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NYSERDA CLEAN DIESEL TECHNOLOGY: NON-ROAD FIELD DEMONSTRATION PROGRAM
Interim Report

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NYSERDA CLEAN DIESEL TECHNOLOGY:
NON-ROAD FIELD DEMONSTRATION PROGRAM
Interim Report

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ABSTRACT

The primary goal of NYSERDA's Non-Road Clean Diesel Program is to demonstrate and evaluate the feasibility and performance of commercially available emission control technologies for reduction of particulate matter (PM) and oxides of nitrogen (NOx) emissions. The demonstrations will employ in-use field testing approaches. Given the broad range of non-road diesel equipment types and classes, and the variety of control technologies and strategies available, detailed pretest research and planning was conducted to maximize the effectiveness of the field demonstration. Research and planning included development of current non-road equipment and emissions inventories for New York State (hereafter "NYS") and the New York City Metropolitan Area (hereafter "NYCMA"), identification of high priority sectors and equipment with regard to PM and NOx emissions, and an assessment of emission control technologies and strategies that are currently commercially available.

A field demonstration test matrix was developed based on the information assembled regarding the future of diesel, high priority equipment, available program funding, and the most effective control technologies or strategies with respect to the selected equipment. Once implemented, the test matrix will provide NYSERDA and the project advisory group with a representative data set regarding the performance of leading emission control technologies on classes of diesel equipment that are having an adverse effect on NYCMA air quality. This Interim Report presents the approaches, rationale, and findings regarding development of the Clean Diesel Program field demonstration test matrix.

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LIST OF ACRONYMS

ADPF	active diesel particulate filter
CAA	Clean Air Act
CCRT	catalyzed continuously regenerating technology
CCV	crankcase ventilation
CDC	clean diesel combustion
CDPF	catalyzed diesel particulate filter
CNG	compressed natural gas
CO	carbon monoxide
CR-DPF	continuously regenerating diesel particulate filter
CRT	continuously regenerating technology
CWMF	catalyzed wire mesh filter
DEP	Department of Environmental Protection
DOC	diesel oxidation catalyst
DMF	diesel multi-stage filter
DPF	diesel particulate filter
ECM	engine control module
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
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
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
NMHC	non-methane hydrocarbons
NOx	oxides of nitrogen
NYCMA	New York City Metropolitan Area
NYS	New York State
NYSDEC	New York State Department of Environmental Conservation
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
PM	particulate matter
SCC	source classification code
SCR	selective catalytic reduction
SOF	soluble organic fraction
THC	total hydrocarbons
tpy	tons per year
Tx-LED	Texas low-emissions diesel
ULSD	ultra-low sulfur diesel
VOC	volatile organic hydrocarbon

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 (NOx) from non-road equipment. The in-use field demonstration portion of the project will be conducted with the participation of equipment owners and operators in NYS with a focus on the NYCMA, as well as emission control technology vendors.

To make the most of project resources, diesel equipment and emission control technology combinations will be selected that provide the most useful data and the highest potential for air quality improvements. Current program funding will allow for field demonstration of 15 to 20 non-road diesel equipment and emission control technology combinations. To accomplish this goal, equipment selection will be based on those comprising large populations and high emission rates paired with effective, feasible control strategies. This Interim Report describes the results of modeling and survey efforts to develop an emission inventory and the approach used to select non-road equipment and control strategies for testing.

Modeling and survey efforts identified the NYCMA as the contributor to the bulk of non-road PM and NOx emissions in the State, and have provided a basis to rank emissions by equipment type and population. Construction and mining equipment was identified as the most significant sector. Attention should be given to the following equipment types:

- tractors, loader, 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

This report provides a description of available control technologies and strategies, and identifies those having the highest potential for effective and feasible PM control, including the following:

- 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)

Emission control strategies and technologies with potential for effective and feasible PM and NOx control include the following:

- selective catalytic reduction (SCR) combined with passive or active DPF
- lean NOx catalyst with DPF
- engine rebuild kits
- idle reduction technologies
- biodiesel

The report also includes a discussion regarding the future of diesel engine use and market trends. This discussion is intended to assess the future of diesel use and emissions in the off road sector by considering how existing and future local, state, and federal regulations, the availability of new diesel technologies, and the potential growth of areas may affect the use of diesel technologies in NYS.

Based on information collected and analyzed, a test matrix is proposed that attempts to collect the maximum amount of relevant and credible field testing data that is cost effective, yet rigorous enough to support off-road diesel emissions control policies, programs, and initiatives in NYS, including further development of approved technology lists for compliance with existing regulations such as NYC Local Law 77 (LL77). In addition, the field test program will provide significant data for end users and fleet owners to assist in purchasing decisions.

1.0 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, off-road applications. These regulations will also require the use of lower sulfur diesel fuel by on- and off-road vehicles, which will be phased in starting in 2006. Existing diesel engines, however, in the on-road and off-road inventory will continue to emit higher levels of pollutants including particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), and air toxics. Within NYS, diesel emissions significantly affect ambient air quality, which contributes to non-attainment of air quality standards in areas such as the NYCMA. In 2002, diesel powered off-road equipment operated in NYS emitted an estimated 91,028 tons per year (tpy) of NOx and 7,311 tpy of PM, an estimated 77% and 64% of the total statewide off-road NOx and PM emissions, respectively.

To address the issues associated with the legacy fleet of diesel engines, several local and state initiatives and laws have been introduced, which focus on reducing pollution from existing diesel engines. As more voluntary programs are initiated, regulations enacted, and emission reductions sought, information regarding the various strategies for emission reductions is needed more and more. 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 off-road equipment operated in NYS. The project is part of a broader Clean Diesel Initiative at NYSERDA that supports development of products and technologies to reduce emissions from diesel engines, funding for school bus and other retrofits across NYS, and demonstration and evaluation of various emission reduction strategies.

The primary goal of this project is to evaluate the in-use performance of commercially available diesel retrofit control technologies to expand energy-efficient diesel emission control technology options for off-road applications in NYS. To ensure the demonstrations are relevant and provide information regarding applications that will result in the most significant emission reductions in the state, the project also includes a thorough review of emissions from non-road diesel engines in the state and an analysis of the feasibility of various control strategies in non-road applications.

Objectives of this project are to:

- Assess the technical suitability, the cost, and energy consequences of commercially available retrofit options.
- Identify applications of commercially available retrofit technologies with the greatest potential air quality improvement at the lowest cost.

- Identify and prioritize sectors/specific applications and emission control technologies warranting field demonstration and evaluation in NYS.
- Develop a field test plan that maximizes the number of retrofit technologies that can be assessed.
- Define an in-use field test protocol that minimizes operator dependent duty-cycle variance.
- Conduct an in-use field demonstration program with the participation of equipment owners/operators and emission control technology vendors.

This report is divided into four additional sections:

- Emission inventory development and refinement (Section 2.0);
- Identification of high priority equipment (Section 3.0);
- Evaluation of technical, economic, and operational impacts of control strategies (Sections 4.0 and 5.0); and
- Planning for field demonstrations (Section 6.0).

The accomplishments under each area are summarized below.

Emission inventory development and refinement (Section 2.0):

- Development of a baseline inventory for NYS and the NYCMA utilizing EPA's NONROAD2004 model and data provided by NYSDEC.

Identification of high priority equipment (Section 3.0):

- Evaluation of off-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 (Sections 4.0 and 5.0):

- 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.
- Assessment of the future of diesel use and emissions in the off road sector by considering the use of new technologies in the off-road sector that may impact diesel use, existing and future local, state, and federal regulations, the potential growth of areas in which diesel technologies are used in NYS, and other factors that may significantly impact use.

Planning for field demonstrations (Section 6.0):

- 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.

This report discusses the first five objectives identified above. These outputs will guide the focus of the project, and may also guide subsequent diesel emission reduction programs/initiatives in NYS.
They will result in the specification of field demonstrations for high priority equipment types and applicable control strategies with the greatest potential for emission reductions. Field demonstrations and control strategy evaluations will be completed separately and a separate report provided describing all testing and evaluation activities.

In addition to this report, there are two additional forthcoming reports. One will discuss a survey of private construction contractors and municipal agencies that was implemented to collect primary data on dollars spent on and allocation of commercial and residential construction and public works projects in the NYCMA, as well characteristics of the equipment fleets utilized in this work. The other report will discuss a survey of the 38 freight railroads and six passenger/commuter rail lines operating in NYS. This survey will provide a more accurate inventory of locomotive and rail equipment allocation, activity, and characteristics. This data, along with available EPA emission factors, will be used to develop county-level PM, NO_x, and CO emissions estimates for locomotive engines in NYS.

2.0 NEW YORK STATE NON-ROAD EMISSIONS AND EQUIPMENT INVENTORY

The NYSERDA Non-Road Field Demonstration Program specifies the completion of a non-road equipment and emissions inventory for NYS and the NYCMA in 2002 as a baseline. The inventories are utilized to discern the impacts of non-road diesel equipment on air quality in NYS and to identify the non-road equipment types that are the primary contributors to air quality problems associated with PM and NOx emissions, as well as other pollutants.

The goals of the inventory task were to (i) develop improved emission inventory data for NYS; (ii) identify opportunities for emission reductions for non-road diesel equipment; and (iii) identify and prioritize equipment sectors or types and emission control technologies which warrant field demonstration. In addition, these outputs may be used to guide subsequent NYS emission reduction programs.

The first subtask to complete in this phase of the program was to establish a baseline emission inventory, evaluate the inventory results, and rank the equipment and sectors specified in the inventory to determine the priority sectors and equipment types. This subtask was followed by the refinement of the emissions inventory, re-evaluation of the prioritization results to ensure an accurate identification of priority equipment, and a feasibility analysis for emission control technologies on the priority equipment.

2.1 BASELINE EMISSION INVENTORY

2.1.1 <u>Model Description</u>

The baseline non-road emission inventory was developed using the EPA's draft NONROAD2004 model[1]. The NONROAD model was created to assist states and local regulatory agencies in developing accurate non-road emission inventories. The model provides emissions, population, activity, and fuel consumption information for equipment of various types, sizes, sectors, and fuel types. Fuel types included in the model are gasoline, diesel, compressed natural gas (CNG), and liquefied petroleum gas (LPG). Sectors, or equipment categories, included are:

- agricultural equipment;
- airport ground equipment;
- commercial equipment;
- construction and mining equipment;
- industrial equipment;
- commercial lawn and garden equipment;
- residential lawn and garden equipment;

- logging equipment;
- pleasure craft;
- railroad equipment; and
- recreational equipment[2].

2.1.2 Model Inputs

The baseline model uses various inputs to estimate emissions for over 200 equipment types for specified time periods. These inputs may be set as default inputs included in the model, or may be modified by users to improve the representativeness of the model for a specific area. The standard model inputs are:

- equipment population by age, power, fuel type, and application;
- average load factor expressed as average fraction of available power;
- available power;
- hours of use per year; and
- emission factor.

For estimating local area or county inventories, the model allocates equipment populations to the county-level using surrogate indicators believed to correlate with equipment activity. EPA technical reports describing the basis for all inputs to the NONROAD model are available at http://www.epa.gov/otaq/nonrdmdl.htm#techrept[3].

To improve the baseline inventory accuracy for NYS, certain non-default inputs were used. These included using non-default inputs for estimating airport ground support emissions and setting ambient temperatures and fuel specifications based on county level data provided by NYSDEC.

Airport ground support emissions for the state were estimated using the Federal Aviation Administration's (FAA) Emissions and Dispersion Modeling System Version 4.2[4]. Airport specific data was acquired from the FAA and used as inputs to the model. The inputs were used to estimate emissions from airport ground service equipment.

Temperature data for 2002 was acquired from the National Oceanic and Atmospheric Administration, and included historical weather data from thirty-three airport locations across the state of New York and other surrounding locations[5]. This information was used to develop average high and low temperatures for each month on a county by county basis, which was then input into the NONROAD model.

Fuel blend data for gasoline engines was acquired from the New York State Department of Agriculture and Markets. This data was based on samples collected across the state from fueling stations and retention areas. These samples were then analyzed for many specifications, including oxygen content, Reid Vapor Pressure, and sulfur content. The data provided average monthly fuel profiles on a county by county basis. These profiles, along with default values for diesel, CNG, and LPG fuel, were input into the NONROAD model.

All model input files and model runs were completed by NYSDEC. Monthly county data was provided to Southern Research Institute (Southern) and its subcontractor, E.H. Pechan & Associates, Inc. (Pechan), for aggregation into state and regional inventories and further analysis. NYSDEC also provided locomotive and commercial marine inventory information for inclusion in the baseline inventory (see section 2.1.3). Model input files are contained in the addendum to this report, titled *NYSERDA Clean Diesel Technology: Addendum to the Non-Road Field Demonstration Program Interim Report – Model Input Data*.

2.1.3 Model Outputs

The NONROAD model was used to generate the following outputs:

- emission data in tons per year (tpy) for THC, PM, NOx, and CO by equipment sector, type, horsepower range, and fuel type; and
- equipment population, activity in hours of use per year, and fuel consumption in gallons per year by equipment sector, type, horsepower range, and fuel type.

For all non-road equipment, NONROAD 2004 incorporates population counts for a base year of 2000. Equipment populations for a base year of 2002, the most recent population data included in the model, were estimated using a linear extrapolation of available historic diesel engine populations[3]. Therefore, the model was run for a base year of 2002. To determine the impacts of future engine developments and fuel specifications, the model was also run for projection year 2009. To estimate future years, the model takes into account growth and retirement rates for equipment, as well as other control options. Fuel inputs for 2009 were estimated based on pending regulations for gasoline and diesel sulfur levels, along with LL77, which requires the use of 15 ppm sulfur diesel for construction projects in the NYCMA.

Both model runs provided outputs for each month and county in NYS. Results were then aggregated to form annual statewide and regional NYCMA inventories including:

- annual emissions;
- ozone season emissions;

- aggregated state-wide emissions;
- aggregated NYCMA (10-county) emissions;
- emissions by off-road sector (construction and mining, agricultural, industrial, airport, etc.); and
- emissions by source classification code (SCC), equipment type, and individual horsepower/ engine size bins.

Emission data for locomotives and commercial marine vessels for a base year of 2002 was also included in the baseline inventory. This data was supplied by NYSDEC and integrated into the 2002 model. Locomotive data was included in the railroad equipment sector and is based on estimated fuel consumption of railroad systems that operate within the boundaries of NYS. This data is based on emissions from 1990 extrapolated to 2002 levels based on existing emission activity, expected changes in activity, and historical emission factor rates. Data for commercial marine vessels was integrated into the model as its own sector. These emission data are based upon the commercial marine vessels emissions report prepared by Starcrest Consulting Group in conjunction with their work on the New York Harbor Deepening Project. The emissions are based on actual 2002 operational data from an intensive survey performed by Starcrest[6].

Locomotive and commercial marine data for projection year 2009 was not provided to Southern, so the 2002 data was integrated into the 2009 model as well so as to not bias the results of the 2009 model by the absence of locomotive and commercial marine data. There were a few differences between the outputs of the NONROAD model and those of the locomotive and commercial marine emission data. THC, NOx, PM, and CO emissions by equipment and fuel type were the only outputs included in the locomotive and commercial marine data. Information on population, activity, and fuel consumption was unavailable. Unlike the NONROAD model, the locomotive and commercial marine emission data was not broken down into horsepower ranges. Addition of the locomotive and commercial marine data also resulted in the introduction of an additional fuel type not included in the NONROAD model: residual fuel, which is utilized in the marine sector.

In addition to the standard model runs, a separate model was run to provide emission and population data by model year for each equipment type. The model year run was completed by Pechan for NYS as a whole. The results of this run are based on a NYS-level run of the NONROAD model for base year 2002, using all national default inputs for fuel specifications and temperature. The output provides the equipment emissions and population by model year of the engine as well as by technology type (SCC). Locomotive and commercial marine data were not available for inclusion in the model year run.

It should be noted that estimates generated by the NONROAD model, although used by the EPA, have inherent inaccuracies due to the limitations of the model. These limitations include how equipment is allocated geographically, assumptions made to estimate equipment activity (hours of use), as well as reliance on limited emission factor data. Model results are estimates and may not represent real conditions. Further investigation is needed before acceptance as a viable estimate of equipment populations and emissions. This is discussed further in section 2.2.

2.1.4 2002 Baseline Modeling Results and Discussion

This section presents the results of the 2002 baseline model. It summarizes key details regarding the impacts of non-road equipment on air quality in NYS and the NYCMA. Complete modeling results are available in the Interim Report data addendum[7]. The data addendum includes:

- summaries of 2002, 2009 non-road emissions, population, activity, and fuel consumption for all fuels;
- tables listing the top 50 2002, 2009 non-road emissions, population, activity, and fuel consumption rankings for all fuels;
- summaries of 2002, 2009 non-road diesel emissions, population, activity, and fuel consumption;
- tables listing the top 50 2002, 2009 non-road diesel emissions, population, activity, and fuel consumption rankings;
- a comparison of the 2002, 2009 non-road model results;
- 2002, 2009 non-road diesel weighted rankings;
- summaries of 2002 NYS emission and population data by model year; and
- summaries of emissions, population, activity, and fuel consumption for the 2002, 2009 refined models.

The non-road sector 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 NOx emissions. In the NYCMA, the non-road sector comprises approximately 29% of all PM and 22% of all NOx emissions[8].

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 Btu so that a comparison between the fuel types could be made. Residual fuel does not include data for population, activity, and fuel consumption because, as indicated in section 2.1.3, data was not available for these outputs.

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

	THC, tpy	PM, tpy	NOx, tpy	CO, tpy	Population, # of units	Activity, hours / year	Fuel Consumption, Btu / year
CNG	4925	8	1651	6549	5082	5.27E+06	1.43E+12
Diesel	8212	7311	91028	38154	275400	1.82E+08	6.51E+13
Gasoline, 2-stroke	78572	3790	1300	171455	2883446	2.15E+08	1.41E+13
Gasoline, 4-stroke	26378	272	10533	886843	4457727	5.77E+08	2.77E+13
LPG	2696	63	13433	52353	39814	4.46E+07	1.06E+13
Residual	31	48	986	129	--	--	--

The focus of this project is on air quality problems associated with non-road PM and NOx emissions. Figure 2-1 and Figure 2-2 show the percentage that each fuel type contributes to these emissions in NYS.

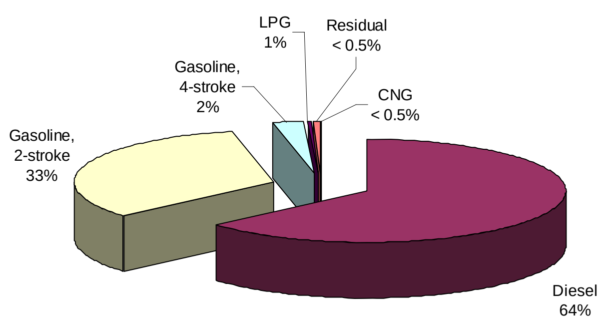

Figure 2-1. 2002 NYS Non-Road PM Emissions by Fuel Type

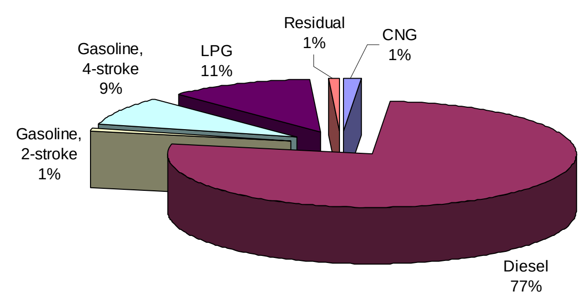

Figure 2-2. 2002 NYS Non-Road NOx Emissions by Fuel Type

Diesel fuel accounts for the largest percentage of non-road PM (64%, or 7,311 tpy) and NOx (77%, or 91,028 tpy) emissions statewide. Similar results are seen for the NYCMA, with diesel responsible for 75% (3,949 tpy) of PM and 75% (44,432 tpy) of NOx emissions. Diesel fuel also accounts for the largest percentage of non-road fuel consumption statewide (55%, or 6.51E+13 Btu/yr) and in the NYCMA (60%, or 3.72E+13 Btu/yr).

Southern also completed an analysis of statewide and NYCMA non-road emissions for all fuel types by equipment sector. Table 2-2 summarizes the results for NYS. The construction and mining equipment sector is responsible for the largest percentage of non-road PM (35%, or 3,980 tpy) and NOx (35%, or 41,182 tpy) emissions statewide. The construction and mining equipment sector is also responsible for the largest percentage of non-road fuel consumption (36%, or 4.24E+13 Btu/yr) statewide. Similar results are seen for the NYCMA, with construction and mining equipment responsible for an even larger portion of overall emissions, as shown in Figure 2-3 and Figure 2-4.

Table 2-2. 2002 NYS Non-Road Emissions for All Fuel Types by Equipment Sector

	THC, tpy	PM, tpy	NOx, tpy	CO, tpy	Population, # of units	Activity, hours / year	Fuel Consumption, Btu / year
Agricultural Equipment	862	799	6391	7268	36613	1.05E+07	5.70E+12
Airport Equipment	92	71	919	1010	1672	1.21E+06	8.90E+11
Commercial Equipment	14791	1017	11413	334600	674111	1.24E+08	1.70E+13
Construction and Mining Equipment	6935	3980	41182	58233	159586	1.02E+08	4.24E+13
Industrial Equip.	6497	737	20426	74167	61492	8.41E+07	1.89E+13
Lawn & Garden Equipment, Commercial	16713	741	3482	250967	377731	1.15E+08	8.46E+12
Lawn & Garden Equipment, Residential	11526	283	1751	206567	5196611	1.12E+08	6.19E+12
Logging Equipment	123	23	231	879	3044	5.33E+05	2.77E+11
Marine Vessels, Commercial	424	506	12266	1790	--	--	--
Pleasure Craft	36417	2168	4784	108387	720659	3.25E+07	1.20E+13
Railroad Equipment	678	410	15345	2110	1637	8.69E+05	1.91E+11
Recreational Equipment	25757	757	741	109506	428313	4.41E+08	6.99E+12

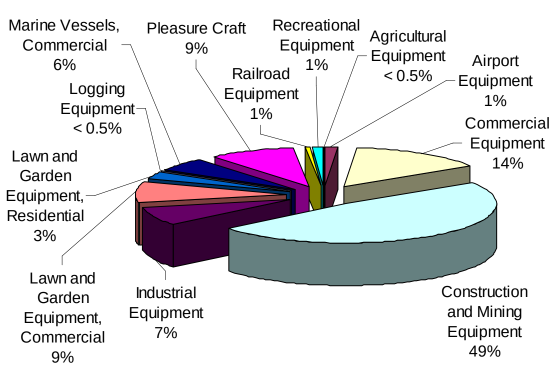

Figure 2-3. 2002 NYCMA PM Emissions for All Fuels by Equipment Sector (5,259 tpy total)

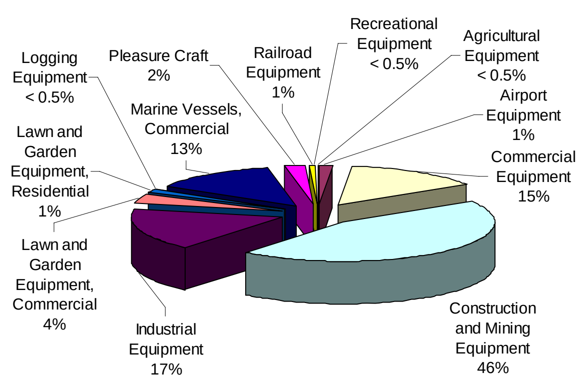

Figure 2-4. 2002 NYCMA NOx Emissions for All Fuels by Equipment Sector (58,570 tpy total)

As demonstrated in the previous tables and figures, diesel fuel use is the primary contributor to PM and NOx emissions in NYS and the NYCMA. Because of this, as well as the future implementation of various rules impacting diesel equipment, the focus of the remainder of this report and the NYSERDA demonstration project is on diesel-fueled non-road equipment.

