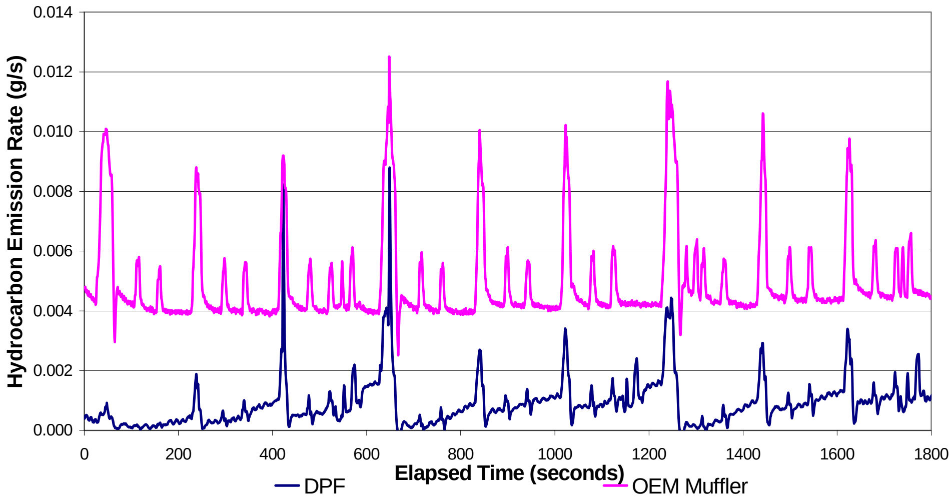

Figure 35: Real-Time HC Emissions: NYGTC Example

10.4 Nitrogen Oxides Emissions

10.4.1 Overview

Within the engine, the two factors that affect the amount of nitrogen oxides (NOx) produced are peak combustion temperature and the duration of combustion at that temperature. Higher combustion temperatures result in higher NOx emissions. The two most prevalent NOx in vehicle exhaust, are nitric oxide (NO) and nitrogen dioxide (NO_2), both of which are formed at the high temperatures that occur during combustion. In addition to VOC, NOx is a precursor to ozone formation. Ozone at ground level, as well as NO and NO_2, are respiratory irritants that have been shown to exacerbate asthma symptoms and to cause lung tissue damage.

10.4.2 NOx Results

NOx emissions from the DPF-equipped vehicles were approximately 4 - 5 percent lower, on average, compared to the trucks with standard (muffler only) exhaust configurations on a low average speed cycle, with negligible to very slight increases on the higher average speed cycle. While this is a modest reduction, it is worth noting that it did not come at the expense of increased CO or HC emissions. The reduction in NOx may be considered a "bonus" benefit, since the DPFs were not designed specifically to address NOx emissions. Table 19 and Figure 36 provide a summary of the test results by DPF technology and test cycle.

Table 19: NOx Emission Test Results

Test Cycle	Fuel	After Treatment	Engelhard DPX™		Johnson Matthey CRT®	
			(g/mi)	% Reduction	(g/mi)	% Reduction
NYGTC	ULSD	None	120.2	---	128.1	---
NYGTC	ULSD	DPF	115.0	4.3 %	123.9	3.3 %
OCRTC	ULSD	None	43.5	---	47.2	---
OCRTC	ULSD	DPF	43.8	- 0.7 %	46.9	0.6 %
Average			***1.85 % Reduction***			

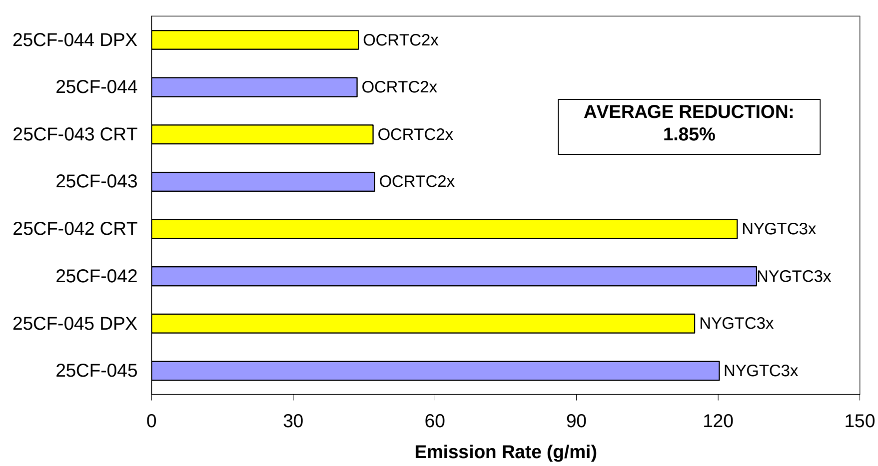

Figure 36: NOx Emission Test Results

10.4.3 NOx Time Series

Although unintended, the DPF does appear to provide slight benefit in reducing NOx. As discussed earlier, the reductions are greater during the NYGTC, where lower average speeds are experienced. Figure 37 provides second-by-second data for one of the tests and shows that the NOx reductions occur mostly at idle.

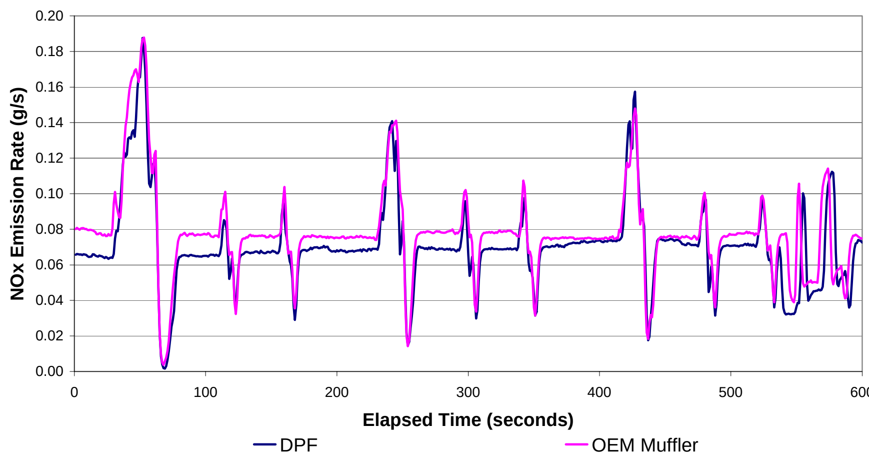

Figure 37: Real-Time NOx Emissions: NYGTC Example

10.5 Fuel Economy

Fuel economy is an important metric to track during retrofit projects because it often constitutes a significant portion of annual operating costs. By deploying DPFs, DSNY committed to also using ULSD in at least a portion of their fleet during the early stages of the project. Test data taken at various intervals throughout the project indicate that ULSD on average contains approximately four percent less energy than on-road diesel fuel, which is expected to correlate with fuel economy. However, because both testing configurations (with and without DPF) were run on ULSD, the testing only indicates a minimal (~0.15 percent) increase in fuel consumption, on average, over the different test cycles, attributed to slightly increased backpressure, attributable to the DPF. Table 20 and Figure 38 provide a summary of the test results by DPF technology and test cycle. As expected, the use of DPF technology in and of itself does not impact fuel economy. However, it is important to keep in mind that all the DPF options verified by both EPA and CARB require the use of ULSD, therefore, it is expected that there will be some impact based on deploying DPFs. In terms of fuel usage, it would correlate to the energy content and be expected to be about a four percent increase in consumption. Coupled with the price premium of ULSD of approximately $0.15 per gallon, this would increase fuel expenditures approximately $1,100 per year per vehicle based on annual mileage of 10,000 miles and average fuel economy of 1.35 mpg.

