# NYSERDA Clean Diesel Technology: Non-Road Field Demonstration Program

Final Report 10-18
August 2010

New York State
Energy Research and
Development Authority

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# NYSERDA Clean Diesel Technology: Non-Road Field Demonstration Program

Final Report

Prepared for the

**New York State Energy Research and Development Authority**

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**NOTICE**

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| | |
|---|---|
| ADPF | active diesel particulate filter |
| CAA | Clean Air Act |
| CARB | California Air Resources Board |
| CCRT | catalyzed continuously regenerating technology |
| CCV | crankcase ventilation |
| CDC | clean diesel combustion |
| CDPF | catalyzed diesel particulate filter |
| CLD | chemiluminescent detector |
| CNG | compressed natural gas |
| CO | carbon monoxide |
| CR-DPF | continuously regenerating diesel particulate filter |
| CRT | continuously regenerating technology |
| CWMF | catalyzed wire mesh filter |
| DOC | diesel oxidation catalyst |
| DMF | diesel multi-stage filter |
| DPF | diesel particulate filter |
| DSNY | NYC Department of Sanitation |
| ECM | engine control module |
| ECT | emission control technology |
| EGBP | exhaust gas backpressure |
| EGR | exhaust gas recirculation |
| EGT | exhaust gas temperature |
| EPA | U.S. Environmental Protection Agency |
| EU | European Union |
| FBC | fuel-borne catalyst |
| FBC-DPF | fuel-borne catalyst – regenerated diesel particulate filter |
| FID | flame ionization detector |
| FTF | flow-through filter |
| FTP | federal test procedure |
| GHG | greenhouse gas |
| HC | hydrocarbon |
| HCCI | homogeneous charge compression ignition |
| HC-SCR | hydrocarbon-catalyzed selective catalytic reduction |
| hp | horsepower |

| | |
|---|---|
| ISS | integrated sampling system |
| LED | low-emissions diesel |
| LL77 | Local Law 77 (of New York City) |
| LNC | lean $NO_X$ catalyst (a type of HC-SCR) |
| LPG | liquefied petroleum gas |
| LTC | low-temperature combustion |
| MY | model year |
| NCDC | National Clean Diesel Campaign |
| NDIR | non-dispersive infrared |
| NDUV | non-dispersive ultraviolet |
| NIST | National Institute of Standards & Technology |
| NMHC | non-methane hydrocarbons |
| $NO_x$ | oxides of nitrogen |
| NYCMA | New York City Metropolitan Area |
| NYS | New York State |
| NYSDEC | New York State Department of Environmental Conservation |
| NYC DEP | NYC Department of Environmental Protection |
| NYSERDA | New York State Energy Research and Development Authority |
| OEM | original equipment manufacturer |
| PANYNJ | Port Authority of New York and New Jersey |
| PDPF | passive diesel particulate filter |
| PEMS | portable emissions measurement system |
| PM | particulate matter |
| SCC | source classification code |
| SCR | selective catalytic reduction |
| SOF | soluble organic fraction |
| THC | total hydrocarbons |
| TPM | total particulate matter |
| tpy | tons per year |
| Tx-LED | Texas low-emissions diesel |
| ULSD | ultra-low sulfur diesel |
| VOC | volatile organic compound |

# SUMMARY

NYSERDA initiated a Non-Road Clean Diesel in-use testing program in March, 2005. The program's goal is to demonstrate and evaluate the feasibility and performance of commercially available emission control technologies in reducing emissions of particulate matter (PM) and oxides of nitrogen ($NO_x$) from non-road equipment through real world demonstration and in-use testing. The in-use field demonstration portion of the project was conducted with the participation of equipment owners and operators in New York State (NYS) with a focus on the New York City Metropolitan Area (NYCMA), as well as emission control technology vendors.

In order to use the project resources effectively, diesel equipment and emission control technology combinations were selected for field testing that would provide the most useful data and the highest potential for air quality improvements. Program funding allowed for field demonstration of 15 non-road diesel equipment and emission control technology combinations. Equipment was selected based on those comprising large populations and high emission rates paired with effective, feasible control strategies.

Modeling and survey efforts that were performed in earlier stages of the project identified the NYCMA as the main contributor to the bulk of non road PM and $NO_x$ emissions in NYS, and provided a basis to rank emissions by equipment type and population. The construction and mining equipment group was identified as the most significant sector. Based on the factors above, the following equipment types were selected for evaluation:

- tractors, loaders, and backhoes in the range of 50 to 175 horsepower (hp)
- rubber tire loaders, 175 to 600 hp
- excavators, 75 to 300 hp
- off highway trucks, 1,200 to 2,000 hp
- skid steer loaders, 40 to 100 hp

As such, the following equipment types and emission control technology (ECT) combinations were selected for field demonstrations:

**Table S-1. Equipment and ECTs Tested**

| Equipment Description | Type of Equipment | ECT Manufacturer | ECT Model | ECT Type[a] |
|---|---|---|---|---|
| Case 821 | Rubber tire loader | CleanAIR Systems | PERMIT | PDPF |
| Daewoo Mega 200 | Rubber tire loader | NETT Technologies | FM 8A085 | FTF |
| Caterpillar D400 | Dump Truck | Huss | MK-System | ADPF |
| Caterpillar D400 | Dump Truck | JMI | CCRT | DPF |
| Daewoo Mega 200 | Rubber tire loader | DCL | Ultra Muffler | FTF |
| Bobcat 863 | Skid steer loader | AirFlow Catalyst | Active-X | DOC |
| Case 821 | Rubber tire loader | AirMeex | Compact Duo | ADPF with Fuel Burner |

**Table S-1. Equipment and ECTs Tested**

| Equipment Description | Type of Equipment | ECT Manufacturer | ECT Model | ECT Type[a] |
|---|---|---|---|---|
| Daewoo Mega 200 | Rubber tire loader | ECS | Purifilter NA8X11 | PDPF |
| Daewoo Mega 200 | Rubber tire loader | Donaldson | DMF | PDPF |
| Case 821 | Rubber tire loader | Extengine | LEV2 | FTF |
| Case 821 | Rubber tire loader | NETT Technologies | BlueMax / FTF | FTF/SCR |
| Case 821 | Rubber tire loader | DCL | MineX Sootfilter | PDPF |
| Case 821 | Rubber Tire Loader | NETT Technologies | PDPF | PDPF |
| Case 590 | Backhoe | NETT Technologies | DL 152 | DOC |

[a] ECT nomenclature:
ADPF -- active diesel particulate filter
DPF -- diesel particulate filter (also known as PDPF for passive diesel particulate filter)
DOC -- diesel oxidation catalyst
FTF – flow through filter
SCR – selective catalytic reduction

This report presents information regarding the fleet and host site selected for field demonstrations, the testing approach, analytical equipment used in testing, and the in-use duty cycle developed for testing. The report provides a description of the control technologies and strategies evaluated, summarizes field test results for each ECT and documents ECT cost, installation, operational performance, including:

- active and passive diesel particulate filters (DPF)
- catalyzed diesel particulate filters (CDPF)
- diesel oxidation catalysts (DOC)
- select combinations of DPFs and DOCs
- flow-through filters (FTF)
- catalyzed wire mesh filters (CWMF)

The results of in-use testing using repeatable duty cycles are presented in Table S-2, which summarizes measured emission reductions. Table S-2 also presents CARB and EPA verified emission reductions, and manufacturers' suggested emission reductions. Emission data was collected and measured during the study using several different measurement systems, including the Environment Canada Dynamic on-Board Emissions Sampling System (DOES2), the Engine, Fuels, & Emissions Engineering Ride-Along Vehicle Emissions Measurement (RAVEM) system, the Clean Air Technologies, Inc. (CATI) system and the Horiba OBS-2200. Note that the RAVEM was not setup to measure total hydrocarbons emitted because of the low hydrocarbon content of diesel exhaust. Data summarized in Table S-2 are from the primary measurement systems used in each test. Additional data from other systems used, (Horiba OBS-2200), are available in the report.

**Table S-2. Summary of Statistically Significant Measured Emission Reductions**

| Equipment Make | Equipment Type | Emission Control Technology | Emissions Measurement System | Verified or Expected Emissions Reduction | | | | Measured Statistically Significant Emission Reductions | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | PM | | | $NO_x$ | % PM Reduction | % $NO_x$ Reduction | % $NO_2$ Reduction | % CO Reduction | % THC Reduction |
| | | | | CARB Verified[a] | EPA Verified[a] | Non-Verified[d] | | | | | | |
| Case 821 | Rubber Tire Loader | CleanAIR PDPF | DOES2 | > 85% | | | | 98.9 | | -66.6 | 88.6 | 81.6 |
| Case 821 | Rubber Tire Loader | NETT PDPF | DOES2 | | | >85% | | 95.0 | | -25.6 | 97.4 | 95.0 |
| Daewoo Mega 200 | Rubber Tire Loader | ECS PDPF | RAVEM | >85% | 90% | | | 93.0 | | n/a | >100 | n/a |
| Daewoo Mega 200 | Rubber Tire Loader | Donaldson PDPF | RAVEM | >85% | | | | 90.0 | | n/a | >100 | n/a |
| Case 821 | Rubber Tire Loader | DCL PDPF | RAVEM | >85% | | | | 90.0 | | n/a | >100 | n/a |
| Caterpillar D-400 | Off-Road Truck | JMI CCRT PDPF | DOES2 | | | >85%[b] 90%[b] | | 95.4 | | | 89.8 | |
| Caterpillar D-400 | Off-Road Truck | HUSS ADPF | DOES2 | >85% | | | | 92.0 | | | | |
| Case 821 | Rubber Tire Loader | AirMeex ADPF | DOES2 | | | > 85% | | 97.4 | | | 17.7 | |
| Daewoo Mega 200 | Rubber Tire Loader | NETT FTF | DOES2 | | | 50-70% | | 60.7 | | | 94.9 | 88.8 |
| Daewoo Mega 200 | Rubber Tire Loader | DCL FTF | DOES2 | | | >50% | | 28.8 | | -43.0 | 96.1 | 68.0 |
| Case 821 | Rubber Tire Loader | Extengine FTF | RAVEM | | | 50-70% | | 68.0 | 21.0 | n/a | 95.0 | n/a |
| Case 821 | Rubber Tire Loader | NETT FTF-SCR | RAVEM | | | 50-70% | 65%[c] | | 57.0 | n/a | >100 | n/a |
| Bobcat 863 | Skid steer loader | Airflow DOC | CATI | | | 20-25% | | 28.0 | 11.0 | n/a | 100.0 | 28.0 |
| Case 590 | Backhoe | NETT DOC | RAVEM | | | 20-25% | | | | n/a | >100 | n/a |

[a]as of November 19, 2009
[b]previously verified at this level(CARB and/or EPA)
[c]based on EPA Emerging Technology List for Nett Bluemax systems (11/19/2009)
[d]estimates provided by technology vendors
Emission reductions greater than 100% include subtraction of ambient background concentrations.
Positive values indicate an emissions reduction; negative values indicate an emissions increase.
"Blank" indicates results were not statistically significant.
"n/a" indicates data was not collected.

As Shown in Table S-2, the majority of the emission control technologies provided emission reductions on the order of, or greater than, the anticipated emission reductions. In several cases, additional emission impacts were observed (both emission reductions and emission increases), but were not statistically significant primarily as a result of variability in emission test results. It should also be noted that several catalyzed DPFs did produce statistically significant increases in $NO_2$ emissions during in use tests.

In all cases, in-use emissions testing procedures used in this project confirmed the verified performance of the emission control technology for the construction applications evaluated. This suggests that in-use testing using portable emission monitors can be used to assess performance of control technologies while in-use. These results also confirm the appropriateness of the control technology and construction equipment matches based on the principles outlined in this report by the engineering team to select these matches. Improvements in portable emissions monitoring systems may make this measurement and monitoring approach practical for validating or monitoring the use of control technologies for non-road or off-road applications, especially where performance is duty-cycle dependent.

Costs for the purchase and installation of each of the technologies were documented. The labor requirements by labor type, custom installation items (brackets, mounts, etc.) were also documented. Table S-3 provides a summary of the ECT costs and installation requirements. For several of the technologies, significant engineering, custom brackets and mounting hardware, and many labor hours were required to complete installations on the nonroad equipment. This was primarily due to requirements to mount technologies in tight spaces within the engine housing to prevent issues with line-of-sight for operators. If not designed as a direct muffler replacement, installation of these technologies can be labor and cost intensive in many cases. It should be noted that in several cases, installations included here were the first of their kind on the specific equipment used, which can result in additional engineering and installation efforts.

**Table S-3. ECT Costs and Installation Labor**

| Equip. Model | Equipment Type | DSNY Vehicle ID | ECT Mfr. | ECT Type[a] | Retail Cost, $ | EPA NCDC Funds, $ | Labor Hours[b], h | | | | Install cost[c], $ | More Info[d] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | A | B | C | D | | |
| Cat D400 | Dump truck | 66J -105 | JMI | DPF | $37123 | $4736 | 40 | | | | ~$4000 | ‡ |
| Cat D400 | Dump truck | 66J-103 | Huss | ADPF | $36498 | $8780 | 30 | 35 | 80 | 80 | $17835[e] | †, *, ‡ |
| Case 821 | Rubber tire loader | 21BH-206 | CleanAIR Systems | PDPF | $8948 | $7647 | 8 | 8 | 32 | -- | $5904 | †, * |
| Case 821 | Rubber tire loader | 21BY-119 | ECS | DPF | $7156 | $7156 | 16 | -- | 16 | -- | $3936 | †, * |
| Case 821 | Rubber tire loader | 21BH-106 | Donald-son | DPF | $7625 | $4640 | 8 | -- | 8 | 8 | $1968 | †, ‡ |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Case 821 | Rubber tire loader | 21BH-204 | ECS | DOC | $3291 | $3291 | -- | -- | 8 | -- | $984 | * |
| Case 821 | Rubber tire loader | 21BH-104 | ECS | DOC | $3291 | $3291 | -- | -- | 8 | -- | $984 | * |
| Mega 200V | Rubber tire loader | 21BY-101 | ECS | DPF | $7156 | $7156 | 8 | -- | 8 | -- | $1968 | * |
| Mega 200V | Rubber tire loader | 21BY-118 | ECS | DPF | $7156 | $7156 | 16 | -- | 16 | -- | $3936 | †, * |
| Mega 200V | Rubber tire loader | 21BY-014 | Donald-son | DPF | $7625 | $4690 | 8 | -- | 8 | -- | $1968 | ‡ |
| This ECT has not yet been installed. | | | ECS | DOC | $3291 | $3291 | -- | -- | -- | -- | -- | -- |
| | | | | *Total:* | *$121685* | *$61834* | -- | -- | -- | -- | *$39483* | -- |

[a] ECT nomenclature:
ADPF -- active diesel particulate filter
DPF -- diesel particulate filter (also known as PDPF for passive diesel particulate filter)
DOC -- diesel oxidation catalyst
[b] Labor description: A = electrician, B = blacksmith, C = mechanic, D = manufacturer's representative
[c] Does not include manufacturer's representative labor. DSNY average labor rate is $123 / h.
[d] See the following tables for more information:
† = brackets, custom parts listed in Table 5-3
* = installation notes in Table 5-3
‡ = maintenance or operations issues described in Table 5-4
[e] Huss currently requires that installation of its device be completed by a Huss technician or a trained and authorized Huss installer, for a cost of $6,260.

# INTRODUCTION

Diesel engines can be highly energy efficient and durable, yet emissions from diesel engines have historically contributed to a number of serious air pollution problems. Recognizing this, the U.S. Environmental Protection Agency (EPA) has passed regulations to reduce emissions from new diesel engines for on-road and, more recently, non-road applications. These regulations will also require the use of lower sulfur diesel fuel by on- and non-road vehicles, which were phased in beginning in 2006. Existing diesel engines, however, in the on-road and non-road inventory will continue to emit higher levels of pollutants, including particulate matter (PM), nitrogen oxides ($NO_x$), carbon monoxide (CO), and air toxins. Within New York State (NYS), diesel emissions significantly affect ambient air quality, which contributes to non-attainment of air quality standards in areas such as the New York City Metropolitan Area (NYCMA).

To address the issues associated with the legacy fleet of diesel engines, several local and state initiatives and laws which focus on reducing pollution from existing diesel engines, have been introduced.. As more voluntary programs are initiated, regulations enacted, and emission reductions sought, additional information regarding the various strategies for emission reductions is needed. As such, NYSERDA initiated a Non-Road Clean Diesel in-use testing program in March 2005. The program's goal is to demonstrate and evaluate the feasibility and performance of commercially available emission control technologies in reducing emissions of particulate matter (PM) and oxides of nitrogen ($NO_x$) from non-road equipment. This project seeks to provide detailed information to interested stakeholders, including end-users, regulators and others, regarding the performance of various emission control strategies on high-priority non-road equipment operated in NYS, and is part of a broader Clean Diesel Initiative at NYSERDA that supports the development of products and technologies to reduce emissions from diesel engines, as well as the deployment of emission control and idle-reduction technologies for school buses and other applications across NYS, and to demonstrate and evaluate various emission reduction strategies. This report is focused on the latter part of a larger project that was divided into four sections listed below:

- Emission inventory development and refinement
- Identification of high priority equipment
- Evaluation of technical, economic, and operational impacts of control strategies
- Field demonstrations

The Emission inventory development and refinement included the development of a baseline inventory for NYS and the NYCMA using EPA's NONROAD2004 model and data provided by NYSDEC, described in detail in the Interim Report identified below. In addition, separate surveys of diesel engine populations and use were also completed for the rail sector state wide and the construction sector in the NYCMA. These survey results are documented in two separate reports:

- *NYSERDA* *Non-Road Clean Diesel Demonstration: Interim Report* Southern Research Institute, February 2007 http://www.nyserda.org/publications/InterimReport_Final_2007-02-09.pdf

- *NYSERDA Clean Diesel Technology Non-Road Field Demonstration Program: Development of the 2002 Locomotive Survey for New York State.* Southern Research Institute. February, 2007. http://www.nyserda.org/publications/LocomotiveSurveyReportwithAppendices.pdf
- *NYSERDA Clean Diesel Technology Non-Road Field Demonstration Program: Development of the 2002 Construction Equipment Survey for the New York City Metropolitan Area.* Southern Research Institute. December, 2009.

Identification of high priority equipment included the evaluation of non-road equipment emissions and other factors to identify high-priority equipment targets via ranking of factors such as total pollutant emissions, emission rates, equipment activity, equipment population, costs, and other factors.

Evaluation of technical, economic, and operational impacts of control strategies consisted of the identification, evaluation, and ranking of control technologies based on factors such as control efficiency, cost, durability, fuel economy, installation and maintenance requirements, and other factors. Plus, the assessment of the future of diesel use and emissions in the non-road sector was also evaluated by considering the use of new technologies in the non-road sector that may impact diesel use, existing and future local, New York State, and federal regulations, the potential growth of areas in which diesel technologies are used in NYS, and other factors that may significantly impact diesel use.

Planning for field demonstrations includes the development of a demonstration program test matrix, structured to allow for testing a range of selected high priority sector equipment with a variety of the most feasible emission control technologies.

Goals of this field demonstration test program were to:

- demonstrate and evaluate the feasibility and performance of commercially available emission control technologies for the reduction of particulate matter (PM) and oxides of nitrogen ($NO_x$) emissions from non-road diesel equipment using in-use field testing approaches
- evaluate the performance of diesel emission control technologies (ECTs) on several pieces of non-road equipment operated by the DSNY
- evaluate ECT economic impacts, including costs, maintenance, and operations effects
- utilize integrated sampling systems (ISS) and portable emission measurement systems (PEMS) to evaluate emissions upstream and downstream of the control device
- evaluate the correlation between the two emission measurement methods

This report discusses the objectives identified above. The following sections present information regarding the baseline nonroad emission inventory estimates, fleet and host site selected for field demonstrations, the testing approach, analytical equipment used in testing, and the in-use duty cycle developed for testing. The report also summarizes field test results for each ECT and shows an analysis of ECT cost, installation, and operational performance.

In addition to the project specified above, the U.S. Environmental Protection Agency (EPA), provided a National Clean Diesel Campaign grant to NYSERDA to perform additional installations of EPA-verified technologies in the host fleet, including monitoring and tracking of equipment use, costs, operational impacts and emission reductions.

# NONROAD SECTOR EMISSION INVENTORY & CONTROL TECHNOLOGY ASSESSMENTS

## 1.1 PRIORITY EQUIPMENT & NON ROAD INVENTORY

To identify the highest priority equipment for the retrofit demonstration, NYSERDA evaluated a statewide and NYCMA emission inventory based on the calendar year 2002 data. This evaluation was based on using EPA's nonroad equipment population and allocation model NONROAD2004, described in the *NYSERDA Non-Road Clean Diesel Demonstration: Interim Report* (2007). The non-road sector, based on NONROAD2004 is responsible for a significant portion of emissions from all sectors, including on-road, area, and point source emissions. In NYS, the non-road sector is responsible for approximately 10% of all PM and 19% of all $NO_x$ emissions. In the NYCMA, the non-road sector comprises approximately 29% of all PM and 22% of all $NO_x$ emissions (Southern Research Institute, February, 2007).

To evaluate the role of different fuels in non-road sector emissions, comparisons were first made of statewide and NYCMA annual non-road emissions by fuel type. Table 2-1 summarizes non-road emissions for NYS. For all fuels, fuel consumption was normalized to BTUs so that a comparison between the fuel types could be made.

**Table 2-1. 2002 NYS Non-Road Emissions by Fuel Type**

| | THC, tpy | PM, tpy | $NO_x$, tpy | CO, tpy | Population, # of units | Activity, hours / year | Fuel Consumption, Btu / year |
|---|---|---|---|---|---|---|---|
| **CNG** | 4,925 | 8 | 1,651 | 6,549 | 5,082 | 5.27E+06 | 1.43E+12 |
| **Diesel** | 8,212 | 7,311 | 91,028 | 38,154 | 275,400 | 1.82E+08 | 6.51E+13 |
| **Gasoline, 2-stroke** | 78,572 | 3,790 | 1,300 | 171,455 | 2,883,446 | 2.15E+08 | 1.41E+13 |
| **Gasoline, 4-stroke** | 26,378 | 272 | 10,533 | 886,843 | 4,457,727 | 5.77E+08 | 2.77E+13 |
| **LPG** | 2,696 | 63 | 13,433 | 52,353 | 39,814 | 4.46E+07 | 1.06E+13 |
| **Residual** | 31 | 48 | 986 | 129 | -- | -- | -- |

Diesel fuel accounts for the largest percentage of non-road PM emissions (64%, or 7,311 tpy) and $NO_x$ emissions (77%, or 91,028 tpy) statewide. Similar results are seen for the NYCMA, with diesel responsible for 75% (3,949 tpy) of PM and 75% (44,432 tpy) of $NO_x$ non-road emissions (Southern Research Institute, February, 2007). These estimates are based on the NONROAD 2004 model using input assumptions set by NYSDEC.

The inventory was evaluated by sector, equipment type, and horsepower range to determine the equipment items that are the sources of the largest amounts of diesel pollution, most populous, and largest fuel consumers. The inventory analysis identified NYCMA construction and mining equipment as the primary sector of interest. NYCMA diesel construction and mining equipment account for 34% and 29% of the total NYS non-road diesel PM and $NO_x$ emissions, respectively. It also constitutes 63% and 59% of the total NYCMA non-road diesel PM and NOx emissions, respectively. To further narrow the target and identify specific equipment types of interest, an aggregated equipment-level inventory was developed. An initial set of priority equipment was identified for the construction equipment sector in the NYCMA. Figure 2-1 and Figure 2-2 summarize non-road diesel PM and $NO_x$ emissions for NYS and the NYCMA by non-road equipment type.

**Figure 2-1. 2002 NYS and NYCMA Non-Road Diesel PM Emissions by Equipment Type**

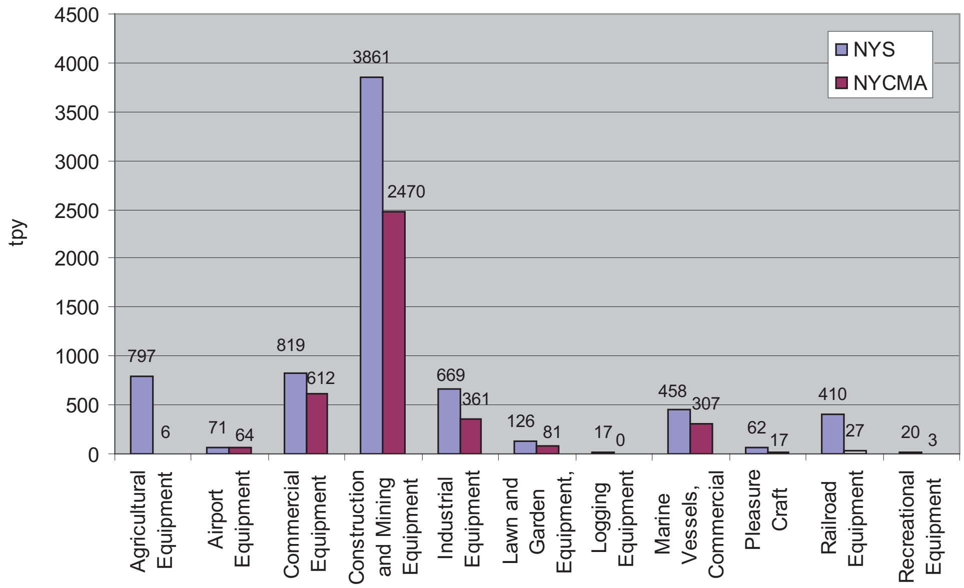
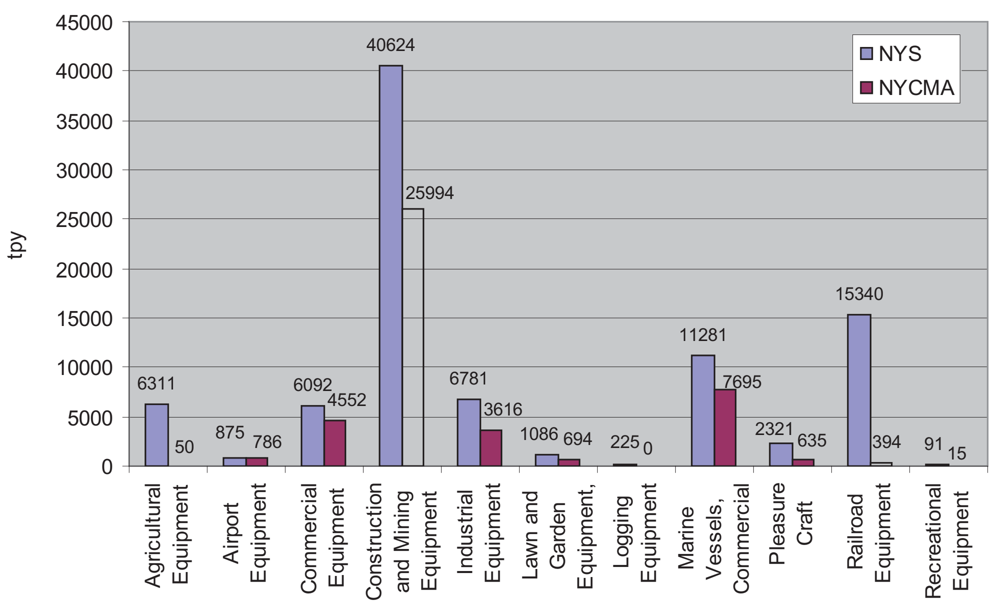



**Figure 2-2. 2002 NYS and NYCMA Non Road Diesel $NO_x$ Emissions by Equipment Type**




Five equipment types were responsible for nearly 50% of all of non-road diesel PM and NOx emissions in the NYCMA. Those equipment types include: Crawler Tractors/Dozers, Excavators, Rubber Tire Loaders, Skid Steer

Loaders, and Tractors/Loaders/Backhoes. Table 2-2 lists the top ten non-road diesel equipment emission sources in the NYCMA. Of these equipment types, rubber tire loaders 300 to 600 HP are the number-one ranked $NO_X$ emission source, and tractors/loaders/backhoes 75 to 100 HP are the number-one PM and CO source (Southern Research Institute, February, 2007).

**Table 2-2. Non-Road Diesel Construction Equipment Emission Sources in the NYCMA**

| Overall Rank | Equipment Type | Horsepower Range |
|---|---|---|
| 1 | Tractors/Loaders/Backhoes | 100 < HP <= 175 |
| 2 (No. 1 for CO & PM) | Tractors/Loaders/Backhoes | 75 < HP <= 100 |
| 3 (No. 1 in population) | Skid Steer Loaders | 50 < HP <= 75 |
| 4 | Skid Steer Loaders | 75 < HP <= 100 |
| 5 (No. 1 for $NO_x$) | Rubber Tire Loaders | 300 < HP <= 600 |
| 6 | Excavators | 100 < HP <= 175 |
| 7 | Rubber Tire Loaders | 175 < HP <= 300 |
| 8 | Rubber Tire Loaders | 100 < HP <= 175 |
| 9 | Rough Terrain Forklifts | 75 < HP <= 100 |
| 10 | Excavators | 175 < HP <= 300 |

A combined ranking of equipment types was completed to determine those types with the most significant overall air quality impacts. Ranking was completed only for diesel fueled equipment. Combined rankings were completed for both NYS and the NYCMA. The process began by developing rankings of emissions, fuel consumption, population, and activity for each equipment type and engine size, and ranking equipment from highest to lowest (for example, the largest single PM emitter received a number-one PM ranking). Individual parameter rankings provided the basis for the combined rankings of equipment, as well as insight into the types of equipment with impacts that may be of interest. Several sets of weighting factors were used to determine the impacts of weighting criteria on the combined rankings. The sets of weighting factors and cases were selected based on priorities of the NYSERDA program, including priority pollutants (PM, NOx), energy impacts (fuel consumption), and equipment population. The actual weighting factors used are shown in Table 2-3.