Figure 2-5 and Figure 2-6 summarize non-road diesel PM and NOx emissions for NYS and the NYCMA by equipment sector.

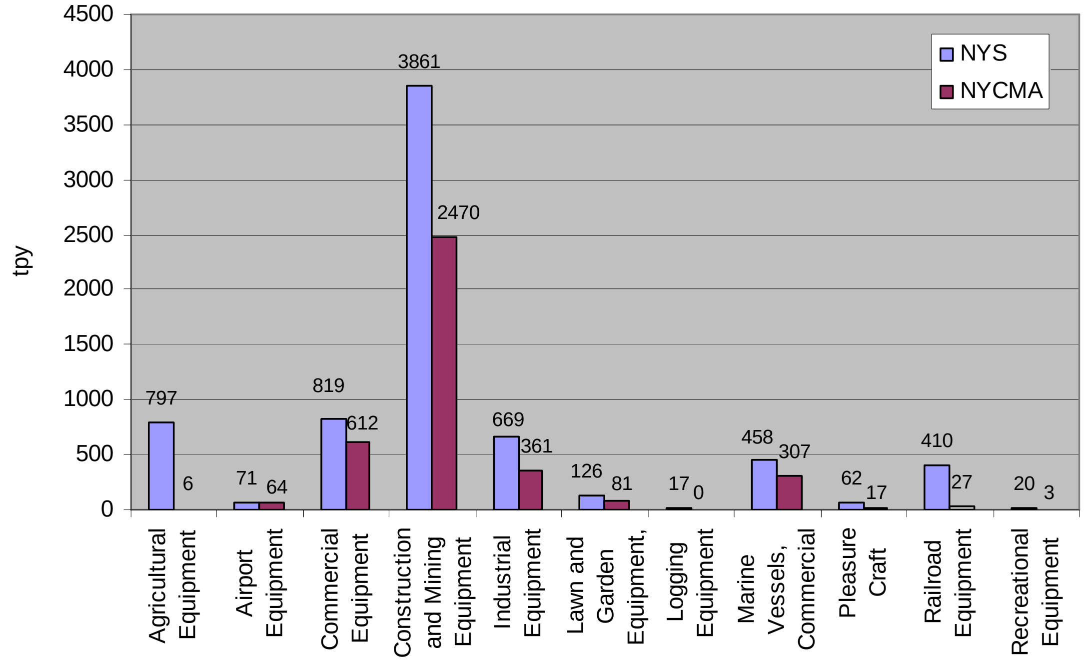

Figure 2-5. 2002 NYS and NYCMA Non-Road Diesel PM Emissions for Diesel Fuel by Equipment Sector

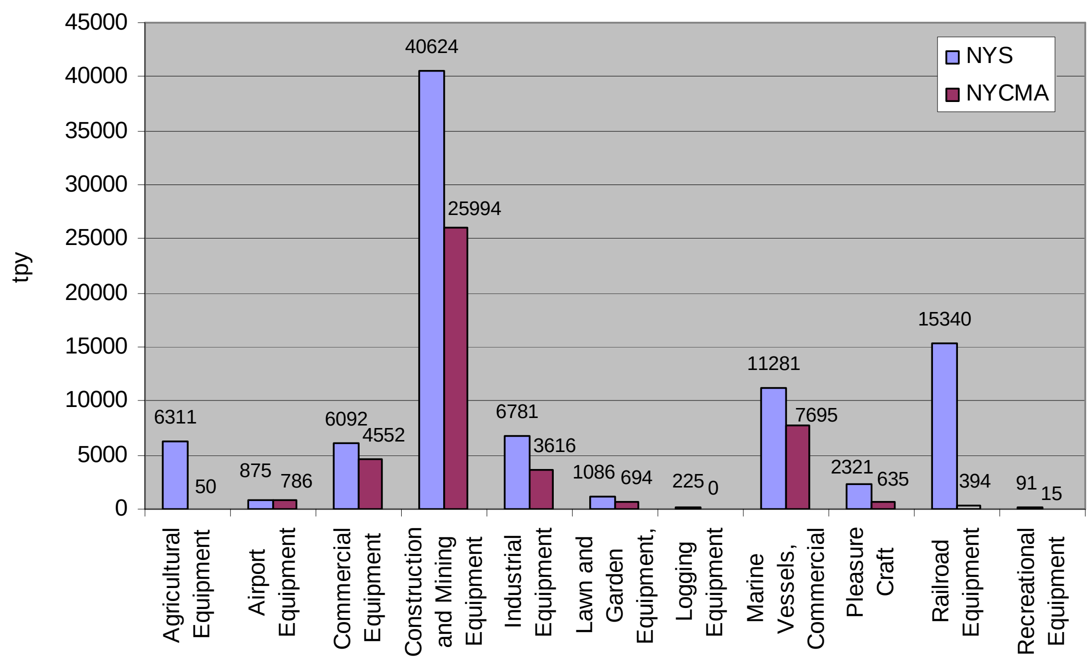

Figure 2-6. 2002 NYS and NYCMA Non-Road Diesel NOx Emissions for Diesel Fuel by Equipment Sector

The analysis of statewide and NYCMA emissions by equipment sector for diesel fuel yielded similar results to those of all fuels. Construction and mining equipment were again responsible for the largest percentage of PM (53%) and NOx (45%) emissions statewide and in the NYCMA (62% and 59%, respectively).

Emissions of each pollutant were next sorted and ranked by equipment type. For both PM and NOx, the top 10 emitters by equipment type accounted for at least 61% (4,467 tpy for PM, 57,681 tpy for NOx)of the total non-road diesel related emissions for the state and at least 68% (2,683 tpy for PM, 30,212 tpy for NOx) for the NYCMA. This is shown in Figure 2-7 through Figure 2-10.

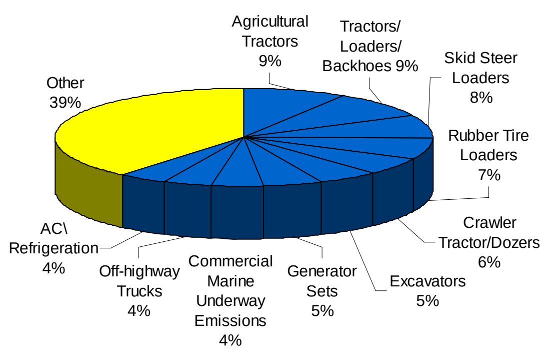

Figure 2-7. Percentage of 2002 NYS Non-Road PM Emissions for Diesel Fueled Equipment (7,311 tpy total)

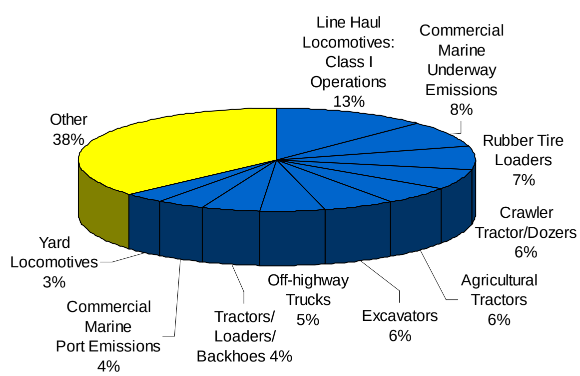

Figure 2-8. Percentage of 2002 NYS Non-Road NOx Emissions for Diesel Fueled Equipment (91,028 tpy total)

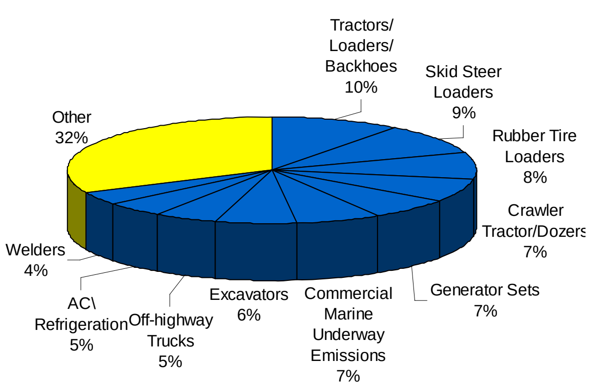

Figure 2-9. Percentage of 2002 NYCMA Non-Road PM Emissions for Diesel Fueled Equipment (3,949 tpy total)

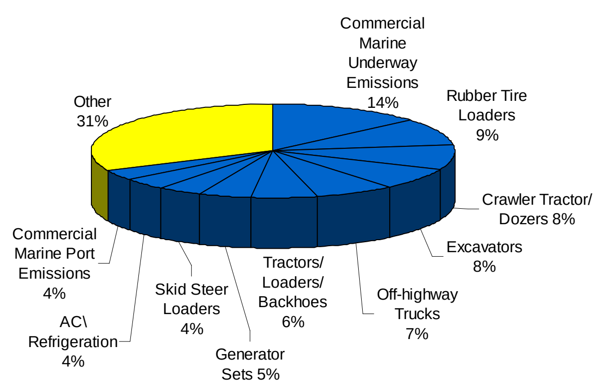

Figure 2-10. Percentage of 2002 NYCMA Non-Road NOx Emissions for Diesel Fueled Equipment (44,432 tpy total)

2.1.5 <u>2009 Baseline Modeling Results and Discussion</u>

Identical evaluations were completed using the 2009 model runs. 2009 runs include impacts of changing fleets and fuels, including:

- growth and retirement rates for equipment;
- pending regulations for gasoline and diesel sulfur levels; and
- LL77, which requires the use of 15 ppm sulfur diesel and "best available technology" (BAT) for construction projects in the NYCMA.

It should be noted that projected data for the locomotive and commercial marine sectors was unavailable for the 2009 model runs. Consequently, the 2002 data was used for the 2009 runs.

Comparisons were first made of statewide and NYCMA annual non-road emissions by fuel type Figure 2-11 and Figure 2-12 show the percentage that each fuel type contributes to non-road PM and NOx emissions in NYS.

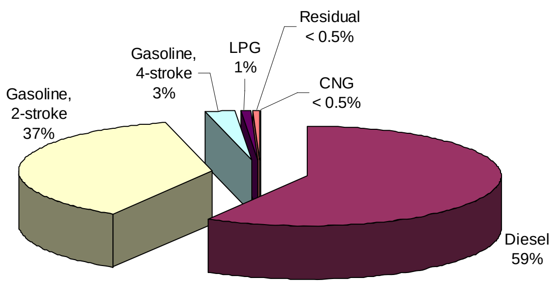

Figure 2-11. 2009 NYS Non-Road PM Emissions by Fuel Type

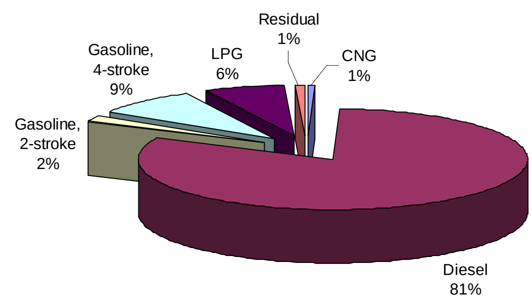

Figure 2-12. 2009 NYS Non-Road NOx Emissions by Fuel Type

Diesel fuel accounts for the largest percentage of non-road PM (59%, or 5,693 tpy) and NOx (81%, 83,029 tpy) emissions statewide. This is a decrease from 2002 levels in percentage of non-road PM emissions, but an increase in percentage of non-road NOx emissions. Similar results are seen for the NYCMA. Diesel remains responsible for the largest percentage of non-road PM and NOx emissions (71%, or 3,053 tpy for PM; 81%, or 39,859 tpy for NOx). Again, this is a decrease from 2002 levels in percentage of non-road PM emissions, but an increase in percentage of non-road NOx emissions.

Southern also completed an analysis of statewide and NYCMA non-road emissions for all fuel types by equipment sector. Table 2-3 summarizes the results for NYS. As with the 2002 model, the construction and mining equipment sector accounts for the largest percentage of non-road PM (30%, or 2,963 tpy) and

NOx (33%, or 34,095 tpy) emissions statewide. This is a slight decrease in the percentages seen in the 2002 model (35% each for both non-road PM and NOx emissions). In the NYCMA, construction and mining equipment are responsible for 43% (1,881 tpy) of non-road PM emissions and 45% (21,819 tpy) of non-road NOx emissions. This, again, is a slight decrease from 2002 levels.

Table 2-3. 2009 NYS Non-Road Emissions for All Fuels by Equipment Sector

	THC, tpy	PM, tpy	NOx, tpy	CO, tpy	Population, # of units	Activity, hours / year	Fuel Consumption, Btu / year
Agricultural Equipment	583	564	5621	6446	42116	1.22E+07	6.64E+12
Airport Equipment	64	53	800	828	2203	1.60E+06	1.18E+12
Commercial Equipment	8536	915	10581	414113	833530	1.54E+08	1.97E+13
Construction and Mining Equipment	4455	2963	34095	53591	180430	1.19E+08	5.00E+13
Industrial Equipment	3316	548	11960	50903	70011	9.81E+07	2.04E+13
Lawn & Garden Equipment, Commercial	8903	746	2946	280458	435927	1.34E+08	9.01E+12
Lawn & Garden Equipment, Residential	6880	274	1522	241308	5959164	1.29E+08	6.28E+12
Logging Equipment	68	17	139	1006	3769	5.79E+05	2.62E+11
Marine Vessels, Commercial	424	506	12266	1790	0	0	0
Pleasure Craft	22935	1723	5911	107299	762086	3.47E+07	1.21E+13
Railroad Equipment	669	404	15337	2140	1886	1.05E+06	2.33E+11
Recreational Equipment	31863	1014	954	135575	667270	7.54E+08	9.49E+12

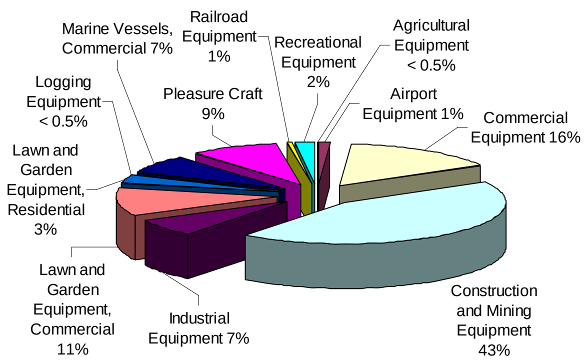

Figure 2-13. 2009 NYCMA Non-Road PM Emissions for All Fuels by Equipment Sector (4,312 tpy total)

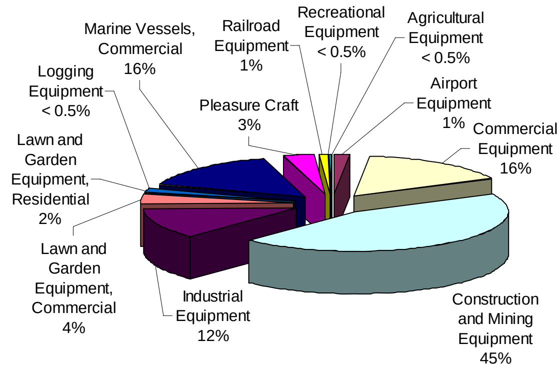

Figure 2-14. 2009 NYCMA Non-Road NOx Emissions for All Fuels by Equipment Sector (49,088 tpy total)

Table 2-4 compares 2002 and 2009 non-road diesel PM and NOx emissions for NYS and the NYCMA by equipment sector. For both NYS and the NYCMA, construction and mining equipment accounts for the largest amount of PM and NOx emissions in 2002 and 2009. Emission levels for this sector decrease by 2009, most likely due to the estimated impacts of the EPA Clean Air Nonroad Diesel Rule regulations that are to be implemented starting in 2008[9] and the continued phase-in of LL77 fuel requirements.

Table 2-4. 2002 and 2009 Non-Road Diesel PM and NOx Emissions by Equipment Sector

	NYS				NYCMA			
	PM (tpy)		NOx (tpy)		PM (tpy)		NOx (tpy)	
	2002	2009	2002	2009	2002	2009	2002	2009
Agricultural Equipment	797	563	6311	5571	6	4	50	44
Airport Equipment	71	52	875	780	64	47	786	700
Commercial Equipment	819	715	6092	6383	612	533	4552	4770
Construction and Mining Equipment	3861	2845	40624	33750	2470	1805	25994	21595
Industrial Equipment	669	472	6781	5900	361	249	3616	3178
Lawn and Garden Equipment	126	104	1086	1178	81	66	694	753
Logging Equipment	17	10	225	133	0	0	0	0
Marine Vessels, Commercial	458	458	11281	11281	307	307	7695	7695
Pleasure Craft	62	51	2321	2622	17	14	635	718
Railroad Equipment	410	404	15340	15333	27	23	394	390
Recreational Equipment	20	20	91	98	3	3	15	17

Emissions of each pollutant were next sorted and ranked by equipment type. For both PM and NOx, the sum of emissions for the top 10 emitters by equipment type accounted for at least 62% (3,514 tpy for PM; 52,016 tpy for NOx) of the total non-road diesel related emissions for the state and at least 67% (2,129 tpy for PM; 27,116 tpy for NOx) for the NYCMA. This is shown in Figure 2-15 through Figure 2-18.

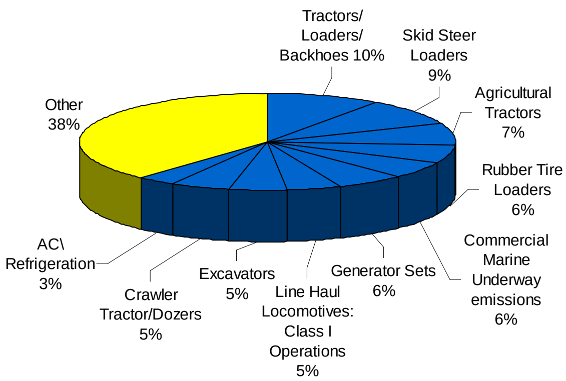

Figure 2-15. Percentage of 2009 NYS Non-Road PM Emissions for Diesel Fueled Equipment (5,693 tpy total)

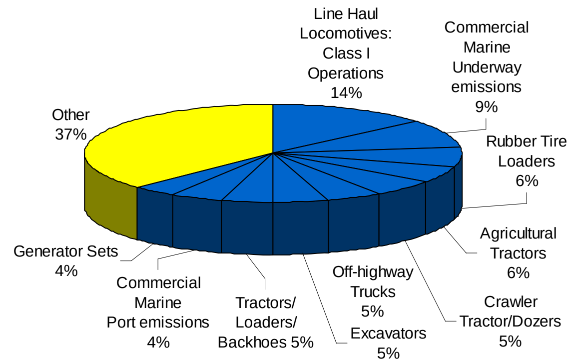

Figure 2-16. Percentage of 2009 NYS Non-Road NOx Emissions for Diesel Fueled Equipment (83,029 tpy total)

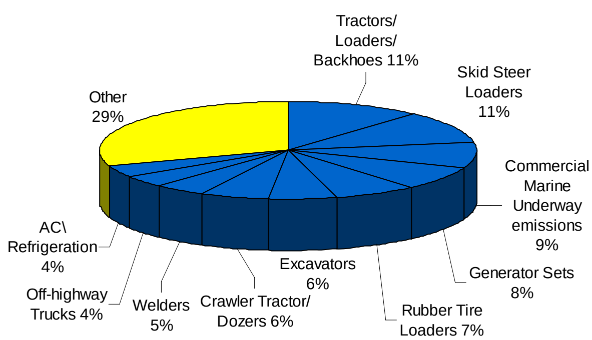

Figure 2-17. Percentage of 2009 NYCMA Non-Road PM Emissions for Diesel Fueled Equipment (3,053 tpy total)

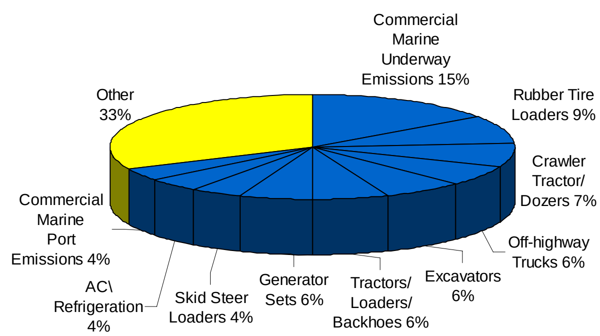

Figure 2-18. Percentage of 2009 NYCMA Non-Road NOx Emissions for Diesel Fueled Equipment (39,859 tpy total)

Analysts also compared the 2002 and 2009 top 20 rankings for PM and NOx emissions for all non-road diesel equipment types included in the model. In NYS, eighteen of the top twenty PM emitters appeared in both the 2002 and 2009 rankings, with slight differences in the order of rank. For NOx emissions in NYS, nineteen of the top twenty emitters appeared in both the 2002 and 2009 lists, differing again only in the order of rank. The top six NOx emitters were identical in the 2002 and 2009 rankings. In the NYCMA, eighteen of the top twenty PM and NOx emitters appeared in both lists, differing slightly in order of rank. The top three PM emitters and the top four NOx emitters were of identical rank in both 2002 and 2009.

The small changes in emission levels between 2002 and 2009 indicate that conclusions based on the 2002 run data are essentially representative of non-road diesel emissions for the immediate future as well.