Table 20: Fuel Economy Test Results

Test Cycle	Fuel	After Treatment	Engelhard DPX™		Johnson Matthey CRT®	
			(mpg)	% Increase	(mpg)	% Increase
NYGTC	ULSD	None	1.35	---	1.30	---
NYGTC	ULSD	DPF	1.34	0.74 %	1.34	- 3.0 %
OCRTC	ULSD	None	2.75	---	2.38	---
OCRTC	ULSD	DPF	2.69	2.18 %	2.38	0 %
Average			***0.15 % Penalty***			

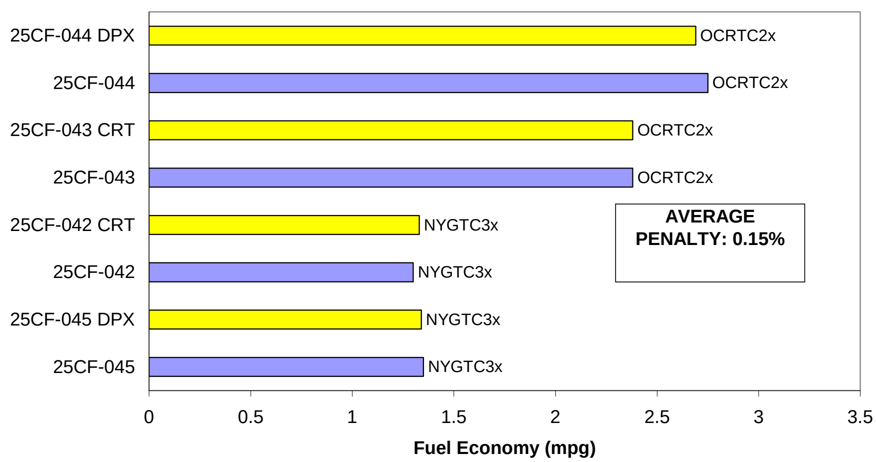

Figure 38: Fuel Economy Test Results

10.6 Carbon Dioxide Emissions

10.6.1 Overview

Over the last decade, increased attention has been given to the impact that industrial and mobile sources have on climate, commonly referred to as global warming. Pollutants that contribute to global warming are referred to as greenhouse gases, of which carbon dioxide (CO_2) is the most prevalent in the United States. CO_2 is generated during the burning of fossil fuels such as diesel. As the first in the nation, California enacted a law in 2002, requiring CARB to adopt regulations that achieve the maximum feasible and cost-effective reduction of motor vehicle emissions of greenhouse gases. The 2002 law also requires CARB to adopt the regulations by 2005.

10.6.2 CO_2 Results

CO_2 emissions from the DPF-equipped vehicles exhibited trends similar to those for fuel economy, ranging from a penalty of less than 3 percent to a benefit of just over 2 percent. Fuel economy and CO_2 emissions are linked in that they both are a measure of efficiency, so these trends were expected to be similar. There was not a noticeable increase in CO_2 due to conversion of carbon, HC and CO because the mass of these when converted to CO_2 is very small compared to the baseline CO_2 emissions from the engine. Table 21 and Figure 39 provide a summary of the test results by DPF technology and test cycle.

Table 21: CO_2 Emission Test Results

Test Cycle	Fuel	After Treatment	Engelhard DPX™		Johnson Matthey CRT®	
			(g/mi)	% Reduction	(g/mi)	% Reduction
NYGTC	ULSD	None	7,482	---	7,802	---
NYGTC	ULSD	DPF	7,573	- 1.2 %	7,620	2.3 %
OCRTC	ULSD	None	3,687	---	4,251	---
OCRTC	ULSD	DPF	3,785	- 2.7 %	4,278	- 0.6 %
Average			*- 0.6 % Reduction*			

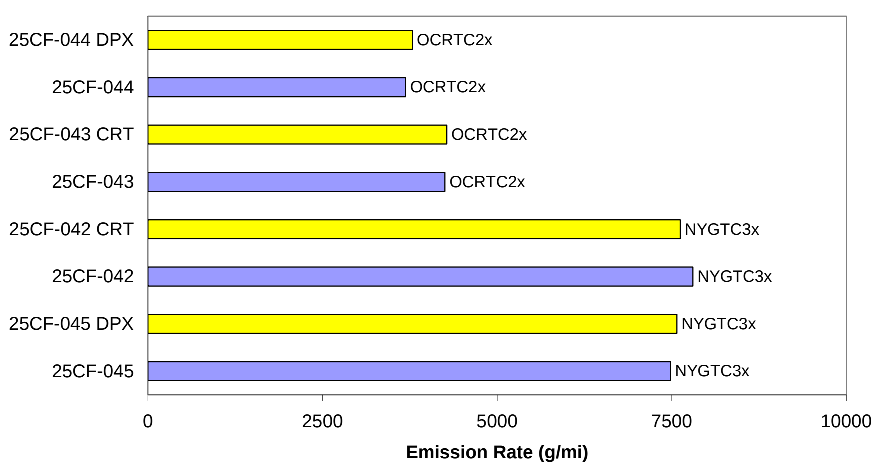

Figure 39: CO_2 Emission Test Results

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11.0 Public Outreach

At two intervals during this project, the project partners participated in public events that would allow the general public and interested fleets the opportunity to get a close-up look at the vehicles and technologies. The first of these public events occurred in August 2001, at a Clean Air Communities press event. The event occurred at Hunt's Point in New York City and showcased a diesel truck electrification initiative as well as various other environmentally beneficial projects that are ongoing in the New York City area. As part of this event DSNY introduced its new CNG sweeper to the public.

The second event occurred in May 2002 at the "Heavy-Duty Clean Vehicle Technology Conference". The conference provided a forum to highlight heavy-duty vehicle technology options that are commercially available and already providing New York City and surrounding areas with emission reductions. The event brought together key players from various projects in New York City, where stakeholders and the media had the opportunity to see the latest in clean air vehicle technology and interact with fleet owners and operators who utilize these technologies daily. Among the participants was then U.S. EPA Administrator, Governor Christie Whitman, who provided the keynote address. Panel sessions addressed operator experiences and infrastructure needs for CNG, hybrid-electric, and diesel retrofit after treatment equipped vehicles. The event also included an outdoor vehicle display with CNG, diesel particulate filter and hybrid electric transit buses, refuse collection trucks, street sweepers, and delivery trucks.

Figure 40: DPF-Retrofit Collection Truck

Figure 41: School Bus Retrofit with Emission Control Technology

Figure 42: CNG-Powered Collection Truck

Appendix A – EPA and CARB Verified Technology List

EPA Verified Technology List As Of October 12, 2005

Manufacturer	Technology	Reductions (%)			
		PM	CO	NOx	HC
Caterpillar, Inc.	Catalyzed Converter/Muffler (CCM)	20	20	n/a	40
Clean Diesel Technologies, Inc.	Platinum Plus Purifier System (fuel borne catalyst plus DOC)	25 to 50	16 to 50	0 to 5	40 to 50
Clean Diesel Technologies, Inc.	Platinum Plus Fuel Borne Catalyst/Catalyzed Wire Mesh Filter (FBC/CWMF) System	55 to 76 [a]	50 to 66 [a]	0 to 9 [a]	75 to 89 [a]
Donaldson	Series 6000 DOC & Spiracle (closed crankcase filtration system)	25 to 33 [b]	13 to 23	n/a	50 to 52
Donaldson	Series 6100 DOC	20 to 26	38 to 41	n/a	49 to 66
Donaldson	Series 6100 DOC & Spiracle (closed crankcase filtration system)	28 to 32 [b]	31 to 34	n/a	42
Engelhard	DPX Catalyzed Diesel Particulate Filter	60	60	n/a	60
Engelhard	CMX Catalyst Muffler	20	40	n/a	50
International Truck & Engine Corporation	Green Diesel Technology-Low NOx Calibration plus Diesel Oxidation Catalyst with Ultra Low Sulfur Diesel Fuel	0 to 10	10 to 20	25	50
Johnson Matthey	Catalyzed Continuously Regenerating Technology (CCRT) Particulate Filter	60	60	n/a	60
Johnson Matthey	Continuously Regenerating Technology (CRT) Particulate Filter	60	60	n/a	60
Johnson Matthey	CEM™ Catalytic Exhaust Muffler and/or DCC™ Catalytic Converter	20	40	n/a	50
Johnson Matthey	CEM Catalyst Muffler	20	40	n/a	50

Manufacturer	Technology	Reductions (%)			
		PM	CO	NOx	HC
Lubrizol	PuriNOx Water emulsion fuel	16 to 58	-35 to 33	9 to 20	-30 to -120
Lubrizol Engine Control Systems	Purifilter - Diesel Particulate Filter	90	75	n/a	85
Lubrizol Engine Control Systems	AZ Purimuffler or AZ Purifier Diesel Oxidation Catalyst with Low Sulfur Diesel Fuel (30 ppm S max)	35 to 40	40	n/a	70
Lubrizol Engine Control Systems	AZ Purimuffler AZ Purifier	20	40	n/a	50
Various	Biodiesel (1 to 100%)	0 to 47	0 to 47	0 to -10	0 to 67
Various	Cetane Enhancers	n/a	n/a	0 to 5	n/a

a – These effectiveness figures are provisional values subject to change pending final review of the test data.

b – Total PM reduction figures reflect reductions from both tailpipe and crankcase emissions.