**Table 2-3. Weight Assignments for Each Parameter**

| Case / Parameter | CO | $NO_X$ | THC | PM | Fuel | Population | Activity |
|---|---|---|---|---|---|---|---|
| Case 1 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | -- | -- |
| Case 2 | 0.6 | 1.0 | 1.0 | 0.6 | 0.6 | 0.6 | 0.6 |
| Case 3 | 0.6 | 1.0 | 0.6 | 1.0 | -- | -- | -- |
| Case 4 | -- | 1.0 | -- | 1.0 | -- | -- | -- |

Regardless of weighting factors, the weighted rankings show similar equipment types within the top ranked items for all cases within the NYCMA and NYS. For example, the top 10 for every case of weighting criteria includes the following categories: tractors/loaders/backhoes, A/C and refrigeration, rubber tire loaders, skid steer loaders, off-highway trucks, and excavators. The order of rank changes slightly depending upon the weighting criteria; however, the equipment types and horsepower ranges included do not. A/C and refrigeration units were not included in the prioritization for demonstrations under this program, as shown in Table 2-2, to allow for a direct focus on the single primary sector responsible for the largest total quantity of diesel emissions in NYS and the NYCMA – construction; and because other NYSERDA programs have focused on clean refrigeration systems for the trucking industry.

Table 2-4 lists the priority equipment types and horsepower ranges to be addressed in the field demonstration portion of this project, based on the above considerations. The list represents a group of equipment of similar engine types and a variety of size ranges within similar sectors of use. Addressing similar equipment types or sectors (in this case, construction and mining equipment) allowed for a focused, efficient demonstration project using a small group of host sites with similar equipment duty cycles and configurations.

In developing the list of priority equipment types, analysts examined the NYS and NYCMA PM and NOx rankings for equipment type, as well as the emissions normalized by population. Several of the top ranked equipment types in the weighted rankings also appear among the highest in normalized rankings (for example, off-highway trucks, crawler tractors/dozers, excavators, rubber tire loaders, and graders). Not only do these equipment types rank highly when normalized by population, but they are also large contributors to annual PM and NOx emissions.

**Table 2-4. Recommended Priority Equipment for Field Demonstration**

| Sub-Category | SCC | Equipment Sector | Equipment Type | Hp |
|---|---|---|---|---|
| 1 | 2270002066 | Construction and Mining | Tractors / Loaders / Backhoes | 50 – 175 |
| | 2270002060 | Construction and Mining | Rubber Tire Loaders | 175 – 600 |
| | 2270002036 | Construction and Mining | Excavators | 75 – 300 |
| | 2270002051 | Construction and Mining | Off-highway Trucks | 1200 – 2000 |
| 2 | 2270002072 | Construction and Mining | Skid Steer Loaders | 40 – 100 |
| | 2270002069 | Construction and Mining | Crawler Tractor / Dozers | 75 – 300 |
| | 2270002060 | Construction and Mining | Rubber Tire Loaders | 75 – 175 |
| | 2270002069 | Construction and Mining | Crawler Tractor / Dozers | 300 – 750 |
| 3 | 2270002057 | Construction and Mining | Rough-Terrain Forklifts | 50 – 175 |
| | 2270002036 | Construction and Mining | Excavators | 300 – 600 |
| | 2270006005 / 2270006015 | Construction and Mining / Commercial | Generator Sets / Air Compressors | 40 – 100 |
| | 2270002048 | Construction and Mining | Graders | 75 – 300 |

The equipment types in Table 2-4 are grouped into three sub-categories. Those grouped in the first sub-category were considered the equipment types of highest priority for field testing and were the focus of the testing program. They were selected as the highest priority because of their high contributions to non-road diesel PM and NOx emissions, as well as the feasibility with which they can be retrofitted for emission control. The equipment types in the second sub-category were also of high priority, but slightly lesser so than those in sub-category-one. These equipment types rank slightly lower for non-road diesel PM and NOx emissions than those in sub-category one. Finally, the equipment types in sub-category-three were considered the lowest priority for field testing. These equipment types rank lowest for non-road diesel PM and NOx emission and may pose the most difficulties with emission control retrofits (Southern Research Institute, February, 2007).

# FIELD TEST PROGRAM DESIGN

To ensure the demonstration program addressed ECTs that provided the most effective emission reductions, NYSERDA evaluated the construction equipment population and emissions within the NYCMA, as well as the feasibility of various verified retrofit applications. The result of this analysis was the selection of the non-road equipment fleet for testing combined with selected ECTs as discussed below. Primary considerations for establishment of the demonstration program included the ability to match the priority equipment types identified in the inventory analysis with equipment available in NYCMA fleets, ability of host fleets to provide assistance and cooperation, and the ability to match emission control technologies with the selected fleet equipment. Primary considerations for the development of the test procedures focused on the development of an in-use testing procedure that captured impacts of the technologies in real world operating scenarios, used appropriate instrumentation to measure desired performance characteristics, and used a repeatable duty cycle that allowed for controlled testing, but that also represented actual vehicle operations as well. These considerations are further described in this section.

## 1.1 FLEET IDENTIFICATION

Criteria for selecting fleets to participate in the demonstration program included: fleet equipment inventory / availability of targeted equipment; equipment activity (fleets with more active equipment were preferred); equipment duties (common duty cycles are more widely applicable); fleet replacement rate (those with high turnover rates were less preferred); locations of work (fleets with equipment located near sensitive populations were preferred); and existence of an Environmental Management System, community based toxics reduction programs, air quality improvement policies, idle reduction policies, extensive O&M practices, or other policies and practices maintained by the fleet with the goal of reducing air emissions from diesel and other sources.

NYSERDA selected the New York City Department of Sanitation's (DSNY) fleet for the demonstration program. DSNY operates citywide, employing 59 district facilities and commanding a fleet of over 5,000 vehicles. DSNY has a large fleet of nearly 300 rubber tire loaders used mainly for lot cleaning, snow removal, and salt loading. These activities occur mainly during colder months, providing a high use of equipment during these time periods. The equipment available ranged in age from the 1990s to 2004, and included equipment from several manufacturers, such as: Caterpillar, Case, Daewoo, and others. DSNY's array of equipment represents different equipment types, ages, engine sizes, manufacturers, and duty cycles. The majority of their equipment is well within its useful life cycle, has significant activity levels, and is owned, operated, and maintained by DSNY. The replacement rate for their equipment is typically around 10 years. DSNY's varied pool of equipment allowed for demonstration of retrofits on a variety of applications in a single, well managed fleet.

Because DSNY is working everyday in every part of the city, its recognizable equipment and vehicles are highly visible and easily identified. Its equipment is used regularly in areas that are the current target of environmental justice grants and activities related to air pollution and impacts on asthma. DSNY has evaluated various data on their operations, including the proximity of its equipment fleet operations to schools, hospitals, and areas with high levels of asthma. Any reduction of emissions from diesel construction equipment would significantly benefit air quality and public health. DSNY was eager to serve as a host and model for other fleets to emulate, resulting in a reduction of the possible negative effects of non-road construction equipment in its fleet and helping to protect sensitive populations.

DSNY has also initiated many voluntary emission control strategies. The DSNY fleet is one of the first in the country to participate in the EPA's Voluntary Diesel Retrofit Program. Approximately one third of its fleet is equipped with various advanced diesel exhaust after-treatment technologies. In 2004, it voluntarily switched its entire diesel fleet to ultra-low sulfur diesel fuel, and in 2007, voluntarily converted to a B5 biodiesel blend. DSNY has also tested B20 biodiesel on a fleet of vehicles. DSNY also has a fleet of 500 flexible fuel vehicles, 250 hybrid electric vehicles, 26 compressed natural gas (CNG) powered collection trucks, and 29 CNG powered mechanical brooms. DSNY is also participating in a pilot project using hydrogen fuel cells to power a fleet of experimental vehicles. DSNY has rigorous operations and maintenance policies to adhere to, with ample shop space for maintaining the fleet. DSNY also recently built a heavy-duty chassis dynamometer facility for performing emissions research on its equipment. These significant activities are a strong indicator of DSNY's commitment to reducing emissions from its fleet through a variety of policies, voluntary programs, and managed practices.

The majority of field testing took place at the DSNY's Central Repair Shop located in Woodside, NY. The Central Repair Shop is primarily a repair, maintenance, upgrade, and modification facility for DSNY vehicles. Additional field testing took place at the Fresh Kills Landfill located in Staten Island, NY.

In addition, tests were undertaken to evaluate the in-use performance of biodiesel and high percentage biodiesel blends in non-road diesel construction equipment. A single piece of construction equipment was evaluated per the in-use test protocol while operating over a simple duty cycle using ultra-low sulfur diesel (ULSD), a 50% biodiesel-ULSD blend (B50), and 100% biodiesel (B100). Testing took place during September 10 – 12, 2007 at the Destiny USA Carousel Mall site in Syracuse, NY. The test fleet manager contacted NYSERDA, expressing an interest in evaluating its usage of biodiesel in large construction activities at the site. Based on the mutual interest in demonstrating biodiesel impacts and the availability of the fleet equipment for testing, the site was included in the test program. A Volvo L90F front end loader with a D6E LAE3 engine served as the test vehicle. Details regarding the test program are provided in the *In-Use Evaluation of Emissions From Non-Road Diesel Equipment Using Biodiesel Fuel* (Southern Research Institute , March, 2008).

## 1.2 EMISSION CONTROL TECHNOLOGY SELECTION

Emission control technology ratings and recommendations were completed as part of the first phase of the project. Detailed discussions are provided in the Interim Report (Southern Research Institute, February, 2007). ECT recommendations were based upon the following criteria and a qualitative weighting approach:

**Table 3-1. Technology Ranking Criteria (In Priority Order)**

| Criteria | Comments |
|---|---|
| Emissions Reduction Performance | For PM and NOx, primarily. Based on available data. |
| Commercial Availability | Incorporates history of deployment in non-road applications |
| Durability | Incorporates regulatory compliance concerns as well as fleets operations downtime impacts |
| Cost – Unit | Based on manufacturer supplied information and literature. |
| Cost – Maintenance & Operation | Incorporates variable costs such as fuel penalty or urea consumption |
| Cost – Installation | Incorporates ease of installation and custom installation costs |
| User Acceptance By Fleets And Equipment Operators | Based on literature and anecdotal information. |
| ARB or EPA Certified / Verified | (Additives also based on TxLED approval) |

A series of ranking tables were developed for each of the following potential types of technologies:

- Diesel Particulate Filters (DPF) - Wall Flow
    - Non-catalyzed
    - Catalyzed
- DOC + DPF (i.e. CRT, CCRT)
- Active DPF (catalyzed and non-catalyzed)
    - Shore power regeneration
    - On board electrical regeneration
    - On board catalytic fuel combustion
    - On board fuel burner
- DPF with Fuel Borne Catalyst
- Diesel Particulate Filter - Flow Through (FTF)
    - Honeycomb
    - Wire mesh
    - Other (i.e. sintered metal)
- Diesel Oxidation Catalyst
- Closed Crankcase Ventilation
- Selective Catalytic Reduction (SCR) - Urea Injection
    - With and without DPF
- Lean Nox Catalysts (with DPF)
- Engine Repower
- Engine Rebuild Kits
- Exhaust Gas Recirculation (with DPF)
- Fuel additives
    - Non-metallic
    - Metallic

- Alternative Fuels
    - Biodiesel
    - E-diesel (ethanol)
    - Water Emulsions
- Idle Reduction Technologies

Other technologies were evaluated, but were not considered commercially viable or not economically viable alternatives for the majority of fleets in the region, including technology such as homogeneous charge compression ignition engines, diesel-electric hybrids, fuel cells, gasoline, LPG, CNG engines, etc.

The above technologies were evaluated according to a series of criteria in terms of direct feasibility issues. The technology ranking parameters were as follows:

- Engine/chassis configuration
    - Space constraints
    - Movement challenges: many machines, such as excavators in particular, operate under complex movement patterns or regimes, that further complicate control technology deployment
    - Operator sight-line constraints
- Engine horsepower
    - High-horsepower engines make technology sizing (such as DPFs) more challenging, with correspondingly increased installation complexity
    - Lower horsepower engines may produce insufficiently low exhaust gas temperatures for proper operation of many aftertreatment technologies such as DPFs and SCR
- Machine duty-cycle
    - Compromises predictable and/or sufficiently elevated exhaust gas temperatures

In addition, each technology was evaluated based on cost (capital, installation, operating, maintenance), and potential for emission reductions (i.e. percent control).

Verification status by EPA or California Air Resource Board (CARB) was also considered. EPA and CARB maintain lists of verified diesel retrofit technologies. To qualify for EPA or CARB funding programs that support the installation of diesel retrofit technologies, as well as many other programs that use the verification lists, diesel retrofits must undergo a rigorous testing program to determine the performance of the technologies on specific engine types and applications. Based on the results of the testing programs, EPA specifies a verified PM, CO, THC and NOx reduction level for each listed technology. CARB uses the test results to categorize the retrofit technologies according to the verified level of emission control achievable by the technology. CARB verifies technologies at three levels:

- Level 3 verified technologies achieve >85% PM reduction
- Level 2 verified technologies achieve greater than 50% PM emissions reduction, but less than 85%
- Level 1 verified technologies achieve greater than 25% PM reduction, but less than 50%

In addition, CARB and EPA instituted a requirement in 2009 specifying that verified diesel ECTs cannot increase $NO_2$ emissions from an engine by more than 20% vs. the baseline case for that specific engine.

Still, for the NYSERDA program, verification status was not a requirement for participation, as the intent was to evaluate commercially available technologies, many of which have not yet been verified or have been verified in other equipment/vehicle applications. Other impacts, such as fuel penalties, operational impacts, etc. were also considered.

Details regarding the ECT feasibility evaluation, ranking and selection are provided in the *NYSERDA Clean Diesel Technology: Non-Road Field Demonstration Program – Interim Report* (Southern Research Institute, February, 2007).

There exists an inherent challenge in trying to rank technologies for a wide variety of machines with diverse engine/chassis configurations, engine power ratings and operating profiles, each of which, when judged both separately and in combinations, affects the viability of specific technologies in different ways. For example, at one end of the spectrum, application of many technologies to stationary machines such as compressors, generators and pumps is straightforward. Since engine horsepower is typically low (less than 300), the non-mobile chassis is amenable to even the most complex installations such as SCR, and the quasi-steady state duty-cycle (typically constant-speed with predicable variable load) attenuates exhaust temperature excursions that can compromise the performance effectiveness of many aftertreatment devices. At the other end of the spectrum, on the other hand, are large machines with complex engine/chassis configurations, high horsepower ratings, and highly variable duty cycles, which when taken together, diminish the feasibility of deployment and performance efficiency of otherwise attractive technology options.

Based on the feasibility assessment and ECT ranking, control technologies recommended for the field demonstration as the primary, most feasible technologies with significant potential emission impacts, and acceptable by fleet managers, were identified as follows:

- PM Control Technologies:
  - Catalyzed DPFs – on all priority equipment types
  - DOC + DPF (CRT / CCRT) – on all priority equipment types
  - Active DPF – on large equipment with variable duty cycles
  - Flow Through Filters – on all priority equipment, with a focus on smaller, lower horsepower equipment (i.e. backhoe, skid steer, loader)
  - Diesel oxidation catalysts on small, lower horsepower equipment only (i.e. skid steer, backhoes)
- PM & NOx Combination Control Technologies

  - o Urea SCR + DPF – on medium to large, heavily used equipment
- Fuels and Additives Technologies
  - o Biodiesel

Once technology categories were selected, technology vendors were contacted regarding participation in the field demonstration program.

Vendors were provided exhaust temperature profile data from the fleet equipment proposed for the demonstration program, if requested. Exhaust temperature was monitored and data-logged over several hours for equipment being used in its normal operation by the DSNY. These operations included lot clearing and debris loading activities performed by loaders. Vendors used the data provided to determine if the equipment duty cycles met specified minimum exhaust temperature criteria required for regeneration of catalysts.

Once vendors determined that equipment installations were feasible for the specified equipment types participating in the program at the DSNY fleet, quotes were provided by vendors for each ECT installation. In many cases, vendors provided the ECTS at no cost or at a significant discount. In addition, funding from the EPA National Clean Diesel Campaign allowed for the purchase of additional ECTs for demonstration as well. Those equipment items that met the feasibility criteria and provided the best fund use for the demonstration program were selected for participation.

## 1.3 TESTING APPROACH

The testing approach was based on the *Generic In-Use Test Protocol for Non-road Equipment* (generic protocol) developed by Southern for NYSERDA (Southern Research Institute, November, 2007). The generic protocol provides overall test campaign designs, procedures for developing duty cycles, instrument specifications, step-by-step test procedures, and analytical techniques. Site-specific protocols were written to provide information about individual test sites, non-road diesel construction equipment, emission control strategies, and other details unique to a particular test campaign.

### 1.3.1 Testing Protocol Development

Non-road equipment emissions under real field conditions may vary considerably from those seen during laboratory testing. Regulators, engine manufacturers, and control strategy developers have expressed an increasing need for in-use emissions testing data, which would facilitate new designs, estimate impacts from fleet aging and retrofit options enhance regulatory compliance activities, or to meet other needs. The generic protocol provides a consistent in-use testing approach for evaluation of vehicle emissions while non-road equipment is performing actual work. This protocol is applicable to any diesel fueled non-road equipment powered by mechanically-controlled engines or electronically-controlled engines equipped with engine control modules (ECM). Engines may be naturally aspirated, turbocharged, or equipped with exhaust gas recirculation-equipped (EGR) The testing concepts of the protocol may be extended to other transportation sectors such as marine, locomotive, stationary, or on-highway vehicles with suitable modifications. The generic protocol provides overall test campaign designs, procedures for developing simple, synthesized, and in-use duty cycles, instrument specifications, step-by-step test procedures, and analytical techniques.

Based on the generic protocol, site-specific protocols provide information about individual test sites, non-road equipment, control strategies, and other details unique to a particular test campaign. For this case, the protocol guidelines were followed and a simple cycle was developed based on an actual in-use cycle for the field testing program at DSNY (Southern Research Institute, May, 2007). Proper implementation of the protocol and associated site-specific protocols allow the assessment of control strategy performance, in-use emissions, extended interval performance trends, and comparisons between different types of emissions measurement equipment, including portable emissions monitoring systems (PEMS) and portable integrated bag- or filter-sampling systems (ISS). PEMS units include constant-volume sampling equipment for gaseous emissions or partial flow proportional dilution sampling systems (DSS) for gaseous and particulate emissions.

### 1.3.2 Test Site Duty Cycle Development

Duty cycles are detailed descriptions of the non-road equipment maneuvers during testing. Non-road equipment maneuvers may be described as individual "events" such as backing, travel forward, bucket extension, or digging, etc. Composite events consist of a combination of individual events over varying time periods. A rubber-tired loader, for example, may combine simple forward travel, reverse travel, bucket extension, tilting, and lifting events over a repeatable time period into a single "load bucket" composite event. A *simple* duty cycle is an arbitrary arrangement of single or composite events of specified duration performed in sequence under controlled conditions. The simple cycle should:

- be representative of a typical work activity
- last between 1/4 and 1 hour to allow a reasonable number of test runs during a typical day
- be repeatable as determined by the appropriate cycle criteria

Southern personnel developed a simple duty cycle for construction equipment used in testing by observing the equipment in normal operation. Test personnel logged the events that comprised equipment maneuvers and organized them into a repeatable cycle. Tables 3-2 and 3-3 show the events logged during in-use equipment observation and the corresponding duty cycle developed for all equipment tested at the Central Repair Shop (rubber tire loaders and skid steer loaders). These vehicles are used heavily during the winter for snow removal and salt loading, and during the summer for lot clearing. Tables 3-4 and 3-5 show the events logged during in-use observation and the corresponding duty cycle developed for all equipment (off-road dump trucks) tested at the Fresh Kills site. These vehicles are used for regular hauling of materials throughout the landfill site. A cycle similar to the loader cycle was used for the biodiesel testing at the Destiny USA site.

**Table 3-2. Events Logged During In-Use Operations of Rubber Tire Loader at the Central Repair Shop**

| Event_ID | Description |
|---|---|
| A.1 | Begin at starting Point A, approx. 50 feet from salt pile |
| A.2 | Forward Travel Unloaded: Begin at Point A – Lift bucket and move forward in 2nd gear to pile (Point B) with bucket down. |
| A.3 | Fill: At Point B – Crowd pile and fill bucket. |
| A.4 | Reverse Travel Loaded: At Point B – Reverse gear, travel backward loaded with bucket at mid-height back to Point A. |
| A.5 | Forward Travel Loaded: At Point A – Move forward in 2nd gear with bucket at mid-height back to pile (Point B). |
| A.6 | Dump: Raise bucket to full height at pile (Point B) and dump. |
| A.7 | Reverse Travel Unloaded: At Point B – Travel backward unloaded to Point A, lowering bucket and coming to a full stop. |
| B | Idle with bucket down. |
| Series A | Composite of events A.1 – A.7 |

**Table 3-3. Duty Cycle for Rubber Tire Loader Equipment Tested at the Central Repair Shop**

| Event_ID | Description | Approx. Duration (mm:ss) |
|---|---|---|
| B | Idle with bucket down for 1 minute | 01:00 |
| Series A | Perform Series A (1 of 5 times) | 01:10 |
| Series A | Perform Series A (2 of 5 times) | 01:10 |
| Series A | Perform Series A (3 of 5 times) | 01:10 |
| Series A | Perform Series A (4 of 5 times) | 01:10 |
| Series A | Perform Series A (5 of 5 times) | 01:10 |
| B | Idle with bucket down for 1 minute | 01:00 |
| Series A | Perform Series A (1 of 5 times) | 01:10 |
| Series A | Perform Series A (2 of 5 times) | 01:10 |
| Series A | Perform Series A (3 of 5 times) | 01:10 |
| Series A | Perform Series A (4 of 5 times) | 01:10 |
| Series A | Perform Series A (5 of 5 times) | 01:10 |
| B | Idle with bucket down for 1 minute | 01:00 |
| Series A | Perform Series A (1 of 5 times) | 01:10 |
| Series A | Perform Series A (2 of 5 times) | 01:10 |
| Series A | Perform Series A (3 of 5 times) | 01:10 |
| Series A | Perform Series A (4 of 5 times) | 01:10 |
| Series A | Perform Series A (5 of 5 times) | 01:10 |
| B | Idle with bucket down for 1 minute | 01:00 |
| | **Total Duty Cycle** | **21:30** |

**Table 3-4. Events Logged During In-Use Operations of an Off Road Truck at the Fresh Kills Landfill**

| Event_ID | Description |
|---|---|
| A.1 | Begin at loading site and idle while dump truck is loaded. |
| A.2 | Travel (loaded) to dump location. |
| A.3 | Raise truck bed to dump, moving forward slightly while dumping to spread load; Lower truck bed. |
| A.4 | Travel (unloaded) back to loading site. |
| B | Idle (unloaded). |
| Series A | Composite of events A.1 – A.4 |

**Table 3-5. Duty Cycle for Off-Road Truck Equipment Tested at the Fresh Kills Landfill**

| Event_ID | Description | Approx. Duration (mm:ss) |
|---|---|---|
| B | Idle while unloaded for 1 minute | 01:00 |
| Series A | Perform Series A one time | 10:00 |
| B | Idle while unloaded for 1 minute | 01:00 |
| | **Total Duty Cycle** | **12:00** |

Evaluations performed on equipment at the Fresh Kills Landfill used an actual in-use duty cycle – performance of the vehicle's normal work cycle throughout the day. This was selected for two reasons: (1) the repeatability of the normal cycle in terms of time and use and (2) the difficulty in removing the vehicles from service for long testing periods. For this method of testing there were a number of uncontrolled events. For example, in some cases, other trucks had the right-of-way, requiring test vehicles to stop. In other cases, test vehicles were required to follow a slightly different route, based on unloading requirements at slightly different locations. Nevertheless, after logging each event (loading, travel, dumping, and travel back to the loading site) the cycle times were within the required statistical limits of variation.

### 1.3.3 Test Schedule

Testing occurred in three phases based on the installation schedule for the ECTs and the availability of the testing organizations and the test site. The three phases took place on the following dates, with the biodiesel testing program occurring at a separate time:

- Phase I: May 29, 2007 to June 7, 2007
- Phase II: June 18, 2007 to June 22, 2007
- Phase III: May 30, 2008 to June 6, 2008
- Biodiesel Tests: September 10, 2007 to September 12, 2007

### 1.3.4 Analytical Equipment

This project incorporated the following types of performance tests: control strategy performance tests with portable emissions measurement systems (PEMS) and integrated sampling systems (ISS); and emissions measurement comparisons between PEMS and ISS. Test personnel evaluated ECT performance using both PEMS and ISS.

Phases I and II of testing used a Horiba OBS-2200 and a Clean Air Technologies International (CATI) system for PEMS testing. Environment Canada's Dynamic Off-Road Emissions Sampling System (DOES2) served as the ISS during Phases I and II. Phase III of testing used Engine, Fuels, & Emissions Engineering's (EF&EE) Ride Along Vehicle Emissions Measurement (RAVEM) system.

The Horiba OBS-2200 [2] is an on-board emission measurement system that analyzes vehicle emissions in real-world conditions in real time. It consists of compact vibration proof gas analyzers, a laptop personal computer programmed to control the system and data logging, heated tailpipe exhaust transfer line, and a Pitot tube for exhaust flow measurement. Carbon monoxide and carbon dioxide are measured by a NDIR analyzer without water extraction, total hydrocarbon concentrations are measured by a FID detector, and the NOx concentration is measured by a chemiluminescence detector. A GPS is used to track equipment movement and is logged into the computer. Time-trend profiles and integrated values can also be obtained for both mass emission and fuel consumption. The Horiba PEMS system generally conforms to 40 CFR 1065 requirements for in-use field testing of engine emissions. Accuracy for all analyses is better than ± 2.5 % full scale (FS), while linearity is better than ± 1.0 % FS. Figure 3-1 shows the Horiba OBS-2200 installed for in-use testing and Table 3-6 shows the Horiba OBD PEMs system specifications.

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**Figure 3-1. Horiba OBS-2200 PEMS**

**Table 3-6. Horiba OBD PEMs System Specifications**

<table>
<tr><th></th><th>Inputs - (range)</th><th>OBS 2200</th><th>Logging Frequency</th><th>Accuracy</th><th>Repeatability</th></tr>
<tr><td rowspan="6">Measuring components/ input signals</td><td>CO (0 – 10%)</td><td>HNDIR (wet)</td><td rowspan="6">1 Hz</td><td rowspan="4">+/- 2.5% of full scale</td><td rowspan="4">+/- 1.0% of full scale</td></tr>
<tr><td>$CO_2$ (0 – 20%)</td><td>HNDIR (wet)</td></tr>
<tr><td>THC (0 – 10,000 ppmC)</td><td>HFID (wet)</td></tr>
<tr><td>$NO_x$/NO (0 – 3000 ppm)</td><td>HCLD (wet)</td></tr>
<tr><td>Exhaust flow (0 – 65$m^3$/min)</td><td>Pitot flow meter</td><td>+/- 1.5% of full scale or 2.5% of reading</td><td>2.0% of reading</td></tr>
<tr><td>Exhaust Temperature (0 – 800$^o$C)</td><td>Pitot thermocouple</td><td>+/- 1.0% of full scale</td><td>+/- 1.0%</td></tr>
</table>

| | Inputs - (range) | OBS 2200 | Logging Frequency | Accuracy | Repeatability |
|---|---|---|---|---|---|
| | Ambient Temperature (0 – 40°C) | Temperature Station | | +/- 1.5% at 23oC | +/- 1.0% |
| | Atmospheric Pressure (0 – 115kPa) | Pressure Station | | 1.5% of full scale | +/- 1.5% |
| | Ambient Humidity (0 – 100%) | Humidity Station | | +/- 0.3oC at 23oC | +/- 1.5% |
| | GPS Signals $10^{-6}$ resolution | Standard Input | | 10-6 degree resolution | N/A |
| | OBD Data | Standard Input | | | |
| **System Specification** | Power supply | 20V to 30V DC | | | |
| | Power consumption | Approx. 0.5 kW | | | |
| | Dimension | 350(W)x330(H)x500(D) mm | | | |
| | Weight | 29 kg | | | |
| | Recommended Battery | Deep cycle, 24V DC | | | |
| **Application** | Diesel Vehicles | Yes | | | |
| | Gasoline, LPG and CNG | Yes | | | |
| | FR 1065 subpart J Conformity | Yes | | | |

The following data can be displayed in real time and logged to a file:

- Concentration of CO, $CO_2$, THC, and $NO_x$
- Exhaust flow rate [$m^3$/min]
- Exhaust Temperature [ºC]
- Exhaust pressure [kPa]
- Ambient Temperature [ºC]
- Atm. pressure [kPa]
- Ambient humidity (relative humidity) [%]
- GPS velocity [km/h]; Altitude [m]; Position
- External inputs (optional)
- OBD inputs (optional)

The following items can be calculated and displayed in real time and logged to file based on the above measurements:

- Mass emission of CO, $CO_2$, THC, and $NO_x$ [g/s, g/h]
- Fuel consumption [g/s]
- Fuel economy [km/L, mile/L, L/100km, g/kWh or g/bhph]
- A/F (calculated by carbon balance method)
- Power [kW] (calculated from engine speed and torque/%torque, if available)

Values input to the system by users and used in calculations are as follows:

- Time alignment delay of CO, $CO_2$, THC, $NO_x$ analyzer response
- H,C, O content and density of fuel

The following calculated data (for a complete test cycle) can be calculated, displayed, and logged to file using input data:

- Mass emission of CO, $CO_2$, THC and $NO_x$ [g]
- Fuel consumption [g]
- Fuel economy [km/L, g/mile, L/100km, g/kWh or g/bhph]
- Traveling distance [km]
- Work [kWh]

The CATI OEM 2100 PEMS measures second-by-second mass emissions from vehicle tailpipes with electronically controlled spark ignition and compression ignition engines. The unit provides $NO_x$, CO, $CO_2$, $O_2$, PM readings for diesel vehicles. The unit provides second-by-second emissions, fuel consumption, vehicle speed, engine rpm and temperature, throttle position, and other parameters. The CATI PEMS includes: Touch-screen computer (256MB RAM, USB, Serial, Parallel, Network Ports) · Dual Gas Analyzer $NO_x$, CO, $CO_2$, $O_2$ · Light-Duty Engine Scanner · Heavy-Duty Engine Scanner · Sensor Array (for nonelectronically controlled vehicles) · Particulate Matter (PM) Monitor (diesel only);· Weatherproof Case · Keyboard · Back-up Battery. The unit weighs 44lbs. The system uses power directly from a vehicle's 12V or 24V electrical system, consuming 8 amps at 12V DC, or AC power can be used in the case of stationary testing. Engine data can be sensed directly, using an array of analytical sensors. This method involves attaching several analog sensors to the engine itself. For vehicles with a supported computer diagnostic port, engine and vehicle data is acquired using this interface. The unit is equipped with ECU scanners that will communicate with the ECU and obtain any needed engine parameters. The diagnostic port interface cable is routed directly to the unit from the port connector. For sensor array installations, sensors are installed on the applicable engine systems, and are then routed to the unit.