2.1.6 2002 Ozone Season

Annual non-road diesel PM and NOx emission data for NYS and the NYCMA were also compared to data for the ozone season (April 1 – October 31). Table 2-5 and Table 2-6 compare the top emitters for annual and ozone season non-road diesel PM and NOx emissions in the NYCMA. It should be noted that locomotive and commercial marine data was not available for the ozone season, so it was removed from the annual period as well for this comparison. For both PM and NOx, the top emitters are nearly identical for the annual period and ozone season, differing in some cases only in the order of rank. Similar results were seen when comparing non-road diesel PM and NOx emissions during the annual and ozone seasons for NYS. Like the NYCMA, the top emitters were nearly identical. Specifically, the top 16 ranked non-road diesel PM emitters were identical in the annual and ozone seasons, differing only slightly in order of rank. The top 20 non-road diesel NOx emitters in NYS were identical, differing slightly in order of rank. This indicates that season is relatively unrelated to which equipment types are the largest emitters. Because of the similarity of the annual and ozone season emission sources, analysts at Southern determined that additional evaluation of ozone-season specific equipment usage and impacts is not warranted under this project.

While season does not impact which equipment types are responsible for the most emissions, it is interesting to note that season does impact the quantity of emissions. The ozone season accounts for 72% (4,645 tpy) of total statewide non-road diesel PM emissions and 72% (46,819 tpy) of total statewide non-road diesel NOx emissions. Similarly, the ozone season is responsible for 70% (2,558 tpy) of total NYCMA non-road diesel PM emissions and 71% (25,975 tpy) of total NYCMA non-road diesel NOx emissions.

Table 2-5. Top Ranked NYCMA Non-Road Diesel Annual and Ozone Season PM Emissions

		Annual Emissions		Ozone Season Emissions	
Equipment Type	**HP**	**PM, tpy**	**Rank**	**PM, tpy**	**Rank**
Tractors/Loaders/Backhoes	100	221	1	165	1
Skid Steer Loaders	75	147	2	110	2
AC\Refrigeration	75	146	3	93	5
Skid Steer Loaders	100	142	4	105	3
Tractors/Loaders/Backhoes	175	137	5	102	4
Rubber Tire Loaders	600	114	6	85	6
Excavators	300	85	7	63	7
Excavators	175	78	8	58	8
Off-highway Trucks	2000	77	9	58	9
Rubber Tire Loaders	300	75	10	56	10
Rough Terrain Forklifts	100	75	11	56	11
Generator Sets	100	67	12	39	14
Air Compressors	100	62	13	36	16

		Annual Emissions		Ozone Season Emissions	
Equipment Type	**HP**	**PM, tpy**	**Rank**	**PM, tpy**	**Rank**
Crawler Tractor/Dozers	300	60	14	45	12
Crawler Tractor/Dozers	600	59	15	44	13
Rubber Tire Loaders	175	51	16	38	15
Welders	75	48	17	28	21
Crawler Tractor/Dozers	175	45	18	34	17
Tractors/Loaders/Backhoes	75	45	19	33	18
Excavators	600	41	20	31	19
Crawler Tractor/Dozers	750	40	24	30	20

Table 2-6. Top Ranked NYCMA Non-Road Diesel Annual and Ozone Season NOx Emissions

		Annual Emissions		Ozone Season Emissions	
Equipment Type	**HP**	**PM, tpy**	**Rank**	**PM, tpy**	**Rank**
Rubber Tire Loaders	600	1554	1	1156	1
AC\Refrigeration	75	1315	2	832	6
Excavators	300	1230	3	915	2
Off-highway Trucks	2000	1191	4	886	3
Tractors/Loaders/Backhoes	100	1166	5	868	4
Tractors/Loaders/Backhoes	175	1162	6	864	5
Excavators	175	1047	7	779	7
Rubber Tire Loaders	300	1038	8	773	8
Crawler Tractor/Dozers	600	890	9	662	9
Crawler Tractor/Dozers	300	859	10	639	10
Skid Steer Loaders	75	699	11	520	11
Rubber Tire Loaders	175	674	12	502	12
Skid Steer Loaders	100	672	13	500	13
Excavators	600	648	14	482	14
Crawler Tractor/Dozers	175	605	15	450	15
Crawler Tractor/Dozers	750	584	16	434	16
Graders	300	526	17	391	17
Air Compressors	100	521	18	304	22
Off-highway Trucks	600	499	19	371	18
Rough Terrain Forklifts	100	489	20	364	19
Off-highway Trucks	750	464	22	345	20

2.1.7 Normalized Non-Road PM and NOx Emissions

Analysts also calculated non-road diesel PM and NOx emissions by equipment type, normalized to the population of each equipment type. This shows the approximate contribution to emissions of a single piece of equipment and is useful in determining priority equipment types for field testing. The normalized rankings help to identify the biggest "bang for the buck"; that is, on which equipment types will there be the largest potential emissions reductions using the fewest number of retrofits. Table 2-7 and Table 2-8 show the top twenty non-road diesel PM and NOx emitters for NYS, normalized by population. The tables also show the percentage each equipment type contributes to total annual emissions.

Non-road diesel equipment types that ranked highly in total annual PM and NOx rankings (off-highway trucks, crawler tractor/dozers, rubber tire loaders) were generally also highly ranked in the normalized rankings. Equipment types that did not rank highly in the annual rankings but did in the normalized rankings (scrapers, snowblowers, pavers) may contribute high amounts of emissions per unit of equipment, but contribute a very small percentage to overall emissions (typically less than 1%). This leads to the conclusion that these are not necessarily priority equipment types. Rather, more significant emissions reductions could potentially be achieved by using retrofits on the higher ranking equipment types.

Table 2-7. 2002 NYS Non-Road Diesel PM Emissions, Normalized by Population

Rank	Equipment Type	PM (tpy)	Population (# units)	PM / Population	% of Total PM
1	Off-highway Trucks	312	926	0.34	4.26%
2	Off-Highway Tractors	54	241	0.23	0.74%
3	Gas Compressors	0	0	0.22	0.00%
4	Scrapers	109	998	0.11	1.48%
5	Other Oil Field Equipment	1	14	0.09	0.02%
6	Other Construction Equipment	60	717	0.08	0.83%
7	Crawler Tractor/Dozers	418	5669	0.07	5.72%
8	Forest Eqp - Feller/Bunch/Skidder	17	228	0.07	0.23%
9	Rubber Tire Loaders	510	8162	0.06	6.97%
10	Forklifts	148	2419	0.06	2.03%
11	Terminal Tractors	73	1246	0.06	0.99%
12	Graders	95	1759	0.05	1.31%
13	Excavators	395	7376	0.05	5.40%
14	Snowblowers	2	36	0.05	0.02%
15	Other Agricultural Equipment	17	341	0.05	0.23%
16	Airport Ground Support Equipment	71	1474	0.05	0.97%
17	Cranes	89	1921	0.05	1.21%
18	Railway Maintenance	33	748	0.04	0.45%
19	Pavers	48	1310	0.04	0.66%
20	Crushing/Proc. Equipment	19	520	0.04	0.26%

Table 2-8. 2002 NYS Non-Road Diesel NOx Emissions, Normalized by Population

Rank	Equipment Type	NOx (tpy)	Population (# units)	NOx / Population	% of Total NOx
1	Off-highway Trucks	4993	926	5.39	5.48%
2	Off-Highway Tractors	696	241	2.89	0.76%
3	Gas Compressors	0	0	2.07	0.00%
4	Scrapers	1550	998	1.55	1.70%
5	Other Oil Field Equipment	21	14	1.46	0.02%
6	Crawler Tractor/Dozers	5711	5669	1.01	6.27%

Rank	Equipment Type	NOx (tpy)	Population (# units)	NOx / Population	% of Total NOx
7	Forest Eqp - Feller/Bunch/Skidder	225	228	0.99	0.25%
8	Other Construction Equipment	687	717	0.96	0.75%
9	Rubber Tire Loaders	6554	8162	0.80	7.20%
10	Cranes	1460	1921	0.76	1.60%
11	Graders	1334	1759	0.76	1.47%
12	Terminal Tractors	925	1246	0.74	1.02%
13	Excavators	5231	7376	0.71	5.75%
14	Airport Ground Support Equipment	875	1474	0.59	0.96%
15	Forklifts	1368	2419	0.57	1.50%
16	Crushing/Proc. Equipment	257	520	0.49	0.28%
17	Snowblowers	16	36	0.46	0.02%
18	Pavers	534	1310	0.41	0.59%
19	Sweepers/Scrubbers	716	2041	0.35	0.79%
20	Other General Industrial Eqp	828	2410	0.34	0.91%

2.1.8 Equipment Model Year Runs

A separate model run of the 2002 data was generated to provide non-road emission data for NYS by equipment type and model year. This information will be useful in determining equipment model years of interest for field testing.

Several equipment types repeatedly appear in the top rankings for non-road diesel PM and NOx emissions. The PM and NOx data for these equipment types were plotted along with equipment population. Figure 2-19 shows plots of PM emissions for non-road diesel off-highway trucks, rubber tire loaders, and tractors/loaders/backhoes by model year, along with their respective populations. The plots show that emissions and population tend to trend upward with model year, with emissions drop-offs at particular model years. These drop-offs roughly correspond to years in which EPA engine regulations were implemented.

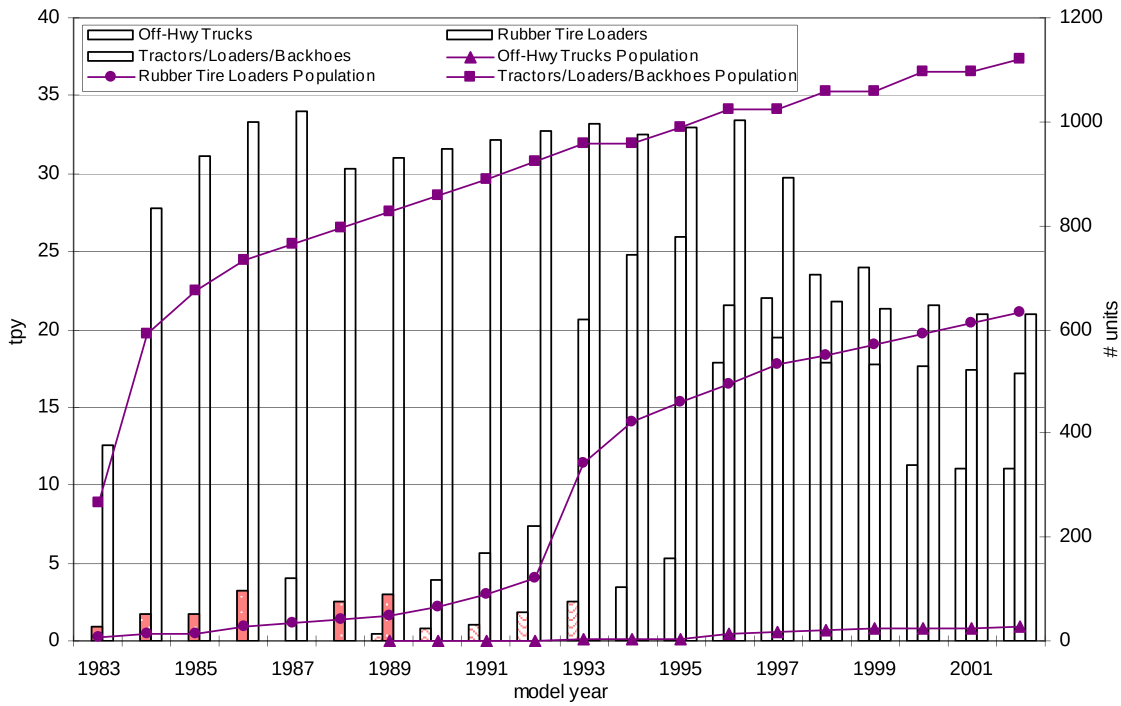

Figure 2-19. PM Emissions and Population by Model Year for Selected Non-Road Diesel Equipment

2.2 CONCLUSIONS

The preceding analyses led to narrowing the focus of this project to diesel-fueled equipment from the construction and mining sector. The project focus was narrowed further to target emissions only in the NYCMA. The NYCMA is responsible for 64% of the total statewide nonroad diesel PM and NOx emissions from the construction and mining sector. This justifies narrowing the scope of the project to only the NYCMA without sacrificing the quality of the field testing portion of the program.

Throughout the analysis of inventory data, a few unexpected observations or anomalies appeared. Investigation of these areas is beyond the scope of this project, but could justify future work. Some observations are discussed in the following paragraphs.

An unusually high number of all terrain vehicles were reported in New York, both statewide (approximately 167,000) and in the NYCMA (approximately 28,000). This large population also resulted in high emissions. However, it is possible that the emission levels and population are overestimated by the model due to lack of credible allocation procedures, as indicated in the EPA's *Geographic Allocation of State Level Nonroad Engine Population Data to the County Level*[10]. The county in which equipment of this type is purchased, registered, serviced, and stored is usually not where the equipment is actually used.

Most recreational equipment, like ATVs, are purchased in urban and suburban areas near to where the owner lives, but is used in more rural areas. Currently, the EPA does not have an allocation procedure designed to take this issue into account. This could be investigated in future projects.

AC/Refrigeration units (typically, truck mounted refrigerated trailer units) consistently appeared in the top 10 emitters for each pollutant in the NYCMA. The accuracy of these emission levels is most likely reliable and these units may be a priority equipment category for further research and evaluation of control strategies.

Commercial Marine Equipment also consistently appeared in the top 10 list of emitters for each pollutant type in the NYCMA. Although this may be a priority equipment category, projects related to the private ferry fleet that are currently being conducted by NYSERDA partially address this sector. Further work in this area may be of interest.

The inventory also showed significant levels of THC and CO emissions predicted by the NONROAD model from gasoline engines. Although THC and CO are not the primary pollutants of concern, this may be an area that should be considered in future projects.

3.0 IDENTIFICATION OF HIGH PRIORITY SECTORS AND EQUIPMENT

3.1 RANKING RATIONALE & PROCEDURE

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.

Each parameter (CO, NOx, THC, PM, activity, population, and fuel consumption) was assigned a weight which was used to calculate a weighting factor. The weighting factor for each parameter is given by:

$$W_i = \frac{w_i}{\left(w_{PM} + w_{NOx} + w_{CO} + w_{THC} + w_{FC} + w_A + w_{POP}\right)}$$

Where: W_i = weighting factor for parameter ‘i’

w_i = individual weight assigned to parameter ‘i'

w_{PM}, w_{NOx}, etc. = individual weight assigned to PM, NOx, etc.

The weighted rank for each parameter was calculated by multiplying the individual numerical rank of a piece of equipment by the weighting factor for each parameter. The combined, weighted ranking parameter was then generated by summing the individual weighted parameter ranks for each equipment type. Equipment was then re-ranked based on this combined ranking factor. The formula for the combined ranking factor is:

$$R_{C,i} = W_{PM}R_{PM,i} + W_{NOx}R_{NOx,i} + W_{CO}R_{CO,i} + W_{THC}R_{THC,i} + W_{FC}R_{FC,i} + W_A R_{A,i} + W_{POP}R_{POP,i}$$

Where: $R_{C,i}$ = combined, weighted rank for equipment type ‘i’

W_{PM}, W_{NOx}, etc. = weighting factors for PM, NOx, etc.

$R_{PM,i}$, $R_{NOx,i}$, etc. = numerical rank for individual equipment type i

Several sets of weighting factors were used to determine the impacts of weighting criteria on the combined rankings. Certain 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 four sets of weight assignments that were evaluated are presented in Table 3-1.

Table 3-1. 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	--	--	--

3.2 WEIGHTED RESULTS AND DISCUSSION

Table 3-2 summarizes the top 20 rankings for the 2002 NYCMA weighted cases. It also presents the rankings for PM and NOx emissions, population, activity, and PM and NOx emissions normalized by population.

Table 3-2. 2002 NYCMA Non-Road Diesel Rankings Summary

Equipment Type	HP	Ranking (out of 596)									
		Case 1	Case 2	Case 3	Case 4	PM	NOx	Pop.	Activity	PM / unit	NOx / unit
Tractors/Loaders/Backhoes	75 - 100	1	1	2	3	2	7	3	2	156	219
AC\Refrigeration	50 - 75	2	2	3	2	4	4	4	1	214	195
Rubber Tire Loaders	300 - 600	3	8	4	4	7	3	42	34	77	67
Tractors/Loaders/Backhoes	100 - 175	4	4	5	6	6	8	8	4	167	178
Skid Steer Loaders	50 - 75	5	3	6	8	3	13	2	3	242	294
Off-highway Trucks	1200 - 2000	6	29	8	7	10	6	185	113	2	2
Excavators	175 - 300	7	7	9	5	8	5	33	17	102	92
Skid Steer Loaders	75 - 100	8	5	7	10	5	15	5	5	187	247
Excavators	100 - 175	9	6	10	9	9	9	21	12	133	122
Rubber Tire Loaders	175 - 300	10	9	11	11	11	10	30	27	114	106
Crawler Tractor/ Dozers	300 - 600	11	17	12	14	16	11	64	52	85	65
Rough Terrain Forklifts	75 - 100	12	11	13	16	12	22	18	18	160	194
Crawler Tractor/ Dozers	175 - 300	13	14	15	13	15	12	45	32	136	102
Rubber Tire Loaders	100 - 175	14	13	17	15	17	14	27	25	165	142
Generator Sets	75 - 100	15	10	16	18	13	23	6	13	289	286
Air Compressors	75 - 100	16	12	18	17	14	20	17	10	211	202
Excavators	300 - 600	17	26	19	20	22	16	84	60	71	56
Crawler Tractor/ Dozers	100 - 175	18	16	20	19	20	17	38	28	212	145
Crawler Tractor/ Dozers	600 - 750	19	31	21	21	24	18	120	101	57	44
Graders	175 - 300	20	25	22	22	27	19	56	45	107	96
Commercial Marine Underway Emissions	--	114	209	1	1	1	1	--	--	--	--
Commercial Marine Port Emissions	--	130	222	14	12	19	2	--	--	--	--
Welders	40 - 50	28	19	29	43	23	60	12	8	307	374
Generator Sets	25 - 40	23	15	26	30	28	39	1	7	423	414
Tractors/Loaders/Backhoes	50 - 75	24	18	23	29	21	45	22	11	208	254
Generator Sets	50 - 75	27	20	28	27	25	37	9	20	338	333

The weighted rankings show similar equipment types within the top ranked items for all cases within the NYCMA. For example, the top 10 for every case of weighting criteria includes the following categories: tractors/loaders/backhoes, A/C 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. Commercial marine equipment appears near the top of the rankings weighted toward PM and NOx. Note, however, that the commercial marine data is not broken down by specific equipment types and includes all horsepower ranges. Therefore, this category may consist of multiple SCCs, whereas the other categories represent a single SCC.

Results are similar for the state-wide inventory. The top ranked equipment types for most cases are: tractors/loaders/backhoes, A/C refrigeration, rubber tire loaders, skid steer loaders, agricultural tractors, off-highway trucks, and excavators. In addition, in the statewide inventory, class I line haul locomotives and commercial marine emissions appear near the top of the rankings when ranks are weighted toward PM and NOx emissions. However, note that the locomotive data, like commercial marine, may comprise multiple SCCs, as described in the preceding paragraph.

For small variations in the weighting factors, little to no impact is seen in the rankings. Even for larger adjustments in weighting (i.e. disregarding CO, THC, fuel consumption, and population) significant changes in the rankings are not observed, except for the increase in the locomotive rankings under high PM and NOx weightings. This indicates that a small group of equipment dominates the non-road diesel sector in the state and the NYCMA.

When comparing state-wide equipment rankings to the NYCMA rankings, the types of equipment ranked highest changes slightly, with the NYS rankings also including agricultural tractors and locomotives. However, within the construction and mining sector, the higher ranked equipment types remain similar, indicating a targeted set of equipment types that impact both statewide and localized (NYCMA) emissions with in the construction and mining sector.

3.3 RECOMMENDED PRIORITY EQUIPMENT FOR FIELD DEMONSTRATION

Table 3-3 lists Southern's suggested priority equipment types and horsepower ranges to be addressed in the field demonstration portion of this project. The preceding discussions form the general basis of the list. The list represents a group of equipment of similar engine types and a variety of size ranges within similar sectors of use. It is likely that addressing similar equipment types or sectors (in this case, construction and mining equipment) will allow for a focused, efficient demonstration project utilizing a small group of host equipment owners and operators 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. The normalized rankings for several equipment types appear in Table 3-2. Several of the top ranked equipment types in the weighted rankings also appear among the highest in the 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. For example, 300 – 600 hp non-road diesel rubber tire loaders in the NYCMA rank in the top 10 for all weighting cases, the top 50 for PM and NOx emissions, and the top 100 for normalized PM and NOx emissions. Additionally, rubber tire loaders of all horsepower ranges are responsible for 8% (326 tpy) of annual non-road diesel PM emissions and 9% (4,193 tpy) of all annual non-road diesel NOx emissions. Conversely, equipment types that ranked highly in the normalized rankings were not necessarily included in the list of priority equipment. For example, 3000 hp off-highway tractors were the fourth ranked emitter of both non-road diesel PM and NOx in the NYCMA when normalized by population. However, this equipment type is responsible for only 1% (35 tpy for PM; 445 tpy for NOx) of annual non-road diesel PM and NOx emissions, so it was not included as a priority equipment type.

Analysts also looked qualitatively at the weighted and normalized rankings to determine priority equipment types. Equipment types that appeared in the rankings under multiple horsepower ranges were often combined into one, larger horsepower range. For example, 175 – 300 hp and 300 – 600 hp rubber tire loaders appear in the top rankings of all weighting cases, so these were combined into one horsepower range for Table 3-3 (175 – 600 hp rubber tire loaders).

Table 3-3. Recommended Priority Equipment for Field Demonstration

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

The equipment types in Table 3-3 are grouped into three sub-categories. Those grouped in sub-category one are considered the equipment types of highest priority for field testing. 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 are 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 are 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.

It should be noted that several equipment types that appeared as high priority targets in the preceding discussion were left off the Table 3-3 recommended priorities list. The following equipment types in particular were ranked highly for PM and NOx emissions but were not included in the list of priority equipment:

- Agricultural tractors appear in the top rankings for both PM and NOx. However, testing agricultural tractors would diminish project resources because they are not typically found in non-attainment areas, but rather in a more rural environment. Testing of agricultural tractors would also require identifying different fleets and host sites than those used for the construction and mining equipment. A major concern for this project is the evaluation of control technologies for the "BAT" portion of LL77. Thus, it was the consensus of project team members that this equipment is not a focus of this project, although it may warrant future investigation.
- Commercial marine engines appear in the top rankings for cases weighted toward PM and NOx emissions. Although significant PM and NOx emitters, projects related to the private ferry fleet that are have previously been or are currently being conducted by NYSERDA, the PANYNJ, and other public and private entities partially address this sector. However, further work in this area may be of interest.
- A/C refrigeration units (typically truck mounted refrigerated trailer units) consistently appear in the top ten rankings for all weighting cases. These units were omitted from this projects for the same reasons indicated for agricultural tractors.
- Class I line haul locomotives appear in the top rankings for cases weighted toward PM and NOx emissions. Locomotives, with their large engines and diesel-electric operation, pose demonstration issues which may be beyond this project's scope. The locomotive data is also not broken down by specific equipment types and includes all horsepower ranges, as discussed in section 3.2. The accuracy of the locomotive data is also questionable. An additional task for this project is to refine the locomotive emission inventory. A survey of freight and passenger/commuter railroads in NYS is currently underway. The survey will collect information on fuel use, locomotive activity, miles traveled per day, idling time, and locomotive engine inventory age. An updated emissions inventory will be developed using the survey data and EPA emission factors.