Note: For after treatment devices the reductions are based on the installation of retrofits to engines that were originally produced without diesel oxidation catalysts or diesel particulate filters.

CARB Verified Technology List As of July 20, 2005

Manufacturer	**Technology**
Level 3 – 85% or Greater PM Reduction	
Engelhard	DPX™ Diesel Particulate Filter (DPF) sold prior to January 1, 2004
Donaldson	DPM Diesel Particulate Filter with Series 6300 Catalyst
International Truck & Engine Corporation	DPX™ Catalyzed Soot Filter System
Johnson Matthey	CCRT™ Particulate Filter
Johnson Matthey	CRT™ Particulate Filter
Lubrizol	Unikat Combifilter
Lubrizol	Purifilter™
Level 3 – 85% or Greater PM Reduction with 25% NOx Reduction	
Cleaire	Flash and Catch™
Cleaire	Longview™
Johnson Matthey	Exhaust Gas Recirculation Technology (EGRT™)
Level 2 – 50% or Greater PM Reduction	
Environmental Systems Worldwide (ESW)	Particulate Reactor™
Level 2 – 50% or Greater PM Reduction with 15% or greater NOx Reduction	
Lubrizol	PuriNOx™
Level 1 – 25% or Greater PM Reduction	
Lubrizol	AZ Purifier, and AZ Purimuffler™
Donaldson	DCM Diesel Oxidation Catalyst (DOC) with 6000 series catalyst formulation
Donaldson	DCM DOC muffler with 6000 Series catalyst formulation and Spiracle™ closed crankcase filtration system
Donaldson	DCM DOC with 6000 series catalyst formulation plus closed loop crankcase with Donaldson Spiracle™ closed crankcase filtration system with commercially available California diesel fuel or fuel with a lower sulfur content
Donaldson	DCM DOC with 6100 series catalyst formulation plus closed loop crankcase with Donaldson Spiracle™ closed crankcase filtration system with 15 ppm or less sulfur diesel fuel
Donaldson	DCM DOC with 6100 series catalyst formulation with 15 ppm or less sulfur diesel fuel
Level 1 – 25% or Greater PM Reduction with 25% or Greater NOx Reduction	
Cleaire	Flash and Match™ oxidation catalyst based system
Extengine Transport Systems	Advanced Diesel Emission Control (ADEC) system

Appendix B – DSNY Trucks Retrofit with DPFs

Truck #	District Location	In-Service Date	Date Retrofit	Mileage @ Retrofit	Hours @ Retrofit	Device	Current Mileage	Current Hours
25CF-034	ME-08	08/29/97	12/27/02	58,731	8,747	CRT	73,757	10,503
25CF-035	ME-08	09/05/97	01/13/03	50,298	7,675	CRT	67,481	9,711
25CF-036	ME-08	09/05/97	01/21/03	53,352	7,907	CRT	77,625	10,852
25CF-037	ME-08	08/29/97	01/31/03	49,016	5,022	CRT	69,962	7,447
25CF-038	ME-08	09/05/97	03/06/03	56,872	8,953	CRT	70,708	10,578
25CF-039	ME-08	09/05/97	03/13/03	55,471	8,159	CRT	74,769	10,318
25CF-040	ME-08	09/08/97	03/18/03	57,622	8,757	CRT	71,968	10,595
25CF-041	ME-08	09/08/97	03/24/03	48,111	7,657	CRT	67,535	10,030
25CF-042	ME-11	09/08/97	08/29/01	33,407	5,199	CRT	67,829	9,506
25CF-043	ME-11	09/08/97	08/29/01	35,020	5,121	CRT	71,740	9,232
25CF-044	ME-11	09/08/97	08/30/01	36,992	4,145	DPX	68,866	5,736
25CF-045	ME-11	09/08/97	08/30/01	36,990	6,181	DPX	66,348	9,888
25CF-077	BXW-01	09/26/97	09/05/03	23,961	6,219	CRT	27,906	7,419
25CF-078	BXE-10	09/24/97	04/09/02	29,140	7,169	DPX	35,918	9,039
25CF-079	ME-11	09/26/97	03/18/03	61,528	8,204	CRT	82,968	11,026
25CF-081	ME-06	09/26/97	07/21/03	53,572	9,975	CRT	58,897	11,116
25CF-082	MW-12	09/29/97	12/31/02	64,536	9,704	CRT	76,585	11,549
25CF-084	MW-01	09/30/97	05/12/03	44,950	2,210	CRT	51,829	3,405
25CF-085	MW-01	09/29/97	05/19/03	52,443	9,724	CRT	64,941	11,830
25CF-092	MW-09	09/30/97	04/28/03	52,914	7,057	CRT	65,496	8,584
25CF-095	ME-08	10/07/97	01/07/03	56,801	6,783	CRT	77,564	9,107
25CF-108	ME-10	10/10/97	04/09/03	47,911	8,014	CRT	61,888	10,206
25CF-109	ME-10	10/10/97	04/22/03	49,201	8,135	CRT	60,968	9,746
25CF-119	MW-01	12/04/97	05/28/03	57,161	10,060	CRT	72,104	12,615
25CF-129	MW-04	11/06/97	05/28/03	368	10,531	CRT	7,940	12,910
25CF-130	MW-12	12/08/97	01/07/03	60,940	9,406	CRT	78,264	11,569
25CF-135	MW-07	12/04/97	05/19/03	42,908	9,597	CRT	61,740	12,517
25CF-136	MW-07	12/04/97	06/18/03	45,282	8,848	CRT	55,040	10,711
25CF-137	MW-07	12/04/97	07/28/03	47,547	9,331	CRT	56,932	11,042