The CATI PEMS measures ppm/second emission data. Theoretical exhaust flow is calculated using engine parameters read from the vehicle's engine control unit or the sensor array. Emission results are calculated by combining the theoretical exhaust flow and the collected ppm/second emission data. Results are reported in grams/second format. From the intake air mass flow, known composition of intake air, measured composition of exhaust, and user supplied composition of fuel, a second by second exhaust mass flow is calculated. Engine power output can be estimated based on ECU torque readings and/or using the fuel consumption and engine rpm data, and the manufacturer's brake specific fuel consumption charts. Figure 3-2 shows the CATI system installed for in-use testing and Table 3-7 shows the instruments specifications.

Figure 3-2. CATI PEMS

**Table 3-7. CATI Montana PEMs System Specifications**

| | Inputs - (range) | CATI | Logging Frequency | Accuracy |
|---|---|---|---|---|
| Measuring components/ input signals | CO 0 – 10.00 %<br>10.01 – 15.00 % | NDIR | 1 Hz | ±0.02 % absolute or ±3% relative<br>±5% relative |
| | $CO_2$ 0 – 16.00 %<br>16.01 – 20.00 % | NDIR | | ±0.3 % absolute or ±3% relative<br>±5% relative |
| | HC hexane 0 – 2000 ppm<br>2001 – 15000 ppm<br>15001 – 30000 ppm | NDIR | | ±4 ppm absolute or ±3% relative<br>±5% relative ±8% relative |
| | $NO_x$ 0 – 4000 ppm<br>001 – 5000 ppm | Electrochemical Sensor | | ±25 ppm absolute or ±4% relative<br>±5% relative |
| | $O_2$ (0 - 25%) | Electrochemical Sensor | | ±0.1 % absolute or ±3% relative |
| | Total Particles | Light Scattering | | N/A |
| | Exhaust flow | Calculated | | N/A |
| | GPS Signals $10^{-6}$ resolution | Standard Input | | 10-6 degree resolution |
| | OBD Data | Standard Input | | N/A |
| System Specification | Power supply | 20V to 30V DC | | |
| | Power consumption | Approx. 0.5 kW | | |
| | Dimension | 21(W)x9(H)x17(D) inch | | |
| | Weight | 44 lbs | | |
| | Recommended Battery | 12V DC at 8 amps | | |
| Application | Diesel Vehicles | Yes | | |
| | Gasoline, LPG and CNG | Yes | | |

Environment Canada's DOES2 system collects and analyzes exhaust from diesel construction equipment in a manner similar to a traditional laboratory, except that it is portable. The DOES2 conforms to the 40 CFR Part 86 standards for exhaust emission testing. The DOES2 system collects a known quantity of a sample of raw exhaust from the exhaust system of an engine and uses dilution tunnel technology to mix this with a known quantity of ambient dilution air. In addition, the sample line is maintained at 375 +/- 20 °F. Diluting the raw exhaust with ambient air, while maintaining a constant temperature and flow velocity, conditions the sample and minimizes condensation. A dilution pump draws ambient air through a 47 mm pre-filter in order to remove any ambient particulate material and then through a variable flow solenoid valve to control the flow rate of the preconditioned dilution air. This air then goes through the dilution pump and is pushed back into a plenum located in the DOES2 and eventually through the dilution air Laminar Flow Element (LFE), which is used to measure the flow rate. The dilution air is introduced into the dilution tunnel at a point approximately three inches from where the vehicle exhaust is introduced. Both streams then pass through a mixing orifice and are thoroughly mixed as they travel approximately 10 tunnel diameters where they reach a number of sample probes. Each probe is connected to a particulate filter that traps PM but allows for the dilute exhaust gas to continue. The amount of diluted exhaust is drawn, using small 5L vacuum pumps, and is set and maintained by separate 2 L/min mass flow controllers. The diluted sample is collected at the end of the sample line in tedlar bags or cartridges. This technique is used in order to determine average weighted emission rates over a test cycle. During operation, the engine functions under various speed and load conditions. As a result, the volume of exhaust varies, as does the concentration of the pollutants. In order to accurately measure the emissions under transient conditions, proportional sampling is employed. This is accomplished by varying the flow rate of the dilution air, indirectly with the volumetric engine inlet air flow. The instantaneous volume of dilution air is determined from the ratio of the engine inlet air mass at any given instant to the engine inlet air mass point at idle. During testing, the air flow rates are measured by a mass air flow sensor connected to the engine air inlet. The DOES2 uses a LFE for air flow, determined on a per second time base. Prior to commencing the actual test sequence the engine inlet air volume is measured with the engine at idle. The DOES2 system is mounted on the test equipment, and like most PEMs units may be cumbersome depending upon space requirements of the equipment and working area.

The instrument setup for the DOES2 is shown in Figure 3-3 on one of the rubber tire loaders. When mounting the main DOES2 enclosure, the concerns of keeping it safe from heat or cold, electrical shock, excessive vibration, and contamination from the vehicle or generator exhaust must be considered. It must also be located such that the heated sample line and electrical connections will easily reach the unit. Although not necessary, the vacuum pump enclosure should be located close to the main DOES2 box.

The primary advantage to this equipment is that it provides laboratory specification equipment in a portable package. The evaluation of the emissions from the dilute exhaust stream is performed by collecting a sample over the test cycle in a tedlar bag for gaseous emissions and filters for PM and EC/OC. The tedlar bag and PM filters are removed from the DOES2 and analyzed using the laboratory instrumentation described in Table 3-8 below. The analysis bench is manually operated and consists of the following instruments.

**Table 3-8. Environment Canada Test Instrumentation Specifications**

| | Parameter | Sensor Mfg | Model | Logging Frequency | Accuracy | Repeatability |
|---|---|---|---|---|---|---|
| Laboratory Reference Method | CO | Horiba | AIA-210 LE | 1 Hz | 2% of point or 1% of measure | 1% of point or 1% of measure |
| | $CO_2$ | Horiba | OPE-115 | | | |
| | NOx | California Analytical Instruments | 400-HCLD | | | |
| | NO | California Analytical Instruments | 400-HCLD | | | |
| | THC | California Analytical Instruments | 300M-HFID | | | |
| | PM filter weight | Sartorius | M5P-000V001 | n/a[a] | | |
| | Gravimetric PM filters | 70 mm Emfab TX40HI20-WW & 47 mm Teflon membrane | | n/a | n/a | n/a |
| | EC/OC filters | 47 mm fired Quartz – Pall Tissuquartz 2500QAT-UP | | n/a | n/a | n/a |
| Environment Canada DOES2 (Field Reference Method) | Instrumental analyzer concentration | Environment Canada | DOES2 | 1 Hz | 2.0 % of point | 1.0 % of point |
| | Gravimetric TPM balance | | | n/a | 0.1 % | 0.5 µg |
| | Main flow rate | | | >1 Hz | 1.0 % FS[b] | n/a |
| | Dilution air flow rate | | | | | |
| | Sample flow rate | | | | | |
| | Differential pressure (if used) | | | | | |
| | Exhaust flow characterization | Environment Canada LFE | | | | |
| | Gravimetric PM filters | 70 mm Emfab TX40HI20-WW & 47 mm Teflon membrane | | n/a | n/a | n/a |
| | EC/OC filters | 47 mm fired Quartz – Pall Tissuquartz 2500QAT-UP | | n/a | n/a | n/a |

[a] Not applicable (n/a)
[b] Full scale (FS)

**Figure 3-3. Environment Canada DOES2 ISS**


The Ride-Along Vehicle Emissions Measurement (RAVEM) system is capable of measuring PM as well as $NO_x$, CO, and $CO_2$. Optional capabilities also allow the measurement and quantification of total hydrocarbons (THC), sulfur dioxide ($SO_2$), ammonia ($NH_3$), and nitrous oxide ($N_2O$), as well as individual species of volatile organic compounds (VOC) and carbonyls such as formaldehyde, acetaldehyde, and acrolein.

The RAVEM system is based on proportional partial-flow constant volume sampling (CVS) from the vehicle exhaust pipe. The CVS principle is widely used for vehicle emission measurements because the air dilution and total flow arrangements are such that the pollutant concentration in the CVS dilution tunnel is proportional to the pollutant mass flow rate in the vehicle exhaust. The total pollutant mass emissions over a given driving cycle are equal to the integral of the pollutant mass flow rate over that cycle. In a CVS system, this integrated value can readily be determined by integrating the concentration measurement alone. The CVS flow rate enters into the calculation as a constant multiplier. The integration of pollutant concentration can be accomplished either numerically or physically. For gases, the RAVEM system uses both numerical and physical integration. Concentrations of $NO_x$, $CO_2$, and CO in the dilute exhaust gas are measured and recorded second-by-second during each test. In addition, integrated samples of the dilute exhaust mixture and dilution air are collected in Tedlar® bags during the test, and analyzed afterward for $NO_x$, $CO_2$, CO and (optionally) other pollutants. Except for the isokinetic sampling system, the RAVEM system closely resembles a conventional single-dilution CVS emission measurement system. Figure 3-4 shows the RAVEM system installed on a rubber tire loader.

**Figure 3-4. EF&EE RAVEM System**

The basic principle of the RAVEM is its sampling system extracts and dilutes only a small, constant fraction of the total exhaust flow. The dilution air requirements and dilution tunnel size can thus be reduced to levels compatible with portable operation. The patented isokinetic proportional sampling system continuously adjusts the sample flow rate so that the flow velocity in the sample probe is equal to that of the surrounding exhaust. Since the velocities are equal ("isokinetic"), the ratio of the flow rates in the exhaust pipe and the sample probe is equal to the ratio of their cross-sectional areas. Pollutant concentration measurements in the RAVEM system follow the methods specified by the U.S. EPA (US CFR Vol 40 Part 86) and ISO standard 8178. The pollutants measured include: oxides of nitrogen ($NO_x$) by chemilumenescent analysis of the dilute exhaust sample (a 0-100 ppm range is normally used, but ranges from 0-10 to 0-3000 ppm are available); carbon monoxide (CO) and carbon dioxide ($CO_2$) by non-dispersive infrared analysis of the dehumidified dilute exhaust sample (a 0-200 ppm range is normally used for CO, but a 0-500 ppm range is available; for $CO_2$, the 0-6000 ppm range is normally used, 0-2000 and 0- 10,000 ppm ranges are also available); particulate matter (PM) – measured by passing the dilute exhaust sample through pre-weighed 47 mm filters of Teflon-coated borosilicate glass fiber, followed by post-conditioning and reweighing. The minimum detectable PM filter mass is approximately 10 micrograms, the maximum practical mass on the filter is more than 3000 micrograms. Filter and CVS flow rates can also be adjusted to increase PM sensitivity or avoid PM overloading. Table 3-9 lists the instrument and sensor accuracy specifications recommended for use with this protocol, as well as the instrument manufacturer and model.

**Table 3-9. RAVEM Specifications**

| | Inputs - (range) | RAVEM | Logging Frequency | Accuracy |
|---|---|---|---|---|
| Measuring components/input signals | CO 0 - 200 ppm<br>0 - 500 ppm | NDIR | 1 Hz | 2.0 % of point |
| | $CO_2$ 0 - 2000 ppm<br>0 - 6000 ppm<br>0 - 10000 ppm | NDIR | | 2.0 % of point |
| | $NO_x$ 0 - 100 ppm<br>0 - 3000 ppm | Chemilumenescent | | 2.0 % of point |
| | Total Particles | Gravimetric TPM balance | N/A | 0.10% |
| | Exhaust flow | Calculated | | |
| System Specification | Power supply | 12V to 18V DC | | |
| | Power consumption | Approx. 0.5 kW | | |
| | Dimension | 16(W)x12(H)x40(D) inch | | |
| | Weight | 80 lbs | | |
| | Recommended Battery | 12V DC | | |
| Application | Diesel Vehicles | Yes | | |
| | Gasoline, LPG and CNG | No | | |
| | FR 1065 subpart J Conformity | No (Part 86) | | |

### 1.3.5 Test Fuel

All tests during Phases I and II of the field demonstration program were run on ultra low sulfur diesel (ULSD). Beginning in July 2007, all DSNY vehicles began using a five percent biodiesel blend (B5). As such, all tests during Phase III were run on B5.

The biodiesel tests were completed using three fuels: B100 (100% biodiesel), B50 (50% biodiesel and 50% ULSD) and 100% ULSD (baseline fuel). B100 tests were conducted first, followed by B50 and ULSD tests. Between the tests for each fuel type, the day tank and day tank fuel lines were drained and refilled with the next test fuel. A small amount of residual fuel from the previous tests remained in the injector pump. As such, the vehicle was conditioned by performing several iterations of loading and dumping. This was also used to warm up the vehicle. Following the conditioning, the day tank was refilled and weighed. Following each test, the day tank was weighed and refilled, if necessary, to prepare for the next test run.

## 1.4 TEST MATRIX - EMISSION CONTROL TECHNOLOGIES AND DIESEL CONSTRUCTION EQUIPMENT

This section provides an overview of selected control technologies for the reduction of diesel PM and $NO_x$ emissions. These control devices were selected based on the control efficiency, durability, operational impacts, costs, and other factors , and were selected at the time as the most feasible systems that can provide the most cost effective impacts to the NYSERDA program and the field demonstration. DSNY provided all diesel construction equipment for the ECT demonstrations. For those tests performed at the Central Repair Shop, DSNY provided Case and Daewoo rubber tire loaders, as well as Case and Bobcat skid steer loaders. Tests that took place at the Fresh Kills site were performed on Caterpillar articulated dump trucks. Table 3-10 lists the construction equipment and ECT combinations that were tested.

**Table 3-10. Equipment and ECTs Tested**

| Test Phase | Equipment Description | Type of Equipment | ECT Manufacturer | ECT Model | ECT Type[a] |
|---|---|---|---|---|---|
| Phase I | Case 821 | Rubber tire loader | CleanAIR Systems | PERMIT | PDPF |
| | Case 70XT | Skid steer loader | NETT Technologies | FM5A036 | Compact FTF[b] |
| | Daewoo Mega 200 | Rubber tire loader | NETT Technologies | FM 8A085 | FTF |
| | Caterpillar D400 | Dump Truck | Huss | MK-System | ADPF |
| | Caterpillar D400 | Dump Truck | JMI | CCRT | DPF |
| Phase II | Daewoo Mega 200 | Rubber tire loader | DCL | Ultra Muffler | FTF |
| | Bobcat 863 | Skid steer loader | AirFlow Catalyst | Active-X | DOC |
| | Case 821 | Rubber tire loader | NETT Technologies | SF1100 | PDPF |
| | Case 821 | Rubber tire loader | AirMeex | Fuel Burner | ADPF |
| Phase III | Daewoo Mega 200 | Rubber tire loader | ECS | Purifilter NA8X11 | PDPF |
| | Daewoo Mega 200 | Rubber tire loader | Donaldson | DMF | PDPF |
| | Case 821 | Rubber tire loader | Extengine | LEV2 | FTF |
| | Case 821 | Rubber tire loader | NETT Technologies | BlueMax | FTF/SCR |
| | Case 821 | Rubber tire loader | DCL | MineX Sootfilter | PDPF |
| | Case 580 | Backhoe | NETT Technologies | DL 152 | DOC |
| Bio-diesel | Volvo L90F | Rubber Tire Loader | Fuel supplied by Ascent Aviation | NA | Biodiesel – 100%<br>Biodiesel blended with ULSD (50%) |

[a] ECT nomenclature:
ADPF -- active diesel particulate filter
DPF -- diesel particulate filter (also known as PDPF for passive diesel particulate filter)
DOC -- diesel oxidation catalyst
FTF – flow through filter
SCR – selective catalytic reduction
[b] Testing was completed, but insufficient data collected to complete a valid analysis in compliance with the test plan

## 1.5 TEST ENGINES

Table 3-11 provides an overview of the engine manufacturers associated with the non-road equipment for ECTs that were tested and for those for which only tracking was done in conjunction with the EPA National Clean Diesel Campaign Grant program. The loaders selected for field demonstration are common, representative of the entire rubber tire loader population, and of the DSNY fleet. For example, DSNY operates 70 Daewoo Mega 200 loaders and several hundred Case 821 loaders.

## Table 3-11. Engines and Equipment Identification with Installed ECTs

| ENGINE MFR. | ENGINE MODEL | ENGINE MODEL YEAR | EPA ENGINE FAMILY | ENGINE S/N | Engine Horsepower | TYPE OF EQUIPMENT | ECT MFR. | ECT TYPE |
|---|---|---|---|---|---|---|---|---|
| DAEWOO* | DB58TIS | 2004 | DWXL05.8C0A | 408455LB | 143 | Rubber tire loader | NETT | FTF |
| CUMMINS* | 6T-830 | 1998 | VX9505R6DTRA | 6T83045572210 | 190 | Rubber tire loader | EXTENGINE | FTF |
| CUMMINS | 6T-830 | 2000 | XX9XL0505AAA | 45897196 | 190 | Rubber tire loader | CleanAIR Systems | PDPF |
| CATERPILLAR | 3406 | 2001 | YCPXL14.6ERK | 3406E9AP01573 | 400 | Dump Truck | Huss | ADPF |
| CUMMINS | 6T-830 | 1999 | WX9XL0505AAA | 45755900 | 190 | Rubber tire loader | NETT | FTF/SCR |
| CUMMINS | 6T-830 | 2000 | XX9XL0505AAA | 45895161 | 190 | Rubber tire loader | AirMeex | ADPF |
| DEUTZ | BF4M1011F | 2002 | 2DZXL02.9012 | BF4M1011FM090781313 | 73 | SKIDSTEER | AirFlow | DOC |
| CUMMINS | 4T-360 | 2004 | 4X9XL0039AAB | 46401076 | 85 | SKIDSTEER | NETT | DOC |
| CUMMINS | 4T-360 | 2004 | 4X9XL0039AAB | 46401093 | 85 | SKIDSTEER | NETT | Compact FTF |
| CATERPILLAR | 3406 | 2001 | YCPXL14.6ERK | 34069AP01583 | 400 | Dump Truck | JMI | CRT/CCRT |
| DAEWOO* | DB58TIS | 2004 | DWX05.8COA | 310164LB | 143 | Rubber tire loader | DCL | FTF |
| CUMMINS | 6T-830 | 1999 | WX9XL0505AAA | 45771458 | 190 | Rubber tire loader | NETT | PDPF |
| CASE | 445T/M2 | 2007 | 7NHXL06.7DTC | 46715734 | 95 | Backhoe | NETT | DOC |
| CUMMINS | 6T-830 | 1999 | WX9XL0505AAA | 6T83045775966 | 190 | Rubber tire loader | DCL | DPF |
| DAEWOO* | DB58TIS | 2005 | DWXL05.8C0A | 404143LB | 143 | Rubber tire loader | ECS | DPF |
| DAEWOO* | DB58TIS | 2005 | DWXL05.8C0A | 501978LB | 143 | Rubber tire loader | AirFlow | DOC |
| CUMMINS | 6T-830 | 2000 | XX9XL0505AAA | 45913249 | 190 | Rubber tire loader | AirFlow | DOC |
| DAEWOO* | DB58TIS | 2005 | DWXL05.8C0A | 408991LB | 143 | Rubber tire loader | ECS | DPF |
| DAEWOO* | DB58TIS | 2004 | DWXL05.8C0A | 401598LB | 143 | Rubber tire loader | Donaldson | DPF |
| CUMMINS | 6T-830 | 1999 | VX9505R6DTRA | 45623530 | 190 | Rubber tire loader | Donaldson | DPF |
| CUMMINS | 6T-830 | 2000 | XX9XL0505AAA | 45906580 | 190 | Rubber tire loader | ECS | DOC |
| CUMMINS | 6T-830 | 2005 | DWXL05.8C0A | 408988LB | 190 | Rubber tire loader | ECS | DPF |
| CUMMINS | 6T-830 | 1999 | WX9XL0505AAA | 45769286 | 190 | Rubber tire loader | ECS | DOC |

The vehicle used for the biodiesel testing was a 2007 Volvo L90F Rubber Tire Loader. Equipment and engine specifications are provided below.

**Table 3-12. 2007 Volvo L90F Specifications**

| | |
|---|---|
| Engine | Volvo D6E LAE3 |
| Configuration | Inline 6 cylinder |
| Max Horsepower | 169 hp |
| Max Torque | 550 lb-ft |
| Peak Torque RPM | 1600 |
| Displacement | 348 cu. in (5.7L) |
| Emission Technology | Air-to-Air Intercooled EGR |
| Emission Level | Tier 3 Compliant |
| Maintenance Interval | 500 hours |
| Oil Sump Capacity | 41 quarts |

## 1.6 DEMONSTRATION PROGRAM & FIELD TEST PROGRAM SUMMARY

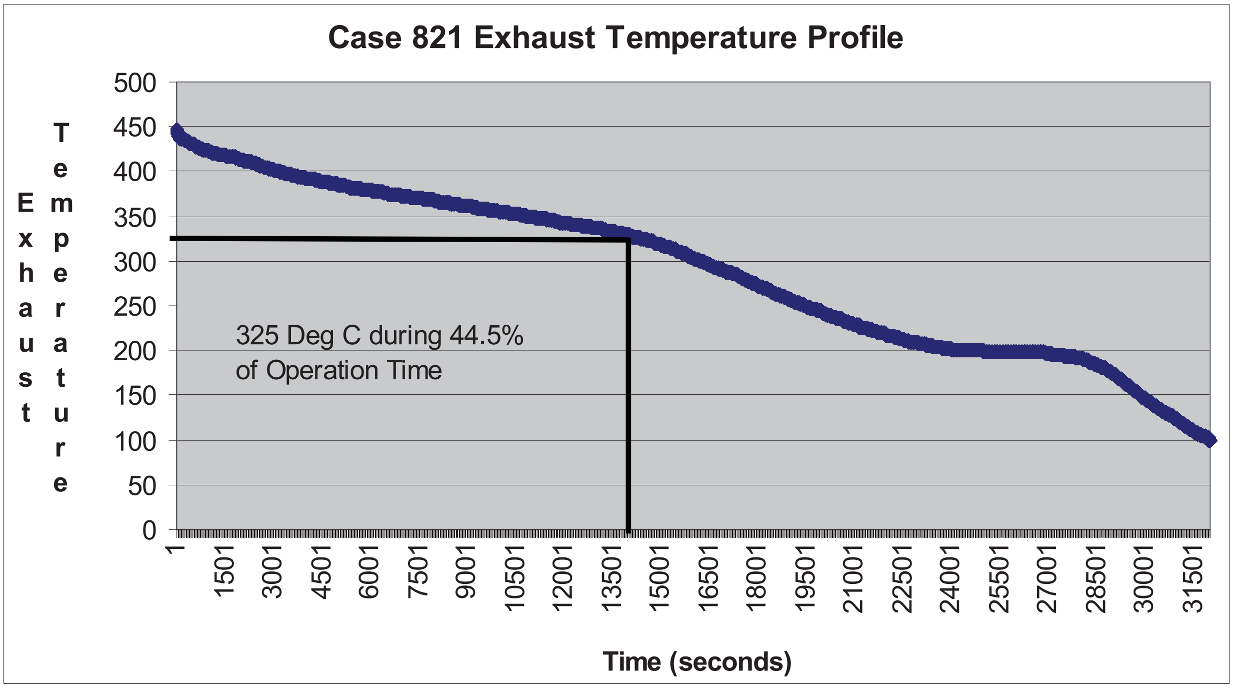
### 1.6.1 Preliminary Datalogging

Test personnel acquired equipment information prior to testing to ensure that the selected machines truly represented the DSNY fleet. The information gathered included:

- time since the last major overhaul
- state of repair
- maintenance history
- major modifications

Data logging of the exhaust temperatures was completed and data distributed to the ECT manufacturers to determine the types of emission control technologies that were acceptable to place into service on the DSNY equipment – those that met manufacturer minimum temperature-time requirements for filter regeneration. Temperature data was collected on one of the older Case rubber tire loaders during normal operation from period beginning August 9th and continuing through August 11th, 2005 for a total of about eight hours operation time. The sorted exhaust data, below in Figure 3-5 showed that the exhaust temperatures were above 325 degrees C for just over 44% of the equipment operation time.

**Figure 0-5. Case 821 Rubber Tire Loader, Temperature Data Logging**




### 1.6.2 ECT Installation

Due to DSNY safety requirements all ECTs were required to be placed underneath the engine cowl so that there would be no limitations to the operator's line of sight. This was a major consideration for most all device manufacturers. Emission control manufacturers were required to redesign the housing for their ECT systems to accommodate for the limited space. This limited manufacturers using off-the-shelf models. ECTs were shipped to the Clean Fuels & Technologies Division, N.Y.C. Department of Sanitation in Woodside, NY. After each device arrived it was logged in and the Supervisor of Mechanics, Spiro Kattan, was notified of its arrival. If assistance for installation was required from the manufacturer's engineers, notification was sent with the device and scheduling was arranged for its installation at a later date. If manufacturer assistance was not required, the DSNY staff mechanics installed the system. During both types of installations DSNY mechanics and staff kept records of installation times and additional parts and equipment required.

### 1.6.3 ECT Degreening

Most of the emission control manufacturers delivered technologies that were already broken-in or degreened. Those that were delivered as new units were degreened according to the individual manufacturer's request. The longest degreening period required was 20 hours for the new Engine Control System's diesel particulate filters. Degreening was completed either through normal operation or during preliminary test runs (i.e. driver training and warm-up).

### 1.6.4 Testing

After the devices had been fully degreened, the DNSY equipment was outfitted with the emission measurement equipment and the non-road equipment was moved to the test area and operated under the prescribed duty cycle until at full operating temperature. All tests used warm-up runs and driver training runs to warm up the engine and ECT to normal operating temperatures to ensure repeatable test runs. All tests were completed as hot-start tests. Cold start tests were not included. An average soak time (rest period) of 20 minutes between test runs was established for each test periods. If soak time exceeded 20 minutes, an additional warm-up test was run to ensure test runs were hot-starts.

Efforts were made to maintain the same equipment operator throughout the test program. Still, if scheduling did not allow the same person, the new operator would undergo training in the operation of equipment under the simple duty test cycle. Operators were provided the duty cycle information and descriptions of its events, and made to understand the importance of keeping consistent movements through the test cycle. The operator also underwent several training sequences of the simple duty cycle while test personnel timed each individual event and coached him at the different events. When the operator's performance was repeatable, as determined by the cycle acceptance criteria, testing began. In addition, for each individual equipment item and ECT, the same operator was generally used for all test runs. This helped reduce cycle-to-cycle variability due to operator influences.