4.0 EMISSION CONTROL STRATEGIES

This section provides an overview of control technologies—including exhaust aftertreatment, as well as fuel and engine strategies—for the reduction of diesel PM and NOx emissions. A comprehensive selection of technologies is covered that is potentially applicable to the control of emissions from non-road equipment. Based on the control efficiency, durability, operational impacts, costs, and other factors, technologies are identified which are believed to be the most feasible and can provide the most cost effective impacts to the NYSERDA program and the field demonstration. Much of the information presented in this section was provided by Emisstar and Ecopoint.

4.1 EXHAUST GAS AFTERTREATMENT TECHNOLOGIES

4.1.1 Diesel Oxidation Catalysts

Overview

A schematic of a catalytic converter is shown in Figure 4-1. A ceramic or metallic catalyst substrate is coated with a layer of refractory oxide material called the washcoat, and impregnated with a catalyst. The catalyzed substrate is packaged into a steel canister and installed in the exhaust system.

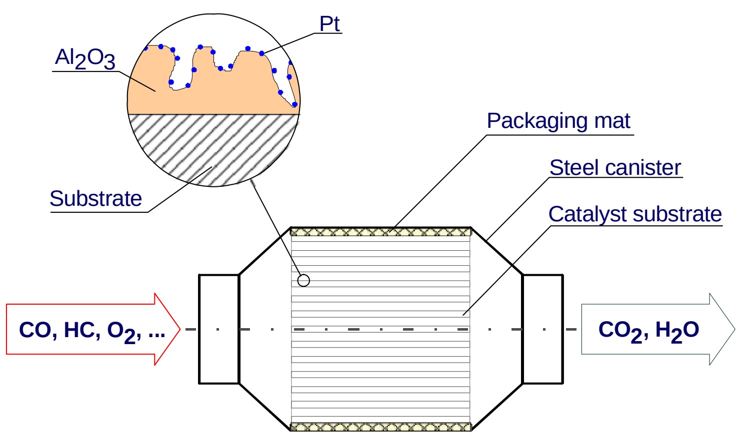

Figure 4-1. Schematic of Catalytic Converter

In diesel oxidation catalysts (DOC), the washcoat is usually based on alumina and the most common catalyst is platinum. However, depending on the application, different catalyst formulations can be used. In European passenger cars—where the DOC must reduce emissions of CO, HC and PM at very low temperatures—very high Pt loadings are used on the order of 100 g/ft^3. On the other hand, some DOC formulations for US highway truck and bus applications, optimized for PM emission reduction, utilize base metal catalysts with small addition of Pt, which can be less than 5 g/ft^3. Such base metal catalysts may have limited activity in reducing gaseous emissions (CO, HC). Advanced DOC formulations also include zeolites which act as HC traps and enhance the catalyst HC performance at low temperatures.

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%, in active Pt-based catalysts, but base metal DOCs may have low CO/HC activity.

The DOC is also active in reducing PM emissions from diesel engines. The PM activity is explained by the combined effect of oxidation and cracking of heavy hydrocarbons which form the soluble organic fraction (SOF) of diesel particulates. It is widely believed that DOCs utilizing conventional flow-through catalyst substrates are not active in oxidizing the carbonaceous portion of diesel PM.

Since the DOC activity is limited to SOF, the potential for total PM reduction depends on the composition of particulates. Figure 4-2 shows an example PM composition from a diesel engine as a function of the engine load and speed[11]. As apparent from the chart, high SOF fractions ("wet particulates") are seen at low engine loads, while little SOF ("dry particulates") is emitted at high load and temperature conditions. Large differences in the SOF fraction also exist between different engine models.

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% are often measured in light duty vehicles over cold test cycles (such as NEDC). In many heavy-duty engines, where the test cycles have higher load factor, total PM emission reductions up to approximately 20-30% can be realized. However, in engines which have a tendency to produce dry particulates, the PM emission reduction using DOC may be less than 10%.

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 be actually 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.

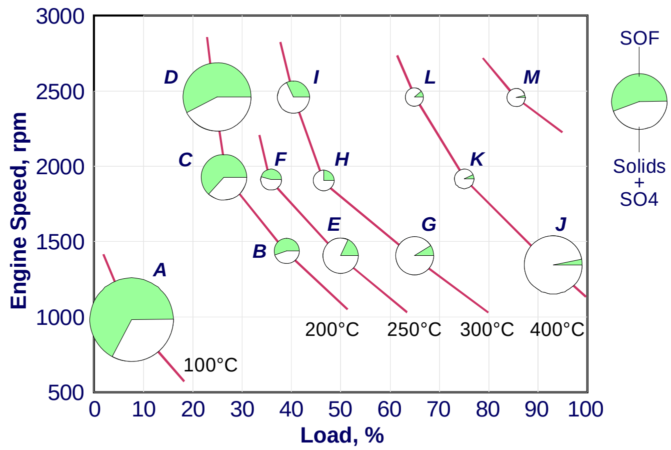

Figure 4-2. SOF Content at Different Engine Conditions

2.8 liter, DI, turbocharged diesel engine; 0.38 wt.% S in fuel; PM emission/SOF content (g/bhp-hr/%): A 2.48/69%; B 0.66/55%; C 1.12/65%; D 1.60/58%; E 0.85/21%; F 0.52/46%; G 0.90/10%; H 0.54/25%; I 0.71/33%; J 1.41/2.7%; K 0.51/8.7%; L 0.45/11%; M 0.45/4.0%

The total NOx emissions remain unchanged in the DOC. Active Pt-based DOCs increase the proportion of NO_2 in the total NOx 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 can enhance the performance of the DOC. DOC + additive emission control strategies have been verified that can provide PM emission reductions in the range of 25-50%. In the absence of a particulate filter, the additive is emitted as metal ash particulate of potential negative health impacts, which is a drawback of this strategy.

Applicability, Feasibility, Installation, and Maintenance of DOCs

The DOC is a mature technology with 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. The verified DOC systems should be conforming to the respective durability requirements (for non-road engines in California, the requirements are 1000 hrs durability demonstration and 5 years/4,200 hrs manufacturer warranty).

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 (see below) and as such, 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 any cleaning. Because of this open flow design characteristic of DOCs, plugging with soot or ash from the engine's lubricating oil is virtually nonexistent, truly a"set it and forget" type of retrofit device. If properly selected and operated on properly maintained engines, DOCs are maintenance free and incur no fuel economy penalty.

Because of their low cost (see Section 3) 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 marquee construction projects including Boston's Central Artery/Tunnel project (a.k.a. the "Big Dig", the most expansive urban construction project ever)[12] and Connecticut's "New Haven Harbor Crossing Improvement Program" (a.k.a. the "Q-Bridge Project", a 7.2-mile highway and bridge construction project started in 2002 and expected to take more than twelve years to complete).[13]

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 technology is the specificity of PM performance to the engine model and duty cycle, and often low PM emission reduction performance. As discussed, DOCs are not effective in controlling the solid fraction of diesel PM and black diesel smoke.

4.1.2 Diesel Particulate Filters

Diesel particulate filters (DPF) are devices that physically trap diesel particulates, thus preventing their release into the atmosphere. The trapped particulates must be then removed from the filter—periodically or continuously—in a process called filter *regeneration*.

Among various types of filter substrates, the ceramic *wall-flow monoliths* have been used almost exclusively for retrofitting of heavy-duty engines in North America. Monolithic diesel filters consist of many small parallel channels, typically of square cross-section, running axially through the part. Diesel filter monoliths are obtained from the *flow-through monoliths* used in catalytic converters by plugging channels, as schematically shown in Figure 4-3. Adjacent channels are alternatively plugged at each end in order to force the diesel aerosol through the porous substrate walls which act as a mechanical filter.

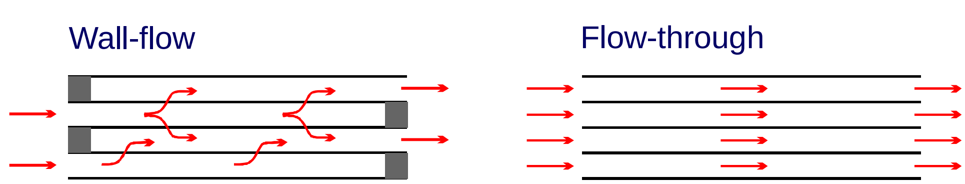

Figure 4-3. Flow Pattern in Wall-Flow and Flow-Through Substrates

Wall-flow monoliths are extrusions made from porous ceramic materials. Two materials most commonly used in commercial filters include *cordierite* and *silicon carbide (SiC)*. Cordierite is a synthetic ceramics developed for flow-through catalyst substrates and subsequently adapted for the filter application. Cordierite filters have been used mostly in heavy-duty engine applications. Silicon carbide filters, on the other hand, have been widely used in filters for diesel passenger cars in Europe. Silicon carbide is characterized by better temperature resistance (~1800°C) than cordierite (~1200°C). Its drawback is higher thermal expansion coefficient and higher cost.

Soot accumulated in the filter must be removed to prevent excessive pressure drop and filter plugging. *Thermal regeneration* is typically used, where the soot is oxidized to carbon dioxide. Two types of oxidation mechanisms are possible:

i. Soot oxidation by oxygen, which requires temperatures of 600°C and above, and

ii. soot oxidation by nitrogen dioxide (NO_2), which is possible at temperatures of less than 300°C.

Active oxidation catalysts, based on platinum, are typically used to lower the soot oxidation temperature and/or to shorten the duration of regeneration. Their catalytic effect is usually explained by the generation of NO_2, but other mechanisms are also possible. Regeneration in many real life DPF systems probably relies on a combination of oxidation by oxygen and NO_2.

Because of the principle of regeneration, particulate filter systems are divided into two categories:

- *Passive filters*—which rely on the heat carried by the exhaust gas for regeneration
- *Active filters*—where heat from external sources is supplied to the filter to trigger regeneration.

It should be emphasized that filter regeneration presents the single biggest challenge in the DPF application. Filters which do not regenerate may require manual cleaning, thus drastically increasing maintenance costs. Poorly regenerating filters which become overloaded with soot are also prone to *uncontrolled regeneration*, where the soot burns rapidly releasing large amount of heat, which can lead to filter failure through melting of the substrate.

4.1.2.1 Passive Diesel Particulate Filters

Overview

The exhaust gas temperature in the diesel engine is not sufficient to sustain soot oxidation by oxygen. In passive systems, 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 through the NO_2, oxygen or a combination of both mechanisms. Three major approaches have been 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 (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 filters 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. Therefore, it can be reasonably anticipated that passive filters installed on Tier 1/2 or older non-road engines will require higher exhaust temperatures than filters on 1994 and later urban bus engines.

Temperature requirements for the regeneration of various passive filter configurations, as determined from North American underground mining experience, are listed in Table 4-1[14]. These results are based on tests with heavy-duty engines used in US mines in the late 1990's.

Table 4-1. 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 which must be exceeded over at least 30% of the engine duty cycle	

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

Catalyzed Diesel Particulate Filter (CDPF)

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

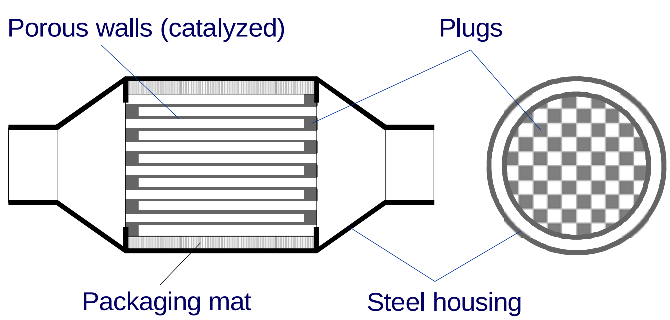

Figure 4-4. Catalyzed Diesel Particulate Filter

The PM control efficiency in the CDPF varies from 60-90% and above. Higher efficiencies—typically above 85%—are seen with ultra low sulfur fuels (15 ppm S). With increasing sulfur content in the fuel, the Pt catalyst produces increasingly more sulfate particulates, which offset the reduction in carbonaceous soot emission. CDPFs can also be used with fuels of very high sulfur content, such as 3000 ppm still common in non-road fuels, but base metal catalysts (e.g., iron-based) must be used to prevent excessive sulfate PM emissions. Base metal catalysts are less active than Pt, and require higher temperatures for regeneration. Most commercial suppliers have discontinued base metal formulations, and offer only platinum-based catalysts.

Pt-catalyzed filters can also provide significant reductions of CO and HC emissions, on the order of 60-90%. NOx emissions are generally not reduced in the CDPF (although Pt catalysts may exhibit some lean NOx activity at low exhaust temperatures of 200-250°C). Small NOx reductions, on the order of up to 5%, 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, which—due to the high toxicity of NO_2—is sometimes considered a counterproductive effect, especially when engines are operated indoors. The US Mine Safety and Health Administration (MSHA) has shown that ambient NO_2 exposure limits at the workplace can be exceeded in the vicinity of diesel vehicles retrofitted with Pt-based CDPFs[15]. In measurements with CDPF-equipped school buses in California, the NO_2 proportion was increased to about 30% of total NOx[16] (CSHVR test cycle).

Ultra low sulfur fuels are recommended, but not required for the use of CDPFs. Using higher sulfur fuels typically increases the regeneration temperature requirements. As discussed, high sulfur fuels also contribute to sulfate PM emissions causing a decrease of PM filtration efficiency.

CRT Filter

"CRT" is an abbreviation of the "Continuously Regenerating Technology" trade name 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, Figure 4-5. Since the filter monolith is not catalyzed, the CRT regeneration relies exclusively on the NO_2 mechanism.

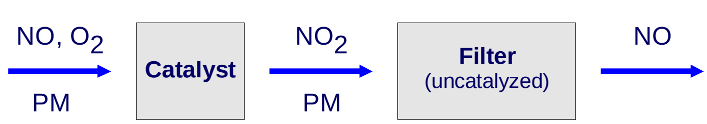

Figure 4-5. CRT Filter Schematic

In comparison to the CDPF configuration, the CRT filter can offer lower regeneration temperatures, especially in high-NOx emitting engines. However, due to the reliance on NO_2 for regeneration, two application limits 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 NOx/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 NOx/PM ratio.

The PM control efficiency of the CRT filter is generally similar to that of the CDPF, and amounts to some 60-90% (typically over 85% 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. In tests with urban buses in California, the proportion of NO_2 in the total NOx was increased up to 45%, depending on the test cycle[17].

The CRT filter is a mature technology, with thousands of installations—in highway and non-road applications—worldwide.

Installation and maintenance of the CRT filter are also similar to those in the CDPF (see below). It is important that CRT applications are carefully selected based on a recording of the exhaust gas temperature. If the exhaust gas temperature is insufficient, the filter will experience increased pressure drop levels, and may need to be manually cleaned. The requirement for a certain minimum NOx/PM ratio may additionally limit the application of the filter on high PM emitting engines. It is recommended that the filter is installed with a temperature and pressure monitor, which would alert the vehicle operator in case of increased pressure drop level.

As a standard maintenance, the CRT filter needs to be cleaned from ash at an interval on the order of 1 year. The CRT filter assembly replaces the vehicle muffler. To minimize the installation time, it can be designed as a direct fit muffler replacement.

Catalyzed CRT Filter (CCRT Filter)

A variation of the CRT filter is the "Catalyzed CRT", or CCRT filter. In this configuration, both the CRT catalyst and the filter substrate are coated with catalyst. Thus, the CCRT is a catalyzed filter with an NO_2 generating catalyst in the upstream position.

By combining both regeneration methods, the CCRT has a lower exhaust gas temperature requirement. Therefore, it can be used on vehicles that are too cold to sustain the regeneration of the CDPF and CRT filters. A drawback of this configuration is its higher cost. The installation and maintenance requirements are similar to those with the CRT/CDPF filters. The filter requires ultra low sulfur fuel.

Applicability, Feasibility, Installation, and Maintenance of PDPFs

For the on-highway sector, PDPFs (CDPF and CRT 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 (first retrofit CDPFs were introduced in the early 1990s in underground mine 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, PDPFs can be used only in selected applications which can guarantee sufficiently high exhaust gas temperatures.

Both on-highway and non-road vehicle candidates for PDPF application are typically evaluated by conducting a recording of the exhaust gas temperature during regular operation of the vehicle. The recording is performed by installing a thermocouple in the exhaust piping, at the planned location of the PDPF, 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 PDPF applicability is determined by the filter supplier based on an analysis of the temperature data.

It is recommended that the filter is supplied with an exhaust gas backpressure (EGBP) 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 EGBP monitor on the vehicle or piece of equipment is mandatory. Installation of the backpressure monitor involves simple wiring, and usually requires connecting to a vehicle's DC power source. Pressure monitors in electronic engines may be also wired to the engine control unit.

If the PDPF 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 PDPF. The cleaning interval can be assumed on the order of one year, but the accumulation of ash depends on the type of engine, lube oil, and duty cycle (with low temperature usage, such as urban driving, resulting in faster ash accumulation). Ash cleaning intervals reported in the literature for onroad trucks and buses vary from some 20,000 to more than 150,000 miles.

If the exhaust temperatures are too low to support the regeneration, the filter becomes gradually filled with soot/aged black carbon deposits. In such case, the unit has to be removed from the vehicle and manually cleaned using such methods as oven treatment and/or compressed air/water washing. Depending on the frequency of cleaning, this may present a major maintenance effort. In the absence of passive regeneration, the soot holding capacity of the CDPF is usually sufficient for only up to a few days of operation, before the pressure drop becomes unacceptably high. Operation at increased backpressure levels will also involve increased fuel economy penalty.

For on-highway applications the PDPF unit typically replaces the vehicle's muffler. It can be supplied as a standard design (in which case a certain modification to the vehicle's exhaust system is necessary) or as a direct fit muffler replacement.

While much of what has been stated above for the on-highway market also applies to non-road construction applications, there are nevertheless a number of significant factors that make PDPF selection a considerable challenge. PDPFs are significantly heavier than OEM mufflers, requiring additional brackets that can be complex and very time-consuming to design and fabricate. Additionally, PDPFs, because of their tight cellular substrate structure, 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 typically considerably larger than the OEM muffler it replaces. As such, installation of the PDPF in the space formerly occupied by the OEM muffler is often impossible, requiring considerable engineering effort to locate the DPF. A number of key considerations in relocating the DPF include ensuring that:

- 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 the EGBP monitor does not interfere with operation of the machine; careful routing of these components is critical.

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, requires considerable engineering and attention to ensure proper performance and minimum intrusion upon the uninterrupted operation of the piece of equipment. The installation exercise is frequently time and labor-intensive, a challenging proposition for the construction industry which survives on minimum operations downtime.

Filters with Metal Based Fuel Additives

A number of metal-based additives have been investigated as soot oxidation catalysts that would facilitate regeneration in passive diesel filter systems. Fuel additives used for that purpose are also called *fuel borne catalysts* (FBC). As the additive is combusted in the engine cylinder, its metal component leaves the combustion chamber in the form of the corresponding metal oxide or other inorganic compound (e.g. sulfate). These compounds can form particles of their own or can be incorporated into diesel particulates. After being collected in the particulate filter, the catalytic metal is distributed throughout the diesel particulate phase and can effectively catalyze the oxidation of carbon particles.

The most common additives used for the regeneration of diesel particulate filters utilize compounds of iron (Fe), cerium (Ce) and platinum (Pt). The filter element is usually not catalyzed, or catalyzed with a small loading of Pt (e.g., 5 g/ft^3) . In the latter case, the catalyst coating allows to lower the additive levels needed to ensure regeneration.

Compared to CDPFs, additive-regenerated filters can regenerate at lower exhaust temperatures. However, there are a number of potential issues with the use these types of additives:

- *Ash deposits on the filter*. Most of the additive is trapped on the filter in the form of an inorganic oxide and/or salt. With time, it accumulates to considerable quantities. The ash deposits contribute to increased pressure drop and require more frequent maintenance (filter cleaning) than in DPF systems without additives.
- *The necessity of introducing the catalyst to fuel*. In most fuel distribution systems doping the fuel with additive is not practical. Since only some vehicles within a given fleet would use the doped fuel, two parallel fueling systems would be needed: one for the additized fuel and one for regular diesel. The ideal solution would be automated on-board dosing devices, such as those used in OEM DPF systems on passenger cars. However, reliable dosing devices are not yet available for retrofit filters. In practice, in heavy-duty engine retrofits, the additive is often manually added to the vehicle fuel tank every time the vehicle is fuelled. This presents an added maintenance and creates room for human error (if the additive is not added, the filter will not regenerate and may require removing from vehicle and manual cleaning).
- *Impact on the engine or its components*. Additives may change fuel properties (e.g., viscosity) thus affecting the fuel injection equipment. Some additives are known to cause fuel injector fouling. Prior to using additives, it is recommended that the additive manufacturer provide comprehensive *do not harm* test results performed by reputable third party labs that indicate that the additive does not damage seals, hoses, interfere with fuel injection equipment or cause engine wear problems.
- *Fuel stability*. Blending the additive with fuel may result in deposit formation, an increase in sedimentation from the fuel itself, and/or increased deposit formation when water is added to the doped fuel.

Additive-regenerated filters (FBC-DPF) use similar substrates (cordierite or SiC) as the CDPF/CRT filters, and offer similar PM emission reduction efficiency, generally of 60-90%, but in most cases better than 85%.

In comparison to the CDPF/CRT, FBC-DPFs produce less or no NO_2 emissions. They also are less active in producing sulfate particulates and, thus, can tolerate high sulfur fuels.

Additive-regenerated filters have been used in new passenger cars by Peugeot in France. Since the time of their introduction in 2000, more than 500,000 units have been sold. The Peugeot system does include engine management based active regeneration support, where the filter inlet temperature is raised to 450°C to trigger regeneration. In this strategy, the additive levels can be kept lower than those required in fully passive retrofit systems. More recent OEM systems for diesel cars in Europe are switching to the CDPF technology and moving away from the use of additives in order to avoid the need for an on-board additive dosing system, as well as to minimize ash accumulation and the related maintenance.