Truck #	District Location	In-Service Date	Date Retrofit	Mileage @ Retrofit	Hours @ Retrofit	Device	Current Mileage	Current Hours
25CF-144	MW-04	12/08/97	06/06/03	32,650	6,660	CRT	38,605	7,856
25CF-148	MW-03	12/18/97	05/28/03	51,539	8,705	CRT	53,497	8,997
25CF-149	MW-03	12/09/97	06/06/03	55,072	9,437	CRT	61,997	10,908
25CF-150	MW-03	12/04/97	06/18/03	52,451	8,916	CRT	57,085	9908
25CF-151	MW-03	12/04/97	07/02/03	47,459	8,271	CRT	53,067	9,406
25CF-157	ME-06	12/04/97	06/06/03	45,573	9,364	CRT	49,107	10,385
25CF-161	MW-05	12/09/97	06/18/03	46,359	9,310	CRT	59,374	9,349
25CF-162	MW-05	12/10/97	06/06/03	48,812	8,323	CRT	55,687	9,457
25CF-163	MW-05	12/09/97	07/21/03	44,734	8,150	CRT	57,243	10,224
25CF-169	MW-07	12/09/97	05/12/03	36,679	5,628	CRT	48,863	6,360
25CF-170	MW-07	12/11/97	07/15/03	42,431	9,180	CRT	51,972	10,912
25CF-171	MW-07	12/10/97	08/08/03	41,298	3,316	CRT	50,924	3,813
25CF-183	MW-04	12/19/97	06/18/03	50,756	9,000	CRT	57,154	10,336
25CF-184	BXW-09	12/23/97	04/03/02	26,227	6,202	DPX	40,940	10,175
25CF-185	BXW-09	12/23/97	04/08/02	26,211	6,611	DPX	33,124	9,009
25CF-189	ME-10	12/19/97	04/30/03	46,115	7,770	CRT	52,633	8,798
25CF-202	MW-12	01/07/98	01/21/03	67,561	9,589	CRT	82,962	12,796
25CF-217	BXW-09	01/22/98	04/12/02	27,727	6,268	CRT	41,562	9,715
25CF-218	MW-04	01/26/98	07/21/03	29,597	8,191	CRT	37,201	10,158
25CF-227	MW-07	01/21/98	07/21/03	48,758	9,030	CRT	73,090	12,084
25CF-228	MW-07	01/26/98	07/28/03	24,444	6,395	CRT	37,270	8,267
25CF-233	ME-06	01/29/98	07/02/03	11,447	8,365	CRT	22,559	10,621
25CF-235	BXE-11	01/29/98	02/04/03	32,317	7,447	CCRT	40,661	9,529
25CF-236	BXE-11	02/06/98	04/12/02	26,096	5,938	CRT	41,959	9,670
25CF-238	MW-12	02/19/98	01/13/03	71,291	10,532	CRT	92,310	14,277
25CF-242	ME-06	01/30/98	07/28/03	40,794	8,321	CRT	48,607	9,653
25CF-243	ME-06	01/29/98	07/10/03	40,395	9,029	CRT	48,403	10,821
25CF-254	MW-02	02/19/98	05/28/03	64,375	8,649	CRT	71,532	11,885
25CF-255	MW-04	02/17/98	07/28/03	37,297	8,757	CRT	48,889	11,591
25CF-258	MW-02	02/20/98	06/06/03	47,618	10,054	CRT	58,972	12,132

Truck #	District Location	In-Service Date	Date Retrofit	Mileage @ Retrofit	Hours @ Retrofit	Device	Current Mileage	Current Hours
25CF-259	MW-05	02/24/98	07/02/03	47,474	8,336	CRT	55,800	9,830
25CF-260	MW-02	02/17/98	06/24/03	46,773	9,862	CRT	50,991	10,777
25CF-264	MW-03	02/19/98	07/21/03	53,878	8,731	CRT	65,314	10,558
25CF-265	ME-11	03/03/98	02/04/03	53,684	7,532	CRT	78,653	10,765
25CF-266	MW-07	02/27/98	08/04/03	201	7,522	CRT	12,791	10,438
25CF-267	ME-08	02/19/98	03/31/03	60,478	7,382	CRT	71,576	8,665
25CF-273	MW-09	02/24/98	05/06/03	54,260	7,785	CRT	73,290	10,485
25CF-277	MW-02	03/03/98	07/02/03	52,134	9,951	CRT	62,359	12,085
25CF-278	ME-10	03/04/98	05/06/03	57,127	9,031	CRT	69,492	10,838
25CF-280	MW-12	03/04/98	02/14/03	65,678	9,679	CRT	83,732	12,656
25CF-281	MW-12	02/27/98	04/07/03	60,923	9,163	CRT	76,791	12,164

Appendix C – DPF Cleaning Procedure

Engelhard DPX™

DPX Diesel Particulate Filter

Cleaning and Maintenance Procedure

MAINTENANCE PROCEDURE

The DPX diesel particulate filter cleaning procedure must be followed to ensure proper operation and durability. Failure to follow this procedure will void the warranty.

DPX unit cleaning must be done on a minimum annual basis, every twelve (12) months, or every 60,000 miles / 100,000 kilometers according to the following procedure. This process is to remove the accumulated ash (from lubricants and oil). **PLEASE NOTE**: with some applications, including higher emission engines, cleaning will be necessary more frequently. Your distributor will advise you if this is necessary for your application.

Cleaning Procedure:

1. Before removing the DPX Centerbody for cleaning, mark the exhaust side (outlet) of the unit.

2. Visually inspect outlet of the catalyst for the presence of black residue on the surface. If the residue is present an increase in frequency of cleaning must be made.

3. Remove the DPX Centerbody and with compressed dry air first clean the inlet face of the unit until minimum ash is detected. Then continue to blow air through the outlet side of the unit until minimum ash is detected. DO NOT APPLY COMPRESSED AIR NOZZLE DIRECTLY ON THE FACE OF THE FILTER. As an alternative a vacuum can be used to remove the accumulated ash.

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MAINTENANCE PROCEDURE

Note: Automated processes may be used to clean the DPX, if approved by Cummins Inc.

4. Replace the DPX Centerbody on the vehicle in the opposite flow direction from which it was removed. Exhaust side with mark will now become the inlet side.

5. Log the completion of procedure. Record of DPX cleaning shall be kept for the life time of the unit.

The use of any other than dry compressed air media may void the manufacturer warranty and may deactivate/destroy the catalyst.

Removed ash must be disposed in accordance with all Federal and State laws and regulations. If local laws do not specify the procedure for ash disposal it is Cummins recommendation to accumulate ash and keep it in a dry enclosed container until such regulations would be issued.

MASK, GLOVES AND SAFETY GLASSED SHALL BE WORN DURING CLEANING PROCEDURE.

The Diesel Particulate Filter does not require any additional maintenance other than routine cleaning. If the unit does become plugged, the centerbody can be removed and cleaned or replaced with the exact same part number catalyst

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Johnson Matthey CRT®

CRT Diesel Particulate Filter

Cleaning and Maintenance Procedure

MAINTENANCE PROCEDURE

The CRT diesel particulate filter cleaning procedure must be followed to ensure proper operation and durability. Failure to follow this procedure will void the warranty.

CRT unit cleaning must be done on a minimum annual basis, every twelve (12) months, or every 60,000 miles / 100,000 kilometers according to the following procedure. This process is to remove the accumulated ash (from lubricants and oil). **PLEASE NOTE**: with some applications, including higher emission engines, cleaning will be necessary more frequently. Your distributor will advise you if this is necessary for your application.

Cleaning Procedure:

1. Before removing the CRT Centerbody for cleaning, mark the exhaust side (outlet) of the unit.

CRT Filter Removal:

Remove the filter section of the CRT by opening the clamps holding the filter module in place. The filter section is between the two clamps closest to the outlet side of the CRT. Check the nameplate on the module for identification. Separate the mating modules by approximately ½" to allow removal over the gasket retainer rings. Note the orientation of the filter in the exhaust flow because it will be reinstalled with the opposite end in the up stream direction.

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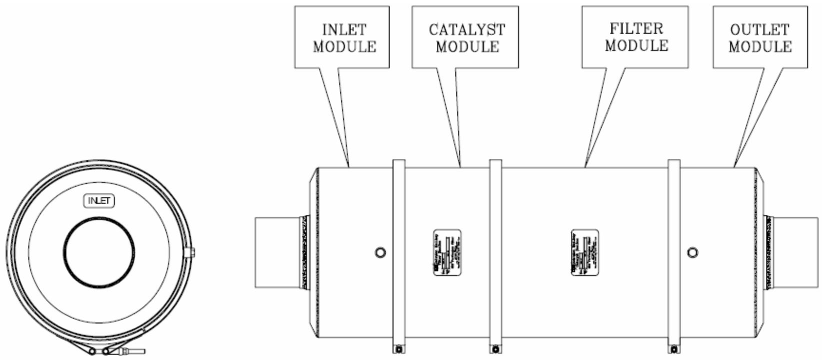


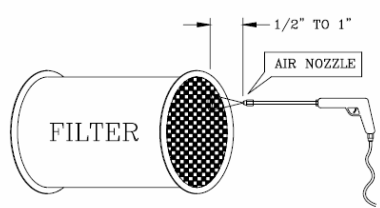
2. Visually inspect outlet of the Filter Module for the presence of black residue on the surface. If the residue is present an increase in frequency of cleaning must be made.