Testing was completed post-ECT first to ensure that lower levels of PM entered the portable dilution tunnel. After the appropriate successful tests were completed, the analytical systems sample point was changed to a location before the ECT device and testing resumed for pre-ECT data. Pre-ECT tests (engine out) were performed by locating a sample port in the exhaust duct prior to the inlet of the ECT device. This allowed testing to continue without removal and switching of the ECT device – a major effort in many cases due to the custom installations required. Before the analytical equipment was removed, test validations were performed to ensure that the test cycle criteria were followed and QA/QC criteria were achieved. A minimum of three baseline and three candidate runs were conducted for each emission control technology (ECT). If any test runs were found to be outliers according to ASTM Standard E178, they were removed from the data set. Analysts, then, for each parameter:

- calculated the mass emissions (g/min) mean and standard deviation ($\sigma_{n-1}$) for all baseline and candidate test runs
- calculated the difference between the baseline and candidate mean results
- evaluated the statistical significance of the difference
- calculated the 95 percent confidence interval on the difference

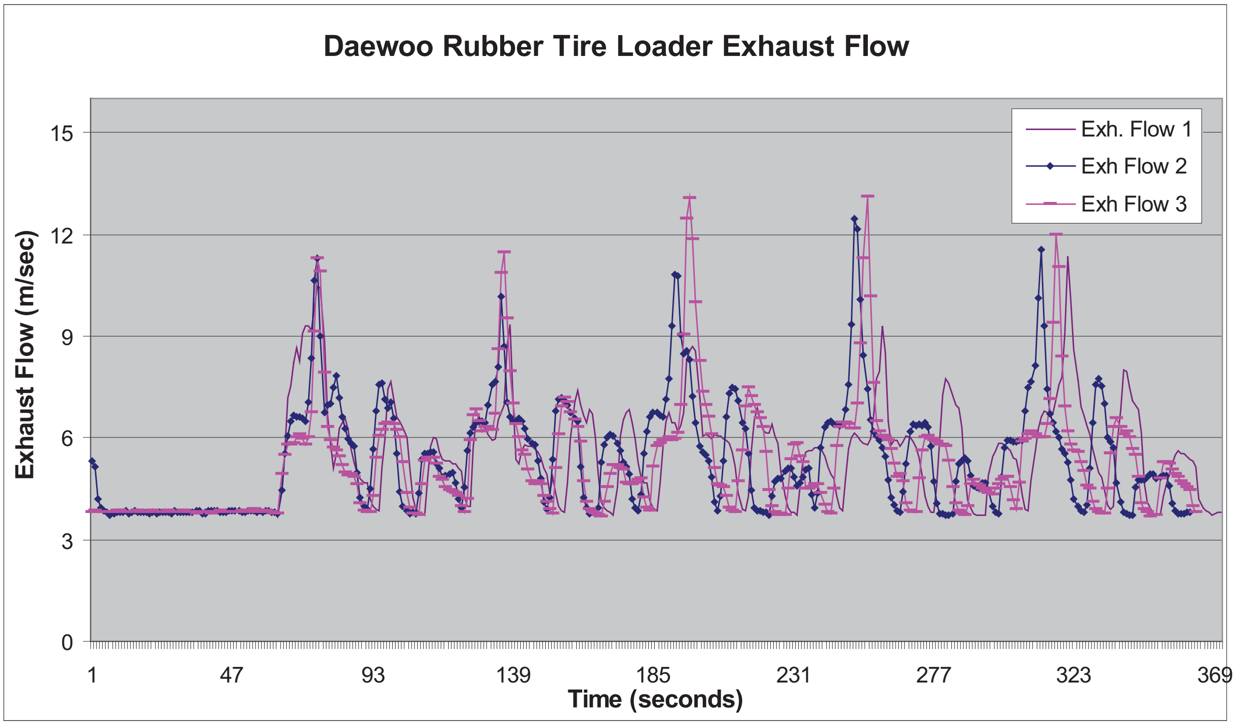
Appendix C of the generic protocol provides the statistical analysis equations and procedures. These include the Student's T test for statistical significance, the F test for evaluating similarity of variance, and the error value calculation for the 95 % confidence interval.

As described in Section 3.3 there were four analytical systems used to measure the ECT performance, and not all systems measured the components of interest using the same measurement methods. For example, in measuring THC, the Horiba PEMs uses the same methodology as emission benches used in laboratories for mobile source regulatory certification testing – a flame ionization detector calibrated with propane standards. The detector used on the CATI for HC measurements is a NDIR based on hexane calibrations. Therefore, one would expect some differences between the measurements of the two analytical systems. Also, some of the measurement systems did not measure all of the emission constituents. For example, the RAVEM system did not measure the HC content of diesel because of the low concentration of HCs emitted from diesel exhaust but can measure real-time NO as well as $NO_x$, which may make it a good candidate for testing urea based ECTs. The DOES2 adds to its analyses of emission components by offering gravimetric particle analyses along with EC/OC analyses, which the Horiba PEMs cannot. Of the tests performed, the DOES2 collected and analyzed samples from seven ECT devices during the Phase 1 and Phase II test periods, which included EC/OC analyses. The CATI performed successful testing on one device, and the RAVEM performed emission measurements on six ECTs during Phase III of the project. The Horiba was run along beside the DOES2 during the Phase 1 and II testing periods and analyzed emissions from three of the ECT systems. Both the RAVEM and the DOES2 analytical equipment measured $NO_x$ and NO during the evaluations for several of the ECTs, and the reported $NO_2$ was difference between the NO and $NO_x$ values.

During ECT evaluations time data for each cycle component is collected and logged. RPM data and exhaust flows are also retrieved after the test and evaluated to verify that all criteria for an acceptable testing were within limits. Figure 3-6 shows that the exhaust flows for three post ECT tests. Although the exhaust flows change at different times they are well within acceptable limits.

Concurrent with this project, the U.S. EPA's National Clean Diesel Campaign (NCDC) requested applications for grants intended to demonstrate the applicability and feasibility of verified diesel emission retrofits in the non-road construction sector. NYSERDA received this funding and acquired additional emission control technologies. This significantly increased the number of retrofits that were evaluated under the NYSERDA program. Each ECT was monitored from the beginning of its installation, as long as through the end of June 2008. To track the systems a spreadsheet was developed and maintained at the DSNY. If problems with ECT occurred, the chief mechanic would note the problem, its remedy, approximate cost of repair, and labor hours spent on repairs.

**Figure 3-6. Daewoo Mega 200 Rubber Tire Loader, Exhaust Flow Data Logging**



# TEST RESULTS

The following subsections provide an overview of the control systems selected for non-road equipment installations. Below each overview are the manufacturer's description of each ECT and a summary of the results collected during the field testing. All technology descriptions are based on information provided by the ECT manufacturers and do not represent verified information.

Note that all test results are provided as a mean emission rate for the baseline vehicle, with the ECT installed, and the change in emissions due to the ECT. Each test result summary also provides a statistical analysis and includes the 95% confidence interval on the result, plus an evaluation of whether observed changes are statistically significant.

Particulate emissions results based on testing using the DOES2 are presented both with and without blank correction. During test periods, analysts also collected ambient air, used for dilution, over test filters, to measure the ambient PM concentration. The PM test results presented without blank correction are an indication of the emission reduction associated with PM produced by the diesel engine directly.

## 1.1 PASSIVE DIESEL PARTICULATE FILTERS

### 1.1.1 Overview

Passive diesel particulate filters (PDPFs) typically use a wall-flow monolithic filter to physically filter particulate matter from diesel engine exhaust. To properly function without negative impact on the diesel engine, filters must be cleaned or regenerated regularly to remove collected particulate matter. Passive DPFs are commercially available in a variety of sizes, and use a variety of configurations for filter regeneration.

The average exhaust gas temperature in the diesel engine is not sufficient to sustain soot oxidation by oxygen. In passive diesel particulate filters, the soot oxidation temperature is lowered to a level allowing for auto-regeneration during regular vehicle operation. This is most commonly achieved by introducing an oxidation catalyst to the system, which can promote oxidation of carbon via $NO_2$, oxygen or a combination of both mechanisms. Three major approaches have been historically used:

i. placing the catalyst directly on the filter media surface (catalyzed diesel particulate filter),

ii. using an $NO_2$ generating catalyst upstream of the filter (continuously regenerating technology (CRT) filter), or

iii. adding a catalyst precursor to the fuel as an additive (filter with fuel additives).

The minimum exhaust gas temperature requirements for the regeneration of passive diesel particulate filters (PDPFs) vary with filter type, catalyst type and loading, and with the engine type. Filters on high-PM emitting engines typically require higher temperatures to regenerate than filters installed on cleaner engines.

Temperature requirements for the regeneration of various passive diesel particulate filter configurations, as determined from North American underground mining experience, are listed in Table 4-1 (Haney, October, 2004). These results are based on tests with heavy-duty engines used in US mines in the late 1990s.

**Table 4-1. Typical Passive Filter Regeneration Temperature Requirements**

| Filter System | T30* |
|---|---|
| Uncatalyzed "bare" filter | 550°C |
| Base metal catalyzed filter | 420°C |
| Pt-catalyzed filter (high loading) | 365°C |
| Fuel additive + lightly Pt-catalyzed filter | 330°C |
| * temperature that must be exceeded over at least 30percent of the engine duty cycle | |

Passive filters often induce a small fuel economy penalty (typically 1-3%) due to increased pressure drop across the filter. In installations with insufficient exhaust temperatures to support regeneration, passive filters may involve significant added maintenance for filter cleaning.

Ultra low sulfur fuels are recommended, but not always required for the use of PDPFs. Using higher sulfur fuels typically increases the regeneration temperature requirements. High sulfur fuels also contribute to sulfate PM emissions causing a decrease of PM filtration efficiency. For on-highway applications, the PDPF devices typically replace the vehicle's muffler and can be supplied as a standard design or as a direct fit muffler replacement. For non-road applications, this is not typically the case. PDPFs are typically heavier than OEM mufflers, often requiring additional support brackets. Additionally, PDPFs frequently cause considerably higher exhaust backpressures if sized to the same dimensions as the OEM muffler. As a result, to maintain the engine manufacturer's specified maximum exhaust backpressures, the retrofitted PDPF is often larger than the OEM muffler it replaces. As such, installation of the PDPF in the space formerly occupied by the OEM muffler is often difficult, requiring considerable engineering effort to locate the PDPF. There are a number of key considerations in relocating a DPF beyond the OEM muffler location:

- The equipment operator's line-of-sight remains unobstructed
- The DPF location does not interfere with access to the engine and other maintenance-intensive components of the piece of equipment
- The DPF is well stabilized in the often harsh working environment of non-road construction equipment
- The DPF is reasonably accessible for routine maintenance such as ash cleaning

- The electrical wiring and pressure line of backpressure monitors do not interfere with operation of the machine

### 1.1.2 Catalyzed Diesel Particulate Filter (CDPF)

A schematic of a CDPF is shown in Figure 4-1. A catalyst—usually a platinum based formulation—is applied directly to the filter's wall-flow substrate.

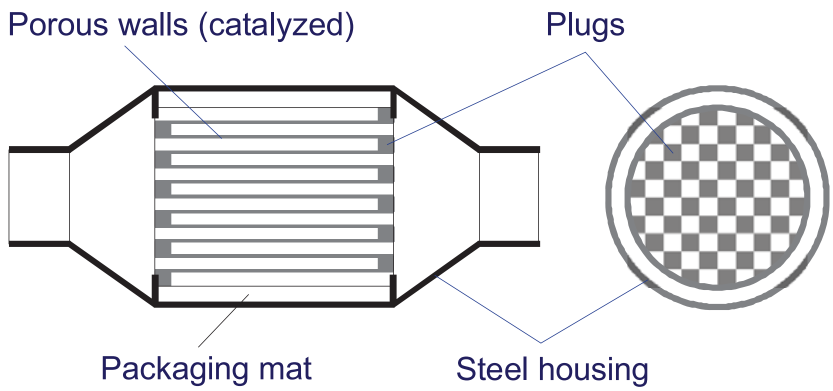



**Figure 4-1. Catalyzed Diesel Particulate Filter**

The PM control efficiency in the CDPF varies from 60-90percent and above. Higher efficiencies—typically above 85percent—are seen with ultra low sulfur fuels (15 ppm Sulfur). Pt-catalyzed filters can also provide significant reductions of CO and HC emissions, on the order of 60-90percent. $NO_x$ emissions are generally not reduced in the CDPF (although Pt catalysts may exhibit some lean $NO_x$ activity at low exhaust temperatures of 200-250°C). Small $NO_x$ reductions, on the order of up to 5 percent, that are sometimes measured with DPFs, may be also caused by internal EGR effects resulting from the increased backpressure. Platinum-based CDPFs have been known to increase the proportion of nitrogen dioxide in the exhaust gas — due to the high toxicity of $NO_2$—, which is sometimes considered a counterproductive effect, especially when engines are operated indoors.

While passive CDPFs represent one of the most effective commercialized PM-reduction strategies, their limited deployment on non-road equipment, especially in the extreme operating environment of non-road construction, can require considerable engineering and attention to ensure proper performance and minimum intrusion upon the uninterrupted operation of the piece of equipment itself. The installation exercise is frequently time and labor-intensive, a challenging proposition for the construction industry, which survives on minimum operations downtime.

Installation, maintenance, and operational issues are generally similar to those of all PDPF filters. As a passive DPF, the filter must be installed on engines of sufficiently high exhaust temperature. It is recommended that the filter is installed with a pressure drop/temperature monitor for early detection of problems.

### 1.1.3 Applicability, Feasibility, Installation, and Maintenance of CDPFs

For the on-highway sector, CDPFs are a mature technology, with considerable experience in heavy-duty retrofit programs worldwide. Some experience also exists in non-road applications. The key requirement for problem-free passive regeneration is sufficient exhaust gas temperature. As exhaust temperatures depend not only on the engine model, but also on its duty cycle, CDPFs can be used only in selected applications, which can guarantee sufficiently high exhaust gas temperatures.

Both on-highway and non-road vehicle candidates for CDPF application are typically evaluated by recording exhaust gas temperature during regular operation of the vehicle. The data collection is performed by installing a thermocouple in the exhaust piping, at the planned location of the CDPF, and a data logger on the vehicle. The duration of the recording varies from a few hours to several days; it is important that the duty cycle during the recording be representative for the regular operation. The CDPF applicability is determined by the filter supplier based on an analysis of the temperature data.

### 1.1.4 CleanAIR Systems PDPF

#### 1.1.4.1 Manufacturer's Technology Description

The CleanAIR PDPF was designed to control PM, CO, and HC emissions from any size diesel engine. The technology uses a wall-flow ceramic filter coated with CleanAIR's unique catalyst. The catalyzed particulate filter dramatically reduces black smoke and odor associated with diesel exhaust.

The trade name of the CleanAIR Systems PDPF filter tested 'PERMIT'. The filter is CARB-verified for stationary genset diesel engines at CARB Level 3 (achieves greater than 85% PM reduction), and meets the CARB/EPA 2009 $NO_2$ requirement ($NO_2$ emissions are not increased by more than 20% vs. the baseline case). Applications for the PERMIT filter include on-road and non-road equipment such as trucks, buses, construction equipment, mining vehicles, and power generation equipment. The PERMIT is applicable to engines with exhaust temperature profiles above 300$^{o}$C for greater than 30% of the time when using ULSD and operating on engines with a PM output of less than 0.2 g/bhp-hr.

The PERMIT filter is available in different options, which include standard designs, muffler combination, and critical or super-critical grade silencer configurations. In many large diesel engine applications multiple PERMIT filters are integrated into a silencer, which can take the place of a standard exhaust silencer. The Clean AIR PERMIT filter is housed in a 304L bead blasted stainless steel shell that is highly corrosion-resistant. Figure 4-2 shows the PERMIT filter/muffler design (left) and with bolt flanges.

**Figure 4-2. CleanAIR Systems PERMIT PDPF** ***(Courtesy CleanAir Systems)***

1.1.4.2 Test Results

Test personnel evaluated the CleanAIR PDPF performance using both PEMS and ISS simultaneously. The PDPF was installed on a Case 821 rubber tire loader at the DSNY Central Repair Shop site. Table 4-2 shows the mean emissions in g/min as measured by the OBS-2200 PEMS unit. Table 4-3 summarizes the emissions as measured by Environment Canada's DOES2 ISS. Figure 4-3 shows the CleanAIR system installed on the Case 821 Rubber Tire Loader.

**Table 4-2. OBS-2200 PEMS Emissions for the CleanAIR PDPF**

| | **Emissions (g/min)** | | | |
|---|---|---|---|---|
| | **$CO_2$** | **NOx** | **CO** | **THC** |
| Pre-ECT Mean Emissions (three test runs) | 386 ± 36 | 5.19 ± 0.46 | 0.557 ± 0.03 | 0.489 ± 0.041 |
| Post-ECT Mean Emissions (three test runs) | 345 ± 42 | 4.66 ± 1.26 | 0.169 ± 0.169 | 0.072 ± 0.012 |
| Mean Emission Change | -41.0 ± 55.8 | -0.527 ± 1.34 | -0.388 ± 0.171 | -0.417 ± 0.043 |
| % Change | -10.6 ± 14.5 | -10.1 ± 25.8 | -69.7 ± 30.7 | -85.2 ± 8.7 |
| Statistically Significant? | No | No | Yes | Yes |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase<br>Means based on three test runs pre-and post-DPF | | | | |

**Table 4-3. DOES2 ISS Emissions for the CleanAIR PDPF**

| | Emissions (g/min) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $NO_2$ | CO | HC | PM | PM (no blank correction) |
| Pre-ECT Mean Emissions | 494 ± 50 | 5.49 ± 0.36 | 1.72 ± 0.15 | 1.18 ± 0.06 | 0.495 ± 0.068 | 0.159 ± 0.030 | 0.162 ± 0.030 |
| Post-ECT Mean Emissions | 485 ± 35 | 5.55 ± 0.49 | 2.86 ± 0.31 | 0.135 ± 0.025 | 0.091 ± 0.093 | 0.002 ± 0.002 | 0.004 ± 0.002 |
| Mean Emission Change | -9.07 ± 60.7 | 0.061 ± 0.606 | 1.14 ± 0.34 | -1.05 ± 0.06 | -0.404 ± 0.115 | -0.158 ± 0.030 | -0.158 ± 0.030 |
| % Change | -1.83 ± 12.28 | 1.10 ± 11.05 | 66.6 ± 19.9 | -88.6 ± 5.4 | -81.6 ± 23.2 | -98.9 ± 18.5 | -97.4 ± 18.3 |
| Statistically Significant? | No | No | Yes | Yes | Yes | Yes | Yes |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase. Means based on three test runs pre-and post-DPF. | | | | | | | |


**Figure 4-3. CleanAIR Systems PDPF Installed on a Case 821 Rubber Tire Loader and Instrumented for In-Use Emissions Testing**

The CleanAIR Systems PERMIT PDPF performed well, significantly reducing emissions of PM, THC, and CO by greater than 80percent (over 98percent for PM) based on the ISS results. Gaseous emissions results from the Horiba OBS PEMS also confirm similar emission reductions and agree, within statistical error levels, with the ISS system results.

As shown in Figure 4-3, the system could not be mounted inside the engine cowling of the loader due to its physical size and space constraints. As a result, the unit was mounted outside the engine housing using custom built brackets and mounting hardware. This configuration was not preferred due to potential impacts on operator line of sight.

### 1.1.5 Nett Technologies PDPF

#### 1.1.5.1 Manufacturer's Technology Description

The Nett PDPF uses a cordierite wall-flow monolith to trap the soot produced by diesel engines. The cylindrical filter element has parallel channels running in the axial direction, separated by thin porous walls. The channels are open at one end and plugged at the other, forcing the particle-laden exhaust gases to flow through the walls. The exhaust gases are able to escape through the pores in the wall material, but particulates too large to escape are trapped in the filter walls. A proprietary catalyst is coated onto the inside surface of the filter monolith, which lowers the soot combustion temperature allowing the filter to regenerate. The accumulated soot is oxidized in the filter during regular operation of the engine. For proper regeneration, the exhaust gas temperature at the filter inlet must be at least 325°C (617°F) over 25% of the duty cycle when ULSD (ultra-low sulfur diesel) fuel is used, which is met on most heavy-duty diesel engine applications, as well as on some medium and light-duty engines. Nett PDPF filters can be used with all fuels, regardless of sulfur content, however, higher exhaust temperatures are required for regeneration with higher sulfur fuels. The Nett PDPF tested here is not currently verified by CARB or the EPA.

#### 1.1.5.2 Test Results

The Nett PDPF was evaluated on a Case 821 rubber tire loader at the DSNY Central Repair Shop site. Emission testing was performed with the DOES2 ISS. Table 4-4 summarizes the results.

**Table 4-4. DOES2 ISS Emissions Results for the Nett PDPF**

| | Emissions (g/min) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **$CO_2$** | **$NO_x$** | **$NO_2$** | **CO** | **HC** | **PM** | **PM (no blank correction)** |
| Pre-ECT Mean Emissions | 424<br>± 45 | 5.16<br>± 0.48 | 1.87<br>± 0.37 | 0.634<br>± 0.039 | 0.059<br>± 0.018 | 0.085<br>± 0.027 | 0.090<br>± 0.027 |
| Post-ECT Mean Emissions | 467<br>± 54 | 5.24<br>± 0.15 | 2.35<br>± 0.18 | 0.017<br>± 0.025 | 0.016<br>± 0.036 | 0.004<br>± 0.007 | 0.009<br>± 0.007 |
| Mean Emission Change | 43.4<br>± 70. 2 | 0.078<br>± 0.499 | 0.479<br>± 0.413 | -0.617<br>± 0.046 | -0.043<br>± 0.040 | -0.081<br>± 0.028 | -0.081<br>± 0.028 |
| Statistically Significant? | No | No | Yes | Yes | Yes | Yes | Yes |
| Percent Change | 10.2<br>± 16.6 | 1.50<br>± 9.66 | 25.6<br>± 22.1 | -97.4<br>± 7.3 | -73.5<br>± 67.8 | -95.0<br>± 33.1 | -89.6<br>± 31.2 |
| Statistically Significant? | No | No | Yes | Yes | Yes | Yes | Yes |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase. Means based on three test runs pre-and post-DPF | | | | | | | |

Statistically significant reductions of CO, HC, and PM were observed when using the Nett PDPF on the Case 821 Loader, with PM reductions of 95%. These levels are consistent with expected reductions for PDPF systems on most engines using ULSD. Note that, although statistically significant and consistent with expectations, the observed reduction for THC has a very large 95 percent confidence interval, and values may be used cautiously. It should also be noted that the Nett PDPF showed a statistically significant increase in $NO_2$ emissions on the order of 25 percent. Still, it should also be noted that the 95 percent confidence interval for the $NO_2$ increase is large, and indicates that the $NO_2$ increase could practically range from 3.5 percent to 47.7 percent.

### 1.1.6 Engine Control Systems (ECS) PDPF

#### 1.1.6.1 Manufacturer's Technology Description

The ECS PDPF systems tested uses a zeolite-containing washcoat and precious metal catalyst to improve low temperature performance. ECS has two versions of this product called the Purifilter DZ and EZ . The DZ series features quick release band clamps that allow the center body to be removed for periodic engine-out opacity measurements or for filter cleaning. Both versions are designed for vibration resistance at low exhaust backpressure.

**Figure 4-4. ECS Diesel Particulate Filter Products (courtesy ECS)**

The Purifilter diesel particulate filter uses a base and precious metal catalyst impregnated onto a silicon carbide surface to passively oxidize accumulated particulate while complying with CARB $NO_2$ limits. The silicon carbide has a honeycomb design with alternating cells, open on one end and plugged at the outlet end to capture the exhaust particles. The filter substrate is coated with a proprietary catalytic layer to reduce soot combustion temperatures to a level within the normal exhaust temperature range of diesel engines.

The Purifilter DPDF has regeneration balance points between 280$^oC$ and 325$^oC$, varying with both vehicle engine and application. Continuous passive filter regeneration occurs during a vehicle duty cycle when the exhaust temperatures are above 280$^oC$ for more than 25 percent of the time. The catalyst also oxidizes more than 90 percent of carbon monoxide and hydrocarbons. ECS PDPF models are available in five different particulate filter muffler types which provide a range of fit. ECS provides a backpressure monitor kit with each Purifilter PDPF system. Non-Road vehicles suited to the Purifilter include construction vehicles, mining vehicles, and other heavy industrial machines. The Purifilter is verified by the EPA for a 90 percent reduction in PM emissions, 75 percent reduction in CO emissions, and 85 percent reduction in THC emissions for certain on highway diesel engine applications. The filter also meets the 2009 $NO_2$ emission limits specified by EPA.

1.1.6.2 Test Results

Test personnel evaluated the ECS PDPF performance using the RAVEM system. Table 4-5 shows the mean emissions in g/min as measured by the RAVEM. The figure below shows the ECS DPF system installed on the Case 821 Rubber Tire Loader.

**Table 4-5. RAVEM Emissions for the ECS PDPF**

| | **Emissions (g/min)** | | |
|---|---|---|---|
| | **PM** | **CO** | **$NO_x$** |
| Pre-ECT Mean Emissions | 0.27 ± 0.05 | 7.2 ± 6.7 | 3.4 ± 0.4 |
| Post-ECT Mean Emissions | 0.02 ± 0.01 | -0.11 ± 0.04 | 2.0 ± 1.6 |
| Mean Emission Change | -0.25 ± 0.05 | -7.3 ± 6.7 | -1.5 ± 1.6 |
| Percent Change | -93% ± 18% | -102% ± 94% | -42% ± 48% |
| Statistically Significant? | Yes | Yes | No |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase<br>Note: Negative values less than 0.0 are due to ambient background subtraction<br>Means based on four test runs pre- and post-DPF | | | |


**Figure 4-5. Left-Side View of the ECS DPF Installed on a Case 821 Rubber Tire Loader**

The ECS DPF provided a 93 percent emission reduction for particulates from the Case 821 loader, consistent with expectations for a PDPF, and the EPA verified reduction level of 90 percent. A nearly 100 percent reduction in CO emissions was also observed, with the correction for background emissions resulting in an emission reduction of slightly over 100 percent. In this case, the large confidence interval on the baseline CO emissions tests result in a large confidence interval for the emission reduction value as well.

### 1.1.7 Donaldson PDPF

#### 1.1.7.1 Manufacturer's Technology Description

The Donaldson system is CARB-verified and covers non-EGR equipped diesel engine models made from 1994 to 2006, 150 to 600 hp (0.10 g/bhp-h PM emissions or less) and requires ultra-low sulfur diesel fuel (less than 15 ppm sulfur). The design uses flow distribution elements to ensure uniform PM loading and temperature distribution. Passive regeneration will occur with exhaust temperatures above 210º C at least 40 percent of the time. The system is designed to be maintenance-free and does not require ash cleaning. The DPF has a take-apart design that allows easy removal of the center-body that is "keyed" to ensure proper orientation when reinstalling.

The system is verified by CARB to meet Level 3 (>85 percent reduction) for the Diesel Risk Reduction Program (DRRP) and also meets the CARB 2009 $NO_2$ limit (<20 percent). The equipment's acceptable fuel types are Ultra Low Sulfur Diesel (ULSD < 15 ppm sulfur) and Biodiesel – maximum B20 blend (20 percent biodiesel/80 percent diesel). Biodiesel blend stock must meet ASTM D 6751 and blend with ASTM D 975 diesel (1-D or 2-D). The DPF system meets U.S. EPA and CARB DRRP warranty requirements. The DPF system is housed in aluminized 409 grade stainless steel for strength and corrosion resistance. The substrate has a patented flow distribution device that enhances catalyst performance, delivers uniform airflow and temperatures across the catalyst, and reduces exhaust backpressure.

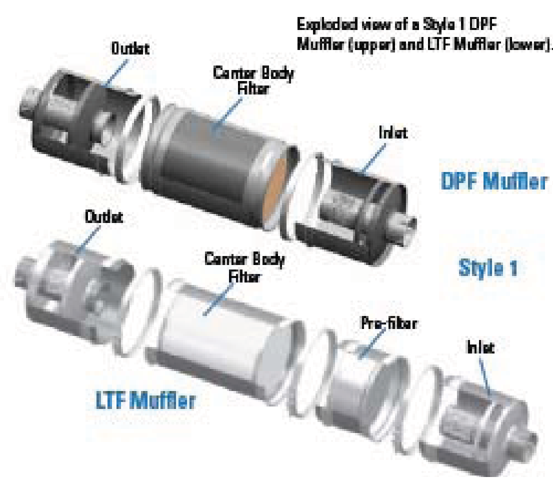



**Figure 4-6. Donaldson DPF (Courtesy Donaldson)**

1.1.7.2 Test Results

Test personnel evaluated the Donaldson DPF performance using the RAVEM system. Table 4-6 shows the mean emissions in g/min as measured by the RAVEM.

**Table 4-6. RAVEM Emissions for the Donaldson DPF**

| | **Emissions (g/min)** | | |
|---|---|---|---|
| | **PM** | **CO** | **$NO_x$** |
| Pre-ECT Mean Emissions | 0.26 ± 0.09 | 1.4 ± 0.4 | 3.3 ± 1.9 |
| Post-ECT Mean Emissions | 0.03 ± 0.04 | -0.09 ± 0.22 | 2.9 ± 0.3 |
| Mean Emission Change | -0.23 ± 0.10 | -1.5 ± 0.5 | -0.4 ± 1.9 |
| Percent Change | -90% ± 39% | -106% ± 37% | -12% ± 58% |
| Statistically Significant? | Yes | Yes | No |

Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase
Note: Negative values less than 0.0 are due to ambient background subtraction
Means based on three test runs pre- and post-ECT

The Donaldson PDPF performed as anticipated, with statistically significant emission reductions of greater than 90 percent for both PM and CO. The PM emission reduction value compares favorably with the CARB verification at Level 3 (>85 percent). No independent assessment of $NO_2$ emissions was completed, so a comparison vs. the CARB $NO_2$ requirement (<20 percent increase) could not be made.