Installation, maintenance, and operational issues are generally similar to those of CDPF/CRT 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 or problems.

The filter pressure drop (which has an impact on fuel economy) is frequently higher with additives due to the accumulation of ash from the additive. Therefore, more frequent maintenance (filter cleaning) may be necessary compared to CDPF/CRT filters. These impacts from additive ash are directly related to the additive dosing level, which can vary in a wide range—such as from some 10 to 100 ppm of the metallic compound in the fuel—depending on the vehicle duty cycle (exhaust temperature) and the engine-out PM emission level. Older technology engines used in construction equipment can be anticipated to require relatively high additive dosing levels.

4.1.2.2 Active Diesel Particulate Filters (ADPF).

Overview

The application of passive DPF technologies is limited by the exhaust gas temperature. In many diesel engine applications, 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 4-6. 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 filters with catalytic combustion of fuel will be widely used on new US 2007 highway truck and bus engines. Retrofit systems have also been under development, but the focus remains on highway engine applications. Donaldson had been working on commercializing a retrofit system, but a non-road version is not yet available. Another DPF system with catalytic combustion of fuel is being developed by the California-based Extengine Company, who expects their ADPF system (called MaxTRAP™) to receive ARB verification by the end of 2006.[18] A prototype of the MaxTRAP system could be made available for the NYSERDA demonstration program.

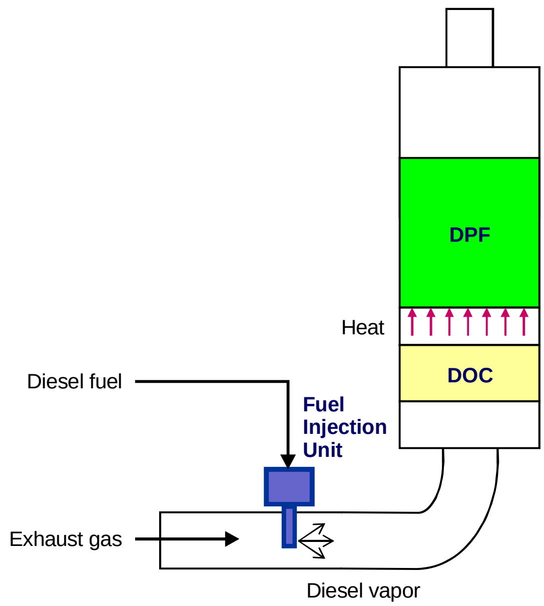

Figure 4-6. Filter with Catalytic Combustion of Fuel

Active DPF systems for non-road engines that are commercially available today could 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 actively 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 utilize cordierite or silicon carbide wall-flow monoliths. In general, their PM filtration efficiency is in the range of 60-90%. The emission performance of active systems that include catalysts (such as that in Figure 6) 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 SOF. 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.

Filters with Electric Regeneration

DPF systems with electric regeneration available for non-road diesel engines utilize shore power as the source of energy for regeneration. The usage 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 4-7). 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.

Figure 4-7. Shore Power Regenerated Filter on Construction Machinery (Switzerland)

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 1 hour, depending on the filter system.

Off-board regenerated systems include two components: (1) the filter unit, which is installed on 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) which may differ in configuration. 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 allows to keep their cost low. If the control of diesel odor, HC and CO emissions is essential, the filter elements can be coated with a catalyst.

Electrically regenerated filters must be regenerated on time. If the vehicle operator allows the filter to become overloaded with soot, the unit may become damaged during regeneration. To avoid such problems, many filter users adopt a maintenance practice where filters are regenerated at the end of each 8 hour work shift, regardless of the soot load.

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. According to that difference, filter systems utilizing 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. Commercial products are not available for non-road engines in the USA.

The regeneration of fuel burner filters is associated with a certain fuel economy penalty. This penalty varies depending on the filter system, vehicle, and its duty cycle. The full flow system by Deutz induced a fuel penalty of 1-2% due to the burner regeneration.

In *single point burner systems*, the machine has to be parked for the period of regeneration. In the first commercial systems (Eberspächer, HUG) the engine had to be operated at idle during regeneration. Through this approach, the regeneration control became simpler and the fuel demand for regeneration lower, at the expense of added maintenance (the regeneration had to be initiated by the operator) and machine down time. Single point systems currently offered in Europe (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 to further minimize the quantity fuel used for regeneration.

Applicability, Feasibility, Installation, and Maintenance of ADPFs

Installation challenges for ADPFs are no less challenging than with PDPFs, as noted above. 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 also 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.

Considerable amount of experience in retrofitting diesel construction equipment has been accumulated in Switzerland. Over the period of 2000-2005, mandatory DPF retrofit requirements have been phased-in for most diesel engines (>18 kW) operated in tunneling projects and in large construction sites, resulting in the installation of several thousand of DPF systems.

While no comprehensive analysis of the DPF technologies is available, the following types of filters are typically used on machinery by Liebherr, a major Swiss supplier of construction equipment. The filters are installed either in the factory or by Liebherr dealers.

iv. Catalyzed DPF—Passively regenerated filters (DPX by Engelhard) are used on engines operated under heavy-load that produce high exhaust temperatures. The filter regeneration is greatly enhanced by using ultra low sulfur diesel.

v. Pre-catalyst + CDPF—This passive configuration (DPX2, similar to the CCRT filter discussed earlier) is used on colder engines, where the CDPF would experience regeneration problems.

vi. Active filters with shore power electric regeneration (HUSS)—Two types of electrically regenerated filters are used: (1) filters which are removed from the machine and regenerated on an off-board regeneration device and (2) filters which incorporate an electric heater and remain onboard during regeneration, but must be connected to a shore power source. The former category is usually used on smaller engines, the latter on larger size equipment.

vii. Active filters with fuel burner regeneration—This type of DPF system is used on cold engines at locations with no access to shore power. A HUSS DPF system is used which incorporates its own source of air, allowing for regeneration with the engine shut down. This feature results in relatively low fuel consumption for regeneration. Compared to the electric filters, the fuel burner DPF is more bulky and complex, more expensive, and less reliable.

An example of equipment operating mostly under heavy load, allowing for passive regeneration of DPX1 filters, is a bulldozer. However, care must be taken to avoid extended idling periods. Once the DPF is allowed to become overloaded with soot, it takes a long time (days or weeks) of regular operation until the increased backpressure returns to normal levels.

Hydraulic excavators are fitted with different types of filters, depending on their duty cycle. While engaged in digging work, they produce exhaust temperatures sufficient for passive filter regeneration. When used in lighter work, e.g., lying pipes, they require active filters. The most critical of Liebherr machines are mobile cranes—with duty cycles including up to 75% of idling time—nearly all of which require active filters.

Similar types of filter technologies—including passive CRT filters and electric filters from other suppliers—are believed to be used on other brands of construction machinery. A database of Swiss DPF retrofits maintained by AKPF, a trade organization of DPF suppliers, is available on the web at http://akpf.org/db/.

As NO_2 emissions from catalytic filters are becoming an increasing concern and subject to various local regulations, fuel additive regenerated filters (which do not increase NO_2) will likely become more widely used for retrofitting construction equipment.

4.1.3 Flow-through Particulate Filters

Overview

“Flow-through filters” (FTF) are relatively new PM emission control devices which have a particulate control efficiency higher than that of the DOC, 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-trough filter” refers to a device which 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. Contrary to the DPF, the device will not plug once filled with soot to its maximum capacity in the absence of regeneration. Rather, the PM conversion efficiency will drop to zero, allowing all PM emission to pass through the structure.

Examples of traditional FTF substrates are wiremesh or ceramic foams. It should be noted that with this type of substrates, the distinction between an FTF device and a deep-bed DPF is not always well defined. A ceramic foam of small pores may perform as a deep-bed DPF, exhibit 90%+ filtration efficiency, and plug with soot if not regenerated. Another foam structure of large pores, on the other hand, may perform as an FTF, where gas passages still exist once the maximum thickness of the soot layer is formed.

The alumina-coated steel wool filter developed by Texaco in the early 1980’s can be considered an early FTF example. The PM mass collection efficiency in the Texaco filter ranged between 50-70%[19]. The collection efficiency initially increased as the particle mass was accumulated, reached a peak, and then decreased. The decrease in efficiency was explained by re-entrainment of agglomerates of collected particles; particle size measurements indicated that the coarse particle mass fraction leaving the filter increased markedly with time.

The developers in the 1980’s and 90’s were seeking DPF materials of high, 90%+ efficiency, not an FTF type of device. Since most filters utilizing ceramic foams, metal fleece, wiremesh and similar materials showed low filtration efficiency and/or had other problems, they were eventually replaced with the wall-flow monolith design. Recently, a renewed interest can be seen in FTF substrates due to certain Euro IV new engine applications which require only modest reductions in PM emissions. First commercial FTF filters were launched 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—verification category in California. At this time two retrofit FTF devices are verified in California: one utilizing a specialized honeycomb substrate, and one using catalyzed wiremesh.

A schematic of an advanced FTF substrate, named the “PM Filter Catalyst”, which has been developed and commercialized by Emitec is shown in Figure 4-8.

Figure 4-8. "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 else catalyst can be applied directly onto the FTF substrate. Due to the use of catalyst, the FTF also produces reductions in HC and CO emissions.

The Emitec substrate has been used on selected models of Euro IV truck engines manufactured by Germany's MAN. The FTF produces about 50% PM emission reduction over the European ESC test cycle. The device has been also introduced on selected models of passenger cars in Germany.

FTF substrates utilizing the above principle are used in the "diesel multi-stage filter" (DMF) device by Donaldson Company, which has been verified by the California ARB as a Level 2 device. The DMF system is a two stage passive FTF incorporated in a muffler unit. The device has been verified in two configurations: with and without the Donaldson Spiracle closed crankcase filtration system. According to Donaldson, the DMF system produced 70-77% PM emission reduction in the verification testing (FTP).

A catalyzed wiremesh filter (CWMF) FTF device has been developed by ESW. The device has been verified as a Level 2 system of 50% PM reduction in California.

A similar wiremesh filter utilizing fuel additive for regeneration, supplied by Clean Diesel Technologies, has been verified by the EPA/ETV at 55-76% PM emission reduction.

Performance and Emission Reduction

FTF filters are potentially an attractive PM emission reduction technology, which can offer relatively high PM reduction efficiency while avoiding numerous problems related to DPF regeneration. However, it must be emphasized that FTF performance has not been fully characterized, and very few reports exist in the published technical literature. If FTF filters are evaluated during the field demonstration, special care should be taken to quantify their performance under real life operation.

A PM emission reduction up to 50-70% is believed to be possible in an FTF. However, the PM emission performance of FTF filters 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). If exhaust temperatures are too low, the PM emission control efficiency will deteriorate. While this dependence on temperature is in general similar to that in a DOC, the light-off temperatures for PM conversion in FTF devices remain unknown.
- 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 drop to zero. It is believed that regulatory emission tests with FTF systems (such as the California verification and European type approval testing) have been performed with clean devices of the highest possible PM activity. In real life service, the FTF can operate partly loaded with soot for extended periods of time, resulting in lower PM reduction efficiency. The real PM reduction efficiency of the FTF in the field should be preferably assessed through continuous emission monitoring using an on-board PEMS capable of PM measurement. A single PM test would not be reliable, as the FTF performance depends on the soot load which in turn depends on the vehicle's history of operation prior to the emission test.

Opponents of the FTF technology—notably the European Commission, who has been supporting "closed" DPFs, as opposed to the "open" FTF devices—suggested that FTF filters are ineffective in controlling particulate number emissions, but this opinion is also based on limited amount of experience and test data with FTF systems.

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. However, there is still a certain degree of complexity in their installation and maintenance. Periodic ash cleaning may be still required, and installation of the exhaust gas backpressure monitor is a requirement for the two ARB and EPA verified systems (Donaldson and ESW). 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.

4.1.4 NOx Reduction Catalysts

4.1.4.1 Ammonia/Urea SCR

Overview

Selective catalytic reduction (SCR) of NOx 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 1970's, followed by widespread application in Europe since the mid-1980's. In the USA, SCR systems were introduced for gas turbines in the 1990's, with increasing potential for NOx control from coal-fired powerplants.

While the application of SCR for mobile diesel engines requires overcoming several problems, SCR remains the only proven catalyst technology capable of reducing diesel NOx 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 NOx limits. First commercial diesel truck applications were launched in 2004 by Nissan Diesel in Japan and by DaimlerChrysler in Europe. In the USA, SCR systems are being developed for meeting the 2010 NOx limit of 0.2 g/bhp-hr for heavy-duty highway engines, as well as the Tier 2 NOx 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 timely replenished by vehicle operators. Talks continue between US engine manufacturers and the EPA regarding these issues.

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 an SCR system for mobile diesel engines is shown in Figure 4-9. The urea solution (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—a static mixer is often provided to ensure good mixing. 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 functionality is incorporated into the SCR catalyst itself. With some types of SCR catalysts, the catalyst performance is increased at 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. The function of that catalyst is to control any NH_3 that was not consumed in the SCR catalyst (so called *ammonia slip*).

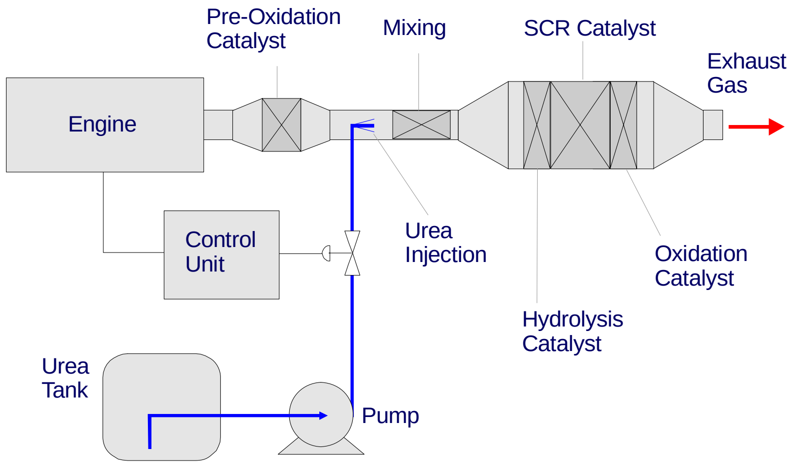

Figure 4-9. Generic Schematic of Urea-SCR System (Open Loop Control)

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 NOx concentration in the exhaust gas. If too much urea is injected, ammonia slip will occur. If too little, the NOx conversion rate will deteriorate. Future SCR systems will likely utilize closed loop control schemes, where the urea injection rate will be controlled based on a feedback from an exhaust NOx sensor. However, due to their slow response time (around 0.75 s), NOx sensors available today are not yet suitable for closed loop SCR control under transient operation/testing of the diesel engine. All commercial SCR systems deployed so far on new diesel truck engines are 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 (however, sensor-based control is used in some retrofit SCR systems).

SCR systems for retrofitting mobile diesel engines are at an early stage of commercialization. Systems which 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. However, the only SCR system currently verified by the California ARB (80% NOx reduction over a steady-state test, Level 1 PM, supplier: Extengine) uses ammonia reductant. Steel cylinders with anhydrous ammonia are replaced by the system supplier.

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

viii. Engine map-based control—This strategy (similar to that used in OEM systems) requires that engine NOx emission map is 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 NOx 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.

ix. NOx sensor-based control—Some retrofit SCR systems are controlled using a feed-forward strategy, based on signals from a NOx sensor positioned upstream of the SCR system (a downstream position is not possible due to high cross-sensitivity of available NOx 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. However, due to the slow response time of commercial NOx sensors, transient NOx performance may be compromised.

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 NOx 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 NOx 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 regenerated through catalytic combustion of fuel has been under development (supplier: Extengine). Such system would allow the application of the SCR+DPF technology—which could provide 80+% NOx and PM reductions—on more non-road engine models, albeit with considerable cost and complexity.

Performance and Emission Reductions

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

- Transient character of the test—NOx 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 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.

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). Particulate filters can be used with SCR systems to provide simultaneous control of NOx and PM emissions. In heavy-duty engines, the DPF is usually placed upstream of the SCR system.

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 is 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. Emissions of *vanadium*—originating from catalyst losses in vanadia-based SCR systems—were detected during field tests of trucks fitted with prototype SCR systems in Japan.

Applicability, Feasibility, Installation, and Maintenance of SCRs

Installation of an SCR system on non-road vehicles can be a daunting proposition, often exacerbated by the greater complexity of the non-road machine and the harsh non-road construction operating environment. For starters, 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, 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 (see above). Furthermore, as shown in Figure 9, the SCR system is quite complex, requiring careful placement on a space-constrained non-road machine of a great number of components. Finally, SCR systems are very prone to urea leakage, especially around fittings in the dosing system that can be quite taxing to resolve.

In addition to installation challenges, there exist a multitude of operations, maintenance and durably 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 (approximately 0.9% of 32.5% urea solution is consumed per 1 g/bhp-hr of NO_x reduced over the FTP transient test).
- *Emission compliance*: The retrofitted engine/vehicle can be operated without replenishing urea (or with water used in place of urea solution) but no NOx reduction will be realized. Since urea presents an added cost component, vehicle operators have a financial incentive not to replenish it.

- *Stability of urea solution:* 32.5% urea solutions crystallize at –11°C (12°F). Freezing problems may occur in 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 NOx 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:* Low or no NOx conversion occurs at low temperatures. For example, the SCR system supplied by HUG requires minimum exhaust temperatures of above 300°C (570°F) for efficient NOx reduction.
- *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 be adopted for US 2010 highway trucks.

These issues need to be carefully considered as part of the process of considering SCR for NOx-reduction for 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. However, 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 NOx reduction capabilities; however deployment for non-road application is not without challenges.

There is no fuel economy penalty or a small fuel economy penalty up to 1% associated with operating the SCR catalyst. SCR catalysts are durable; in stationary applications catalyst suppliers typically guarantee the catalyst performance for a period of 16,000 to 24,000 hours. The experience with urea injection and control systems for retrofitting diesel engines is very limited, the durability and reliability of these components remains unknown.

4.1.4.2 HC-SCR (Lean NOx Catalyst)

Overview

NOx can be also reduced through selective catalytic reduction using hydrocarbons as the reductant. This type of process/device is usually referred to as the *HC-SCR*, the *lean-NOx catalyst* (LNC), or the *DeNOx catalyst*.

The most obvious reductants in the diesel engine application are (1) the HC emissions naturally present in the exhaust gas and/or (2) diesel fuel injected into the exhaust gas. The former configuration, known as the *passive DeNOx*, is simple and attractive, but its potential for NOx reduction is limited by the low HC/NOx ratio in the native diesel exhaust. Higher NOx conversions are possible if additional HCs are introduced to the system—in the *active DeNOx* configuration—by injecting diesel fuel into the exhaust upstream of the catalyst.

The lean NOx catalyst technology should not be confused with NOx adsorber-catalysts (NAC), which are not available as commercial retrofit systems.

Performance, Applicability, Feasibility, and Installation of HC-SCRs

HC-SCR systems have never been widely commercialized due to a number of unresolved issues:

- In passive systems, the maximum possible NOx conversion is usually limited to about 10-15%.
- Even with active exhaust HC enrichment, the maximum NOx conversion is limited to about 30-50% and may not be cost-effective given their high cost and complexity.
- Temperature window of known catalysts is narrow and not always corresponds to the exhaust gas temperature range at which most NOx is emitted from the diesel engine (thus, the catalyst performance is strongly test cycle dependent).
- Durability of various HC-SCR catalysts still needed improvement.

In active HC-SCR systems, a significant fuel economy penalty is incurred due to the continuous injection of fuel into the exhaust. The exact FE penalty depends on the targeted NOx conversion. In the lean NOx system verified in California ("Longview" combined DPF + lean NOx cat system), a 25% NOx reduction was achieved at the expense of 3-7% fuel economy penalty.

The "Longview" system includes three modules—two lean NO_x catalyst substrates followed by a catalyzed silicon carbide diesel particulate filter—connected by quick release clamps. Fuel injection and other functions of the system are controlled by an electronic control unit called the "monitor-logger-controller" (MLC), based on the measured exhaust gas temperature, system pressure drop, and signals from engine sensors.

4.2 FUELS, LUBE OILS, AND ADDITIVES

4.2.1 Diesel Fuel

Certain fuel properties have an impact on emissions. For instance, the California diesel fuel, known as the CARB diesel (48 cetane and 10% aromatics specification), produces lower NOx than the No. 2 diesel. However, the proliferation of “boutique” fuels with different specifications that may be required by states or by environmental authorities creates problems in the nationwide fuel distribution system. After the fuel supply disruptions caused by hurricanes Katrina and Rita, the Congress has adopted the “Gasoline for America’s Security Act of 2005” which limits the number of allowed diesel fuels to two: a national diesel fuel, and one “alternative diesel fuel blend” (presumably the CARB diesel and the virtually identical Texas low emission diesel, Tx-LED).

The more important aspect of fuel quality is *sulfur content*. Ultra low sulfur diesel (ULSD) of 15 ppm sulfur cap will be introduced in 2006 for highway vehicles (June 1^{st} at refinery level, October 15^{th} at the retail level), but not until 2010 for non-road applications. Many advanced emission control technologies envisioned for the field demonstration either require the use of ULSD or show improved performance when used with ULSD. Engines retrofitted with such technologies will have to be operated using ULSD fuels.

Due to the increasing availability of ULSD in the highway sector, no supply problems are anticipated. However, the use of ULSD will present an extra operational cost component for the affected non-road fleets.

4.2.2 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 No. 2 petrodiesel. The quality of the biodiesel blending stock is described by the ASTM standard D 6751. At this time, there are no standards for B20 and other biodiesel blends, nor for neat biodiesel (B100) used as automotive fuel.

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 a guidance for States in claiming emission credits for the use of biodiesel and its blends[20]. According to the EPA study—which is based on the FTP test using commercial heavy-duty on-road engines—the average biodiesel emission effects are –47% for PM and +10% for NOx. For the B20 blend the respective numbers would be about –12% and +2%.

The EPA analysis was limited to pre-1998 engines. Biodiesel emission effects seem to be larger (e.g., higher PM emission reduction and higher NOx increase) in newer engines. Biodiesel emission impacts in non-road engines are even more uncertain than those in highway engines. Non-road engine emissions were predicted poorly by the EPA correlations, but the data set was too limited to allow for statistically valid generalizations.

The increase in NOx emissions with biodiesel can be controlled using fuel additives, such as cetane improvers, but the effectiveness of control is engine specific.

The biggest 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 biodiesel aging 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 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. Guidelines for engine users on the use of biodiesel can be found in the literature[21].

4.2.3 Water-Diesel Emulsions

The addition of water to the diesel combustion chamber has been a known method to reduce NOx emissions. Emulsifying water with diesel fuel is a possible method of water addition. Contrary to the other methods (such as direct water injection or fumigation with intake air), water-diesel emulsions can also reduce diesel PM emissions.