3. Air Requirements:
   All on site cleaning operations listed in this procedure use compressed air supplied through a nozzle to concentrate high-pressure air for cleaning. A Coalescing filter to remove 99.9% of oil and water aerosols as well as solids greater than 1 micron must be installed up stream of the air nozzle. Air pressure must be regulated between 80 psi and 100 psi and supplied through a standard shop blow-gun. The air nozzle outlet must maintain a coupling distance of ½" to 1" from the filter face. To prevent gouging, the nozzle should not touch the filter face. (A rubber tip is recommended to prevent damage from accidental contact.)

Cleaning:

To clean the filter compressed air is blown through the outlet (clean) side of the filter. Slowly move the air nozzle back and forth across the filter face making sure the entire filter face area is uniformly covered. Below is a list of time estimates based on filter diameters.

Filter Diameter (in inches)	Cleaning Duration
5.66	10 minutes
7.5	15 minutes
9.0	20 minutes
9.5	25 minutes
10.5	30 minutes
11.25	35 minutes
12.0	40 minutes



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4. Cleaning Methods:

One of two methods shall be utilized to clean CRT:

4.1 For Facilities with an existing dust collection system:

If the vehicle maintenance facility has an existing dust collection system and compressed air, the following procedure can be performed. Remove the filter and outlet housing from the vehicle. Attach the outlet housing with gasket to the inlet (dirty) side of the filter and attach the dust collection system to the pipe of the outlet housing. Using an air nozzle, direct compressed air through the clean side of the filter, this will blow the ash into the dust collection system. Blow air into each individual cell until all of the ash is removed (see duration time chart for time guidelines) Filters and filter bags from the dust collection system must be disposed in accordance with all applicable federal, state and local laws and regulations.

4.2 Filter bag cleaning:

Filter bags are available through the Cummins Inc. distribution network. Filter bags are intended to trap particles 5 microns in size or larger. Each filter bag is produced to couple to a specific module diameter. The appropriate size filter bag is attached to the dirty side of the filter using the v-band clamp removed with the filter module. Using an air nozzle, direct compressed air through the clean side of the filter, this will blow the ash into the filter bag. Blow air into each individual cell until all of the ash is removed (see duration time chart for time guidelines). Each filter bag should be capable of being used to clean 5 to 10 filters. Disposal of filter bags must be in accordance with all applicable federal, state and local laws and regulations.

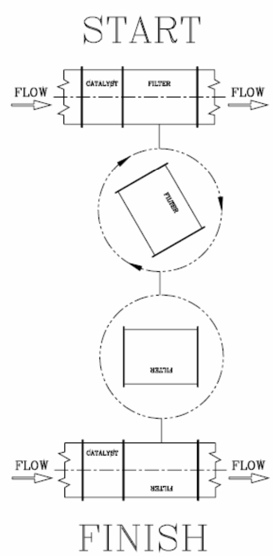
5. Inspection:

1. During the cleaning interval, all installation mounts and brackets should be inspected for fatigue or cracks. Replace components as required.
2. Check the v-band clamps, t-bolts, nuts, and gaskets for damage. Replace damaged parts as required using certified replacement parts. Fleetguard recommends replacing the gaskets at either end of the filter module at each cleaning interval to assure proper sealing. Gaskets are available through the Cummins Inc. distribution network.

6. Assembly:

6.1 Check that the filter module flanges and mating flanges are clean from debris. Clean as required.

6.2 Orient the filter module so that the end that was previously facing the CRT outlet is now facing the CRT inlet. (The flow direction of the filter



is now reversed.)

6.3 Install a gasket on the catalyst gasket retainer ring and connect the filter module using a v-band clamp. Tighten the v-band clamp lock nut to 180 inch pounds. Do not over tighten.

6.4 Install a gasket on the outlet head gasket retainer ring and connect to the filter module using a v-band clamp. Tighten the v-band clamp lock

Page 4 of 5

nut to 180 inch pounds. Do not over tighten.Note: CRT outlet head may require rotation to properly align with the vehicle piping or to orient the test port.

6.5 Reinstall CRT in the vehicle mount and connect inlet and outlet pipes. Check all brackets and fasteners connecting the CRT to the exhaust piping and body frame.

6.6 Start the engine and examine the clamps for leaks.

6.7 Run the engine under normal operating conditions for a period of 15 minutes then perform a back pressure test per the procedure in the installation guide.

MASK, GLOVES AND SAFETY GLASSED SHALL BE WORN DURING CLEANING PROCEDURE.

Appendix D – NYS DEC Ash Disposal Determination Letter

New York State Department of Environmental Conservation
Division of Solid and Hazardous Materials
Bureau of Hazardous Waste Management, 8th Floor
625 Broadway, Albany, New York 12233-7251
Phone: (518) 402-8612 • **FAX:** (518) 402-9025
Website: www.dec.state.ny.us

Erin M. Crotty
Commissioner

October 11, 2001

Mr. David E. Park
Project Manager
NESCAUM
129 Portland Street
Boston, MA 02114

Dear Mr. Park:

This is in response to your October 2, 2001 letter concerning diesel particulate filters to be installed on NYC Department of Sanitation trucks. Each filter will generate approximately 10 ounces of ash per year from the catalytic oxidation of captured particulates that represent primarily residues of burned and unburned fuel from the vehicle.

As we discussed, residues from the burning of fossil fuels are excluded from being a hazardous waste. The federal reference for this exclusion is 40 CFR 261.4(b)(4). The equivalent New York State exclusion is found at 6 NYCRR 371.1(e)(2)(iv).

Consequently, the ash would be regulated as a solid waste under 6 NYCRR Part 360 and, if the amount per shipment exceeded 500 lbs., under 6 NYCRR Part 364 as well. Whether or not the amount of industrial/commercial/institutional wastes exceeds 500 pounds per shipment is relevant only insofar as to whether or not the services of a transporter, permitted under Part 364, are needed. However, the transportation of ash from the burning of fossil fuel may be conditionally exempt from the requirements of Part 364, pursuant to an exemption found at 364.1(e)(2)(xix), copy enclosed. Although the amount of ash is extremely unlikely to ever exceed 500 pounds in one shipment, if you wish to inquire further about the aforementioned exemption, please contact Mr. Peter Pettit of the Bureau of Waste Reduction & Recycling at 518/402-8705.

If I can be of any further assistance, please contact me at (518) 402-8633.

Sincerely,

Lawrence J. Nadler

Lawrence J. Nadler, P.E.
Chief, Technical Determination Section
Bureau of Hazardous Waste Management
Division of Solid & Hazardous Materials

Enclosure

Appendix E – CNG Fueling Stations In/Near New York City As of May 31, 2005

Station Name	Address	City	State	Zip	Type of Access
KeySpan/Mobil Service Station	195 Flatbush Ave	Brooklyn	NY	11217	Public - card key at all times
KeySpan/Canarsie Service Ctr.	8424 Ditmas Ave	Brooklyn	NY	11236	Public - card key at all times
KeySpan - Port Authority of NY/NJ	John F. Kennedy Airport	Queens	NY	11201	Public - card key at all times
KeySpan/Greenpoint Energy Ctr.	287 Maspeth Ave	Brooklyn	NY	11211	Public - card key at all times
Con Edison - East 16th Street Service Ctr.	400 East 16th St.	New York	NY	10009	Public - card key at all times
Port Authority HT CNG Station	13th & Provost St	Jersey City	NJ	07302	Private access only
Consolidated Edison - West 29th St. Service Center	W29th Street and 12th Ave	New York	NY	10001	Public - card key at all times
KeySpan New York City Department of Parks and Recreation	123-30 Roosevelt Ave	Flushing	NY	11368	Private - government only
KeySpan Triboro Bus Company	8501 24th Avenue	East Elmhurst	NY	11370	Private - fleet customers only
BP - LaGuardia Airport	Grand Central Pkwy	Flushing	NY	11371	Public - see hours
PSE&G Jersey City Gas District	444 St Pauls Ave	Jersey City	NJ	07306	Private access only
Con Edison - College Point Service Ctr.	124-15 31st Ave	Flushing	NY	13354	Public - card key at all times
Bronx Zoo	Boston Road	Bronx	NY	10460	Private access only
Con Edison - Van Nest Service Center	1615 Bronxdale Ave	Bronx	NY	10462	Public - card key at all times
KeySpan Staten Island Service Ctr.	200 Gulf Ave	Staten Island	NY	10303	Public - card key at all times
KeySpan Hewlett Service Center	455 Mill Rd	Hewlett	NY	11557	Public - card key at all times
Port Authority Newark Airport CNG Station	Bldg 11 Automotive shop	Newark	NJ	07114	Private access only
Elizabethtown Gas Company	520 Green Lane	Union	NJ	07083	Private access only