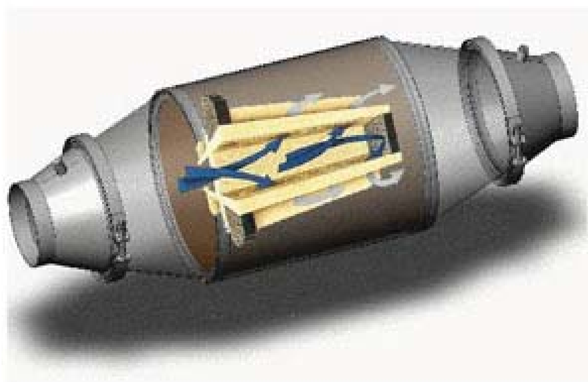
### 1.1.8 DCL PDPF

1.1.8.1 Manufacturer's Technology Description

The DCL MINE-X SOOTFILTER® diesel particulate filters (DPFs) are designed for use on applications such as heavy-duty construction equipment, generator sets, and mining equipment. The DPF effectively captures diesel particulate matter (DPM) while simultaneously converting carbon monoxide (CO) and hydrocarbons (HCs) into carbon dioxide ($CO_2$) and water. Diesel particle collection efficiency should exceed 85 percent (by mass) when used in conjunction with ultra low sulfur diesel fuel (ULSD). The ceramic monolith is coated with a proprietary catalyst and has long narrow channels open at one end and blocked at the other. The exhaust gas is forced to escape by passing through the filter walls, trapping particulate matter (soot) in the filter. The filter also eliminates large percentages of carbon monoxide (CO) and diesel hydrocarbons (HC).

DCL custom manufactures the DPFs to replace the existing muffler (where space permits) making installations as simple as a muffler swap. A DCL Exhaust Monitor and Alarm compliments the DPF and provides the user with a display to inform the operator if backpressure rises to levels where corrective action is required. DCL's non-blocking diesel particulate filters are used to meet EPA or CARB standards for particulate reduction or simply to improve air quality around diesel engines. The MINE-X® Ultra requires diesel fuel with sulfur content less than 500 ppm for proper operation and works best with sulfur content less than 15 ppm (ULSD fuel). The DCL DPDF system has a high conversion efficiency for carbon monoxide, hydrocarbons, odor and particulate matter and effectively removes diesel nano-particles. The system also controls the sound attenuation equivalent to the original muffler.

**Figure 4-7. View of DCL's MINE-X® Ultra substrate showing the alternating tapered trapezoidal ducts and filtration media (courtesy DCL).**



The DCL DPDF has several approvals, which include CARB verification, VERT, Japan MLIT, and Sweden Environmental Zones. DCL DPDF works best in Tier 1 or higher diesel engines, such as construction, earthmoving and mining vehicles, stationary engines, and post-1994 on-road trucks and buses.

1.1.8.2 Test Results

Test personnel evaluated the DCL PDPF performance using the RAVEM system. Table 4-7 shows the mean emissions in g/min as measured by the RAVEM.

The DCL PDPF provided a 90 percent reduction in PM emissions on the Case 821 loader, consistent with CARB verification, and a 100 percent CO reduction. Note the large confidence interval on the CO emission reduction as a result of the variability in both pre- and post- ECT CO emission levels over the test runs. Although statistically significant, due to the large confidence interval, this value should be used with caution.

**Table 4-7. RAVEM Emissions for the DCL PDPF**

| | Emissions (g/min) | | |
|---|---|---|---|
| | **PM** | **CO** | **$NO_x$** |
| Pre-ECT Mean Emissions | 0.18 ± 0.02 | 0.63 ± 0.50 | 6.7 ± 1.4 |
| Post-ECT Mean Emissions | 0.02 ± 0.02 | -0.07 ± 0.06 | 6.3 ± 0.3 |
| Mean Emission Change | -0.16 ± 0.02 | -0.70 ± 0.5 | -0.36 ± 1.43 |
| Percent Change | -90% ± 13% | -111% ± 80% | -5% ± 21% |
| Statistically Significant? | Yes | Yes | No |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase<br>Note: Negative values less than 0.0 are due to ambient background subtraction<br>Means based on three test runs pre- and post-ECT | | | |

## 1.2 CRT AND CCRT FILTERS

### 1.2.1 Overview

"CRT" is an abbreviation of the "Continuously Regenerating Technology" and is a trade name developed by Johnson Matthey. This type of filter is also referred to as the CR-DPF, which stands for "continuously regenerating diesel particulate filter". In this configuration, an $NO_2$ producing Pt-based catalyst is placed upstream of a wall-flow monolith filter, as shown in Figure 4-8. Since the filter monolith is not catalyzed, the CRT regeneration relies exclusively on the $NO_2$ mechanism.

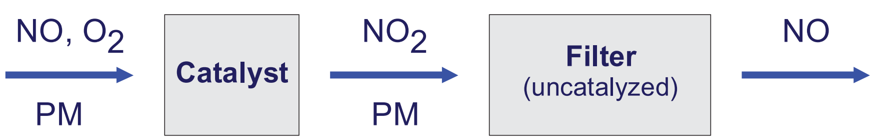



**Figure 4-8. CRT Filter Schematic**

In comparison to the CDPF configuration, the CRT filter can offer lower regeneration temperatures, especially in high-$NO_x$ emitting engines. Nevertheless, due to the reliance on $NO_2$ for regeneration, two application limits, aside from appropriate exhaust temperature profiles, must be observed:

1. Ultra low sulfur fuel must be used (< 50 ppm sulfur). The $NO_2$ forming catalyst becomes deactivated in the presence of sulfur, and the filter fails to regenerate when used with high sulfur fuels (in addition, sulfate particulates are produced if sulfur is present in the fuel).

2. Engine-out $NO_x$/PM ratio should be 25:1 (by weight) or more, to ensure that sufficient quantities of nitrogen dioxide can be generated. The CRT filter may experience regeneration problems on engines of low $NO_x$/PM ratio.

The PM control efficiency of the CRT filter is generally similar to that of the CDPF, and amounts to some 60-90 percent (typically over 85 percent with fuels of less than 15 ppm sulfur). A drawback of the CRT filter is increased emission of nitrogen dioxide, which is not fully consumed in the regeneration process.

### 1.2.2 Catalyzed CRT Filter (CCRT Filter)

A variation of the CRT filter is the "Catalyzed CRT", or CCRT filter. In this configuration, in addition to the upstream $NO_2$ generating CRT catalyst, the filter substrate is also coated with a catalyst. By combining both regeneration methods, the CCRT can typically regenerate at a lower exhaust gas temperature. Therefore, it can be used on vehicles that are too cold to sustain the regeneration of many CRT and CDPF filters. A drawback of this configuration is the higher cost. The installation and maintenance requirements are similar to those with the CRT/CDPF filters. The CCRT filters require ultra low sulfur fuel.

### 1.2.3 Applicability, Feasibility, Installation, and Maintenance of CRT and CCRTs

For the on-highway sector, CRT and CCRT filters are a mature technology, with considerable experience in heavy-duty retrofit programs in the USA and worldwide. Some experience also exists in non-road applications. The key requirement for problem-free passive regeneration is sufficient exhaust gas temperature. As exhaust temperatures depend not only on the engine model, but also on its duty cycle, CRTs can be used only in selected applications that can guarantee sufficiently high exhaust gas temperatures.

It is recommended that CCRT filters, as with other catalyzed DPFs, are supplied with an exhaust gas backpressure and/or exhaust gas temperature (EGT) monitor with warning lights installed at the dashboard, which can alert the vehicle operator in case of increased backpressure levels.  For EPA or ARB verified DPFs, installation of the backpressure monitor on the vehicle or piece of equipment is mandatory.

If the CRT or CCRT device regenerates properly—as indicated by low pressure drop levels—it requires little maintenance. The filter must be periodically cleaned from ashes that gradually accumulate in the filter. Ash cleaning intervals reported in the literature for on-road trucks and buses vary from some 20,000 to more than 150,000 miles.

### 1.2.4 JMI CCRT

#### 1.2.4.3 Manufacturer's Technology Description

The JMI CCRT system is a CRT system, but with a catalytic coating applied to the DPF.  The oxidation catalyst removes CO and HC and oxidizes some of the NO in the exhaust to $NO_2$. This $NO_2$ then reacts with the PM trapped in the filter, producing NO and $CO_2$. Some of the NO is then re-oxidized to $NO_2$ in the filter, which then reacts with more trapped PM. This enables the system to regenerate in applications with very low exhaust gas temperatures or low $NO_x$:PM ratios in the exhaust gases. Figure 4-9 shows the JMI CRT/CCRT.

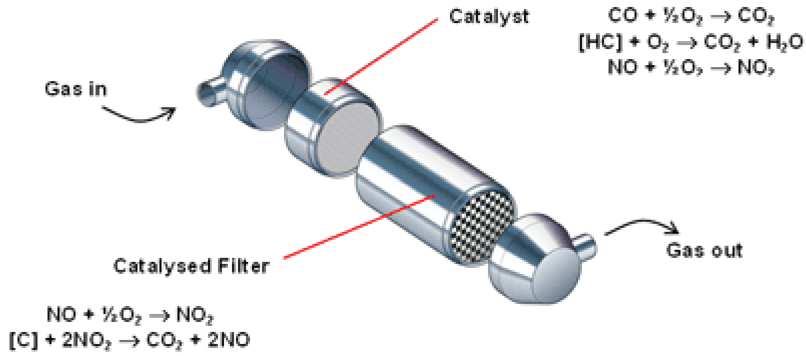



**Figure 4-9. JMI CCRT (courtesy JMI)**

The CCRT system offers all the advantages of a CRT system but is able to operate in applications that have exhaust temperatures too low for a CRT system. It has been verified by the US EPA for applications that have temperatures greater than 210°C for 40% of the operating time. The CCRT system is verified at a PM emissions reduction level of 90% and a CO emission reduction level of 50%. It also meets the 2009 EPA $NO_2$ emissions specifications. It is also able to operate on engines with a $NO_x$:PM ratio that is insufficient for a standard CRT system.

1.2.4.4 Test Results

The JMI CCRT was evaluated on a 2004 CAT D400 articulated dump truck at the Fresh Kills Landfill. Emission testing was performed with the DOES2 ISS. Table 4-8 summarizes the results.

**Table 4-8. DOES2 ISS Emissions for the JMI CCRT**

| | Emissions (g/min) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **$CO_2$** | **$NO_x$** | **$NO_2$** | **CO** | **HC** | **PM** | **TPM (no blank correction)** |
| Pre-ECT Mean Emissions | 1180 ± 86 | 15.1 ± 2.6 | 5.10 ± 1.41 | 3.12 ± 0.18 | 0.262 ± 0.233 | 0.173 ± 0.012 | 0.182 ± 0.012 |
| Post-ECT Mean Emissions | 1050 ± 111 | 12.1 ± 3.1 | 6.63 ± 2.62 | 0.322 ± 0.152 | 0.206 ± 0.023 | 0.008 ± 0.002 | 0.017 ± 0.002 |
| Mean Emission Change | -126 ± 140 | -2.96 ± 4.03 | 1.53 ± 2.98 | -2.84 ± 0.24 | -0.056 ± 0.235 | -0.165 ± 0.012 | -0.165 ± 0.012 |
| % Change | -10.7 ± 11. 9 | -19.6 ± 26.7 | 29.9 ± 58.4 | -89.8 ± 7.5 | -21.3 ± 89.7 | -95.4 ± 6.8 | -90.6 ± 6.5 |
| Statistically Significant? | No | No | No | Yes | No | Yes | Yes |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase. Means based on three test runs pre- and post-ECT | | | | | | | |

As with other DPFs, the JMI CCRT provided PM emission reductions of greater than 90 percent, with a tight confidence interval. CO emission reductions of nearly 90 percent were also observed. Note that the hydrocarbon emission reductions could not be evaluated with any statistical significance due to variability in the hydrocarbon emission baseline values. Also, an $NO_2$ emission increase was observed, but was not statistically significant.

Figures 4-10 and 4-11 show the JMI CCRT installed on the Caterpillar D-400 off-road truck. Note that the installation required two separate filter systems connected through a manifold to provide sufficient filtration capacity. This arrangement was located in the OEM muffler location, but required additional space and mounting brackets for installation.


**Figure 4-10. Johnson-Matthey DPF installed on a CAT D400 Dump Truck**

**Figure 4-11. Front View of the Johnson Matthey DPF Mounting Arrangement**

## 1.3 ACTIVE DIESEL PARTICULATE FILTERS (ADPF)

### 1.3.1 Overview

The application of passive DPF technologies is limited by the exhaust gas temperature. In many diesel engine applications, particularly non-road, temperatures are not sufficient to sustain fully passive regeneration. In those cases, external energy may be supplied to periodically trigger *active regeneration*.

An example concept of an active filter system using diesel fuel as the energy source is shown in Figure 4-12. As the electronic control unit detects increased soot load in the filter (based on the DPF pressure drop and other inputs), it initiates injection of diesel fuel into the exhaust gas at a location upstream of the filter. The fuel is evaporated and oxidized over an oxidation catalyst. This exothermic reaction produces the increased temperatures needed for regeneration. This type of active filter with catalytic combustion of fuel is used on US 2007 highway truck and bus engines. Retrofit systems have also been under development, but the focus remains on highway engine applications.

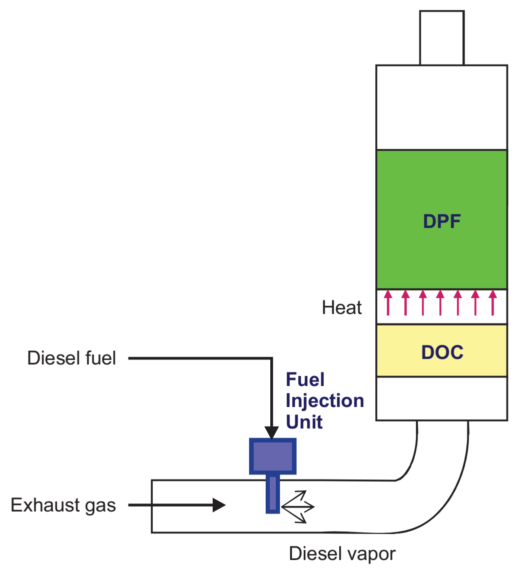



**Figure 4-12. Filter with Catalytic Combustion of Fuel**

Active DPF systems for non-road engines that are commercially available today can be divided into two categories, depending on the type of energy used for regeneration:

- *Systems with electric regeneration*—A number of products exist that use shore power, such as 110 V AC, as the source of energy for regeneration.
- *Systems with fuel burners*—Commercial retrofit systems exist where the filter is regenerated by using a fuel burner upstream of the DPF unit.

Depending on the regeneration control method active DPF systems can be classified into two categories:

- Systems with automated regeneration—In these filters the regeneration process is fully controlled by an electronic control unit (ECU). The ECU monitors the soot load in the filter, determines the right moment to start the regeneration, and controls the regeneration process without an intervention (or even knowledge) of the vehicle operator.

- Systems with manually-assisted regeneration—A number of active regeneration systems require an intervention of the vehicle operator to trigger and complete the regeneration process (for instance, the operator may be required to park the vehicle and connect the DPF system to a shore power source for regeneration).

Most active filters use cordierite or silicon carbide wall-flow monoliths. In general, their PM filtration efficiency is in the range of 60-90% or greater. The emission performance of active systems that include catalysts (such as that in Figure 4-12) is in fact similar to that in passive filters. Active systems without catalysts are less effective in reducing the SOF fraction of diesel particulates. Therefore, their TPM conversion efficiency tends to be lower at colder temperatures, when the engine-out PM contains higher proportion of soluble organic fraction (SOF) particulate. Active filters without catalysts are also ineffective in reducing CO and HC emissions. Certain secondary emissions, including increased CO, may occur during regeneration of active filters, especially in systems without catalysts.

### 1.3.2 Filters with Electric Regeneration

DPF systems with electric regeneration available for non-road diesel engines typically use shore power as the source of energy for regeneration. The use of onboard DC power has been attempted, but has a limited applicability, as the power demand for filter regeneration is very high compared to the on-vehicle supply capacity. Based on system configuration, shore-power regenerated filters can be divided into two groups:

- On-board shore power regeneration systems,
- Off-board regeneration systems.

In the *on-board* regenerated systems, both the filter element and the regeneration hardware—including an electric heater and usually a blower to supply regeneration air—are installed on the vehicle (Figure 4-13). Once the filter is loaded with soot to its nominal capacity, as usually determined by a pressure drop monitor, the driver is notified that the unit must be regenerated. To perform the regeneration, the driver/operator must park the vehicle near a power outlet, connect the DPF system to the power, and initiate the regeneration sequence. The regeneration is usually conducted once a day or once every few days, depending on the vehicle duty cycle and filter capacity (size). The duration of regeneration may vary from about 15-minutes to about one-hour, depending on the filter system.

*Off-board* regenerated systems include two components: (1) the filter unit, which is installed on the vehicle, and (2) an electric regeneration unit, which is usually kept in the maintenance shop. When the filter becomes loaded with soot, it must be removed from the machine and regenerated on the regeneration unit. If spare filter units can be provided, loaded filters can be quickly replaced with regenerated ones, to avoid machine down time.

A number of systems are available from different suppliers (HUSS, UNICAT, ECS, and DCL, for example). In some on-board regeneration systems, the air blower may be a part of a wall-mounted off-board unit. In such cases, the vehicle must be parked for regeneration next to the off-board unit; the connections to be made for regeneration include electric power and air tubing. Typically, these filters are not catalyzed, which keeps their cost low. If the control of diesel odor, HC and CO emissions is essential, the filter elements can be coated with a catalyst.


**Figure 4-13. Shore Power Regenerated Filter on Construction Machinery (Switzerland)**

Regeneration timing is important for manually regenerated ADPFs. If the vehicle operator allows the filter to become overloaded with soot, the ECT can become damaged during regeneration or cause problems with engine backpressure. To avoid such problems, many filter users adopt a maintenance practice where filters are regenerated at the end of each eight-hour work shift, regardless of the soot load.

### 1.3.3 Filters with Fuel Burners

These active filters incorporate a fuel burner upstream of the filter substrate. When the filter is loaded with soot, diesel fuel is supplied to the burner and ignited; the heat from fuel combustion produces the desired increase in filter temperature to regenerate the unit.

Some fuel burner systems are designed to perform the regeneration at any engine operating conditions, others require that the engine operates at low idle speed or is shut down entirely for the time of regeneration. Filter systems using burners can be divided into two categories:

- Full flow burner systems.
- Single point burner systems.

The *full flow burner systems* are automated, and their operation is invisible to the vehicle operator. The regeneration is performed during regular operation of the vehicle. Even though commercial filters have been available in Europe for many years—from such suppliers as Deutz or ArvinMeritor (former Zeuna system)—their usage has been limited due to the high complexity and cost of the system. More recently, a fuel burner DPF system for railroad locomotives has been developed and commercialized in Switzerland and Germany by HUG.

The operation of fuel burner filters imposes a fuel economy penalty. This penalty varies depending on the filter system, vehicle, and its duty cycle, but is typically on the order of 1-2% due to the burner regeneration.

In *single point burner systems*, the machine has to be parked for the period of regeneration. Single point systems currently offered in Europe (e.g. HUSS) perform the regeneration with the engine shut down. These systems include a blower that supplies a small stream of air for the regeneration. This allows this equipment to further minimize the quantity of fuel used for regeneration.

### 1.3.4 Applicability, Feasibility, Installation, and Maintenance of ADPFs

Installation challenges for ADPFs are no less challenging than with PDPFs. Like PDPFs, ADPFs have similar size, weight, and stability challenges. In most cases, the active regeneration mechanism incurs greater installation complexity, regardless of the regeneration strategy. Fully automated active DPF systems tend to be very complex. They often require a number of signals from the engine control module, and their application may be limited to electronic engines. Their wide spread application is limited by typically very high system cost. Many filters with manually-assisted regeneration, on the other hand, are simple, easy to install, and have low system cost. The regeneration, however, becomes an added maintenance item, often performed on a daily basis, which increases their operational costs.

### 1.3.5 Huss ADPF

#### 1.3.5.1 Manufacturer's Technology Description

The Huss MK-System ADPF is integrated in the exhaust piping of the vehicle, directly replacing the original muffler. The filter medium is silicon carbide. The filter, in a typical application, can be used for approximately eight working hours, at which time the maximum allowed backpressure is reached and the filter needs to be regenerated. During regeneration, the diesel burner is ignited while the engine is shut down. Depending on the filter size, regeneration takes from five to thirty-five minutes. Approximately three to 10 ounces of diesel fuel are necessary for each regeneration period. The entire process is managed by an electronic system controller. Figure 4-14 shows the Huss ADPF. Since the Huss ADPF device is independent from external power supply, the regeneration can be started wherever the equipment stops. Because the system is equipped with an additional blower, sufficient air is supplied to the burner so that complete combustion is achieved. Therefore, secondary emissions are not produced, catalytic coatings are not required, and additives are not necessary. Huss MK series filters are CARB verified at Level 3 (>85% PM emission reduction) for most on and non-road applications. The filters also meet the 2009 CARB $NO_2$ emission limits.


**Figure 4-14. Huss ADPF (courtesy Huss)**

1.3.5.2 Test Results

The Huss ADPF was evaluated on a CAT D400 articulated dump truck at the Fresh Kills Landfill. Emissions were measured with the DOES2 ISS. Table 4-9 summarizes the results.

**Table 4-9. DOES2 ISS Emissions for the Huss ADPF**

| | Emissions (g/min) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $NO_2$ | CO | HC | PM | TPM (no blank correction) |
| Pre-ECT Mean Emissions | 1200 ± 132 | 18.0 ± 2.2 | 5.89 ± 0.97 | 3.21 ± 0.19 | 0.238 ± 0.026 | 0.160 ± 0.037 | 0.169 ± 0.037 |
| Post-ECT Mean Emissions | 1140 ± 102 | 16.2 ± 4.0 | 4.92 ± 0.58 | 3.40 ± 1.74 | 0.356 ± 0.154 | 0.013 ± 0.014 | 0.022 ± 0.014 |
| Mean Emission Change | -65.2 ± 167 | -1.77 ± 4.57 | -0.965 ± 1.128 | 0.193 ± 1.75 | 0.118 ± 0.156 | -0.147 ± 0.040 | -0.147 ± 0.040 |
| % Change | -5.43 ± 13.89 | -9.84 ± 25.40 | -16.4 ± 19.1 | 6.02 ± 54.64 | 49.8 ± 65.7 | -92.0 ± 25.0 | -87.1 ± 23.7 |
| Statistically Significant? | No | No | No | No | No | Yes | Yes |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase<br>Means based on three test runs pre- and post-ECT | | | | | | | |

The emission reductions associated with the Huss system were 92% for PM, as expected with a wall flow filtration system. Since this system was not catalyzed, no reductions in CO or THC emissions, nor increases in $NO_2$ emissions were observed. Note that a slight increase in THC emissions was noted, but was not statistically significant.

Figures 4-15 and 4-16 show the Huss MK system installed on the Caterpillar D-400 off-road truck and the in-cabin display. Similar to the other D400 installation, the Huss system required two separate filters to replace the single

OEM muffler, requiring additional space, significant engineering and installation effort, and custom mounting brackets and equipment.


**Figure 4-15. Front (left) and Rear (right) View of the Huss ADPF Dual Filter Retrofit Installed on a CAT D400 Dump Truck**


**Figure 4-16. In-Cab Display of Huss ADPF Control Modules Installed in the CAT D400 Dump Truck**

### 1.3.6 Airmeex ADPF

#### 1.3.6.1 Manufacturer's Technology Description

The Airmeex ADPF has a fuel burner for regeneration consisting of a cylindrical casing with a shock-proof Cordierite. The system is also designed with dual chambers that alternate during engine operation. The exhaust gases are led through one side of the filter medium until the backpressure between the engine and filter increases. When the maximum value is reached, the filter must be regenerated automatically. The "Duo" system diverts the exhaust gases into the other chamber while regeneration takes place, and the engine is not required to be stopped during filter regeneration. All soot particles, as well as hydrocarbons, are converted into CO, $CO_2$, and steam. Figure 4-17 shows the operating principle of the AirMeex ADPF. The AirMeex system is not currently CARB or EPA verified.

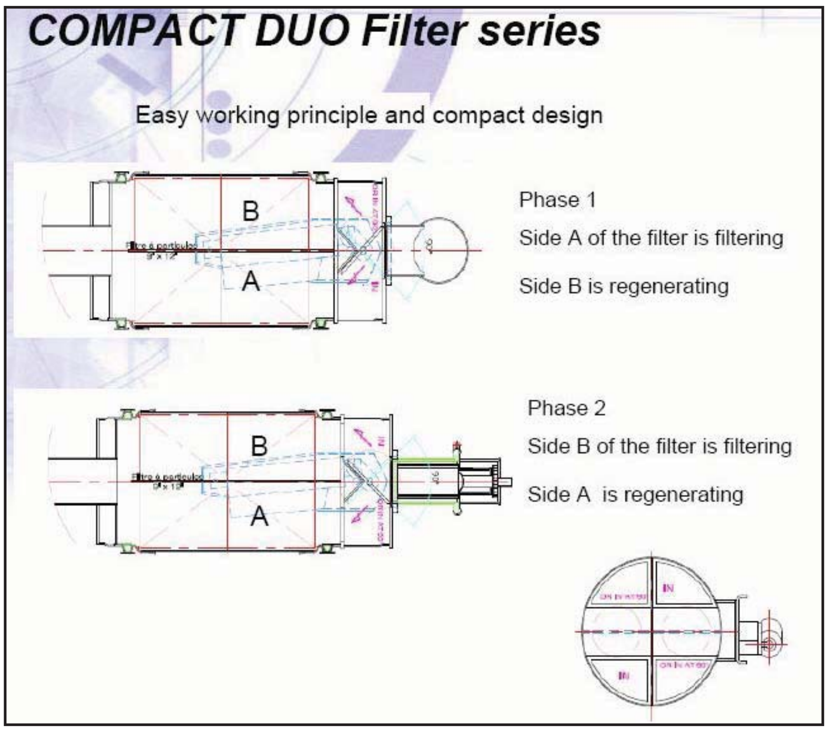



Figure 4-17. AirMeex ADPF (courtesy Airmeex)

#### 1.3.6.2 Test Results

Test personnel evaluated the AirMeex ADPF performance using both PEMS and ISS, simultaneously. The AirMeex ADPF was installed on Case 821 rubber tire loader at the DSNY Central Repair Shop site. Table 4-10 shows the mean emissions in g/min as measured by the OBS-2200 PEMS. Table 4-11 summarizes the emissions as measured by Environment Canada's DOES2 ISS.

**Table 4-10. OBS-2200 PEMS Emissions for the AirMeex ADPF**

| | Emissions (g/min) | | | |
|---|---|---|---|---|
| | $CO_2$ | NOx | CO | THC |
| Pre-ECT Mean Emissions | 277<br>± 26 | 4.66<br>± 0.34 | 0.455<br>± 0.099 | 0.350<br>± 0.033 |
| Post-ECT Mean Emissions | 256<br>± 48 | 4.39<br>± 0.61 | 0.382<br>± 0.081 | 0.344<br>± 0.309 |
| Mean Emission Change | -20.6<br>± 54.4 | -0.271<br>± 0.703 | -0.073<br>± 0.128 | -0.006<br>± 0.311 |
| % Change | -7.43<br>± 19.66 | -5.81<br>± 15.07 | -16.1<br>± 28.2 | -1.79<br>± 88.89 |
| Statistically Significant? | No | No | No | No |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase<br>Means based on four test runs pre- and three runs post-ECT | | | | |

**Table 4-11. DOES2 ISS Emissions for the AirMeex ADPF**

| | Emissions (g/min) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $NO_2$ | CO | HC | PM | TPM (no blank correction) |
| Pre-ECT Mean Emissions | 317<br>± 24 | 4.52<br>± 0.11 | 1.65<br>± 0.31 | 0.607<br>± 0.021 | 0.051<br>± 0.010 | 0.071<br>± 0.010 | 0.073<br>± 0.010 |
| Post-ECT Mean Emissions | 294<br>± 25 | 4.38<br>± 0.17 | 1.38<br>± 0.26 | 0.491<br>± 0.097 | 0.039<br>± 0.016 | 0.002<br>± 0.002 | 0.005<br>± 0.002 |
| Mean Emission Change | -23.1<br>± 34.7 | -0.134<br>± 0.196 | -0.268<br>± 0.408 | -0.116<br>± 0.099 | -0.012<br>± 0.019 | -0.068<br>± 0.010 | -0.068<br>± 0.010 |
| % Change | -7.6<br>± 11.0 | -2.4<br>± 4.3 | -18.2<br>± 24.7 | -17.7<br>± 16.3 | -27.1<br>± 37.7 | -97.4<br>± 14.1 | -94.4<br>± 13.6 |
| Statistically Significant? | No | No | No | Yes | No | Yes | Yes |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase.<br>Means based on four test runs pre- and three runs post-ECT. | | | | | | | |

The Airmeex ADPF showed a significant reduction in particulate emissions on the order of 97% for operations on the Case 821 loader. Based on both the Horiba and DOES2 data, no significant changes in other pollutant emissions were observed, except for CO emissions measured with the DOES2 – a reduction of 17.7%. This value is consistent with the value observed using the Horiba PEMS (16.2%), but the large confidence interval on both measurements require use of caution when using this data.

Also note that the gaseous emissions, and associated reductions measured by both systems are similar for some pollutants (NOx, CO), but are quite different for THC. The data collected using the Horiba on a second by second basis then integrated over the test run, typically displayed slightly more test to test variability, as noted by the 95% confidence interval for each measurement.