PuriNOx water-fuel emulsion commercialized by Lubrizol includes 20% water blended with 77% diesel fuel and 3% additive package (additive 1121A). To enable the use of water blends at low ambient temperatures, winter PuriNOx fuel incorporates methanol. A winter formulation was developed consisting of 16.8% water and 5.7% methanol, blended with 74% diesel fuel and 3.5% winter additive package[22]. PuriNOx blends have opaque, white appearance, resembling milk. Water droplet size in PuriNOx is below 1 µm. The emulsion can be stored in a tank without agitation for up to three months without water separation.

Water-diesel emulsions can provide PM emission reductions of 15-60% and NOx reductions of 10-20%. The emission performance is highly engine specific. The EPA, after reviewing performance data on the PuriNOx emulsion, found that both NOx and PM emissions were reduced by about 20% in non-road engines [23]. A drawback of emulsions is an increase in HC and, in some engines, also CO emissions. These increased HC/CO emissions can be controlled by a diesel oxidation catalyst.

Emulsions can be a potentially attractive approach for some fleets, but two major issues exist:

- Power loss: If emulsions are used in unmodified engines, the fuel injection system is not capable of delivering the increased volume of the diesel+water fluid (i.e., some fuel becomes effectively displaced by water). Due to the lower diesel fuel delivery rate, a power loss is observed, typically of about 15% with the PuriNOx emulsion.
- Logistics: Emulsified fuel must be available from a local supplier. Larger, centrally fueled fleets may be able to lease a portable emulsifying unit from Lubrizol and emulsify fuel on-site.

4.2.4 E-Diesel

The term "E-Diesel" refers to blends of ethanol with diesel fuel. Typically, standard No. 2 diesel fuel is blended with up to 15% (by volume) of ethanol using an additive package that helps maintain blend stability and certain properties, including cetane number and lubricity. The additive package may comprise from 0.2% to 5.0% of the blend. There is currently no specification for E-Diesel, and the fuel must be considered experimental.

E-Diesel can produce certain reductions in regulated emissions. Particulate matter emission reductions in excess of 30% have been reported. E-diesel can also provide reductions in CO and HC emissions, but has little or no effect on NOx.

One of the important issues with E-Diesel is its low flash point—around 10°C, as compared to 52°C in No. 2 diesel—which presents a safety issue. Diesel fuel is a Class II flammable liquid, while E-Diesel blends are Class I flammable liquids, like gasoline. The usage of flame arrestors on fuel tanks has been suggested when handling E-Diesel fuel[24].

4.2.5 Fuel Additives

Overview

Fuel additives can be used to reduce engine emissions and/or improve the fuel economy. Another common use of additives is to facilitate the regeneration of diesel particulate filters. Additized fuels may also enhance the performance of other emission controls, e.g., oxidation catalysts, as discussed in previous sections.

Considering their chemical composition, the EPA distinguishes between two types of additives:

- Typical additives
- Atypical additives

Atypical element means any chemical element found in a fuel or additive product which is not allowed in the baseline category of the associated fuel family, and an "atypical fuel or fuel additive" is a product which contains such an atypical element. In case of the diesel fuel, the baseline formulation is composed of (and must not include other elements than) carbon, hydrogen, oxygen, nitrogen, and/or sulfur[25].

In the combustion process, typical additives are not likely to produce emissions other than those with the baseline fuel itself. Atypical additives, on the other hand, may produce new kinds of emissions, not seen with the baseline fuel alone. These may include metal and/or metal oxide emissions from metal-based additives or non-metallic compounds from additives containing atypical non-metallic elements (e.g., phosphorus).

Additives for use in highway fuels must be registered in the EPA additive registration program. Atypical additives face much more rigorous testing requirements in the registration process, due to the possible health effects of their emissions.

Additives for non-road use do not require EPA registration, unless required by other pertinent regulations (for instance, US mining authorities do require that diesel fuels for underground mine use be EPA registered).

At the refinery and the fuel terminal levels additives play an increasingly important role in modern diesel fuels. They are being used to affect diesel fuel properties, such as increasing cetane number, stabilizing fuel for longer storage, and, now with reduced sulfur levels of on-highway fuel, maintaining lubricity. Since the oil crises in the 1970's and with the added focus on emissions, many companies have marketed aftermarket additives with fuel economy or emissions reduction claims. While some of these claims have been true, many additives have had other negative effects, not been registered, or reduced some emissions at the expense of increasing other emissions. Fuel additive technologies should be scrutinized and their third party test data analyzed to determine the viability of the claims. At a minimum the fuel additive technologies must have creditable third party test results done in accordance with applicable EPA and/or SAE protocols to be taken into consideration. In addition, the additive technology manufactures must be willing to provide complete copies of test reports to ensure that the results clamed are the same results indicated in the reports.

Metallic Additives

Metal based fuel additives were first studied as smoke suppressants and cetane improvers. Several metals, including Ba, Ca, Fe, Ce, and Mn, have been found effective in lowering the amount of soot formed during combustion in both diesel and SI engines. This effect was explained by a combination of mechanisms, including catalytic effects by the metal component. Metallic additives could also reduce PM mass and other emissions, and improve fuel economy.

The emission benefit from additives is very engine and fuel specific. In old technology diesel engines, using metallic fuel additives (e.g., 10 to 100 ppm of Fe, Ce) could reduce engine-out PM emissions by as much as 30-40% and improve fuel economy by as much as 10%. However, in advanced diesel engines (e.g., US 2004 on-highway engines) the emission reduction and fuel economy improvement from additive use tends to be very small.

Currently, the main interest in metal based fuel additives is related to diesel particulate filters, as opposed to reducing engine-out emissions. There are two major reasons for this shift of focus: (1) diminishing emission effect from additives in modern diesel engines, and (2) health concerns related to metallic particulate emissions.

Health experts and clean air authorities worldwide have been concerned with emissions resulting from the use of metallic fuel additives. If additives are used in conjunction with a particulate filter, typically over 99% of the additive metal is retained in the DPF. On the other hand, when additives are used without aftertreatment (or with an "open" device such as a DOC) high particle number emissions are likely to occur. These metal-containing nanoparticle emissions have been suspected to cause various adverse health effects. Some regulatory agencies (e.g., German UBA) as well as some additive suppliers (Rhodia) adopted a policy that metallic additives should be used only in conjunction with particulate filters. The recent concerns with additive use by the EPA may go even further; questions seem to be raised about the effectiveness of the DPF (this also includes such events as filter failures) in protecting public health from metallic particle emissions.

All metallic additives currently registered with the EPA are supplied by smaller size manufacturers who—based on a small business exemption—are not required to complete the comprehensive testing program that is normally required for atypical additives.

Another issue with metals that should be mentioned is *fuel stability*. The presence of such oxidation catalyst as copper or iron in the diesel fuel has been known to potentially cause serious fuel stability problems (in fact, a special class of fuel additives, known as metal deactivators, has been developed to protect diesel fuels from dissolved metals that can catalyze reactions involved in fuel instability).

Non-Metallic Additives

This category includes organic (typical) additives, as well as additives containing atypical inorganic elements. A fairly common additive is EHN which can be added at the refinery to increase cetane numbers to meet fuel specifications. Other products may reduce emissions and/or improve fuel economy through such mechanisms as improved lubrication properties and reduced friction losses. The activity of still other additives is explained by various impacts on fuel combustion reactions in the engine cylinder, but the exact mechanisms are often not understood. With the limited understanding of how these products work and their single digit emissions reductions, reputable third party testing is critical in determining which technologies provide real emission reductions.

Texas and California have low emissions diesel fuel (LED) requirements which require fuel producers to make diesel fuel with minimum cetane requirements and reduced aromatics. This fuel produces 5-7% less

NOx and additional minor reductions in PM (see the section on Texas LED and California LED programs below). As an alternative, fuel producers in these states can use an additive or other formulations of diesel fuel to meet these requirements, as long as the emissions profile of the alternative formulation is comparable to Tx-LED. Texas has approved three different formulations of diesel fuel that used additives to produce equivalent emission levels of Tx-LED.

4.2.6 Engine Lubricating Oils

While engine lube oils are contributors to some unregulated emissions—e.g., the SOF fraction of TPM, the ash fraction of TPM, or such catalyst poisons as phosphorus and zinc—there is no indication that better quality oils can produce a measurable improvement in regulated diesel emissions.

The significance of lube oil quality lies in their compatibility with advanced emission controls. The two major aspects are: (1) low ash production, to maximize the maintenance intervals of diesel particulate filters, and (2) low levels of catalyst poisons to maximize the lifespan of emission control catalysts. Advanced new lube oil formulations are being developed which are characterized by low content of Sulfated Ash, Phosphorous, and Sulfur (SAPS), as well as by lower volatility than current lubricants. These new oils, referred to as the *PC-10 lubricants*, will be introduced to the market in the 4^{th} quarter of 2006, and will be designed for the US 2007 compliant heavy-duty highway engines operated with ultra low sulfur fuels. The PC-10 lubricants are also being designed to be backward compatible, to allow their use in older technology engines.

It is recommended that engines retrofitted with particulate filters and/or other catalyst-based emission controls use low SAPS oil formulations, provided such lubricants are available and approved by the engine manufacturers. It can be anticipated that the added cost of higher quality lubricants will be off-set by the reduced DPF maintenance, and will provide longer life of the emission control catalysts.

4.3 ENGINE TECHNOLOGIES

4.3.1 Engine Power and Rebuild

Engine repower with cleaner engine technology may be an effective means of emission reduction. By replacing a Tier 0 engine with a Tier 3 unit, both NOx and PM emissions can be cut by more than 50%. Since the engines are emission certified, the emission reductions can be easily quantified.

Engine technology—mechanical vs. electronic—may present a limitation in re-powering equipment. It may not be possible to replace a mechanical engine by an electronic one; in such cases the repower is limited to the newest generation of mechanical engines, typically Tier 2. However, it may be more cost effective to replace a Tier 0 engine with a Tier 1 engine, because the engine block is often the same, making it straightforward to fit the newer engine into the machine. Even though the overall emission benefit is less, the cost for emission reduction on a dollar per ton basis is lower. Therefore, if funding is limited, higher emission reductions can be achieved by Tier 0 to Tier 1 repowers than by repowering Tier 0 with Tier 2/3 engines. In some cases, it can be even more cost-effective to replace the entire machine with a new one than it is to repower with a Tier 2/3 engine.

Engine manufacturers have been also developing engine rebuild kits which upgrade the engine to a cleaner emission standard. Such engine rebuild kits are usually emission certified, which allows quantifying the achieved emission reductions. This approach has been common in rebuilding locomotive engines, where the EPA regulations require that Tier 0 locomotive engines be upgraded during engine overhaul to meet Tier 1 standards. In mobile engines, Caterpillar offers an “upgrade kit” to reduce the emission of the Tier 0 3608 model engine to Tier 1 levels.

4.3.2 Exhaust Gas Recirculation

Overview

Exhaust gas recirculation (EGR) is a method by which a portion of engine’s exhaust gas is returned to its combustion chambers via the inlet system in order to reduce NOx emissions. The EGR method involves displacing some of the oxygen inducted into the engine as part of its fresh charge air with inert gases, thus reducing the rate of NOx formation. In most modern implementations, the EGR stream is cooled in an EGR cooler before being mixed with the intake air.

It has been shown that EGR is a very effective method for NOx reduction. In general, two principles are believed to be responsible for the NOx reduction effect of EGR, as follows:

- Dilution of the intake air with inert gases, leading to a decrease of oxygen concentration in the combustion process.
- Heat absorption by the EGR stream, primarily due to the heat absorbing capacity of CO_2 (thermal effect), as well as through the dissociation of CO_2 (chemical effect), leading to a reduction in combustion pressures and temperatures.

In diesel engines, EGR was first introduced in Euro 1-2 (1992-96) passenger cars, followed by US heavy-duty highway engines in October 2002. EGR has been also introduced on some Tier 3 non-road engines by John Deere (in spite of the challenges with heat dissipation in non-road applications where no ram air is available as the cooling medium).

EGR is an emission control technology. Its NOx emission benefit comes at a certain cost: increased PM, HC, and CO emissions, as well as fuel economy penalty. Potential engine wear and durability issues also exist due to the introduction of soot laden gas into the combustion chamber. Both the engine wear issue and the increased PM emissions can be controlled if the EGR stream is drawn from downstream of a particulate filter (in so-called low pressure loop, LPL, EGR configuration).

A retrofit EGR kit has been developed by the Swedish company STT Emtec (it is available in the USA through Johnson Matthey). The main components of the system include and EGR valve/throttle, EGR cooler, electronic control system, as well as diesel particulate filter (components in the shaded background in Figure 4-10). This system has been used on many heavy-duty, mostly urban bus, engines in Europe and the USA. In the US market, the particulate filter is typically a CRT unit by Johnson Matthey.

The STT Emtec system is a *low pressure loop* configuration where EGR is taken from a point downstream of the diesel particulate filter. This feature is one of the major strengths of this system since the EGR in this case is mostly clean and free of particles—potentially damaging to the turbocharger and the engine—that are normally a part of unfiltered exhaust. Exhaust gas then travels through the EGR pipe to the EGR cooler. The latter is a shell-and-tube cooler and uses engine jacket water as cooling medium. Cooled EGR flows through an emergency filter (not shown in Figure 4-10) designed to keep any foreign objects out of the EGR valve/throttle assembly.

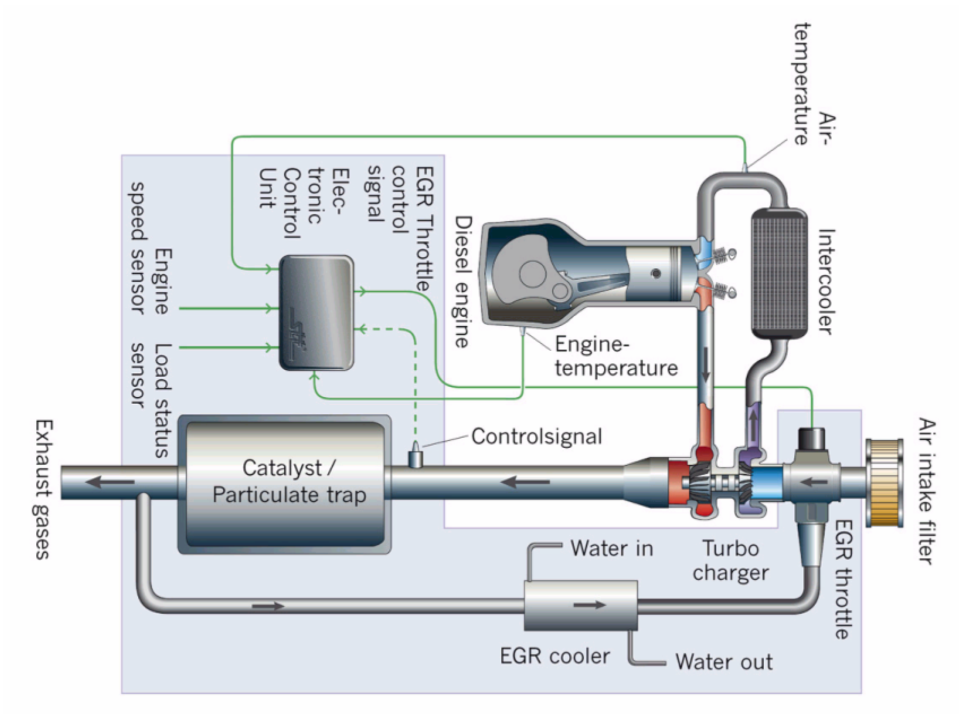

Figure 4-10. Retrofit EGR System (STT Emtec)

The rate of EGR is controlled based on the EGR valve position and the pressure differential across this valve. If the pressure difference is not adequate to flow the desired EGR rate, throttling is applied to the intake air to force more EGR. As a consequence of this action, less fresh air flows into the engine. The mixture of cleaned EGR and fresh air flows into the compressor where it is further mixed into a more homogeneous fluid. Additional EGR and fresh air mixture cooling is performed through the air-to-air intercooler where care must be exercised to avoid forming condensate prior to inducting this mixture into the engine. The entire system is controlled by a microprocessor-based unit (ECU) that receives its signals from the engine and has a stored look up table for valve positions that correspond to the various engine operating conditions.

Performance and Control Efficiency

The STT system is being marketed as capable of 40% NOx reduction. In some applications, it is possible to achieve even greater NOx reductions, at the expense of some degradation in fuel economy.

Applicability, Feasibility, and Installation

Existing experience with EGR retrofits is limited mostly to urban bus engines. For non-road applications, the system is believed to be feasible for smaller size mobile and stationary engines operated under medium loads. In large engines, as well as in engines operated under high load for extended periods of time, urea-SCR may be a more suitable control strategy due to the potential heat release issues.

Since the system requires signals for engine load, speed, and other parameters, it is more compatible with electronic engines, where the information is obtained directly from the ECM. Mechanical engine application is possible, but it requires the installation of necessary sensors. This typically includes sensors for the engine speed, load, intake or boost air temperature, coolant temperature, and exhaust backpressure.

The EGR kit is typically supplied as a retrofit with the CRT filter. The use of a passive DPF may present a limitation on high PM emitting engines, where the NOx/PM ratio and the exhaust temperature may be too low to ensure reliable regeneration. The contradictory demands from the CRT component (which is preferably installed on hot engines) and the EGR component (which is preferably installed on medium-load applications of lower exhaust temperature) may present a serious limitation of the applicability of this system on non-road equipment.

Since the EGR control relies on an engine map strategy, prior to the installation, an engine emission map has to be determined for each engine model. In most cases, this engine characterization is performed on an engine dynamometer (even if a generic control map can be used, dynamometer testing is required to confirm the required level of performance). A steady state application, such as generator sets, can be characterized in the field using portable test equipment.

The system installation is a major operation, as the retrofit kit interacts with several major engine systems, including the charge air system, cooling system, exhaust system, and the engine control system. Since the system includes a CRT filter, comments on the installation and maintenance given in the section on passive DPFs are applicable to the STT kit. There is no substantial added maintenance due to the operation of the EGR throttle and cooler.

The following potential issues may apply to the operation of the EGR system:

- The efficiency of the turbocharger compressor may decrease due to using hotter gas, as well as due to the throttling on the intake air.

- The EGR cooler puts an extra load on the engine cooling system. Non-road engines have been traditionally more sensitive to heat management issues than highway engines due to the lack of ram cooling air.
- Due to the operation of the EGR throttle, the turbocharger may operate under vacuum. This may increase the likelihood of breaking the seal and leakage of the lubricating oil from the turbocharger.

4.3.3 Crankcase Emission Control

Overview

Traditionally, diesel engines have had open crankcase breather systems. Future emission standards require measuring of crankcase emissions during emission certification testing and adding them to exhaust emissions. Closed crankcase ventilation systems will be introduced for 2007 highway engines, and for Tier 4 non-road engines.

The open crankcase is a source of blow-by emissions resulting from pressure leaks through the piston rings during their reciprocating motion. These blow-by emissions—emitted through the "draft tube"—are composed of aerosol and coalesced droplets made of lubricating oil, carbon soot, and wear debris. While the blow-by composition is similar to that of the tailpipe PM emission, the particle size is larger, with about 50% of mass in particles above 1 micron.

Depending on the mode of operation, the magnitude of the blow-by emission is typically from about 1 to 10 g/hr in a US 1998 heavy-duty highway engine of 500 hp power rating. In terms of specific emissions, blow-by typically ranges from 0.02-0.03 g/bhp-hr at most steady-state test modes (with the exception of idle, when it could be more than 5 g/bhp-hr).

Retrofit *closed crankcase ventilation* (CCV) systems have been developed which control blow-by emissions by filtering the gas and routing it back into the turbocharger inlet. The CCV unit includes an integrated filter and pressure regulator. The role of the pressure regulator is to maintain pressure balance between the crankcase and the intake system. The role of the filter—which can have an efficiency of 80-90%—is to prevent the fouling of turbocharger and intercooler. The oil separated in the filter is routed to the engine oil sump. The filter element is serviceable and requires periodic maintenance.

Commercial blow-by emissions control kits also exist—called the *open crankcase ventilation* (OCV) systems—where the crankcase emissions are filtered using a serviceable filter element, but the gas is not routed to the intake system.

In some of verified retrofit kits (e.g., Donaldson), CCV devices are offered together with oxidation catalysts or flow-through filters. In those cases, the verified PM emission control efficiency refers to the combined exhaust and crankcase emissions.

Performance, Applicability, Feasibility, and Installation

CCV systems remove small quantities of PM, compared to exhaust system aftertreatment systems, as noted above. Their benefit lies not in reducing air emissions but rather in minimizing personal exposure to PM, especially in confined areas. Towards this end, it comes as little surprise that CCV deployment has been most prevalent on front-engine school buses, where studies has indicated that their use significantly improves in-cabin exposure for pupil riders.[26]

4.3.4 Idle Reduction

Long duration idling of diesel engines is a source of emissions. It also contributes to increased engine maintenance costs, shortened engine life, and elevated noise levels. The EPA has developed a national idling program to address environmental, energy, and transportation related issues associated with long-duration engine idling. As part of the program, the EPA published guidelines to assist states in using idle reduction in their SIP plans. So far, these initiatives have focused on highway trucks[27] and railroad locomotives[28].

In highway trucks and railway locomotives, the following idle reduction strategies are being implemented:

- Automatic engine shut-down and start up systems
- Battery powered cabin heating and air conditioning devices
- Diesel driven heating systems
- Auxiliary power units/generator sets
- Advanced truck stop electrification (ATE)

Among these strategies, automatic engine shut down systems appears to have the most significance in non-road diesel engines, such as those used in construction machinery.

Automatic engine shut down systems can be also recommended for non-road vehicles retrofitted with passive DPF systems. Passive filters can experience increased pressure drop levels and plugging as a result of extended idling, when temperatures are too low to sustain regeneration. This type of common problems with passive DPFs can be avoided by using automatic shut down devices.

4.3.5 Engine Maintenance

There is a correlation between engine maintenance and emissions. Emissions of all regulated pollutants and a number of unregulated diesel emissions have been linked to such factors as intake & exhaust restriction, timing advance, overfueling, or worn injectors[29]. Even though the maintenance effects have been known for a long time, they have been never quantified, making it difficult to predict the emission benefits of a given more rigorous maintenance program. Rather, most published reports have a case study character.