Station Name	Address	City	State	Zip	Type of Access
MTA - Long Island Bus	50 Banks Ave	Rockville Center	NY	11570	Private - government only
PSE&G Orange Gas District	284 N Park St	East Orange	NJ	07017	Private access only
Bergen County Department of Public Works	70 Zabriskie Street	Hackensack	NJ	07601	Private - government only
MTA - Long Island Bus - Mitchell Field	700 Commercial Ave	Garden City	NY	11530	Private - government only
PSE&G Clifton Gas District	240 Kuller Rd	Clifton	NJ	07011	Private access only
PSE&G Springfield GBU Headquarters	24 Brown Avenue	Springfield	NJ	07081	Private access only
KeySpan Long Island Headquarters	175 E Old Country Road	Hicksville	NY	11801	Public - card key at all times

Courtesy of http://afdcmap.nrel.gov/locator/LocatePane.asp

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Appendix F – Development of Street Sweeper Test Cycle

An ad hoc dynamometer driving cycle was developed by West Virginia University specifically to represent the in-use operation of DSNY street sweepers. M.J. Bradley & Associates collected two days of in-use vehicle activity data from DSNY street sweepers. The vehicle speed versus time database was provided to West Virginia University in spreadsheet form at a rate of 1 hertz.

The continuous data were parsed into “microtrips”. Microtrips are defined as vehicle operation (speed greater that 0.5 mph) from a starting point until the vehicle has arrived at a destination (vehicle speed less than 0.5 mph). Statistics from the database were evaluated to characterize vehicle activity for the test cycle.

- 13.1 total hours of data were collected.
- 1.6 hours for lunchtime were excluded and 11.6 hours of activity were considered in the analysis.
- The activity included 4.5 hours of idle time (idle considered to be activity less than 0.5 mph) comprising 39.1% of the total activity.
- Analysis identified 668 microtrips.
- A total of 72.9 miles was traveled.
- The average vehicle speed was 6.3 mph with idle considered.
- The average speed excluding idle was 10.4 mph.
- The standard deviation (with idle excluded) was 6.7 mph.

The target time length for the sweeper cycle was 30 minutes. A random process was used to select and concatenate microtrips in a sequence string until a defined length of time for a candidate cycle was accumulated. This process was iterated until 30,000 candidate strings of trips were created.

Each of these candidate strings now represented a possible basis for the creation of a cycle. Statistical measures of each string were then compared to the overall statistical measures for that data set, with all idle excluded from the data set. The following three measures were used:

- Average speed (AS) [with idle time removed]
- Standard deviation of speed (SS) [with idle time removed]
- Percentage idle time (IT)

A measure of the difference between a string and the whole data set is given by:

$$RMS = \sqrt{\left(\frac{AS_{string} - AS_{set}}{AS_{set}}\right)^2 + \left(\frac{SS_{string} - SS_{set}}{SS_{set}}\right)^2 + \left(\frac{IT_{string} - IT_{set}}{IT_{set}}\right)^2}$$

The RMS error ranged from 0.7% to 2.2% for the top 25 candidate cycles created. It was agreed that the 25^{th} candidate cycle was as valid as the 1^{st} candidate cycle therefore all 25 were considered. The first 241 candidate cycles were an under 5% RMS error.

Each of the top 25 candidate cycles was visually contrasted to the data trace of the database. The database was distinct in that the vehicle left the depot in “travel” mode, which allows the vehicle to reach speeds up to 40 mph, while transporting to the sweeping area. The vehicle was then stopped to engage the hydraulic system and proceed in “sweep” mode. Sweep mode limits the vehicle speed to 20 mph. Typical sweeping is done at 6 to 8 mph yet can reach speeds of 15 mph. The vehicle would then stop, disengage the hydraulic system, engage the travel mode and return to the depot. WVU and M.J. Bradley & Associates evaluated the candidates and selected a cycle string with an RMS error of 1.9%.

As stated before, the microtrips were selected in random order; therefore, rearranging the order of the microtrips in the selected candidate cycle would have no effect on the selection criteria. High-speed microtrips were moved to the beginning and end of the speed trace to simulate behavior at the beginning and end of the day. Sweeping activity was moved to the center of the cycle. A three point smoothing was performed on the raw data to eliminate dithering and improve drivability. Due to mechanical limitations of the chassis dynamometer, maximum accelerations are often curtailed. In this study they were evaluated and it was determined that no modifications to the acceleration rates were necessary. Maximum decelerations were limited to 2.5 mph/s. Single length test cycles were used on the sweepers and no warm-up ramps were performed at the beginning of the cycle.”

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Appendix G – Chassis Dynamometer Background Information

Chassis Dynamometer Background Information

The WVU Transportable Heavy Duty Vehicle Emissions Testing Laboratory measures emissions from heavy-duty diesel and alternatively fueled vehicles across North America. The main objective of the research performed is to contribute information to a database that can be used to ascertain emissions performance and fuel efficiency of heavy-duty vehicles. In addition, the laboratories have performed extensive work to support the development of heavy duty driving cycles and to assess emissions from new engine and fuel technologies. West Virginia University (WVU) designed, constructed and now operates two Transportable Heavy Duty Vehicle Emissions Testing Laboratories. These laboratories travel to transit agencies and trucking facilities where the laboratory is set up to measure alternatively fueled and diesel control vehicle emissions. Several technical papers have been presented on the design of the two laboratories and on emissions data collected from both conventional and alternatively fueled vehicles.

The transportable laboratory consists of a dynamometer test bed, instrumentation trailer and support trailer. The test bed is transported to the test site by a tractor truck where it is lowered to the ground. On vehicles with a two drive wheel setup, the vehicle is prepared by removing the outer drive wheels and replacing them with special hub adapters. If the vehicle has a single drive wheel setup, the drive wheels are removed and replaced with different rims and tires that are equipped with an adapter to allow for connection to the dynamometer. The subject vehicle is then driven onto the test bed where it is supported with jacks and secured with chains. The hub adapters are then attached to provide a connection between the drive axle of the vehicle and the inertial flywheels and power absorbers of the dynamometer. Speed-increasing gearboxes transmit drive axle power to flywheel sets. The flywheel sets consist of a series of selectable discs used to simulate vehicle inertia. During the test cycle, torque cells and speed transducers at the vehicle hubs monitor axle torque and speed.

The instrumentation trailer holds both the emissions measurement system for the laboratory and the data acquisition and control hardware necessary for the operation of the test bed. Exhaust from the vehicle is piped into a 45-cm dilution tunnel at the instrumentation trailer. The tunnel mixes the exhaust with ambient air, which both cools and dilutes the exhaust. Dilution tunnel flow is controlled using a critical flow venturi system (CVS). A two-stage blower system maintains critical flow through the venturi throat restrictions to maintain a known and nearly constant mass flow of dilute exhaust during testing. The flow can be varied from 500 to 3000 scfm by adjusting the CVS.

Dilute exhaust samples are drawn, using heated sampling probes and sample lines, from a sample plane located 15 feet from the mouth of the dilution tunnel. Levels of carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NOx) and hydrocarbons (HC) are measured continuously then integrated over the complete test time. A sample of the ambient (dilution) air is continuously collected throughout the test in a Tedlar bag and analyzed at the end of each test to establish background. These background measurements are then subtracted from the continuous measurements. Details of the analyzers used by the transportable lab are given in the following table.