## 1.4 FLOW-THROUGH PARTICULATE FILTERS

### 1.4.1 Overview

"Flow-through filters" (FTF) are relatively new PM emission control devices, which have a particulate control efficiency higher than that of the diesel oxidation catalyst, but lower than diesel particulate filters. These devices may use different types of substrates, and are known by several names, including:

- Open particulate filters
- Partial flow filters
- PM oxidation catalysts
- PM filter catalyst
- Flow-through PM filters

The name "flow-through filters" properly reflects the operating principle of this class of devices and is consistent with the nomenclature used in the California verification program. The name "flow-through filter" refers to a device that can capture and store carbonaceous PM material for a period of time sufficient for its catalytic oxidation, while having open flow-through passages that allow exhaust gases to flow, even if the PM holding capacity is saturated. In other words, the flow-through filter is a specialized diesel oxidation catalyst with a capacity to hold solid soot particles. When filter capacity is reached, the PM conversion efficiency will drop to zero, and all PM emissions pass through the filter structure, so the filter will not plug.

FTF substrates are typically wire mesh or ceramic foams. The first commercial FTFs were sold in 2005 in Europe. In the USA, development of FTF devices for retrofit applications has been stimulated by the introduction of a Level 2 device—a 50-85% PM emission reduction that is a verification category established by CARB. At this time two retrofit FTF devices are verified in California: one using a specialized honeycomb substrate, and one using catalyzed wire mesh. A schematic of Emitec's FTF substrate, named the "PM Filter Catalyst", is shown in Figure 4-18.

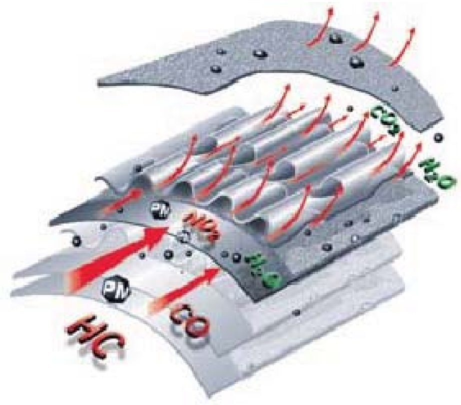



**Figure 4-18. "PM Filter Catalyst" Honeycomb Substrate (Emitec)**

The substrate consists of alternating layers of a corrugated metal foil and a porous sintered metal fleece. The corrugated foil is specially formed to direct the gas flow so it impinges onto the metal fleece layer. Thus, a part of the gas flows through the sintered metal layer, which acts as a filter. When the sintered metal is fully loaded with particulates, the corrugated channels remain open and let the untreated gases pass through. The alternating foil and sintered metal layers are wound and brazed into a cylindrical honeycomb structure resembling a conventional metallic catalyst substrate.

The collected PM can be regenerated using an upstream $NO_2$ forming catalyst (in a manner similar to the CRT filter) or catalyst can be applied directly onto the FTF substrate. Due to the use of catalyst, the FTF also shows a reduction in HC and CO emissions.

### 1.4.2 Performance and Emission Reduction

FTFs are potentially an attractive PM emission reduction technology, which can offer relatively high PM reduction efficiency while avoiding numerous problems related to DPF regeneration.  A PM emission reduction up to 50-70% is possible in an FTF. Still, the PM emission performance of FTFs depends on two important parameters:

- Exhaust gas temperature—A certain minimum exhaust gas temperature is necessary for the FTF to sustain its PM emission reduction activity (or to "regenerate" the FTF).
- Soot load—The FTF device cannot be clogged by soot, even if no regeneration is taking place. This indicates that under prolonged low temperature operation, the PM reduction efficiency will decrease and eventually drop to zero.

### 1.4.3 Applicability, Feasibility, Installation, and Maintenance of FTFs

FTFs fall somewhere between DPFs and DOCs regarding deployment feasibility. They are heavier than DOCs but typically not as heavy as DPFs.  The flow-through design is not as restrictive for exhaust backpressure, resulting in smaller, more manageable units.  Nevertheless, there is still a certain degree of complexity in their installation and maintenance. Periodic ash cleaning may still be required, and installation of the exhaust gas backpressure monitor is a requirement for CARB and EPA verified systems. On the other hand, their lower susceptibly to soot plugging, lighter weight and smaller size for large engine displacement non-road equipment, makes them an attractive alternative to the DPF. FTF devices are typically maintenance free. Their operation results in a low pressure drop and a negligible fuel economy penalty. The installation is similar to that of conventional DOCs.

### 1.4.4 Nett Technologies FTF

#### 1.4.4.1 Manufacturer's Technology Description

The Nett® FM-Series FTF was installed on a Daewoo Mega-200 rubber tire loader. The Nett FTFs use a metal foam monolith to trap the soot produced by diesel engines. The cylindrical filter element is made of rigid open-cell metallic foam that allows exhaust gases to flow through the element, but heavier particulate matter becomes trapped in its structure. The pores in the filter element are large enough to allow exhaust gases and particulates to pass through the filter in the event that the soot storage capacity is reached. In this case, the engine and equipment are able to operate normally, even though the filter is full. A proprietary catalyst is coated onto the inside surface of the filter monolith. The catalyst lowers the soot combustion temperature, allowing the filter to regenerate. The accumulated soot is oxidized in the filter during regular operation of the engine. The FTF begins PM regeneration at or below 275°C (525°F). The catalyzed filter monolith is wrapped in a fiber mat and packaged into a stainless steel housing, which is installed in the vehicle's exhaust system. FTFs are available in direct fit configurations for simplified installation or universal-fit models suitable for virtually any diesel engine as shown in Figure 4-19 below. The Nett FTF is not yet verified by EPA or CARB.

**Figure 4-19. FTF available in Universal-Fit Models (courtesy Nett)**

Generally, the soot filtration efficiency of the Nett® FM-Series FTF increases with the soot loading in the unit until it reaches capacity. Visible smoke is greatly reduced and may be completely eliminated by the filter in some applications. Due to the presence of the catalyst, reductions in carbon monoxide and hydrocarbon emissions are also observed.

1.4.4.2 Test Results

There were two Nett FTFs tested during this test program. The difference between Nett's standard FTF and the Compact FTF is the number of cores within the compact system and its design complexity to make it a compact unit for installation directly on non-road equipment without modification or additional support.

The Nett Compact FTF was installed on a Case 70XT skid steer loader and was evaluated using the CATI PEMS system. Due to a leak in the sample line only one test was valid for the compact FTF. Therefore, data for this device was not summarized.

Nett's standard FTF performance was evaluated using both PEMS and ISS, simultaneously. The FTF was installed on a Daewoo Mega 200 rubber tire loader at the DSNY Central Repair Shop site. Table 4-12 shows the mean emissions in g/min as measured by the OBS-2200 PEMS. Table 4-13. DOES2 ISS Emissions for the Nett FTF summarizes the emissions as measured by Environment Canada's DOES2 ISS.

**Table 4-12. OBS-2200 PEMS Emissions for the Nett FTF**

| | **Emissions (g/min)** | | | |
|---|---|---|---|---|
| | **$CO_2$** | **NOx** | **CO** | **THC** |
| Pre-ECT Mean Emissions | 589 ± 52 | 4.35 ± 0.18 | 1.48 ± 0.63 | 1.19 ± 0.06 |
| Post-ECT Mean Emissions | 564 ± 47 | 3.91 ± 0.33 | 0.058 ± 0.333 | 0.136 ± 0.113 |
| Mean Emission Change | -24.8 ± 69.9 | -0.427 ± 0.371 | -1.42 ± 0.72 | -1.06 ± 0.13 |
| % Change | -4.21 ± 11.87 | -9.83 ± 8.54 | -96.1 ± 48.4 | -88.6 ± 10.7 |
| Statistically Significant? | No | Yes | Yes | Yes |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase.<br>Means based on three test runs pre- and post-ECT. | | | | |

**Table 4-13. DOES2 ISS Emissions for the Nett FTF**

| | Emissions (g/min) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **$CO_2$** | **$NO_x$** | **$NO_2$** | **CO** | **HC** | **PM** | **TPM (no blank correction)** |
| Pre-ECT Mean Emissions | 502 ± 108 | 3.31 ± 0.39 | 0.877 ± 0.157 | 1.59 ± 0.64 | 0.164 ± 0.047 | 0.259 ± 0.103 | 0.260 ± 0.103 |
| Post-ECT Mean Emissions | 412 ± 104 | 2.79 ± 0.81 | 0.673 ± 0.269 | 0.118 ± 0.098 | 0.017 ± 0.001 | 0.133 ± 0.041 | 0.134 ± 0.041 |
| Mean Emission Change | -90.1 ± 150 | -0.516 ± 0.896 | -0.204 ± 0.311 | -1.47 ± 0.65 | -0.148 ± 0.047 | -0.126 ± 0.111 | -0.126 ± 0.111 |
| % Change | -28.1 ± 29.9 | -29.6 ± 27.1 | -39.8 ± 35.5 | -94.9 ± 41.0 | -88.8 ± 28.5 | -60.7 ± 42.8 | -60.3 ± 42.5 |
| Statistically Significant? | No | No | No | Yes | Yes | Yes | Yes |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase. Means based on three test runs pre- and post-ECT | | | | | | | |

As expected, the Nett FTF demonstrated significant reductions in THC (>88%) and CO emissions (>94%), as measured by both emission testing systems. The PM emission reduction was also within the expected range of 50-70%, with a reduction of 60.7%. Note also that, although not statistically significant, there was no $NO_2$ emission increase observed when using this unit.

### 1.4.5 DCL FTF

#### 1.4.5.1 Manufacturer's Technology Description

The DCL FTF is designed to achieve >50% PM collection efficiency by mass when used in conjunction with ULSD fuel. The device works by its unique trapezoidal design, which forces the untreated exhaust gas through a catalytically coated sintered metal fleece. The coated fleece effectively filters the PM while also converting CO and HCs into $CO_2$ and water.

DCL custom packages the FTFs to replace the existing muffler (where space permits) making installation as simple as a muffler swap. The device is non-blocking and as such does not require backpressure monitoring or maintenance. The DCL FTF is not currently CARB or EPA verified.

#### 1.4.5.2 Test Results

The DCL FTF was evaluated on a Daewoo Mega 200 rubber tire loader at the DSNY Central Repair Shop site. Emission testing was performed with the DOES2 ISS. Table 4-14 summarizes the results.

**Table 4-14. DOES2 ISS Emissions for the DCL FTF**

| | Emissions (g/min) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $NO_2$ | CO | HC | PM | TPM (no blank correction) |
| Pre-ECT Mean Emissions | 305 ± 29 | 2.53 ± 0.30 | 0.736 ± 0.080 | 1.38 ± 0.20 | 0.160 ± 0.046 | 0.209 ± 0.034 | 0.212 ± 0.034 |
| Post-ECT Mean Emissions | 328 ± 21 | 2.56 ± 0.14 | 1.05 ± 0.09 | 0.053 ± 0.041 | 0.051 ± 0.004 | 0.149 ± 0.033 | 0.151 ± 0.033 |
| Mean Emission Change | 22.8 ± 35.8 | 0.027 ± 0.325 | 0.316 ± 0.122 | -1.32 ± 0.20 | -0.109 ± 0.046 | -0.060 ± 0.047 | -0.060 ± 0.047 |
| % Change | 7.49 ± 11.75 | 1.07 ± 12.84 | 43.0 ± 16.6 | -96.1 ± 14.4 | -68.0 ± 29.0 | -28.8 ± 22. 5 | -28.5 ± 22.2 |
| Statistically Significant? | No | No | Yes | Yes | Yes | Yes | Yes |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase. Means based on three test runs pre- and post-ECT. | | | | | | | |

The DCL FTF achieved statistically significant CO emission reductions of 96.1%, and THC reductions of 68%, well within typical ranges for catalyzed filters. The system achieved a 28.8% reduction in PM emissions, which is slightly below the expected emission reduction of 50%. In addition, a statistically significant increase in $NO_2$ emissions was observed when using the catalyzed filter, on the order of 43%.

### 1.4.6 Extengine FTF

#### 1.4.6.1 Manufacturer's Technology Description

Extengine's LEV2 Hybrid Diesel Particulate Catalyst is an open-flow diesel oxidation catalyst that reduces PM emissions by 50-70% in many on-highway and non-road equipment applications. Like most FTFs they are less expensive, are not cycle-dependent, and will not clog with diesel particles. Extengine incorporated an open-flow design and a proprietary wash coat and unique metallic cross-flow substrate. The LEV2™ can be adapted and used as a muffler, or it can be located outside the muffler, so if there is space permitting, there is no need to replace the muffler during retrofit. The system is verified by CARB as a Level 2 emission control device (>50% PM reduction).

#### 1.4.6.2 Test Results

Test personnel evaluated the Extengine FTF performance using the RAVEM system on a 1998 Case 821 rubber tire loader. Table 4-15. RAVEM Emissions for the Extengine FTF shows the mean emissions in g/min as measured by the RAVEM.

**Table 4-15. RAVEM Emissions for the Extengine FTF**

| | Emissions (g/min) | | |
|---|---|---|---|
| | **PM** | **CO** | **$NO_x$** |
| Pre-ECT Mean Emissions | 0.26 ± 0.01 | 0.78 ± 0.32 | 6.7 ± 0.1 |
| Post-ECT Mean Emissions | 0.08 ± 0.02 | 0.04 ± 0.17 | 5 ± 1 |
| Mean Emission Change | -0.17 ± 0.02 | -0.74 ± 0.36 | -1.4 ± 1.2 |
| % Change | -68% ± 7% | -95% ± 46% | -21% ± 19% |
| Statistically Significant? | Yes | Yes | Yes |

Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase.
Means based on three test runs pre- and post-ECT.

The Extengine FTF provided statistically significant reductions in all three parameters measured: PM, CO, and NOx. The significant reduction of PM on the order of 68% confirms the CARB verification level of 50-85% PM reduction. While it is interesting to note the observed NOx reduction, it must be noted that the confidence interval on the difference is large and borders on being not significant. In addition, a separate $NO_2$ measurement was not included. Since this is a catalyzed filter, there is potential for an increase in $NO_2$ emissions, which should be evaluated further.

## 1.5 AMMONIA/UREA SCR

### 1.5.1 Overview

Selective catalytic reduction (SCR) of $NO_x$ by nitrogen compounds such as *ammonia* or *urea*—commonly referred to as simply "SCR"—has been developed for and well proven in industrial stationary applications. The SCR technology was first applied in thermal power plants in Japan in the late 1970s, followed by widespread application in Europe since the mid 1980s. In the USA, SCR systems were introduced for gas turbines in the 1990s, and subsequently to control $NO_x$ emissions from coal-fired power plants.

While the application of SCR for mobile diesel engines requires overcoming several problems, SCR remains the only proven catalyst technology capable of reducing diesel $NO_x$ emissions to levels required by future diesel emission standards. Urea-SCR has been selected by a number of manufacturers as the technology of choice for meeting the Euro V (2008) and the JP 2005 $NO_x$ limits. First commercial diesel truck applications were launched in 2004 by Nissan Diesel in Japan and by DaimlerChrysler in Europe. In the United States, SCR systems are being developed for meeting the 2010 $NO_x$ limit of 0.2 g/bhp-hr for heavy-duty highway engines, as well as the Tier 2 $NO_x$ standards for light-duty vehicles. From the regulatory perspective SCR poses enforcement problems, both in terms of ensuring that the reductant (urea) is available together with diesel fuel throughout the nationwide distribution network, and that it is always replenished by vehicle operators.

Two major types of SCR catalysts are used in mobile applications: (1) vanadia/titania ($V_2O_5/TiO_2$) catalysts and (2) zeolite catalysts.

A schematic of a typical SCR system for mobile diesel engines is shown in Figure 4-20. The urea solution (typically 32.5% urea in water) is pumped from the urea tank and sprayed through an atomizing nozzle into the exhaust gas stream. It is important that the injected urea solution be thoroughly mixed with the gas. Once mixed with the hot exhaust gas, urea undergoes hydrolysis and thermal decomposition, producing ammonia. In some systems, the urea hydrolysis is additionally promoted by a dedicated hydrolysis catalyst, but in most systems this function is incorporated into the SCR catalyst itself. With some types of SCR catalysts, the catalyst performance is increased at an elevated $NO_2$:NO ratio in the feed gas. In such cases, an $NO_2$ forming oxidation catalyst can be installed upstream of the urea injection point. In most systems an oxidation catalyst is also included downstream of the SCR catalyst to control any $NH_3$ that was not consumed in the SCR catalyst (so-called *ammonia slip*).

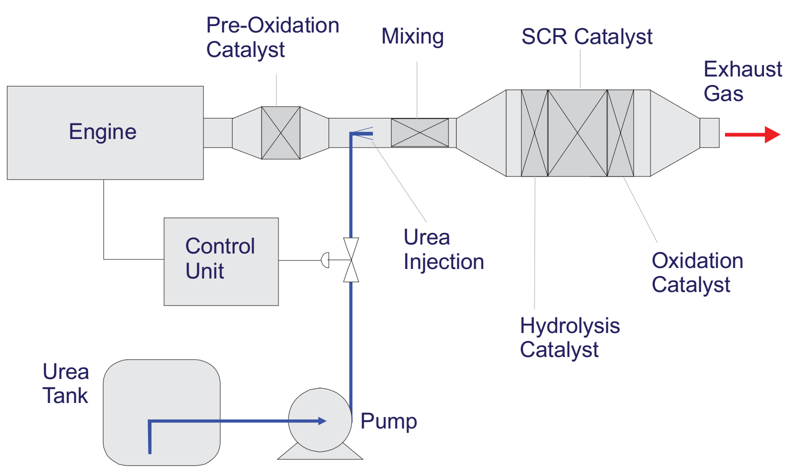



**Figure 4-20. Generic Schematic of Urea-SCR System (Open Loop Control)**

The control of urea injection rate presents a big challenge in SCR systems operating under transient conditions. The injected amount of urea must closely follow the changing $NO_x$ concentration in the exhaust gas. If too much urea is injected, ammonia slip will occur. If too little, the $NO_x$ conversion rate will deteriorate. Future SCR systems will likely use closed loop control schemes, where the urea injection rate will be controlled based on a feedback from an exhaust $NO_x$ sensor. Nevertheless, until NOx sensors improve in terms of speed and cost, many SCR systems will be controlled based on a lookup table strategy, where the system control unit computes the urea injection rate based on the engine speed and load conditions.

SCR systems for retrofitting mobile diesel engines are at an early stage of commercialization. Systems that are being developed by different suppliers differ by the reductant type (ammonia vs. urea), as well as system configuration and control strategy. From the safety point of view, urea is the preferred solution. Still, the only SCR system currently verified by the California ARB (80% $NO_x$ reduction over a steady-state test, Level 1 PM reduction using a DOC provided by Extengine) uses ammonia reductant. Several urea SCR systems are currently identified on the EPA Emerging Technologies list, which lists technologies that are new and unverified, but are in the process of seeking verification. These systems are provided by Nett Technologies, Johnson Matthey (JMI), and Engine Control Systems (ECS), and Tinnerman-Shadowood.

Retrofit SCR systems, depending on the supplier, can use two types of urea injection control strategy:

i. Engine map-based control—This strategy (similar to that used in OEM systems) requires that an engine $NO_x$ emission map be determined and stored in the control unit memory. Engine dynamometer testing may be required to determine the engine map. Some suppliers are developing data logging units that can determine the engine $NO_x$ emission map while installed on the vehicle during regular operation. SCR systems that use engine map strategies require engine speed and load signal hook-up. Therefore, they are more compatible with electronic engines. Additional sensors would have to be installed for use on mechanical engines.

ii. $NO_x$ sensor-based control—Some retrofit SCR systems are controlled using a feed-forward strategy, based on signals from a $NO_x$ sensor positioned upstream of the SCR system (a downstream position is not possible due to high cross-sensitivity of available $NO_x$ sensors to ammonia) and from an inlet air flow sensor. Sensor-based control does not require engine mapping, and allows for easier installation, especially on mechanical engines. Nevertheless, due to the slow response time of commercial $NO_x$ sensors, transient $NO_x$ performance may be reduced.

Most retrofit SCR systems use compressed air-assisted urea atomization/injection systems to achieve improved mixing of the reductant with the exhaust gas, which results in better $NO_x$ reduction efficiency. Compressed air is also used to purge urea from the injector during shutdown. An air compressor is a part of such systems. If the vehicle has compressed air available, it can save cost, as a separate compressor will not be required.

Retrofit SCR systems can be supplied with a DPF for simultaneous $NO_x$ and PM control. Application of a passive DPF is limited to engines of sufficiently high exhaust temperatures. A system combining SCR with an active DPF would allow the application of the SCR+DPF technology—which could provide >80% $NO_x$ and PM reductions—on more non-road engine models, albeit with considerable cost and complexity.

### 1.5.2 Performance and Emission Reductions

$NO_x$ conversion rates in excess of 90% are possible with SCR systems in steady-state operation, such as in many stationary applications. Under the transient diesel engine conditions, $NO_x$ conversions from about 50 to 90% have been reported in SCR systems targeting OEM applications (W.R. Miller, 2000). The observed $NO_x$ conversion efficiency depends on two major factors:

- Transient character of the test—$NO_x$ conversion in real life operation and over transient test cycles is a function of the quality of control of the urea injection rate.

- Low temperature performance—Urea-SCR technology is ineffective at low exhaust temperatures (< approx. 300°C) due to (1) limitation of the catalyst activity and (2) the need to cut off urea injection below about 200-250°C to avoid formation of ammonium nitrate and other undesired species that can cause catalyst fouling (B. Scarnegie, 2003).

The SCR catalyst has little impact on CO/HC, but these emissions are typically reduced in SCR systems through oxidation in the pre-catalyst and in the ammonia slip catalyst. The conversion efficiency depends on system configuration and the test cycle. SCR systems do not reduce PM emissions (in fact, an increase in PM emissions is possible due to formation of ammonium nitrates and sulfates in the SCR catalyst).

While the SCR catalyst can operate with high sulfur fuels, ULSD fuels are necessary to prevent formation of sulfate particulates in the pre-catalyst and in the ammonia slip catalyst. There are a number of undesirable *unregulated emissions* that may be created in SCR catalyst systems. In addition to the ammonia slip, ammonium nitrates and sulfates, SCR catalysts can produce *nitrous oxide* ($N_2O$), *hydrogen cyanide* (HCN), various urea decomposition products (other than $NH_3$), and possibly other compounds.

### 1.5.3 Applicability, Feasibility, Installation, and Maintenance of SCRs

Installations of SCR systems on non-road vehicles are typically more challenging than on-highway vehicles and are often exacerbated by the greater complexity of the non-road machine and the harsh non-road construction operating environment. One major difficulty with SCR retrofits is the requirement for compressed air. On-board air compressors are a rarity on non-road construction equipment, requiring retrofit not just of the SCR system with all its complexity and numerous components (see Figure 4-20), but of the air compressor as well. In addition to severe space constraints on many types of non-road machines, air compressors consume energy, potentially compromising the operating power of the machine. Additional deployment issues with SCR are not dissimilar from those associated with DPFs—the SCR catalyst itself is typically as heavy and bulky as a DPF unit with all the associated challenges of installation.

In addition to installation challenges, there exist a multitude of operations, maintenance and durability issues that have been impediments to widespread SCR deployment. All issues with OEM SCR systems for highway engines fully apply—often to an even larger degree—to retrofit SCR kits for non-road equipment:

- *Urea replenishment*: Urea solution must be periodically replenished, which represents extra maintenance and operational cost. The urea solution consumption can vary from 1-5% (by vol.) relative to the diesel fuel consumption .

- *Stability of urea solution:* 32.5% urea solutions crystallize at –11°C (12°F). Freezing problems may occur during winter in cold climate areas. In hot climates, on the other hand, urea may decompose while exposed to increased temperatures during storage or in vehicle tanks.

- *Transient performance:* Steady-state $NO_x$ reduction in retrofit systems is often as high as 80-95%, but transient performance may be significantly lower. Transient urea injection control issues may also result in high ammonia slip. Steady-state testing can provide realistic measure of performance in (mostly) steady-state applications, such as generator sets, but not in non-road engines operated under transient duty cycles.

- *Low temperature performance:* At low temperature, the $NO_x$ conversion may be low or completely eliminated.

- *High cost:* High cost of the system is in part caused by the urea injection and control components, which do not change with the engine size. Therefore, from the cost perspective, SCR systems more suitable for retrofitting large diesel engines. The cost of SCR components can be expected to drop drastically if the SCR technology is adopted for US 2010 highway trucks.

These issues need to be carefully considered as part of the process of considering SCR for $NO_x$-reduction on non-road construction equipment. On the other hand, some of the inherent difficulties of SCR deployment are mitigated by the nature of the non-road construction environment. Issues of urea replenishment and freezing for example may be rectified since some types of equipment are frequently located on a central site for a considerable length of time. Still, other types of equipment, such as compressors and smaller machines, are frequently moved from site to site. Selection of SCR is attractive because of its impressive $NO_x$ reduction capabilities; however deployment for non-road application is not without challenges.

### 1.5.4 NETT FTF/SCR

#### 1.5.4.1 Manufacturer's Technology Description

Nett's FTF/SCR system uses a metal foam monolith FTF to trap the soot produced by diesel engines, coupled with a urea injection system and SCR catalyst. The particulate filter element is made of rigid open-cell metallic foam that allows exhaust gases to flow through the element, but diesel particulate matter becomes trapped in the structure. The pores in the filter element are large enough to allow exhaust gases and particulates to pass through the filter in the event that the soot storage capacity is reached, which will allow the engine to continue to operate normally, even though the filter is full.

The main components of the BlueMAX™ system include the SCR catalytic converter, the urea dosing system (UDS), and the urea tank. The urea control strategy relies on a $NO_X$ concentration measurement by a sensor positioned upstream of the SCR converter. Based on the $NO_X$ sensor signal, in combination with an engine mass air flow sensor and temperature sensors, the necessary urea dosing rate is calculated by the control software. The $NO_X$ sensor-based control strategy makes the system very suitable for retrofit applications. The system can be installed on a wide range of diesel engines, including mechanical engines.

Urea (in the form of a 32.5% water-based solution) is stored in the urea tank and is metered by a precise dosing pump. The urea solution is introduced to the exhaust pipe upstream of the SCR catalyst through an injection nozzle. Urea atomization is supported by compressed air supplied by a compressor. The exact emission performance of the BlueMAX™ system depends on the catalyst size, exhaust temperature, and raw exhaust composition. A minimum temperature of approximately 180°C (360°F) is required for conversion. The highest catalyst performance occurs at temperatures above 250-300°C (480-570°F). Conversion of diesel particulate matter in the catalyst depends on the composition of the particulates and the sulfur content of the fuel. Low sulfur diesel fuel is strongly recommended for the best catalyst performance.

The Nett BlueMax and BlueMax 200 SCR systems are currently listed on the EPA Emerging Technology list for non-road applications. The emerging technology list specifies a control efficiency of 25% for PM, 60% for CO, 65% for NOx, and 60% for HC.

1.5.4.2 Test Results

Test personnel evaluated the NETT FTF/SCR system performance installed on a Case 821 loader using the RAVEM system. Figure 4-21 shows the SCR-FTF systems installed on the loader. Table 4-16 shows the mean emissions in g/min as measured by the RAVEM.

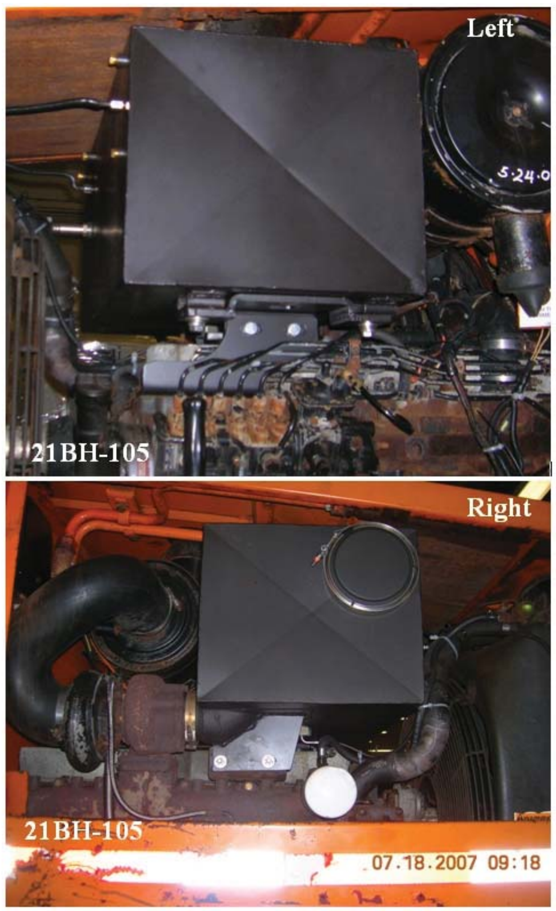



**Figure 4-21. Nett SCR-FTF System**

**Table 4-16. RAVEM Emissions for the NETT FTF/SCR**

| | Emissions (g/min) | | |
|---|---|---|---|
| | **PM** | **CO** | **$NO_x$** |
| Pre-ECT Mean Emissions | 0.31 ± 0.23 | 0.77 ± 0.30 | 6.8 ± 1.8 |
| Post-ECT Mean Emissions | 0.15 ± 0.03 | -0.10 ± 0.03 | 2.9 ± 0.6 |
| Mean Emission Change | -0.16 ± 0.23 | -0.88 ± 0.30 | -3.8 ± 1.9 |
| % Change | -52% ± 75% | -113% ± 39 % | -57% ± 28% |
| Statistically Significant? | No | Yes | Yes |

Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase.
Note: Negative values less than 0.0 are due to ambient background subtraction
Means based on three test runs pre- and post-ECT

The Nett SCR system provided NOx reductions operating over the transient loader cycle on the order of 57%. This is consistent with the NOx reduction value of 65% as provided on the EPA Emerging Technology list. The system provided a 100% CO reduction (including ambient background reduction). The particulate emissions reduction observed was 52%, similar to the reductions observed for the Nett FTF (without SCR) evaluated in this program (a 60% reduction), and significantly higher than the 25% reduction specified on the EPA Emerging Technology list. Nevertheless, due to significant variability in the pre-ECT PM emissions measurements, the statistical significance of the PM emission reduction is not seen.