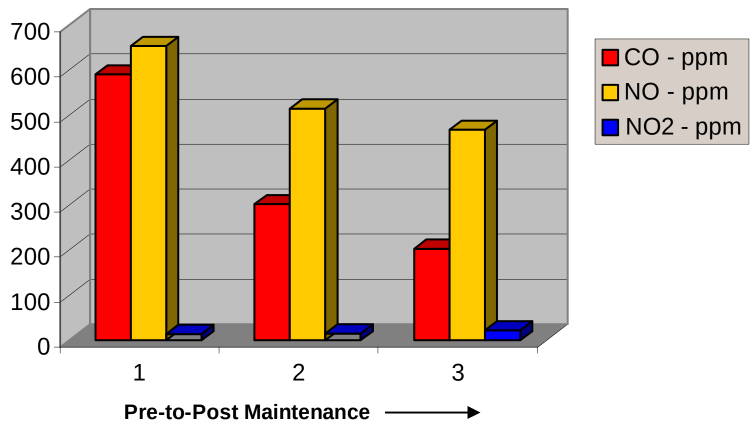

Figure 4-11. Maintenance Effect on Emissions

The maintenance effect on emissions can be illustrated by Figure 4-11, which shows a sample test from a DEEP case study with a Deutz BF4M1013 mining engine[30]. Exhaust emissions of CO, NO and NO_2 were reduced by correcting engine and maintenance faults. Point (1) was measured (a steady-state one point test) at the baseline condition. Point (2) was measured after correcting intake system leaks and restoring turbo boost. Point (3) was after replacing worn injectors.

Emissions assisted maintenance procedures have been developed for diesel engines operated in underground mining and implemented by some US mines[31].

Maintenance & Aftertreatment Technologies. Good maintenance program is very important in vehicles fitted with catalytic emission controls, including DOCs and catalytic DPF systems:

- Poorly maintained engines might be consuming high volumes of lubricating oil, and producing emissions of phosphorus, zinc, and other elements originating from lube oil additives which can cause poisoning and deactivation of catalysts.
- Catalysts might also become contaminated with lube oil from leaks in the turbocharger. Such contamination may result in immediate and complete deactivation of the catalyst.
- Poor engine maintenance often results in increased PM emissions. In engines fitted with passive DPF systems, increased engine-out PM emissions will adversely affect the regeneration and may lead to increased pressure drop and filter plugging.

4.4 OTHER ADVANCED ENGINE AND EMISSION TECHNOLOGIES

A number of advanced diesel engine and emission technologies have been under development, which are not applicable for the control of emissions from mobile non-road diesel engines. Some of them require very high degree of integration with the engine and its control system, thus being developed primarily for new engine applications. Others are still experimental and not available as commercial systems.

At this time, the following advanced technologies have been under development:

- **Advanced Combustion Technologies.** Homogeneous Charge Compression Ignition (HCCI), alone and in combination with conventional diesel combustion in "mixed mode" engines, as well as Low Temperature Combustion (LTC) and other advanced combustion regimes are being the focus in new diesel engine development. Mixed mode HCCI is likely to be commercialized as an important NOx/PM reduction strategy in heavy-duty highway engines in the 2007-2010 timeframe, as well as in light-duty diesel engines. These technologies would be applicable to in-use non-road engines only in the form of engine repower, presumably at the Tier 4 (2011-2014) timeframe.
- **Hybrid Powertrains.** Hybrid gasoline- and diesel-electric vehicles have been commercialized for various onroad applications, including passenger cars and urban transit buses. Among non-road applications, hybrid powertrains are being developed for switch-duty locomotives (Green Goats). Development of hybrid tug boats has been also reported. It is believed that no hybrid powertrains are currently available for construction machinery.
- **NOx Adsorbers.** The NOx adsorber-catalysts (NAC), also known as lean NOx traps (LNT) operate through storage of NOx in a special catalyst washcoat, followed by periodic reduction. The adsorber reduction has to be performed under rich air-to-fuel condition, which presents a major challenge in the diesel engine. Another major problem with the NAC technology is its extreme sensitivity to sulfur poisoning. Since no commercial retrofit products are available, the NAC technology is not discussed.
- **Plasma Technologies.** Plasma-assisted catalyst systems have been developed that allow to control NOx emissions with an efficiency similar to that offered by lean NOx catalysts (HC-SCR). Due to the increased complexity with the plasma generating system, they have not been commercialized. There were also early reports on plasma-regenerated particulate filters, but no commercial systems are available.
- **Hydrogen Technologies.** On-board generation of hydrogen through various technologies (such as fuel reformers or electrolysis) has been suggested, mostly as a means to enhance to regeneration of NOx adsorbers. The beneficial effect of H_2-enriched gas on NOx adsorbers has been reported by a number of authors. As a different H_2 technology, at least one company has been developing H_2-enrichment charge air systems for emission control and improved fuel economy. However, the benefit of H_2 addition to diesel combustion has never been scientifically confirmed

or quantified, and the technology must be considered experimental. At this time, the suppliers are not able to provide test results generated using standard test methods for the given diesel engine application.

4.5 VERIFICATION STATUS

Overview

Emission control systems for use in diesel retrofit programs usually require a formal verification or approval, typically issued by the environmental authority who oversees the retrofit program. The purpose of such approval is to verify the emission reductions and other performance aspects of a given device based on a standardized emission testing protocol(s). In some cases, the approved devices must also meet standard performance criteria. The two most important verification programs for diesel emission control technologies in the USA are:

- *EPA/ETV verification*—This program verifies the percentage emission reductions for all regulated diesel emissions based on standard test protocols. The verified emission reductions can be used by states in claiming SIP credits. EPA/ETV verification is required for devices used under the EPA Voluntary Diesel Retrofit Program.
- *California ARB verification* – established under the California Diesel Risk Reduction program, it verifies the PM emission reduction effectiveness of a given technology and classifies it as a Level 1, 2, or 3 strategy of 25%, 50%, or 85%, respectively, effectiveness. NOx reduction can be verified in 5% increments, starting at a minimum of 15%.

The EPA and the California ARB signed a Memorandum of Agreement (MOA) for the Coordination and Reciprocity in Diesel Retrofit Device Verification. The MOA establishes reciprocity in verifications of hardware or device-based retrofits, and commits EPA and ARB to work toward accepting PM and NOx verification levels assigned by the other's verification program.

The status of EPA/ARB verification should be considered in selecting technologies for the diesel demonstration program (see the following sections for detailed listing of verified technologies). Since few technologies currently exist that have been verified for non-road engines, verifications for highway engines should be also considered.

An important aspect of the EPA/ARB verification is the confirmation of the durability of the technology. In general, verification programs may include (1) a durability demonstration requirement, where a device that undergoes emission testing must be aged prior to the test, and (2) manufacturers' warranty requirements. The durability and warranty requirements established by the California ARB verification program are shown in the following tables.

Table 4-2. California Minimum Durability Demonstration Periods

Engine Type	Durability Demonstration Period
On-road	50,000 miles or 1000 hours
Off-road (including portable) & stationary	1000 hours
Stationary emergency standby engines	500 hours

Table 4-3. California Minimum Warranty Periods

Engine Type	Engine Size	Warranty Period
On-road	Light heavy-duty, 70 - 170 hp, GVWR < 19,500 lbs	5 years or 60,000 miles
	Medium heavy-duty 170 - 250 hp, GVWR 19,500 - 33,000 lbs	5 years or 100,000 miles
	Heavy heavy-duty, above 250 hp, GVWR > 33,000 lbs	5 years or 150,000 miles
	Heavy heavy-duty, above 250 hp, GVWR > 33,000 lbs, and the truck is: 1. Typically driven over 100,000 miles per year, and 2. Has less than 300,000 miles on the odometer at the time of installation	2 years, unlimited miles
Off-road & stationary	P < 25 hp, and constant speed engines < 50 hp with rated speeds ≥ 3,000 rpm	3 years or 1,600 hours
	25 hp ≤ P < 50 hp	4 years or 2,600 hours
	P ≥ 50 hp	5 years or 4,200 hours

Texas LED and California LED Programs

Producers and importers of diesel fuel in Texas and California are required to produce a fuel with higher cetane and lower aromatics, or a fuel blend or alternative formulation that has low emissions. For example, in the eastern half of Texas (110 counties) producers and importers of on-highway/road and non-road # 1 and/or #2 diesel fuel must satisfy the TxLED fuel standards on one of the following different methods. They can,

x. Produce or import diesel fuel that has a maximum aromatic hydrocarbon content of 10 percent by volume and has a minimum cetane number of 48.

xi. Produce or import diesel fuel that complies with the specifications of a California ARB certified alternative diesel formulation that was approved by ARB before January 18, 2005, to meet California diesel regulations in effect as of October 1, 2003. ARB certified alternative diesel formulations that were approved for compliance with California’s small refinery specifications for diesel fuel are not acceptable.

xii. Produce or import diesel fuel that complies with California diesel fuel regulations in effect as of January 18, 2005, except for those regulations established for small refineries. Diesel fuel produced to comply with the "designated equivalent limits" specified in the California diesel regulations would also be considered compliant with the Tx-LED fuel standards.

xiii. Produce or import diesel fuel that complies with an alternative diesel fuel formulation that has been approved by TCEQ as achieving comparable or better emission reductions.

xiv. Produce diesel fuel under an alternative emission reduction plan that has been approved by TCEQ and the U.S. EPA which contains a substitute fuel strategy that will achieve equivalent emission reductions.[32]

Tx-LED and CARB low emissions diesel average 5-7% NOx reduction based on mid 1990's on-highway engine emissions tests. Texas approvals of fuel additives should be considered in selecting fuel additive strategies for the NYSERDA program.

Other Approval Programs

One of the most significant approval programs in other countries is the Swiss VERT program. Particulate filters meeting the VERT criteria are required under the Swiss mandatory retrofit program for diesel engines used in construction and tunneling work.

The VERT approval involves testing over a standard test protocol and includes standardized performance criteria (PM emission reduction of 90% by mass and 95% by particle number) and durability demonstration requirement (2000 hours). Approved technologies are limited to diesel particulate filters. Listing of approved DPFs—the *VERT Filter List*—can be found on the web at http://www.umwelt-schweiz.ch/buwal/de/fachgebiete/fg_luft/vorschriften/industrie_gewerbe/filter/

Among various approval programs worldwide, standardized test protocols and performance criteria have been followed in approvals under the Tokyo diesel retrofit program and the Swedish Environmental Zones program.

ETV Canada. An environmental technology verification program exists in Canada, known as the "ETV Canada". This program is not administered by Environment Canada. Rather, it is maintained by the "Ontario Centre for Environmental Technology Advancement" under a license agreement with Environment Canada. ETV Canada focuses on general environmental technologies. Very few diesel engine related products are currently verified; those that are do not represent the technology mix currently used for diesel retrofits in Canada.

ETV Canada is a voluntary program, where technology providers specify their own performance goals and provide test results to support their claims. At this time, the program does not include testing protocols and/or any performance criteria for diesel emission controls. Therefore, ETV Canada cannot be considered a Canadian equivalent of the US EPA and Cal ARB diesel emission control verification programs. The status of ETV Canada verification is not considered a criterion in the selection of emission control strategies for the NYSERDA project.

4.5.1 EPA ETV Verified Technologies

Emission control products verified under the EPA program are listed in Table 4-4. Updated listing is available on the web at http://www.epa.gov/otaq/retrofit/retroverifiedlist.htm

Table 4-4. EPA ETV Verified Technologies (December 2005)

Manufacturer	Technology	Applicability	Reductions (%)			
			PM	CO	NOx	HC
Caterpillar, Inc.	Catalyzed Converter/Muffler (CCM)	Highway, heavy-heavy and medium-heavy duty, 4-cycle, non-EGR, model year 1998 - 2003, turbocharged or naturally aspirated	20	20	n/a	40
Caterpillar, Inc.	Diesel Particulate Filter	Non-road, 4-cycle, non-EGR equipped, model year 1996-2005, turbocharged engines with power ratings $130 \leq kW < 225$ ($174.2 \leq hp < 301.5$)	89	90	n/a	93
Clean Diesel Technologies, Inc.	Platinum Plus Purifier System (fuel borne catalyst plus DOC)	Highway, medium-heavy and heavy-heavy duty, 4 cycle, model year 1988 - 2003, turbocharged or naturally aspirated	25 to 50	16 to 50	0 to 5	40 to 50
Clean Diesel Technologies, Inc.	Platinum Plus Fuel Borne Catalyst/Catalyzed Wire Mesh Filter (FBC/CWMF) System	Highway, medium-heavy duty, 4 cycle, model year 1991 - 2003, non-EGR, turbocharged or naturally aspirated	55 to 76*	50 to 66*	0 to 9*	75 to 89*
Donaldson	Series 6000 DOC & Spiracle (closed crankcase filtration system)	Highway, heavy-heavy and medium-heavy duty, 4 cycle, non-EGR, model year 1991 - 2003, turbocharged or naturally aspirated	25 to 33[a]	13 to 23	n/a	50 to 52
Donaldson	Series 6100 DOC	Highway, heavy-heavy and medium-heavy duty, 4 cycle, non-EGR, model year 1991 - 2003, turbocharged or naturally aspirated	20 to 26	38 to 41	n/a	49 to 66
Donaldson	Series 6100 DOC & Spiracle (closed crankcase filtration system)	Highway, heavy-heavy and medium-heavy duty, 4 cycle, non-EGR, model year 1991 - 2003, turbocharged or naturally aspirated	28 to 32[a]	31 to 34	n/a	42

Manufacturer	Technology	Applicability	Reductions (%)			
			PM	CO	NOx	HC
Engelhard	DPX Catalyzed Diesel Particulate Filter	Highway, heavy-duty, 4 cycle, model year 1994 - 2002, turbocharged or naturally aspirated	60	60	n/a	60
Engelhard	CMX Catalyst Muffler	Heavy Duty, Highway, 2 cycle engines	20	40	n/a	50
Engelhard	CMX Catalyst Muffler	Heavy Duty, Highway, 4 cycle engines	20	40	n/a	50
International Truck & Engine Corp.	Green Diesel Technology-Low NOx Calibration plus Diesel Oxidation Catalyst with Ultra Low Sulfur Diesel (ULSD)	Highway Light Heavy-Duty, 4-cycle, Navistar/International engines, model years 1999 - 2003 in the following families: XNVXH0444ANA, YNVXH0444ANB, 1NVXH0444ANB, 2NVXH0444ANB, 3NVXH0444ANB	0 to 10	10 to 20	25	50
Johnson Matthey	Catalyzed Continuously Regenerating Technology (CCRT) Particulate Filter	Highway, heavy-heavy, medium-heavy, light-heavy duty, urban bus, 4-cycle, non-EGR model year 1994 - 2003, turbocharged or naturally aspirated engines.	60	60	n/a	60
Johnson Matthey	Continuously Regenerating Technology (CRT) Particulate Filter	Heavy Duty, Highway, 2 & 4 cycle, model year 1994 - 2002, turbocharged or naturally aspirated engines	60	60	n/a	60
Johnson Matthey	CEM™ Catalytic Exhaust Muffler and/or DCC™ Catalytic Converter	Highway, heavy-heavy, medium-heavy, light-heavy duty, non-urban bus, 4-cycle, non-EGR model year 1991 - 2003, turbocharged or naturally aspirated engines	20	40	n/a	50
Johnson Matthey	CEM Catalyst Muffler	Heavy Duty, Highway, 2 cycle engines	20	40	n/a	50
Lubrizol	PuriNOx Water emulsion fuel	Heavy Duty, Highway & Non-road, 2 & 4 cycle	16 to 58	-35 to 33	9 to 20	-30 to -120
Lubrizol Engine Control Systems	Purifilter - Diesel Particulate Filter	Highway: Heavy Heavy-Duty, Medium Heavy-Duty; Urban Bus; 4 cycle; model years 1994 - 2003; turbocharged or naturally aspirated; non-EGR engines	90	75	n/a	85

Manufacturer	Technology	Applicability	Reductions (%)			
			PM	CO	NOx	HC
Lubrizol Engine Control Systems	AZ Purimuffler or AZ Purifier Diesel Oxidation Catalyst with Low Sulfur Diesel Fuel (30 ppm S max)	Highway Medium Heavy-duty, 4- cycle, model years 1991 - 2003 Cummins and Navistar/International engines originally manufactured without any aftertreatment which are turbocharged or naturally aspirated, non-EGR engines	40	40	n/a	70
Lubrizol Engine Control Systems	AZ Purimuffler or AZ Purifier Diesel Oxidation Catalyst with Low Sulfur Diesel Fuel (30 ppm S max)	Highway Heavy Heavy-Duty, 4-cycle, model years 1991 - 1993 Cummins engines originally manufactured without exhaust aftertreatment which are turbocharged or naturally aspirated, non-EGR engines	35	40	n/a	70
Lubrizol Engine Control Systems	AZ Purimuffler AZ Purifier	Heavy Duty, Highway, 2 cycle engines	20	40	n/a	50
Lubrizol Engine Control Systems	AZ Purimuffler AZ Purifier	Heavy Duty, Highway, 4 cycle engines	20	40	n/a	50
Various	Biodiesel (1 to 100%)	Heavy Duty, Highway, 2 & 4 cycle	0 to 47	0 to 47	0 to -10	0 to 67
Various	Cetane Enhancers	Heavy Duty, Highway, 4 cycle, non-EGR-equipped	n/a	n/a	0 to 5	n/a

[a] - Total PM reduction figures reflect reductions from both tailpipe and crankcase emissions.
* - These effectiveness figures are provisional values subject to change pending final review of the test data.
Note: For aftertreatment devices the reductions are based on the installation of retrofits to engines that were originally produced without diesel oxidation catalysts or diesel particulate filters.

4.5.2 California ARB Verified Technologies

Emission control products verified under the California verification program are listed in Table 4-5. Verification levels 3, 2, and 1 correspond to PM emission reduction efficiency of 85%, 50%, and 25%, respectively.

Updated listing is available on the web at http://www.arb.ca.gov/diesel/verdev/currentlyverifiedtech.htm

Table 4-5. California ARB Verified Technologies (December 2005)

PM Level	Product	Technology Type	PM Reduction	NOx Reduction	Applicability
Level 3	Cleaire Flash and Catch CRT	DPF	85%	25%	1994+ on-road (limited - Cummins defeat device); 15 ppm sulfur diesel.
	Cleaire Flash and Catch DPX	DPF	85%	25%	1994+ on-road (limited - Cummins defeat device); 15 ppm sulfur diesel.
	Cleaire Horizon	DPF	85%	N/A	1994-2005 on-road; 15 ppm sulfur or CARB diesel.
	Cleaire Longview	Lean NOx Catalyst and DPF	85%	25%	1993-2003 model year on-road; 15 ppm sulfur diesel.
	CleanAIR Systems PERMIT	DPF	85%	N/A	Stationary emergency generators; 15 ppm sulfur diesel.
	Donaldson	DPF	85%	N/A.	1994-2002 on-road; 15 ppm sulfur diesel.
	International Truck and Engine Corporation DPX	DPF	85%	N/A.	1994-2003 on-road Navistar (International); 15 ppm sulfur diesel.
	Johnson Matthey CRT	DPF	85%	N/A.	1994-2004 on-road; 2002-2006 Cummins ISM and ISB with EGR;15 ppm sulfur diesel or B20.
	Johnson Matthey CCRT	DPF	85%	N/A.	1994-2004 on-road; 2002-2006 Cummins ISM and ISB with EGR;15 ppm sulfur diesel.
	Johnson Matthey EGRT	EGR/DPF	85%	40%	2000 International DT-466, 2000 Cummins ISM 2001 Cummins ISB, 1998 - 2002 Cummins ISC, 2001 Cummins ISL, 2001 MY DDC - 50, and 2001 DDC - 60. on-road; 15 ppm sulfur diesel.
	Lubrizol ECS Purifilter	DPF	85%	N/A	1994-2003 on-road; 15 ppm sulfur diesel.
	Lubrizol ECS Unikat Combifilter	DPF	85%		1996-2004 off-road; 15 ppm sulfur diesel or carb diesel.
Level 2	Donaldson DFM DMF with/without Spiracle	Flow Through FIlter	50%	N/A	1991-2002 on-road; 15 ppm sulfur diesel.
	Environmental Solutions Worldwide Particulate Reactor	Flow Through Filter	50%	N/A	1991-1993 on-road, CARB diesel.
	Lubrizol PuriNOx	Alternative Fuel	50%	15%	1988-2003 on-road.
	Lubrizol AZ Purimuffler/Purifier	DOC + Alt Fuel	50%	20%	1996-2002 off-road; PuriNOx
Level 1	Cleaire Flash and Match	DOC	25%	25%	1993+ on-road (limited - Cummins defeat device); 15 ppm sulfur diesel or CARB diesel.

PM Level	Product	Technology Type	PM Reduction	NOx Reduction	Applicability
	Donaldson	DOC	25%	N/A	1988-1990 on-road; 15 ppm sulfur diesel or CARB diesel.
	Donaldson	DOC + crankcase filter	25%	N/A	1988-1990 on-road; 15 ppm sulfur diesel or CARB diesel.
	Donaldson	DOC + crankcase filter	25%	N/A	1991+ on-road/1996 + off-road port equipment; CARB diesel.
	Donaldson	DOC	25%	N/A	1991+ on-road; 15 ppm sulfur diesel.
	Donaldson	DOC + crankcase filter	25%	N/A	1994+ on-road/1996 + off-road port equipment; 15 ppm sulfur diesel.
	Extengine	DOC + SCR	25%	80%	1991-1995 Cummins 5.9 liter off-road; 15 ppm sulfur diesel or CARB diesel.
	Lubrizol ECS AZ Purifier & Purimuffler	DOC	25%	N/A	1991-2003 Cummins and Navistar on-road; 15 ppm sulfur diesel. 1973-1993 DDC 2 stroke; CARB diesel. 1991-2002 certain model Cummins, DDC HHD 4 stroke; 15 ppm sulfur fuel.
	Lubrizol ECS AZ Purifier & Purimuffler	DOC	25%	N/A	1996-2002 off-road; 15 ppm sulfur diesel.

4.6 FIELD DEMONSTRATION RECOMMENDATIONS

4.6.1 <u>Introduction</u>

Technology recommendations have been subdivided into three broad areas based upon the emissions constituent that is the focus of reduction. Because PM and NOx are the constituents from diesel engines of greatest concern, our focus in on reduction of these two species, both alone and in combination with each other. Clearly, the largest selection of emission control technologies is available for the reduction of PM emissions (indeed, it is paradoxical that PM reduction technologies are more straightforward and mature than NOx reduction technologies, while from an in-use measurement perspective, NOx is more amenable to accurate sampling via PEMS systems). Finally, combination systems that simultaneously reduce both PM and NOx are becoming more commercialized, and represent the most favored emission reduction approach for the non-road sector, assuming a number of implementation and cost challenges can be surmounted.