Transportable lab analyzers used for emissions measurement.

Emission Parameter	Measurement Method	Equipment Specification
Hydrocarbons	Flame ionization detector	Rosemount Analytical Model 402
Carbon Monoxide	Non-dispersive infrared	Rosemount Analytical Model 880A
Carbon Dioxide	Non-dispersive infrared	Rosemount Analytical Model 880A
Oxides of Nitrogen	Chemiluminescent	Rosemount Analytical Model 955
Non-methane HC	Gas Chromatograph	Varian 3600
Particulate Matter	Gravimetric	70-mm Fiberglas Filters

In addition to continuous, integrated and background samples, additional exhaust samples are drawn from the dilution tunnel and collected in 3 liter Tedlar bags for test runs on vehicles powered by CNG. Background samples are also collected in Tedlar bags to correlate with CNG vehicle testing. These samples are then sent to the WVU speciation laboratory to determine non-methane hydrocarbon (NMHC) and methane concentrations using gas chromatography (GC) analysis.

A gravimetric measurement of particulate matter (PM) is obtained using 70-mm fiberglass filters. The filters are conditioned for temperature and humidity in an environmental chamber before each weighing to reduce error due to variation in water content per CFR 40, Part 86, Subpart N.

Specific Test Procedures

Preparation of the Chassis Dynamometer

After the chassis dynamometer and the instrumentation laboratory have been set up on site, calibrations on the dynamometer bed are performed. These include calibration of the torque cells on the power absorbers used to help in applying road load to the vehicle and calibrations of both power absorber and in-line hub torque cell speed sensors. Each calibration, which contains at least 10 data points, is used to derive constants in a polynomial equation, which is, in turn, used to convert digital information from a sensor conditioning system into engineering units.

Each vehicle is then run through a series of ‘coastdown’ cycles. The coastdown cycle consists of getting the vehicle up to an operating speed, putting the gearshift in neutral, and coasting to a stop. This provides an estimation of rolling resistance and an alternative method for setting the power absorbers.

Vehicle Preparation

Each vehicle, upon receipt by WVU, is inspected prior to mounting on the test bed. Vehicle information that could not be ascertained prior to testing is gathered from the vehicle, most importantly, tire size, vehicle weight and frontal area. Prior to testing each vehicle, a visual inspection is performed to locate lift points, look for damage, and examine exhaust connections. In addition, vehicle information is gathered such as mileage, identification numbers (chassis and engine), type of muffler, catalyst and DPF (if applicable). Information from the vehicle is logged into a database as per normal transportable laboratory operating procedures.

After appropriate vehicle statistics are gathered the vehicle is mounted on the chassis dynamometer. The vehicle is driven onto the test bed so that the inner rear drive wheels (or modified adapter-wheels in the case of the sweepers) are resting between the dynamometer rollers and the hub adapters are connected to the inertial flywheels and power absorbers. Vehicle GVWR is used along with passenger capacity to determine the vehicle test weight. This value is then be used to determine the most appropriate selection of flywheels on the dynamometer test bed for that vehicle. Based on the test weight of the vehicle, the rear of the vehicle is elevated by means of hydraulic jacks placed on scales to monitor that the vehicle is elevated to the appropriate level. The jacks raise the vehicle to an appropriate height so that friction between the tires and dynamometer roller is negligible. It is necessary to remove as much of this rolling resistance as possible to avoid problems associated with overheating tires. The dynamometer simulates the appropriate rolling resistance for the vehicle. The front of the vehicle is also elevated so that the vehicle is on a level horizontal plane during the test procedure.

Preparation of the Dilution Tunnel and Blower

Dilution tunnel flow rate is selected such that emissions concentrations will fall within the ranges used on the emissions analyzers. It is preferable to select a flow rate that results in peak CO_2 concentrations at no less than 60 percent of the full span analyzer calibration and select appropriate span concentrations for the other analyzers based upon that flow rate.

In addition to normally performed propane injections, CO_2 injections, which are not a regular procedure for the laboratories, were conducted under this contract. This procedure served as an additional quality control check because CO_2 was used in determining vehicle fuel economy. The amount of CO_2 injected into the dilution tunnel necessary to raise the concentration to a level comparable to that found during vehicle testing is quite large compared to that of propane injections. For CO_2 injections, a bottle of 100% CO_2 was discharged into the mouth of the dilution tunnel while being continuously weighed to determine the amount injected. Comparison of the amount injected to the amount recovered by the CO_2 analyzers served as both a quality check on the analyzers and a check of the integrity of the dilution tunnel.

Preparation of the Gas Sampling System

Proper operation of the gas sampling system, associated analyzers, and test bed instrumentation is checked using a comprehensive calibration schedule after setup of the laboratory. In particular, the gas analysis instrumentation is calibrated and checked using 'zero' air (air free of any contaminants) and 'span' gas (air containing a known quantity of the gas under consideration) as well as evenly spaced concentration levels of the calibration gas. Information from these tests is used to develop a linear calibration curve used to translate instrument response in volts to emissions level in parts per million (ppm). The integrity of the dilution tunnel and associated plumbing is verified using a propane injection. This procedure involves introducing a known amount of propane into the dilution tunnel using a critical flow orifice injection rig. The HC concentration measured using the HC analyzer is then compared to that calculated from the injection rig to verify propane mass recovery. An absolute difference of less than 2% indicates that there are no leaks and that the analysis system is operating satisfactorily. The 2% value is customarily used because it follows the requirements for engine and vehicle emissions testing presented in the Code of Federal Regulations Title 40, Part 86, Subpart N.

Vehicle Testing

Prior to performing a test sequence (which is made up of at least 3 repeatable test cycles), the vehicle is operated on the dynamometer through a complete test cycle to bring the vehicle's engine and transmission as well as associated dynamometer equipment up to operating temperature in addition to allowing the operator to become familiar with the drive cycle. This procedure helps to ensure that losses associated with vehicle and dynamometer drivetrain components are consistent from test to test. At the completion of this pre-conditioning test, the engine idles for 30 seconds, then shut down and allowed to soak for a period of 20 minutes. The engine is then started one minute prior to beginning the test.

Test to test variation is monitored to assure quality of the research conclusions. Testing is considered to be complete when a minimum of three complete tests are performed and the test to test variation shows acceptable repeatability. This is typically when all readings are within 5 percent.

Monitored Information

Emissions Measurement

During an emissions test, continuous dilute exhaust samples from the dilution tunnel are monitored and recorded in the instrumentation using methods and analyzers described herein. Non-methane hydrocarbons (NMHC) and methane from CNG fueled vehicles are determined using gas chromatographic methods. A separate chromatography laboratory operated by the Mechanical and Aerospace Engineering department analyzes exhaust samples sent back from the field using a Varian 3600 GC equipped with a J&S Scientific

DB-MS column. This enables the identification of volatile organic compounds including methane in both gaseous fuel samples and emissions samples.

Particulate matter (PM) emissions are measured gravimetrically using standard 70-mm filters as outlined in the procedures of CFR 40, Part 86, Subpart N. Particulate data are not available until the filters can be appropriately conditioned after the test. This involves placing the filters in an environmental chamber where they are left for at least 24 hours prior to weighing.

At the completion of the test cycle, integrated bag samples are analyzed and recorded and particulate filters are changed. Data from each test are recorded and preparations for the next test are initiated.

Fuel Measurement

For both diesel and CNG vehicles, a carbon balance is be used to verify fuel usage measurements. This analysis method uses the mass of carbon present in the dilute exhaust (CO_2, CO, and HC) along with the fuel hydrogen to carbon atomic ratio and tunnel dilution ratio to determine fuel consumption. Both gaseous and liquid fuels used in this testing were analyzed using laboratory methods to determine hydrogen to carbon atomic ratio. Fuel samples were also sent out for lab analysis of heat and carbon content.