## 1.6 DIESEL OXIDATION CATALYSTS

### 1.6.1 Overview

A schematic of a diesel oxidation catalyst is shown in Figure 4-22. A ceramic or metallic catalyst substrate is coated with a layer of refractory oxide washcoat, and impregnated with a catalyst. The catalyzed substrate is packaged into a steel canister and installed in the exhaust system.

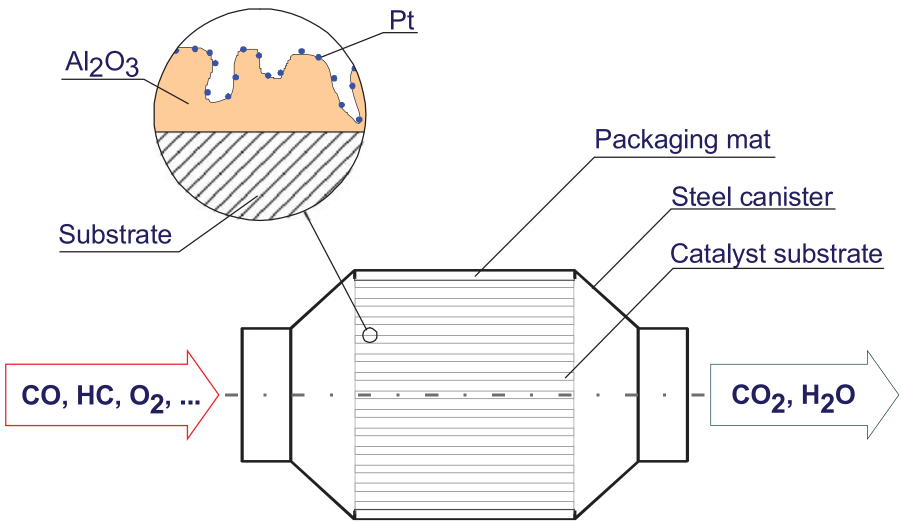



**Figure 4-22. Schematic of Diesel Oxidation Catalyst**

In diesel oxidation catalysts (DOC), the washcoat is usually based on alumina and the most common catalyst is platinum. Still, depending on the application, different catalyst formulations can be used to target specific pollutants (i.e. PM vs. CO and HC).

### 1.6.2 Performance and Emission Reduction

The emission reductions in the DOC occur through chemical oxidation of pollutants occurring over the active catalytic sites. The DOC performance is a function of temperature. The catalyst shows no activity at low exhaust gas temperatures. As the temperature increases, so does the oxidation rate of CO and HC. This is called catalyst "light-off". The DOC light-off depends on the species, catalyst formulation, and other factors, but light-off temperatures in most catalysts range from about 180 to 250°C.

Conversion rates for CO and HC emissions can be very high, in excess of 90 percent, in active Pt-based catalysts, but base metal DOCs may have low CO or HC activity.

The DOC is also active in reducing PM emissions from diesel engines. PM emission reductions result from the combined effect of oxidation and cracking of heavy hydrocarbons that form the soluble organic fraction of diesel particulates. Since the DOC activity is limited to SOF, the potential for total PM reduction depends on the composition of particulates.

Due to the variability in SOF fraction between engines and operating conditions, the PM emission reduction in the DOC is strongly engine and test cycle specific. Total PM emission reductions in excess of 50 percent are often measured in light duty vehicles over cold test cycles. In many heavy-duty engines, where the test cycles have higher load factor, total PM emission reductions up to approximately 20-30 percent can be realized. However, in engines which have a tendency to produce little to no SOF, the PM emission reduction using DOC may be less than 10 percent.

The DOC is also active in oxidizing sulfur dioxide to sulfur trioxide, which combines with water to form sulfuric acid. This is a counterproductive process, as the generated hydrated sulfuric acid and its salts are measured as particulate matter. This fraction of PM is referred to as *sulfate particulates*.

If active Pt-based DOCs are used with high sulfur fuels, the PM emissions may actually be increased, as the generated sulfates can easily outweigh the SOF reductions. “Sulfate suppressed” DOC formulations have been developed that have somewhat reduced sulfate activity, but the ultimate solution to this problem is the use of ultra low sulfur fuels.

The total $NO_x$ emissions remain unchanged in the DOC. Active Pt-based DOCs increase the proportion of $NO_2$ in the total $NO_x$ emissions due to the catalytic oxidation of NO. In some applications, especially in occupational health environments (such as when engines are operated indoors) the increased $NO_2$ emissions may present air quality problems.

Metallic fuel additives that can provide PM emission reductions in the range of 25-50%. can enhance the performance of the DOC. DOC + additive emission control strategies have been verified.

### 1.6.3 Applicability, Feasibility, Installation, and Maintenance of DOCs

The DOC is a mature technology with a proven durability record for on-highway applications. Since 1994, DOCs have been used on all urban bus engines in the USA and on some highway truck engines. A number of DOCs have been verified by the EPA and by California ARB for retrofitting highway as well as non-road engines. DOC installation is comparatively straightforward even for most non-road construction applications. Because they are nearly the same size as the OEM muffler on the piece of equipment, they are frequently installed as a direct replacement. DOCs are typically heavier than mufflers, but not a heavy as DPFs and generally require only minimal, if any, additional support brackets as part of the installation process.

DOC maintenance is minimal, and for most types of non-road equipment operating under duty cycles typical to construction applications, never requires cleaning. Because of the open flow design characteristic of DOCs, plugging with soot or ash from the engine’s lubricating oil is virtually nonexistent. If properly selected and operated on properly maintained engines, DOCs are typically maintenance free and incur no fuel economy penalty. Because of their low cost, ease of installation, and minimal maintenance requirements, DOCs are the most favored retrofit technology by construction fleets, and have been deployed with considerable success on a number of large construction projects

On engines with high SOF emissions, DOCs may present the lowest cost PM control option. Furthermore, when deployed on a large-scale fleetwide basis, significant reductions can be garnered. Their drawback as a PM control

**Table 4-15. RAVEM Emissions for the Extengine FTF**

| | Emissions (g/min) | | |
|---|---|---|---|
| | **PM** | **CO** | **$NO_x$** |
| Pre-ECT Mean Emissions | 0.26 ± 0.01 | 0.78 ± 0.32 | 6.7 ± 0.1 |
| Post-ECT Mean Emissions | 0.08 ± 0.02 | 0.04 ± 0.17 | 5 ± 1 |
| Mean Emission Change | -0.17 ± 0.02 | -0.74 ± 0.36 | -1.4 ± 1.2 |
| % Change | -68% ± 7% | -95% ± 46% | -21% ± 19% |
| Statistically Significant? | Yes | Yes | Yes |
| Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase. Means based on three test runs pre- and post-ECT. | | | |

The Extengine FTF provided statistically significant reductions in all three parameters measured: PM, CO, and NOx. The significant reduction of PM on the order of 68% confirms the CARB verification level of 50-85% PM reduction. While it is interesting to note the observed NOx reduction, it must be noted that the confidence interval on the difference is large and borders on being not significant. In addition, a separate $NO_2$ measurement was not included. Since this is a catalyzed filter, there is potential for an increase in $NO_2$ emissions, which should be evaluated further.

## 1.5 AMMONIA/UREA SCR

### 1.5.1 Overview

Selective catalytic reduction (SCR) of $NO_x$ by nitrogen compounds such as *ammonia* or *urea*—commonly referred to as simply "SCR"—has been developed for and well proven in industrial stationary applications. The SCR technology was first applied in thermal power plants in Japan in the late 1970s, followed by widespread application in Europe since the mid 1980s. In the USA, SCR systems were introduced for gas turbines in the 1990s, and subsequently to control $NO_x$ emissions from coal-fired power plants.

While the application of SCR for mobile diesel engines requires overcoming several problems, SCR remains the only proven catalyst technology capable of reducing diesel $NO_x$ emissions to levels required by future diesel emission standards. Urea-SCR has been selected by a number of manufacturers as the technology of choice for meeting the Euro V (2008) and the JP 2005 $NO_x$ limits. First commercial diesel truck applications were launched in 2004 by Nissan Diesel in Japan and by DaimlerChrysler in Europe. In the United States, SCR systems are being developed for meeting the 2010 $NO_x$ limit of 0.2 g/bhp-hr for heavy-duty highway engines, as well as the Tier 2 $NO_x$ standards for light-duty vehicles. From the regulatory perspective SCR poses enforcement problems, both in expected for a DOC. A 28% PM reduction was also observed, which is within a typical range for many verified DOC PM emission reductions (on the order of 25%). It is also interesting to note that a 11% NOx reduction was observed during testing.

Because of the small size of the equipment that the DOC was placed on, the use of the larger PEMS and ISS systems would have been difficult, making it an ideal candidate for use of the CATI PEMS system. As shown in Table 4-17, the CATI system provided consistent, repeatable results, with fairly narrow confidence intervals, and emission reductions that are within expected ranges for this application.

### 1.6.5 NETT DOC

#### 1.6.5.1 Manufacturer's Technology Description

The NETT DOC includes hydrocarbon traps for improved low temperature activity and diesel odor control. The emission performance of the catalyst depends on the catalyst size, exhaust temperature, and raw exhaust composition. A minimum temperature of approximately 180°C (360°F) is required for conversion. Best catalyst performance occurs at temperatures above 250-300°C (480-570°F) when the conversion of carbon monoxide exceeds 90%. Conversion of diesel particulate matter in the catalyst depends on the composition of the particulates and the sulfur content of the fuel. Low sulfur diesel fuel is strongly recommended for the best catalyst performance.

#### 1.6.5.2 Test Results

Test personnel evaluated the NETT DOC performance on a Case 580 backhoe using the RAVEM system. Table 4-18 shows the mean emissions in g/min as measured by the RAVEM.

**Table 4-18. Emissions for the NETT DOC**

| | **Emissions (g/min)** | | |
|---|---|---|---|
| | **PM** | **CO** | **$NO_x$** |
| Pre-ECT Mean Emissions | 0.09 ± 0.06 | 0.31 ± 0.01 | 2.6 ± 0.6 |
| Post-ECT Mean Emissions | 0.06 ± 0.06 | -0.2 ± 0.4 | 3 ± 0.2 |
| Mean Emission Change | -0.03 ± 0.09 | -0.5 ± 0.4 | 0.4 ± 0.7 |
| % Change | -35% ± 94% | -158% ± 114% | 15% ± 27% |
| Statistically Significant? | No | Yes | No |

Note: Negative values indicate an emissions reduction; Positive values indicate an emissions increase.
Note: Negative values less than 0.0 are due to ambient background subtraction
Means based on three test runs pre- and post-ECT.

Emission reductions measured for the Nett DOC are within expected ranges for PM (35%) and CO (100%). Nevertheless, significant variability in the test data results in the inability to identify the changes as statistically significant. In addition, with background correction, the CO emission reduction of 158% indicates that a significant background concentration of CO was present, and that the oxidation catalyst was producing emission levels of CO that were much below the background concentration seen in the engine intake and RAVEM dilution air. Although results are within expected ranges, the data from this test should be used with caution due to the large confidence intervals.

## 1.7 BIODIESEL

Biodiesel is defined as the mono alkyl (typically methyl) esters of long chain fatty acids derived from renewable lipid feedstocks, such as vegetable oils and animal fats, for use in compression ignition (diesel) engines. The most common source of biodiesel in the USA is soybean oil. Other significant biodiesel resources are greases and animal fats. On the worldwide scale, the most cost effective biodiesel feedstock is palm oil.

In North America, most experience exists with the use of B20 biodiesel blend, containing 20% soy-based biodiesel blended with diesel. The quality of the biodiesel blending stock is described by the ASTM standard D 6751.

Biodiesel typically produces emission reductions of PM, CO, and HC, and an increase in NOx, but actual results are extremely specific to engine technology and test cycle. A comprehensive summary of biodiesel emission effects was compiled by the US EPA as guidance for states in claiming emission credits for the use of biodiesel and its blends (U.S. EPA, 2002). According to the EPA study—which is based on the FTP test using commercial heavy-duty on-road engines—the average impacts of 100% biodiesel on emissions are –47% for PM and +10% for NOx. For a B20 blend, the respective numbers would be correspondingly lower. Biodiesel is listed as a verified technology for diesel emission reductions by the EPA.

A significant issue with biodiesel is fuel stability. Biodiesel is biodegradable, which is an advantage from environmental point of view, but a drawback for engine users, as breakdown products can cause problems with fuel injection equipment (fouling, corrosion, etc.). Furthermore, biodiesel may be not compatible with certain materials (e.g., elastomers) used in fuel injection systems. In general, engine/fuel injection equipment manufacturers allow, under warranty, a maximum of 5% biodiesel in blends, but increasing number of engine models are designed to be biodiesel-tolerant and can be operated using any biodiesel blends or neat biodiesel fuel. To prevent moisture and other aging products, engine operators using biodiesel must keep storage and vehicle tanks as full as possible, protect storage tanks from extreme temperatures, avoid extended storage of biodiesel fuel, and conduct routine monitoring of the fuel’s water content. Ambient temperature is also a significant consideration, as biodiesel may gel at low temperatures.

### 1.7.1 Test Results

Biodiesel testing was completed using a Volvo L90 front end loader at the Destiny USA construction site in Syracuse, NY. Testing was completed using the same simple duty cycle used for loaders in the other ECT tests. Table 4-19 displays the percentage reductions and associated 95% confidence intervals for emissions of B100 and B50 fuels as compared with ULSD fuel. The table shows the percentage reduction as calculated using the g/test data and with the g/min data, for comparison. Emission reductions for PM, CO, and $CO_2$ are based on data from integrated samples, collected over each test run. The NOx reductions are based on second-by-second data collected during the test run and integrated over the test period. NOx emissions are reported from this modal testing data because these results are generally considered more accurate than the integrated results, due to reactions in the sample bag that can alter NOx concentrations slightly.

**Table 4-19. Percentage Reduction in Emissions when Compared with ULSD Fuel**

| | | PM | $CO_2$ | CO | NOx |
|---|---|---|---|---|---|
| **B100** | **g/test** | 68 ± 20 | 12 ± 4 | 59 ± 18 | -28 ± 10 |
| | **g/min** | 68 ± 20 | 12 ± 4 | 59 ± 18 | -28 ± 10 |
| **B50** | **g/test** | 44 ± 23 | 5.5 ± 3.1 | 19 ± 22[a] | -8.5 ± 9.2[a] |
| | **g/min** | 44 ± 23 | 5.5 ± 3.1 | 19 ± 22[a] | -8.5 ± 9.2[a] |

[a] Results are not statistically significant

Consistent with published data on biodiesel emission impacts, the evaluations showed a significant reduction in PM emissions (68% for B100 and 44% for B50), significant reductions in CO emissions (59% for B100), and an increase in NOx emissions (28% for B100). It should be noted that any $CO_2$ reductions do not account for full life cycle emissions associated with the conversion from petroleum-based fuel to a renewable fuel. The $CO_2$ reductions reported here are for the exhaust stack only and do not necessarily indicate a net greenhouse gas emission reduction through the use of biodiesel.

## 1.8 ELEMENTAL AND ORGANIC CARBON RESULTS

Test personnel evaluated seven of the ECT devices for elemental and organic carbon (EC/OC) for tests performed during the candidate and engine out condition. There were two ADPFs that were evaluated that included tests that were performed during ECT regeneration. To ensure a sufficient sample was collected for EC/OC analyzes a single prefired quartz filter was used for all of the post ECT EC/OC sampling, and the same filter was used for sampling over multiple test runs. For the engine out condition, in some cases individual filters were collected and the results averaged, but in others with lower emission levels, a single filter was used to collect sample over multiple test runs. Table 4-20 shows the EC/OC emissions in microgram per filter and the percent as measured by the DOES2. It also provides the duration of time over which PM samples were collected on a single filter, as well as the EC and OC emissions in g/min.

For the majority of the ECT types for which EC/OC emissions were evaluated, the ratio of EC to OC remained consistent between engine-out and ECT-out. This is an indication that the filters were effective in reducing both EC emissions, primarily by filtration, and also reducing OC emissions, potentially by both filtration and oxidation via the filter catalysts. Still, it should be noted that the same effect occurred in both catalyzed and non-catalyzed filters, so the OC fraction reductions may not be directly attributed to catalytic effects or filtration effects. In one case, the Clean Air PDPF, it appears that the ratio of EC to OC inverted between engine-out and DPF-out conditions. Because of the very small volumes of particulate collected over three test runs, readers should be cautious of putting significant weight on the post-DPF EC:OC ratio.

### 1.8.1 Active DPF Regeneration PM Emissions

Testing was also completed during two sets of regeneration events. Due to the nature of the active DPF, testers were able to initiate a regeneration event on the Huss and Airmeex DPFs, during which particulate samples were collected from the exhaust, as a separate test period using a fresh PM sample filter. The sampling was completed using the DOES2 system during the regeneration events, and EC/OC analysis completed. Each regeneration event was sampled for a period of approximately 15 minutes, during which regeneration was occurring (as discussed previously, regeneration events for the Huss system may take upwards of 30 minutes).

As shown in table 4-19 above, the regeneration events resulted in the emissions of particulate with a much higher ratio of organic carbon than engine out conditions. Still, the particulate emission rates were very small when compared to engine out emissions, and were below DPF out emission levels in some cases. Therefore, it appears that the emissions from regeneration in these cases will have little to no impact on the overall emissions from a vehicle operating with a DPF installed.

**Table 4-20. EC/OC Emissions**

| Exhaust Setting | Organic Carbon (ug/filter) | Elemental Carbon (ug/filter) | TOTAL Sample Time During Test (min) | OC Mass (g/min) | EC Mass (g/min) | %OC | %EC |
|---|---|---|---|---|---|---|---|
| Clean Air PDPF | 2.42 | 0.33 | 58.00 | 0.000 | 0.000 | 88 | 12 |
| Engine Out - Test #1 | 71.1 | 318 | 17.80 | 0.030 | 0.140 | 18 | 82 |
| Engine Out - Test #2 | 61.7 | 281 | 18.22 | 0.027 | 0.121 | 18 | 82 |
| Engine Out - Test #3 | 65.0 | 306 | 17.80 | 0.029 | 0.134 | 18 | 82 |
| Engine Out - Mean | 65.9 | 301.4 | 17.9 | 0.028 | 0.132 | 18 | 82 |
| Nett FTF | 186 | 1015 | 64.88 | 0.018 | 0.102 | 16 | 84 |
| Engine Out | 153 | 1926 | 67.05 | 0.016 | 0.199 | 7 | 93 |
| Huss ADPF | 1.32 | 8.94 | 33.60 | 0.001 | 0.003 | 13 | 87 |
| Engine Out | 46.9 | 322 | 30.40 | 0.020 | 0.133 | 13 | 87 |
| Regeneration | 1.29 | 1.70 | NA | NA | NA | 43 | 57 |
| JMI CCRT | bdl | 1.0 | 34.05 | bdl | 0.000 | bdl | >99 |
| Engine Out | 80.3 | 511 | 39.40 | 0.027 | 0.171 | 14 | 86 |
| DCL FTF | 236 | 2127 | 66.13 | 0.016 | 0.142 | 10 | 90 |
| Engine Out | 231 | 2649 | 66.38 | 0.015 | 0.174 | 8 | 92 |
| Nett PDPF | bdl | 42.5 | 51.90 | bdl | 0.004 | bdl | >99 |
| Engine Out | 198 | 620 | 53.00 | 0.019 | 0.060 | 24 | 76 |
| Airmeex ADPF | bdl | 7.73 | 55.72 | bdl | 0.001 | bdl | >99 |
| Engine Out | 52.2 | 663 | 53.48 | 0.004 | 0.053 | 7 | 93 |
| Regeneration | 7.74 | 1.71 | 16.62 | 0.002 | 0.000 | 82 | 18 |

## 1.9 TEST METHOD COMPARISONS

Test personnel evaluated the performance of several of the emission control technologies using both the Horiba 2200 PEMS and Environment Canada's ISS simultaneously. All control devices were installed on the Case 821 or the Daewoo rubber tire loaders at the DSNY Central Repair Shop site. Tables 4-20, 4-22, and 4-23below show the mean emissions in g/min as measured by the OBS-2200 PEMS and as measured by Environment Canada's DOES2 ISS. Note that the values for $CO_2$ were divided by 100 to make the chart more readable.

Figure 4-23and Figure 4-24 show side-by-side comparisons of the pre- and post-ECT CO, $CO_2$, THC, and $NO_x$ results for the Horiba PEMS and the Environment Canada DOES2 during evaluations preformed on CleanAIR PDPF system.

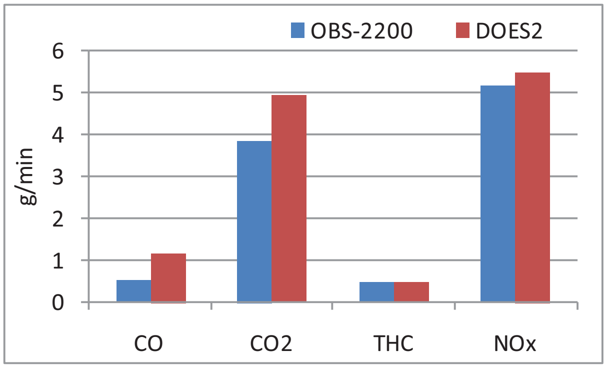



**Figure 4-23: Pre-CleanAIR PDPF Emissions Results from the OBS-2200 and the DOES2**

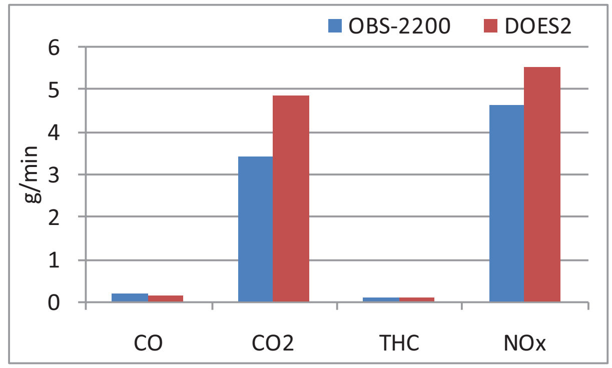



**Figure 4-24: Post-CleanAIR PDPF Emissions Results from the OBS-2200 and the DOES2**

Figure 4-25 and Figure 4-266 show side-by-side comparisons of the pre- and post-ECT CO, $CO_2$, THC, and $NO_x$ results for the Horiba PEMS and the Environment Canada DOES2 during evaluations on the AirMeex ADPF system.

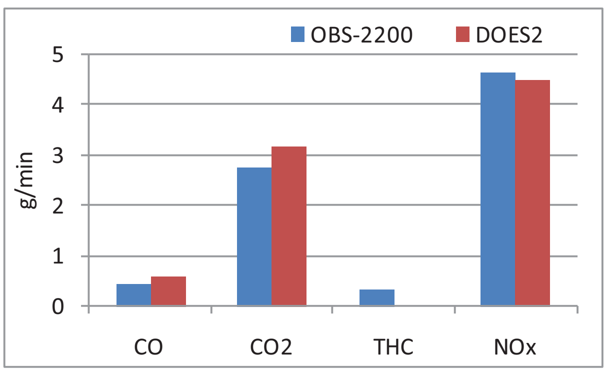



**Figure 4-25: Pre-AirMeex ADPF Emissions Results from the OBS-2200 and the DOES2**

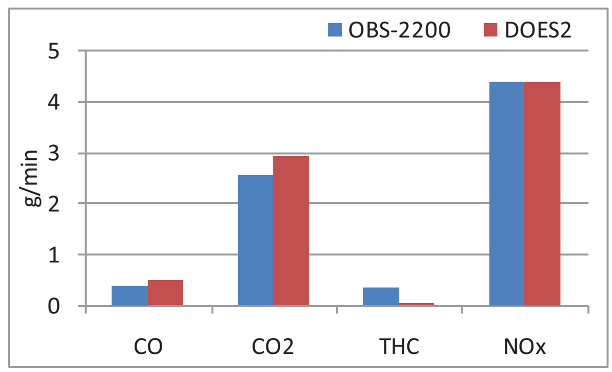



**Figure 4-26: Post-AirMeex ADPF Emissions Results from the OBS-2200 and the DOES2**

Figure 4-27 and Figure 4-28 show side-by-side comparisons of the pre- and post-ECT CO, $CO_2$, THC, and $NO_x$ results for the Horiba PEMS and the Environment Canada DOES2 collected during evaluation on Nett's FTF device.

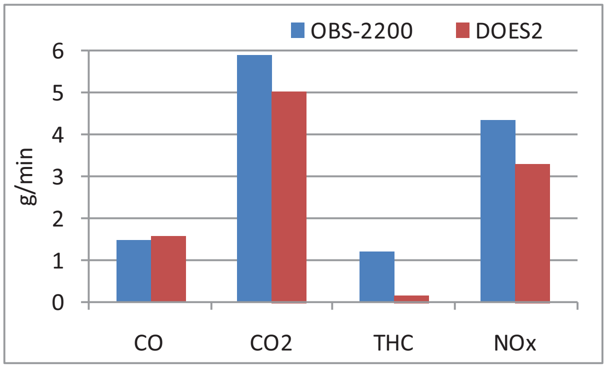



**Figure 4-27: Pre-Nett FTF Emissions Results from the OBS-2200 and the DOES2**

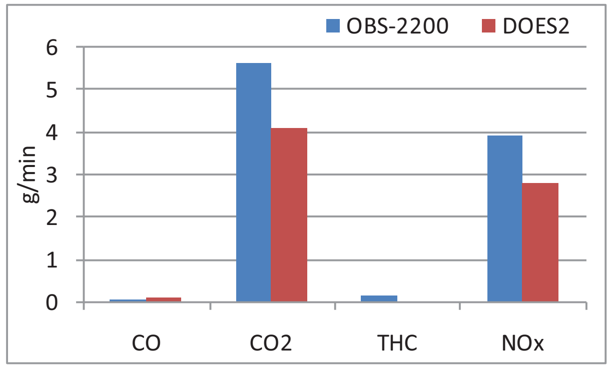



**Figure 4-28: Post-Nett FTF Emissions Results from the OBS-2200 and the DOES2**

Tables 4-21 through 4-23 summarize the actual test results and comparisons of the statistical significance of the differences between the two measurement system results. In most cases, there is no statistically significant difference between the two systems. In several cases, THC analyzers on the Horiba system malfunctioned as a result of the inability to maintain THC analyzer temperature due to a failed heating element. This resulted in poor correlation with the DOES2 reference system for THC emissions in most cases.

These comparisons highlight the ability of the PEMS systems, such as the Horiba OBS, to be used in evaluations of real world performance of engines and control devices. In addition, results discussed for each of the ECTs, demonstrate the ability of the gaseous PEMS systems to provide repeatable results, with confidence intervals that allow for the determination of statistically significant changes in $NO_x$, CO, $CO_2$, and THC emissions of equipment on the order of those observed due to ECT installation or fuel changes. In addition to instrument performance, the low test-to-test variability in most cases are also an indication of the ability to use a site or equipment, specific, simple, or synthesized duty cycle to perform real-world activities in a repeatable fashion in the performance of such emission testing programs.