Data Quality Assurance

Upon completion of a vehicle test, data is stored and a preliminary analysis is performed to identify vehicle emissions and performance trends and to ensure proper operation of the laboratory. The data is then electronically transferred to WVU for further analysis and quality control. After completion of testing at a site, individual vehicle and fleet summary data are combined and a test report is generated. This report identifies trends in the data and vehicle-to-vehicle emissions/performance discrepancies, compares emissions data to data from previously tested similar vehicles, and contains any special procedures followed at the test site.

Quality assurance procedures are performed on different systems of the testing equipment and the data results to ensure uniformity of data for comparison purposes. Quality assurance on the testing equipment includes checks on the emission monitors, dilution tunnel and blower, and dynamometer test bed.

Analyzer and Equipment Calibration

Emissions data are gathered by diluting the exhaust and measuring the concentration of constituents in the diluted exhaust. To determine mass emissions rates, the product of the dilution tunnel flowrate and concentration of each species are used.

Propane Injections

In order to ascertain the performance of the dilution tunnel, venturi, and associated blowers for the laboratory, a propane injection is performed. This procedure is useful in determining whether any leaks are present in the line between the dilution tunnel sample zone and the intake to the blower venturi. This also reveals that the venturi system is operating as designed. Using a calibrated orifice, propane gas is fed into the entrance of the dilution tunnel. While the injection is in progress, a continuous sample is drawn and analyzed using the HC analyzer and a continuous background sample is retained in a Tedlar sample bag.

The propane injection duration is 5 minutes. At the conclusion of the injection procedure, the background bag is analyzed and the quantity of HC present is subtracted from the continuous result to get a total volume of the propane recovered from the tunnel. This amount is then compared to the amount of propane injected to determine a percent over/under recovery. In agreement with the Code of Federal Regulations, propane injections are considered satisfactory if the absolute percentage error in volume recovered against volume injected is less than 2% and the error between three subsequent injections is within 1%. Both the chassis and engine laboratories successfully performed propane injections prior to correlation tests.

Analyzers

To determine the appropriate range for an analyzer, the test vehicle is operated through a practice test. Using the current calibration range, the available calibration gases concentration is determined. The concentration of the calibration gases have to be in the range where no more than 80% of the scale is used. The lowest of the qualifying concentrations is then used to calibrate the analyzer.

NO_x Analyzer

The Heavy Duty Transportable Vehicle Emissions Testing Laboratory (HDTVETL) uses the Model 955 NO_x Analyzer, which automatically and continuously analyzes the gas sample flowing from the dilution tunnel.

This instrument is designed for analysis of sample streams containing high water vapor concentrations such as the emissions of heavy-duty vehicle engines. To prevent internal condensation of water vapor, the sample is kept at an elevated temperature of 350 °C from the tunnel probe through the lines into the analyzer. The analyzer uses the chemiluminescent method of detection with an output signal range of 0 – 5 volts DC.

Zero Calibration

The same parts-per-million (ppm) range that is used for sample analysis is selected and the SPAN control is set at normal operation or midrange if normal setting is not known.

The system is then placed in NO_x zero-mode so that zero air is supplied to the rear-panel SAMPLE inlet of the analyzer.

The zero control is adjusted to read zero, and the control is then locked.

Upscale Calibration

With the range selected that is appropriate to the span gas, the system is placed in NO_x SPAN mode. The sample-handling system is now supplying standard gas of accurately known NO_x content to the heated probe located at the dilution tunnel where it is pumped through a heated line to the rear of the analyzer.

The Span Control is then adjusted so that the reading on the meter shows 100%, corresponding with the desired ppm concentration of NO_x in span gas. In typical operation, the NO_x ranges between 250 and 1000 parts-per-million.

Decremental adjustments of 10% are made from 100% to 0% span gas to obtain the required linearity results of 10 points. The results are used to determine the calibration curve used to translate voltage to ppm.

Hydrocarbon Analyzer (HC)

The HDTVETL uses the Model 402 HC Analyzer, which is designed to measure the HC content of the exhaust emissions from heavy-duty truck and bus engines. The analysis is based on flame ionization, a highly sensitive method. The sample is drawn in to the analyzer through a sample line. To prevent the loss of higher-molecular-weight hydrocarbons, the temperature of the sample line and the analyzer is elevated to 375 °C using a single-front panel adjustable switch.

Calibration

- Attach regulator to desired bottle of span gas and open valve on bottle
- Turn on valve for "zero air"
- Turn selector valve to "span"
- On side of analyzer rack, turn HC knob to "calibrate" set gas divider to "100%”
- Adjust pressure on the bottle regulator so the reading on top of the analyzer bench is 21psi.
- Adjust pressure on the air regulator (located on the wall between the bottles and the bench) so the reading on the gage on top of the analyzer bench is 18psi
- Set the gas divider to "0%"

- Adjust the zero pot (potentiometer) on the analyzer to read zero. On the main computer, select "sensor calibration"
- Type "HC"
- On module #12 in the ADC rack, adjust the v-zero pot with a small screwdriver until the reading on the computer is 0 ADC
- Set the gas divider to "100%"
- Adjust the span pot on the analyzer to read 100.0
- On module #12 in the ADC rack, adjust the v-span pot with a small screwdriver until the reading on the computer is 2000 ADC
- Set the gas divider to "0%" and check zero on the analyzer display
- Repeat Zero and Span adjustments if necessary
- Set the gas divider to "100%," allow the reading to stabilize and press the space bar
- Set the gas divider to "90%" and repeat until 0% is reached

The computer displays the calibration results. If there is more than a 2% difference between the actual and calculated readings repeat the calibration.

CO & CO_2 ANALYSIS

The HDTVETL uses the Model 868 Infrared Analyzer, which continuously determines the concentration of a particular component of interest in the exhaust emissions. The analysis is based on the absorption of infrared energy. The analyzer calibration consists of setting a zero point and one or more upscale points, with an output signal range of 0 – 5 volts DC.

Zero Calibration

The same parts-per-million (ppm) range that is used for sample analysis is selected and the SPAN control is set at normal operation or midrange if normal setting is not known.

The system is then placed in CO/CO_2 zero-mode so that zero air is supplied to the rear-panel SAMPLE inlet of the analyzer.

The zero control is adjusted to read zero, and the control is then locked.

Upscale Calibration

With the range selected that is appropriate to the span gas, the system is placed in CO/CO_2 SPAN mode. The sample-handling system is now supplying standard gas of accurately known CO/CO_2 content to the heated probe located at the dilution tunnel where it is pumped through a heated line to an air dryer and through heated pump filters.

The Span Control is then adjusted so that the reading on the meter shows 100%, corresponding with the desired ppm concentration of CO/CO_2 in span gas. In typical operation, the CO/CO_2 ranges between 250 and 1000 parts-per-million.

Decremental adjustments of 10% are made from 100% to 0% span gas to obtain the required linearity results of 10 points. The results are used to determine the calibration curve used to translate voltage to ppm.

Dilution Tunnel Flowrate

During dynamometer testing of a vehicle, its exhaust is transferred into an 18-inch diameter full-scale dilution tunnel where it is mixed with ambient background air. Samples of the mixture are then taken through heated probes located 15 feet from the mouth of the tunnel. Flow through the tunnel is controlled using a critical flow venturi system, which is connected to the dilution tunnel via a flexible rubber cloth hose and the blower draws air through the mouth of the tunnel. The dilution tunnel volume flowrate is calculated using the equation

$$\dot{V} = K\nu P / \sqrt{T} \qquad (1)$$

where:

V = Flowrate (cfm)

K = Venturi Calibration Coefficient

ν = Conversion Factor for Flowrate Units

P = Tunnel Pressure (psfa)

T = Tunnel Temperature (K)

This requires continuous monitoring of tunnel pressure and temperature. Experience shows that dilution tunnel pressure is steady while temperature rises slightly over the duration of a test, and responds to transients in the test cycle. This causes the instantaneous mass flowrate to vary over the cycle. The deviations are modest, with the long-term change and the short-term variation being 2% of the total flow.