**Table 4-21. Comparison of Horiba OBS and DOES2 Systems – CleanAir PDPF**

| Case Loader 21BH-206; CleanAir PDPF | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Post -ECT | | | | | Pre-ECT | | | |
| **Emission Parameter** | **CO g/min** | **CO2 g/min** | **THC g/min** | **NOx g/min** | | **CO g/min** | **CO2 g/min** | **THC g/min** | **NOx g/min** |
| **Horiba** | | | | | | | | | |
| ***Average*** | 0.168 | 344.4 | 0.072 | 5.63 | | 0.71 | 383.6 | 0.49 | 5.12 |
| ***St. dev.*** | 0.068 | 17.16 | 0.005 | 1.69 | | 0.26 | 27.98 | 0.027 | 0.32 |
| **DOES2** | | | | | | | | | |
| ***Average*** | 40.135 | 85.3 | 0.09 | 5.55 | | 4 1.18 | 94.3 | 0.089 | 5.49 |
| ***St. dev.*** | 0.010 | 14.1 | 0.037 | 0.19 | | 0.024 | 19.97 | 0.0025 | 0.14 |
| **Difference (Horiba-DOES2)** | 0.033 | -140.9 | -0.02 | 0.08 | | -0.47 | -110.7 | 0.41 | -0.36 |
| **% Difference** | 24.3% | -29.0% | -21.0% | 1.4% | | -40.1% | -22.4% | 453.6% | -6.6% |
| **Statistically significant?** | NO | YES | NO | NO | | NO | NO | YES | NO |

**Table 4-22. Comparison of Horiba OBS and DOES2 Systems – AirMeex ADPF**

| Case Loader 21BH-208; Air Meex ADPF | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Post -ECT | | | | | Pre-ECT | | | |
| **Emission Parameter** | **CO g/min** | **CO2 g/min** | **THC g/min** | **NOx g/min** | | **CO g/min** | **CO2 g/min** | **THC g/min** | **NOx g/min** |
| **Horiba** | | | | | | | | | |
| ***Average*** | 0.35 | 231.5 | 0.30 | 3.95 | | 0.38 | 232.9 | 0.29 | 3.92 |
| ***St. dev.*** | 0.029 | 11.93 | 0.032 | 0.18 | | 0.023 | 9.74 | 0.007 | 0.15 |
| DOES2 | | | | | | | | | |
| ***Average*** | 0.49 | 294.0 | 4 0.039 | .38 | | 0.61 | 317.1 | 4 0.051 | .52 |
| ***St. dev.*** | 0.039 | 9.96 | 0.0065 | 0.066 | | 0.0083 | 9.82 | 0.0041 | 0.043 |
| **Difference (Horiba-DOES2)** | -0.14 | -62.5 | 0.26 | -0.44 | | -0.22 | -84.1 | 0.24 | -0.59 |
| **% Difference** | -28.0% | -21.2% | 674.4% | -10.0% | | -37.0% | -26.5% | 482.5% | -13.2% |
| **Statistically significant?** | NO | YES | YES | NO | | YES | YES | YES | YES |

**Table 4-23. Comparison of Horiba OBS and DOES2 Systems – Nett FTF**

| Daewoo Mega-200 Loader; Nett FTF | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Post -ECT | | | | | Pre-ECT | | | |
| **Emission Parameter** | **CO g/min** | **CO2 g/min** | **THC g/min** | **NOx g/min** | | **CO g/min** | **CO2 g/min** | **THC g/min** | **NOx g/min** |
| **Horiba** | | | | | | | | | |
| ***Average*** | 0.063 | 573.7 | 0.12 | 3.87 | | 1.55 | 599.5 | 4 1.21 | .37 |
| ***St. dev.*** | 0.028 | 18.49 | 0.025 | 0.076 | | 0.45 | 30.29 | 0.008 | 0.11 |
| **DOES2** | | | | | | | | | |
| ***Average*** | 4 0.12 | 12.1 | 0.017 | 2.79 | | 1.59 | 502.2 | 0.16 | 3.31 |
| ***St. dev.*** | 4 0.040 | 2.0 | 0.00046 | 0.32 | | 4 0.26 | 3.6 | 0.019 | 0.16 |
| **Difference (Horiba-DOES2)** | -0.055 | 161.6 | 0.10 | 1.07 | | -0.039 | 97.3 | 1.05 | 1.06 |
| **% Difference** | -46.4% | 39.2% | 623.2% | 38.5% | | -2.5% | 19.4% | 636.2% | 32.0% |
| **Statistically significant?** | NO | NO | Yes | NO | | NO | NO | Yes | Yes |

# ECT COST, INSTALLATION, AND OPERATIONAL PERFORMANCE ANALYSIS

## 1.1 COST AND INSTALLATION ANALYSIS

Analysis of ECT costs consists primarily of collecting and reporting the following cost data:

- capital purchases
- shop labor for installations
- installation downtime
- maintenance and repair costs and downtime
- operations and maintenance issues

The descriptions below and Tables 5-1 and 5-2 summarize each ECT's costs, operational impacts, and operational performance for the ECTs participating in the evaluation program. ECTs were monitored from the installation date until July 2008. Table 5-3 summarizes the monitoring period for each installation, and the total hours accumulated on each vehicle and ECT combination.

**Table 5-1. Hours Accumulated on ECTs During Demonstration Program**

| DSNY VEHICLE ID | ENGINE MFR. | ENGINE MODEL YEAR | TYPE OF EQUIPMENT | ECT Type | ECT HOURS IN SERVICE (Through April, 2008) |
|---|---|---|---|---|---|
| 21BY-114 | DAEWOO | 2004 | Rubber tire loader | Nett FTF | 296 |
| 21BH-001 | CUMMINS | 1998 | Rubber tire loader | Extengine FTF | 317 |
| 21BH-206 | CUMMINS | 2000 | Rubber tire loader | CleanAir PDPF | 243 |
| 66J-103 | CATERPILLAR | 2001 | Dump Truck | Huss ADPF | 90 |
| 21BH-105 | CUMMINS | 1999 | Rubber tire loader | Nett SCR/FTF | 36 |
| 21BH-208 | CUMMINS | 2000 | Rubber tire loader | Airmeex ADPF | 63.9 |
| 21BT-001 | DEUTZ | 2002 | SKIDSTEER | Airflow DOC | 97 |
| 21BZ-002 | CUMMINS | 2004 | SKIDSTEER | Nett DOC | 54.1 |
| 21BZ-001 | CUMMINS | 2004 | SKIDSTEER | Nett DOC | 52 |
| 66J -105 | CATERPILLAR | 2001 | Dump Truck | JMI CCRT | 369 |
| 21BY-012 | DAEWOO | 2004 | Rubber tire loader | DCL FTF | 48 |
| 21BH-107 | CUMMINS | 1999 | Rubber tire loader | Nett PDPF | 157 |
| 13E-002 | CASE | 2007 | Backhoe | Nett DOC | 185.8 |
| 21BH-110 | CUMMINS | 1999 | Rubber tire loader | DCL DPF | 162 |
| 21BY101 | DAEWOO | 2005 | Rubber tire loader | ECS DPF | 52 |
| 21BY-126 | DAEWOO | 2005 | Rubber tire loader | Airflow DOC | 234 |
| 21BH-211 | CUMMINS | 2000 | Rubber tire loader | Airflow DOC | 54 |

| DSNY VEHICLE ID | ENGINE MFR. | ENGINE MODEL YEAR | TYPE OF EQUIPMENT | ECT Type | ECT HOURS IN SERVICE (Through April, 2008) |
|---|---|---|---|---|---|
| 21BY-118 | DAEWOO | 2005 | Rubber tire loader | ECS DOF | 172 |
| 21BY-014 | DAEWOO | 2004 | Rubber tire loader | Donaldson DPF | 69 |
| 21BH-106 | CUMMINS | 1999 | Rubber tire loader | Donaldson DPF | 97 |
| 21BH-204 | CUMMINS | 2000 | Rubber tire loader | ECS DOC | 157 |
| 21BY-119 | CUMMINS | 2005 | Rubber tire loader | ECS DPF | 21 |

**Table 5-2. ECT Costs and Installation Labor**

| Equip. Model | Equipment Type | DSNY Vehicle ID | ECT Mfr. | ECT Type[a] | Retail Cost, $ | EPA NCDC Funds, $ | Labor Hours[b], h | | | | Install cost[c], $ | More Info[d] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | A | B | C | D | | |
| Cat D400 | Dump truck | 66J -105 | JMI | DPF | $37123 | $4736 | 40 | | | | ~$4000 | ‡ |
| Cat D400 | Dump truck | 66J-103 | Huss | ADPF | $36498 | $8780 | 30 | 35 | 80 | 80 | $17835[e] | †, *, ‡ |
| Case 821 | Rubber tire loader | 21BH-206 | CleanAIR Systems | PDPF | $8948 | $7647 | 8 | 8 | 32 | -- | $5904 | †, * |
| Case 821 | Rubber tire loader | 21BY-119 | ECS | DPF | $7156 | $7156 | 16 | -- | 16 | -- | $3936 | †, * |
| Case 821 | Rubber tire loader | 21BH-106 | Donald-son | DPF | $7625 | $4640 | 8 | -- | 8 | 8 | $1968 | †, ‡ |
| Case 821 | Rubber tire loader | 21BH-204 | ECS | DOC | $3291 | $3291 | -- | -- | 8 | -- | $984 | * |
| Case 821 | Rubber tire loader | 21BH-104 | ECS | DOC | $3291 | $3291 | -- | -- | 8 | -- | $984 | * |
| Mega 200V | Rubber tire loader | 21BY-101 | ECS | DPF | $7156 | $7156 | 8 | -- | 8 | -- | $1968 | * |
| Mega 200V | Rubber tire loader | 21BY-118 | ECS | DPF | $7156 | $7156 | 16 | -- | 16 | -- | $3936 | †, * |
| Mega 200V | Rubber tire loader | 21BY-014 | Donald-son | DPF | $7625 | $4690 | 8 | -- | 8 | -- | $1968 | ‡ |
| This ECT has not yet been installed. | | | ECS | DOC | $3291 | $3291 | -- | -- | -- | -- | -- | -- |
| | | | | *Total:* | *$121685* | *$61834* | -- | -- | -- | -- | *$39483* | -- |

[a] ECT nomenclature:
ADPF -- active diesel particulate filter
DPF -- diesel particulate filter (also known as PDPF for passive diesel particulate filter)
DOC -- diesel oxidation catalyst
[b] Labor description: A = electrician, B = blacksmith, C = mechanic, D = manufacturer's representative
[c] Does not include manufacturer's representative labor. DSNY average labor rate is $123 / h.
[d] See the following tables for more information:
† = brackets, custom parts listed in Table 3-5
* = installation notes in Table 3-5
‡ = maintenance or operations issues described in Table 3-6
[e] Huss currently requires that installation of its device be completed by a Huss technician or a trained and authorized Huss installer, for a cost of $6,260.

**Table 5-3. Custom Parts and Installation Notes**

| Equip. Model | Equip. Type | DSNY Vehicle ID | ECT Mfr. | ECT Type | Custom Parts | Installation Notes |
|---|---|---|---|---|---|---|
| Cat D400 | Dump truck | 66J-103 | Huss | ADPF | 2 brackets; 1 wiring harness; 1 in-cab control box; 1 fuel line; temperature monitor; backpressure monitor | Complicated installation required significant DSNY and manufacturer's representative labor[a]. |
| Case 821 | Rubber tire loader | 21BH-206 | CleanAIR Systems | PDPF | 2 brackets; 1 wiring harness; temperature monitor; backpressure monitor; 4" x 4" reinforcement plate; 4' long x 4" dia. flex pipe; 6 elbows, 4" dia.; 6" x 6" bulkhead plate with 4" hole | Extended exhaust pipe from turbocharger outlet to top rear outside of engine cover. Drilled engine cover and made reinforcement plates to secure the unit. |
| Case 821 | Rubber tire loader | 21BY-119 | ECS | DPF | 2 brackets; 1 wiring harness; temperature monitor; back pressure monitor | As-received exhaust inlet and outlet ends on ECT were the wrong size and were replaced. As-received mounting brackets did not fit, so DSNY modified existing brackets on the loader. |
| Case 821 | Rubber tire loader | 21BH-106 | Donaldson | DPF | 1 wiring harness; temperature monitor; back pressure monitor | Used existing brackets on the loader for mounting the ECT. |
| Case 821 | Rubber tire loader | 21BH-204 | ECS | DOC | -- | Easy installation. Used existing brackets on the loader for mounting the ECT. |
| Case 821 | Rubber tire loader | 21BH-104 | ECS | DOC | -- | Easy installation. Used existing brackets on the loader for mounting the ECT. |
| Mega 200V | Rubber tire loader | 21BY-101 | ECS | DPF | 2 brackets; 1 wiring harness; temperature monitor; back pressure monitor | As-received exhaust inlet and outlet ends on ECT were the wrong size and were replaced. As-received mounting brackets did not fit, so DSNY modified existing brackets on the loader. |
| Mega 200V | Rubber tire loader | 21BY-118 | ECS | DPF | 2 brackets; 1 wiring harness; temperature monitor; back pressure monitor | As-received exhaust inlet and outlet ends on ECT were the wrong size and were replaced. As-received mounting brackets did not fit, so DSNY modified existing brackets on the loader. |
| Mega 200V | Rubber tire loader | 21BY-014 | Donaldson | DPF | 1 wiring harness, temperature monitor, back pressure monitor | Used existing brackets on the loader for mounting the ECT. |

[a] Huss currently requires that installation of its device be completed by a Huss technician or a trained and authorized Huss installer, for a cost of $6,260.

***CleanAir Systems PDPF*** was installed on a Case 821 rubber tire loader DSNY ID 21BH-206. The retail cost of the unit was $8,948. Installation of the device required 48 hours, which included eight hours labor for an electrical technician to install a wiring harness, temperature monitor and backpressure monitor. A welder/blacksmith was required for eight hours for the fabrication two 4" X 4" reinforcement plates and other custom parts, including a bulkhead plate for mounting the DPF system. A mechanic was required for 32 hours to install the system and extended exhaust pipe from turbocharger outlet to top rear outside of engine cover and to modify the engine cover and make reinforcement plates to secure the unit. Installation costs totaled $5,904. No maintenance or operational issues were detected during its operation.

The ***Nett PDPF*** system was installed and tested on a Case 821 rubber tire loader. The retail cost of the NETT PDPF system was $9,034. Installation of the device required 24 hours, which included eight hours labor for an electrical technician to install a wiring harness, temperature monitor and backpressure monitor. A mechanic was required for 16 hours to fabricate brackets, and install the system. The air cleaner required relocating because of the tight fit to install the system. Installation costs amounted to $2,952. No maintenance or operational issues were detected during its operation.

The *Donaldson PDPF* was installed and tested on a Daewoo Mega 200. The retail cost of the unit was $7,625. Installation of the device required 16 hours, which included eight hours labor for an electrical technician to install a wiring harness, temperature monitor and backpressure monitor. A mechanic was required for eight hours to install the system using the existing brackets from the original muffler. Installation costs amounted to $1,968. After running the equipment for several days, the backpressure sensor alarmed, the ECT was removed and cleaned off-board. The equipment was down for approximately two months, with approximately five days of staff time required for maintenance.

The ***DCL MINE-X SOOTFILTER® diesel particulate filter*** (DPF) was installed and tested on a Case 821 rubber tire loader. The retail cost of the unit was $11,988. Installation of the device required 24 hours, which included eight hours labor for an electrical technician to install a wiring harness, temperature monitor and backpressure monitor. A mechanic was required for 16 hours to install the system, which required a minor modification of the backpressure monitor. Installation costs totaled $2,952. No maintenance or operational issues were detected during its operation.

The ***Huss MK-system*** was installed and tested on a Caterpillar D-400 off-road truck. The retail cost of the unit was $36498. Installation of the device required 225 hours, which included 30 hours labor for an electrical technician to install a wiring harness, temperature monitor, backpressure monitor, and the in-cabin control box. A welder/blacksmith was required for 35 hours for the fabrication of custom parts and brackets. A mechanic was required for 80 hours to install the system and 80 hours was required from the manufacturer's representative. Installation costs totaled $17,835. This was a complicated installation and required significant labor from the user, and the operators dislike the regeneration process. The truck cannot operate during the 20 to 25 minute regeneration. The ignition key must be on during regeneration which, if forgotten, can lead to discharged batteries. The manufacturer also recommends running the regeneration process during the operator's lunch break to prevent unnecessary downtime.

The ***AirMeex ADPF*** was installed and tested on a Case 821 rubber tire loader. The retail cost of the unit was $11,500. Installation of the device required 62 hours including eight hours labor for an electrical technician to install a wiring harness, temperature monitor, backpressure monitor, and the in cabin control box. A welder/blacksmith was required for six hours for the fabrication of two brackets. A mechanic was required for 24 hours to install the system and install a turbo pipe and an extra support bracket for the controller heat shields around the injector and relocating the engine door lock and exhaust outlet pipe. 24 hours was also required by the manufacturer's representative. Installation costs totaled $4,674. This was a complex installation and required significant labor from the user. After operation for only several hours, part of the switching device cracked, and the device and equipment was down for several days. A heavier switching device was installed and during operation of the loader, no other maintenance or operational issues have been detected during its operation. Approximately 1/5 gallon of diesel fuel is used during device regeneration.

The ***JMI CRT/CCRT*** system was installed on at Caterpillar D-400 off-road truck. The retail cost of the JMI CCRT system was $37,123. Installation of the device required 40 hours, which was performed by the local Caterpillar dealer. Installation costs amounted to approximately $4,920. Only one maintenance issue was detected during its operation, this was the mounting brackets were too lightly-built for the ECT. After only several hours of operation the brackets cracked and bent, and were replaced by the Caterpillar dealer. Afterwards no other operational issues arose.

The ***Nett® FM-Series FTF*** was installed on a Daewoo Mega-200 rubber tire loader. The retail cost of the unit was $3,650. Installation of the device required eight hours the time it took the mechanic to install the system. Installation costs totaled $984. This was an easy installation and was an exact muffler replacement. No maintenance or operational issues have been detected during its operation.

The ***DCL MINE-X® FTF*** was installed and tested on a Daewoo Mega – 200 rubber tire loader. The retail cost of the unit was $3,495. A mechanic was required for eight hours to install the entire system. Installation costs totaled $984. This was an easy installation and was a muffler replacement that used the existing hardware. No maintenance or operational issues have been detected during its operation.

***Extengine's LEV2 Hybrid Diesel Particulate Catalyst*** was installed and tested on a Case 821 rubber tire loader. The retail cost of the unit was $3,000. Installation of the device required 44 hours, which included eight hours of labor for a welder/blacksmith for the fabrication of two brackets, exhaust elbows, and a mounting plate. A mechanic was required for 32 hours to install the system, which included extending the outlet pipe from the turbocharger to the outside of the engine cover, and reinforcing the engine cover for mounting the FTF brackets. Installation costs totaled $4,920. This FTF system was not as straightforward as others that were installed and required significant labor from the user. No maintenance or operational issues have been detected during its operation.

The ***Nett FTF/SCR BlueMAX***™ was installed and tested on a Case 821 rubber tire loader. The retail cost of the NETT SCR system was $35,803. Installation of the device required 68 hours, which included 16 hours of labor for an electrical technician to install a wiring harness, temperature monitor, and backpressure monitor. A welder/blacksmith was required for four hours for the fabrication of two brackets and a mechanic was required for 24 hours to fabricate brackets, mount and install the urea tank and the SCR system. A manufacturer's representative was also required for 24 hours. The SCR system was a very large and heavy unit and the engine cover required removal before installation. The installation kit came with all necessary hardware and peripherals and the fit was almost perfect, but the temperature sensor needed to be moved due to the sensor hitting the radiator hose. Installation costs amounted to $5,412. No maintenance or operational issues were detected during its operation.

***AirFlow Catalyst's Active-X*** DOC was installed and tested on a BobCat 863 skid-steer loader. AirFlow's DOC has a wide operating temperature range because of its unique environmentally friendly washcoat material. The AirFlow DOC retail cost was $986. Installation of the device included eight hours for the mechanic to install the system. Installation costs totaled $984. This was an easy installation and was a muffler replacement that used the existing hardware. No maintenance or operational issues have been detected during its operation. Initially the device did not fit and was returned to the manufacturer for correction. Once returned, installation was easy.

***NETT's diesel oxidation catalyst*** was installed on a Case 580 backhoe. The NETT DOC includes hydrocarbon traps for improved low temperature activity and diesel odor control. The retail cost of the Nett DOC was $958. Installation of the device required two hours of a blacksmith/welder for fabrication of brackets and four hours for the mechanic to install the system. Installation costs totaled $738. This was an easy installation and was a muffler replacement that used the existing hardware. No maintenance or operational issues have been detected during its operation.

The majority of the ECTs had little impact on operational performance. Regeneration or other routine ECT functions were generally transparent to the equipment operators. Maintenance and repair records provided by DSNY were the primary data source, supplemented by interviews with DSNY mechanics and technicians.

## 1.2 INSTALLATION / OPERATIONAL PROBLEMS IDENTIFIED AND LESSONS LEARNED

The single canister, muffler-type ECTs required the simplest and most straightforward installations. Those with the shortest installation times were direct muffler replacements and presented no particular installation, operational, or maintenance problems. Emission control technologies that require an in-cab control unit required more complicated installations and more resources from hourly workers.

Some devices have not yet made the transition from on-highway to non-road applications, as shown by inadequate brackets, shapes, and sizes, which did not easily fit non-road machines, or other design flaws. Technicians at DSNY were generally able to "work around" such problems. Two as-received ECTs, an Engine Control Systems DOC intended for a Case 580 backhoe, and a Clean Air Systems DPF intended for a Daewoo rubber tire loader, could not be made to fit their designated machines and were returned to the manufacturer.

Consistent backpressure and exhaust temperature monitoring and operator training for appropriate responses to these parameters will continue to be extremely important. In-house DPF cleaning capability became important to DSNY for the ongoing development of routine maintenance strategies and for quick recovery from backpressure faults.

Those ECTs requiring manual regeneration or operator-initiated regeneration, inconvenienced operators and mechanics and resulted in lower approval from an operational standpoint due to interference with normal routines and activities.

The Urea-SCR system has not been problematic from the standpoint of urea use and filling. This likely results from a sufficient on-board storage capacity to allow for urea replenishment in conjunction with standard maintenance or fueling events.

**Table 5-4. Maintenance and Operational Issues**

| **Table 4-4.** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Equip. Model** | **Equipment type** | **DSNY Vehicle ID** | **ECT Mfr.** | **ECT type** | **Problem description and resolution** | **Equip-ment down, days** | **Repairs, approx. h** |
| Cat D400 | Dump truck | 66J -105 | JMI | DPF | Mounting brackets were too lightly-built for the ECT. They cracked, bent, and were replaced by the Caterpillar dealer. | 36 | 8 |
| Cat D400 | Dump truck | 66J-103 | Huss | ADPF | Operators dislike the regeneration process. The truck cannot operate during the 20 to 25 minute regeneration. The ignition key must be on during regeneration which, if forgotten, can lead to discharged batteries.[a] | -- | -- |
| Case 821 | Rubber tire loader | 21BH-106 | Donald-son | DPF | Backpressure alarm. ECT was removed and cleaned off-board. | 5 | 8 |
| Mega 200V | Rubber tire loader | 21BY-014 | Donald-son | DPF | Backpressure alarm. ECT was removed and cleaned off-board. Mechanics tried various cleaning strategies | $\approx 60^{b}$ | 40 |

[a] The manufacturer recommends running the regeneration process during the operator's lunch break to prevent unnecessary downtime.
[b] Equipment was down for approximately two months, with approximately five days of staff time required for maintenance.

# DATA QUALITY ASSESSMENT

The emissions and performance determinations described in this report require numerous contributing measurements, sensors, instruments, analytical procedures, and data loggers. This section documents the general specifications that helped ensure repeatability within the test campaign and comparability with other programs.

## 1.1 MEASUREMENT QUALITY OBJECTIVES

Table 6-1 lists the instrument and sensor accuracy specifications used in the test campaign. It also indicates the instrument manufacturer, model, and specification verification dates.

**Table 6-1. DOES2 and Horiba OBS Measurement Quality Objectives**

| Parameter | Logging Frequency | Accuracy | Repeatability | Manufacturer | Model(s) | Date Verified |
|---|---|---|---|---|---|---|
| Engine speed | 1 Hz | 5.0 % of point or 1.0 % of max[a] | 2.0 % of point or 1.0 % of max | Baumer Electric | FPAM 18N3151 | 5/1/2007 |
| Ambient barometric pressure | 1 Hz | 0.07 "Hg (250 Pa) | 0.06 "Hg (200 Pa) | Horiba | OBS-2200 | 1/25/2007 |
| Ambient Temperature | 4 Hz | 1.0 % of point or 5.0 $^{o}$C | 0.5 % of point or 2.0 $^{o}$C | Horiba | OBS-2200 | 1/25/2007 |
| Dewpoint / RH[b] | 4 Hz | 5.0 $^{o}$F | 2.0 $^{o}$F | Horiba | OBS-2200 | 1/25/2007 |
| Exhaust flow | 1 Hz | 5.0 % of point or 3.0 % of max | 2.0 % of point | Horiba | OBS-2200 | Factory Calibration |
| Instrumental analyzer concentration | 1 Hz | 4.0 % of point | 2.0 % of point | Horiba | OBS-2200 | 4/25/2007 |
| **ISS Only** | | | | | | |
| Instrumental analyzer concentration | 1 Hz | 2.0 % of point | 1.0 % of point | Environment Canada | DOES2 | Before and After each Sample |
| Gravimetric TPM balance | n/a[c] | 0.1 % (see §1065.790) | 0.5 µg | Environment Canada | DOES2 | 5/25/2007 |
| Main flow rate | 2 Hz | 1.0 % FS[d] | n/a | Environment Canada | DOES2 | 5/2/2007 |
| Dilution air flow rate | | | | Environment Canada | DOES2 | 5/2/2007 |
| Bag flow rate | | | | Environment Canada | DOES2 | 4/27/2007 |
| Differential pressure (if used) | | | | Environment Canada | DOES2 | 4/26/2007 |

[a]"max" refers to the maximum value expected during testing.
[b]relative humidity (RH)
[c]Not applicable (n/a)
[d]Full scale (FS)

Table 6-2 lists recommended calibration intervals and performance checks. Test personnel performed some of the performance checks, such as leak checks, analyzer zero and spans, etc. before and after each test run while others were performed either in the field or laboratory.

**Table 6-2. Recommended Calibrations and Performance Checks**

| System or Parameter | Description / Procedure | Frequency | Date Completed |
|---|---|---|---|
| Engine speed | 11-point linearity check | At purchase / installation | 5/1/2007 |
| Temperature transducers ($T_{amb}$) | NIST-traceable[a] calibration | Within 12 months | 3/12/2007 |
| Dewpoint / RH | | | 3/12/2007 |
| All instrumental analyzers | 11-point linearity check | Within 12 months | 4/25/2007 |
| $CO_2$ (NDIR detectors)[b] | CO, C3H8 interference | Within 12 months | 2/7/2007 |
| CO (NDIR detectors) | $CO_2$, C3H8 interference | | 2/7/2007 |
| Hydrocarbons (FID)[c] | Propane ($C_3H_8$) calibration | | 4/25/2007 |
| | FID response optimization | | 4/25/2007 |
| | $C_3H_8$ / methyl radical ($CH_3$) response factor determination | | 4/25/2007 |
| | $C_3H_8$ / $CH_3$ response factor check | | 4/25/2007 |
| $NO_X$ | $CO_2$ and $H_2O$ quench (CLD)[d] | | N/A |
| | $NO_2$ to NO converter efficiency | Within six months or immediately prior to departure for field tests | 2/05/2007 |
| Horiba PEMS | Comparison against laboratory CVS system | At purchase / installation; after major modifications | 5/16/2007 |
| | Zero / span analyzers (zero ≤ ± 2.0 % of span, span ≤ ± 4.0 % of point) | Before and after each test run or as needed during in-use evaluations | 5/30/07, 6/1/07, 6/22/07 |
| | Perform analyzer drift check (≤ ± 4.0 % of cal gas point) | After each test run | 5/30/07, 6/1/07, 6/22/07 |
| | NMHC contamination check (≤ 2.0 % of expected conc. or ≤ 2 ppmv) | Once per test day | Once per test day |
| Exhaust gas or intake air flow measurement device | Differential pressure line leak check (ΔP stable for 15 seconds at 3 "$H_2O$) | Once per test day | Once per test day |
| ISS | Comparison against laboratory CVS system | At purchase / installation; after major modifications | 5/16/2007 |
| | Zero / span analyzers (zero ≤ ± 2.0 % of span, span ≤ ± 4.0 % of point) | Before and after each test run | Before and after each test run on all test days |
| | Inspect sample lines, filter housings, and sample bags for visible moisture (none is allowed) | After each test run | |
| | Perform analyzer drift check (≤ ± 4.0 % of cal gas point) | | |

| System or Parameter | Description / Procedure | Frequency | Date Completed |
|---|---|---|---|
| | NMHC background check and dilution tunnel blank | Once per test day | Once per test day |
| | TPM background check and dilution tunnel blank | | |
| | Dilution tunnel leak check | | |
| | Sample bag leak check (< 0.5 % of normal system flow rate) | | |
| | TPM filter face temperature (not to exceed 47 °C or 117 °F) | Continuously during sampling | Continuously during all test runs |
| TPM gravimetric balance | NIST-traceable calibration | Within 12 months | 5/25/2007 |
| ISS main, dilution, and sample flow rates | 11-point linearity check | Within 12 months | 4/13/2007 |
| [a]National Institutes of Standards and Technology (NIST)<br>[b]non-dispersive infrared (NDIR)<br>[c]flame ionization detector (FID)<br>[d]chemilumenescence detector (CLD)<br>[e]non-dispersive ultra violet (NDUV) | | | |

All data collected was reviewed and validated, in conjunction with the regular QA/QC evaluations and results after each test period, and separately prior to analysis. Any invalid data was discarded, based on invalid QA/QC results (i.e. zero/span checks), not meeting duty cycle criteria, or other such reasons, based on data quality specifications summarized above and specified in the Test Plan.

Instrumentation and monitoring equipment used in the test programs met required specifications, as indicated in the above tables.

## 1.2 AUDIT OF DATA QUALITY

This test campaign was supported by an audit of data quality. An independent reviewer examined the test results. The analyst or author, who produced a result table or text, submitted it and the associated raw data to the reviewer. Review procedures included:

- review of technical systems audits (calibrations, QA checks, etc.) generated during field tests
- audits of data quality and analysis techniques
- manual cross-checking a portion of source data and calculation of final results

Southern's QA checks indicate that data collection was appropriate, analyses are correct, and the final results are acceptable for reporting.

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