In making our assessment and subsequent recommendation of PM, NOx and PM/NOx technologies, we reviewed the list of deliverables from the October 11, 2005 SRI memo and the PON itself. From that review, we concluded that there was sufficient information to provide preliminary technology recommendations based upon the equipment inventory performed for this project, but insufficient information to conduct a more detailed equipment-specific ranking until the target fleet for technology deployment has been identified (see below for further explanation of our ranking methodology by equipment type). Furthermore, there is insufficient information to provide specific supplier recommendations until a number of precepts have been clearly identified. Specifically, they include a clear delineation of the commitments specific technology providers have made or will make in providing their technology at reduced costs, with significant technical and deployment support, and within a schedule that will make timely deployment for the selected non-road fleet a meaningful reality.

Finally, it is impossible to pre-select a specific technology provider until both the types of machines and the fleets themselves have been clearly identified. Specific technology providers may be unable to provide product for certain machine types; similarly, certain fleets may be unwilling to provide the necessary extensive maintenance and monitoring that otherwise desirable technologies require. For example, SCR is the most effective NOx reduction technology, but if candidate vendors are unwilling to provide a certain degree of in-kind services or cost reduction for this expensive technology, and/or fleets are unwilling to perform required urea replenishment, then SCR become a less attractive option for this project. As such, we have limited this first assessment of technologies to the technologies themselves, and will follow up with more specific vendor recommendations as more information is made available.

4.6.2 Methodology

Our technology assessment rating and recommendations are based upon the following criteria and qualitative weighting approach:

Table 4-6. Technology Ranking Criteria (In Priority Order)

Criteria	Comments
Emissions Reduction Performance	
Commercial Availability	Incorporates history of deployment in non-road applications
Durability	Incorporates regulatory compliance concerns as well as fleets operations downtime
Cost – Unit	
Cost – Maintenance & Operation	Incorporates variable costs such as fuel penalty or urea consumption
Cost – Installation	Incorporates ease of installation
User Acceptance By Fleets And Equipment Operators	
ARB or EPA Verified	(Additives also based on TxLED approval)

Based upon these precepts, we developed the following, somewhat arbitrary, rating system:

- A – Strongly recommended
- B – Recommended
- C – Somewhat recommended
- D – Not recommended

The five tables that have been developed below represent an initial attempt at technology ratings. 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 adjudged 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 deployment feasibility and performance efficiency of otherwise attractive technology options. The technology ranking parameters, therefore, are 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.

This challenge of technology ranking is exacerbated by not having yet defined the target fleet for aftertreatment and/or fuels deployment. As such, we needed to develop a methodology that accounted for generic fleet diversity without the luxury of fleet equipment specificity. Our approach references the complimentary non-road equipment inventory work on this NYSERDA Project, performed by Southern which ranked equipment prevalent in both New York State and the New York Metropolitan area, and provided recommendation for "priority equipment" to be used in the technology demonstration. The results of their analysis are summarized below[33]:

Table 4-7. Recommended Priority Equipment for Field Demonstrations

Rank	SCC	Category	Type	hp
1	2270002066	Construction and Mining	Tractors / Loaders / Backhoes	75 - 175
2	2270002060	Construction and Mining	Rubber Tire Loaders	300 - 600
3	2270002036	Construction and Mining	Excavators	100 - 300
4	2270002072	Construction and Mining	Skid Steer Loaders	50 - 100
5	2270002069	Construction and Mining	Crawler Tractor / Dozers	300 - 600
6	2270002060	Construction and Mining	Rubber Tire Loaders	100 - 300
7	2270002051	Construction and Mining	Off-highway Trucks	1200 - 2000
8	2270002057	Construction and Mining	Rough-Terrain Forklifts	75 - 175
9	2270006005 / 2270006015	Construction and Mining / Commercial	Generator Sets / Air Compressors	50 - 100
10	2270005015	Agricultural Equipment	Agricultural Tractors	100-600

The technology entries in the tables are arranged in priority order of recommendation for the one type of non-road machine that was assigned the highest ranking. That machine has been identified as a Tractor/Loader/Backhoe of between 75 – 175 HP, used in the construction or mining industry. The recommendations for each technology are then modified for the remaining types of machines from the inventory study through comments denoted in the "Engine/Equipment 'Sub-Ranking'" column of Tables 8 through 11, below. Because of the complexity in trying to assess technologies for ten machine categories, we combined the remaining ten priority equipment rankings in the table into three categories, for a total of four equipment types from which we based our technology rankings. Our methodology for this categorization is as follows:

- Define the most prevalent/"highest ranked" machine:
    - 75-175 hp tractors/loader/backhoe
    - Base the technology rankings on this type of machine, taking into account the three parameters, described above, that typically influence technology "attractiveness": engine/chassis configurations, engine horsepower, and machine operating duty-cycle.
- Identify the *more complex machine* for which application of technologies becomes *more challenging*; we have identified two, as follows:
    - 100 – 300 hp excavators: more challenging due to complex engine/chassis configurations making technology installation more difficult.
    - 300 – 600 hp loaders/tractors/dozers: more challenging due to difficulties of sizing and installing control technologies on high horsepower engines.

- Identify the *least complex machine* for which application of technologies becomes *less challenging:*
  - 50 – 100 stationary, low horsepower equipment (generator sets, compressors and pumps)
  - Less challenging due to:
    - Uncomplicated engine/chassis configurations – ample room, no complex movements during operation.
    - Low hp promotes ease of sizing and small control technology (DPF et al) unit size.
    - Quasi steady-state duty-cycle promotes predictable exhaust gas temperatures (and to some extent, backpressure), ensuring more consistent NOx or PM-reduction efficiencies due to attenuated temperature excursions.
- Assign an "ID-Identifier" to denote the type of machine being referenced in Tables 8 through 11 for the machine-based "sub-ranks." This "ID" is denoted in the left-most column of Table 4-8.

Table 4-8. Equipment Designations for Technology Ranking

"ID"	Rank According to Retrofit Deployment Complexity	Rationale	Category	Type	hp
M1	"Common Machine" Used As Baseline For Ranking	Most Prevalent in NY as per inventory summary report	Construction and Mining	Tractors / Loaders / Backhoes	75 - 175
M2	More Complex	Complex Engine/Chassis Configuration	Construction and Mining	Excavators	100 - 300
M3	More Complex	High Horsepower	Construction and Mining	Rubber Tire Loaders and Crawler Tractor / Dozers	300 - 600
M4	Least Complex	Less Constricted Engine/Chassis Configuration; Low Horsepower; Quasi Steady-State Duty-Cycle	Construction and Mining / Commercial	Generator Sets / Air Compressors	50 - 100

Clearly, as more specifics regarding vendor and fleet participation and equipment specificity are defined, these technology ratings may be reassessed and fine-tuned.

4.6.3 <u>Recommended Technologies</u>

4.6.3.1 <u>Technology Types</u>

Control technologies recommended for the field demonstration have been grouped by the type of technology, and listed in five tables in Section 4.6.3.3:

- PM Control Technologies (Table 4-9)
- NOx Control Technologies (Table 4-10)
- PM & NOx Combination Control Technologies (Table 4-11)
- Fuels and Additives Technologies (Table 4-12)
- Idle Reduction Technologies (Table 4-13)

4.6.3.2 Technical Remarks

Engine Maintenance

In addition to the recommended technologies, engine maintenance plays a very important role in any diesel engine emission reduction program. While difficult to evaluate through a field demonstration, engine maintenance not only provides direct emission reductions, but it is also a necessary component of a number of aftertreatment technologies listed below. Indeed, poor engine maintenance compromises the life of most catalyst-based aftertreatment devices.

Fuel Additives and Fuel Technologies

Most fuel additive and alternative fuel technologies—with the exception of water-diesel emulsions—have very low emission reduction effect, on the order of a few percent. Since the emission effects are often comparable with the error of measurement, the determination of emission benefits is challenging. Furthermore, several fuel technologies can also produce small emission increases of certain species, in some engines, under certain conditions. We have recommended certain additive and fuel technologies, based primarily on their verification status under the EPA, California and the TxLED program. Due to the variability of duty cycle and other operating conditions, it may not be possible to quantify their emission effects through field testing. Rigorous laboratory testing under controlled, repeatable conditions may be more appropriate for fuel additive and fuel technologies.

Regarding *metallic fuel additives,* one type of device—the FBC regenerated DPF—has been recommended. As discussed in previous sections, when metallic additives are used without a DPF, secondary emissions of metallic nanoparticles are created which, as suggested by some authors, may present a health hazard. However, from a regulatory point of view, metallic additives have been approved and/or verified for use with flow-through filters and DOCs (though that verification, specifically by EPA, is now undergoing considerable scrutiny). If such technologies are deployed, enclosed space applications (e.g., inside buildings) should be avoided, because the secondary emissions can accumulate to higher levels. A disclosure should be also made to the vehicle operator(s) about the possible health concerns.

Technical and Scientific Novelty

Some of the recommended technologies or their performance aspects are somewhat unique for mobile source applications, and are highlighted in this sub-section. The testing performed under the NYSERDA demonstration program could have long term reference value, filling gaps in existing knowledge. The performance uncertainties and measurement issues were discussed earlier, in sections describing the particular control technologies. The following is a summary of two key technologies of this type that are part of the set of recommended strategies:

- *Urea-SCR*: The application of selective catalytic reduction has been limited to stationary industrial applications and, on a very limited scale, marine engines. First OEM applications on diesel truck engines were launched in 2005 in Europe and Japan. There is little documented performance data from mobile non-road vehicles. While NOx reductions under steady-state conditions are very impressive, one of the most important aspects (and one of the biggest challenges in adapting SCR to mobile applications) is the NOx reduction performance under transient conditions.
- *Flow-Through Filters*: As discussed earlier, some of the flow-through filter designs are very new, having been first commercialized in 2005, while others are older designs that attract renewed interest. In both cases, PM reduction performance depends on the “history” of operation of the device before the beginning of the test. Available performance data was generated with clean filters operated over regulatory test cycles. Transient PM emission reduction performance under real life field operation may be different, but it remains largely unknown.

The recommendations also include a number of technologies that have been already deployed in numerous retrofit programs, often on similar type of engines and equipment. In some cases, the scope of testing can be limited to avoid unnecessary repetition of research already conducted and published by others.

Diesel oxidation catalysts are a technology that has been commercialized in the 1980’s and tested extensively in various applications. However, due to the engine and duty cycle specificity of the PM performance in the DOC, emission testing may still yield valuable information pertaining to the potential benefits from using that technology on non-road equipment in the New York state.

Diesel particulate filters represent another well established technology with significant record of test data, especially in regards to passive filters. The focus in evaluating DPF systems should be on the filter regeneration and durability issues, which present the real challenge in wider deployment of retrofit DPF technologies on diesel engines in both on-highway and non-road applications. PM emission performance, on the other hand, typically depends more on the type of filter substrate, than on the design of the filter system. In most filters utilizing wall-flow substrates and operated with ultra-low sulfur fuel, the PM emission reduction is consistently measured at about 90%, regardless of the engine type or test cycle.

Therefore, valuable information about PM emission performance of a DPF can often be provided by a simplified pass/fail test (such as visual smoke, smoke opacity, and/or filter outlet face appearance) which would detect if the substrate still maintains its mechanical integrity and, thus, performance level. This approach is important to consider when evaluating in-use technology emissions performance due to the technical challenges of field PM emission measurements.

4.6.3.3 <u>Recommendations and Rankings</u>

Tables 4-9 through 4-13 list recommended control technologies and their rankings.

Table 4-9. Recommended PM Control Technologies

Technology	Rank ('M1')	PM Reduction	Equipment "Sub-Rank"	Benefits	Drawbacks	Suppliers **AV**: ARB Verified **EV**: EPA Verified
Catalyzed DPF	A	80-90%	1. M2 = B+ 2. M3 = B 3. M4 = A+	1. Reduces HC, CO, and PM (including ultrafine particulate and SOF). 2. Reduces smoke and odor. 3. Considerable verification – port dockside and construction equipment, trucks. 4. Occasionally a direct replacement for the current muffler (lower bhp) 5. Best compromise between maximum PM reductions, cost and installation and operations challenges.	1. Require higher operating temperatures (compared to active regeneration) and appropriate duty cycles to work properly. 2. Requires maintenance for ash removal 3. Requires operation with ULSD	CleanAIR (AV, stationary) DCL Donaldson/Engelhard (AV, EV) ECS (AV, EV) Nett Miratech (AV, stationary)
DOC+DPF (CRT)	A	80-90%	1. M2 = B+ 2. M3 = B 3. M4 = A+	1. Reduces HC, CO, and PM (including ultrafine particulate and SOF). 2. Reduces smoke and odor. 3. Considerable verification – port dockside and construction equipment, trucks. 4. Occasionally a direct replacement for the current muffler (lower bhp) 5. Regenerates at somewhat lower EGTs than the conventional DPF, potentially expanding applications.	1. Potential increase in NO_2 production. 2. Potential space constraints – longer in length than typical catalyzed DPF. 3. Still EGT-dependent (less than conventional DPF). 4. Requires operation with ULSD	JMI (AV, EV)

Technology	Rank ('M1')	PM Reduction	Equipment "Sub-Rank"	Benefits	Drawbacks	Suppliers **AV**: ARB Verified **EV**: EPA Verified
Active DPF, shore power (un-catalyzed)	A	80-90%	1. M2 = B 2. M3 = B- 3. M4 = A+	1. Reduces PM (including ultrafine particulate) 2. Reduces some smoke and odor 3. Operation far less constrained by low or unknown EGTs 4. Operates on LSD (<500 ppm for ECS, <300 for Cleaire).	1. Maintenance intensive. 2. Requires unique electrical infrastructure (often 280 or even 480 volts). 3. Requires centrally domiciled fleet. 4. Requires machine accessibility to regeneration station, or easily removal filter element on a periodic basis. 5. Will not remove SOF of TPM and only trace amounts of HC and CO (un-catalyzed). 6. Will typically not self-regenerate (un-catalyzed), relying on consistent use of shore power.	Cleaire (AV) ECS (AV) HUSS

Technology	Rank ('M1')	PM Reduction	Equipment "Sub-Rank"	Benefits	Drawbacks	Suppliers **AV**: ARB Verified **EV**: EPA Verified
Active DPF, shore power (catalyzed)	B	80-90%	1. M2 = B 2. M3 = B- 3. M4 = A+	1. Reduces HC, CO, and PM (including ultrafine particulate) 2. Reduces smoke and odor 3. Operation far less constrained by low or unknown EGTs	1. Maintenance intensive. 2. Requires unique electrical infrastructure (often 280 or even 480 volts). 3. Requires centrally domiciled fleet. 4. Requires machine accessibility to regeneration station, or easily removal filter element on a nightly basis. 5. Removes SOF of TPM, HC and CO (catalyzed). 6. Will typically not self-regenerate (un-catalyzed), relying on consistent use of shore power. 7. Requires operation with ULSD	ECS (close to commercialization)
DOC+CDPF (CCRT)	B	80-90%	1. M2 = B+ 2. M3 = B 3. M4 = A+	1. Reduces HC, CO, and PM (including ultrafine particulate and SOF). 2. Reduces smoke and odor. 3. Considerable verification – port dockside and construction equipment, trucks. 4. Occasionally a direct replacement for the current muffler (lower bhp). 5. Regenerates at significantly lower EGTs than the conventional DPF (200 ^{o}C v 250+ ^{o}C), expanding applications.	1. Potential increase in toxic NO_2 production. 2. Significantly more costly than conventional DPFs (est. 50% more) 3. Potential space constraints – longer in length than typical catalyzed DPF. 4. Still EGT-dependent (less than conventional DPF). 5. Requires operation with ULSD	JMI (AV, EV) Engelhard (?)

Technology	Rank ('M1')	PM Reduction	Equipment "Sub-Rank"	Benefits	Drawbacks	Suppliers **AV**: ARB Verified **EV**: EPA Verified
Flow-through filter—honeycomb	B	50%	1. M2 = B+ 2. M3 = B+ 3. M4 = B	1. Reduces HC, CO, and PM (incl. SOF). 2. Reduces smoke and odor 3. Less prone to plugging than DPF. 4. Superior PM-reduction performance than DOC. 5. Operates on LSD (<500 ppm) sulfur fuel. 6. Less maintenance than DPF; may not require ash cleaning.	1. Just verified (AV), so in-use performance and durability still comparatively (to DPFs and DOCs) unknown. 2. Poor PM-reduction performance than DPF. 3. Only one current supplier may keep unit price artificially high.	Donaldson (AV)
Flow-through filter—wire mesh	B	50%	1. M2 = B+ 2. M3 = B+ 3. M4 = B	1. Reduces HC, CO, and PM (incl. SOF). 2. Reduces smoke and odor 3. Less prone to plugging than DPF. 4. Superior PM-reduction performance than DOC. 5. Operates on LSD (<500 ppm) sulfur fuel. 6. Less maintenance than DPF; may not require ash cleaning.	1. Currently only verified (AV) for very limited on-highway applications. 2. Limited deployment to-date; in-use performance and durability still comparatively (to DPFs and DOCs) unknown. 3. Only one current supplier may keep unit price artificially high.	ESW (AV)
Active DPF, on-vehicle electric power	B	50-60%	Difficult to apply to M2, M3 & M4; highly vehicle dependent, but is a more favorable for the following vehicle characteristics: • Low EGT • High HP w/high engine electrical capacity • Few space or operators line-of-sight constraints.	1. Reduces PM (including ultrafine particulate) 2. Reduces some smoke and odor 3. Operation far less constrained by low or unknown EGTs 4. Operates on LSD 5. Does not require electrical infrastructure.	1. Requires centrally domiciled fleet. 2. Requires considerable on-board electrical supply or engine modification (larger alternator). 3. Will not remove SOF of TPM and only trace amounts of HC and CO (un-catalyzed). 4. Unproven in smaller bhp (< 700) applications	Rypos (AV, stationary)

Technology	Rank ('M1')	PM Reduction	Equipment "Sub-Rank"	Benefits	Drawbacks	Suppliers **AV**: ARB Verified **EV**: EPA Verified
DOC	C	10-40%	1. M2 = C 2. M3 = C 3. M4 = C	1. Reduces HC, CO, and PM. 2. Reduces SOF of TPM. 3. Reduces smoke and odor. 4. Established PM-reduction performance, and durability for on-highway and non-road applications (35 +years). 5. Requires no maintenance. 6. Operates on LSD (<500 ppm sulf. wt.). 7. Verified for dockside and construction equipment, trucks. 8. Typically a muffler replacement, regardless of engine/chassis configuration or hp.	1. Comparatively poor (DPFs, etc.) PM-reduction performance. 2. Diesel fuel w/high sulfur content (typically >2000 ppm) make cause 'sulfate make' increasing PM emissions; Works better with lower sulfur diesel (< 350 ppm); Works best with ULSD.	CleanAir DCL Donaldson (AV, EV) ECS (AV, EV) JMI (AV, EV) Nett Miratech
FBC + DPF (FBC metal based)	C	80-90%	1. M2 = C- 2. M3 = C- 3. M4 = B	1. Reduces HC, CO, and PM (including ultrafine particulate). 2. Reduces smoke and odor. 3. Considerable verification – port dockside and construction equipment, trucks. 4. Regenerates at lower EGTs than the conventional DPF due to presence of FBC. 5. Reported fuel economy improvement of 2-5%. 6. Alternative to some catalyzed DPFs if low NO_2 emissions are required.	1. Potential issues with metals toxicity. 2. Labor intensive – tanks must be filled (though quantities are small). 3. Continual replenishment incurs variable cost for fleets. 4. Compliance issues – reliance on humans to replenish tanks, or install automatic filler (either on-board vehicle or at centrally fuelling tank, incurring additional costs. 5. DPF regeneration still EGT-dependent (though diminished due to use of FBC).	CleanAIR/CDTI (EV)

Technology	**Rank ('M1')**	**PM Reduction**	**Equipment "Sub-Rank"**	**Benefits**	**Drawbacks**	**Suppliers** **AV**: ARB Verified **EV**: EPA Verified
Active DPF—catalytic combustion of fuel	C	80-90%	1. M2 = D 2. M3 = D 3. M4 = C+	1. Reduces HC, CO, and PM (including ultrafine particulate and SOF). 2. Reduces smoke and odor. 3. Not EGT dependent. 4. Most promising PM-reduction approach once commercialized: consistent, EGT-independent, significant PM-reductions. 5. 2007 on-highway OEM PM-reduction equipment for all new engines/trucks.	1. Lack of commercially available product to-date. 2. 3-7% (estimated) fuel economy penalty. 3. Increased degree of complexity when compared to passive filter systems. 4. More costly than passive systems – unit, installation and variable (fuel use).	Extengine, Donaldson (?)
Closed Crankcase Ventilation (CCV)	C	5-7%	1. M2 = C 2. M3 = C 3. M4 = C	1. Reduces PM. 2. Effective strategy for reducing in-cabin PM exposure (health). 3. Inexpensive (unit & installation). 4. Verified CCV system available in combination with flow-through filters & DOCs.	1. Requires periodic change of a disposable filter, typically at every oil change or other preventative maintenance schedule. 2. Engine compartment space constraints for some applications. 3. Only one current supplier may keep unit price artificially high (soon to have three suppliers, however).	Donaldson (EV) FES ECS (?)

Technology	**Rank ('M1')**	**PM Reduction**	**Equipment "Sub-Rank"**	**Benefits**	**Drawbacks**	**Suppliers** **AV**: ARB Verified **EV**: EPA Verified
Active DPF—fuel burner	C	80-90%	1. M2 = D 2. M3 = D 3. M4 = C+	1. Reduces HC, CO, and PM (including ultrafine particulate). 2. Reduces smoke and odor. 3. Not EGT dependent.	1. Not commercially available in the USA. 2. Not verified (except under VERT) – no US performance or durability history. 3. Does not reduce SOF (typically un-catalyzed). 4. Fuel economy penalty (quantitatively unknown).	ArvinMeritor Miratech/HUG Huss

Table 4-10. Recommended NOx Control Technologies

Technology	Rank ('M1')	NOx Reduction	Equipment "Sub-Rank"	Benefits	Drawbacks	Suppliers **AV**: ARB Verified **EV**: EPA Verified
SCR	B	50-90%	1. M2 = D 2. M3 = D 3. M4 = B+	1. Most effective, commercially available NOx-reduction technology. 2. Earmarked as NOx-reduction strategy for on-highway OEM 2010.	1. High system unit, installation and variable (urea) cost. 2. Complex – requires either pre-installation engine mapping and/or unproven NOx feedback to ensure correct urea dosing. 3. Significant maintenance requirements. 4. Limited commercial product for mobile-source applications. 5. EGT-dependent for peak efficiency; EGT does not effect ability to operate, however.	Argillon/Extengine (AV) Miratech/HUG CCA

Table 4-11. Recommended PM/NOx Combination Control Technologies

Technology	Rank ('M1')	NOx Reduction	PM Reduction	Equipment "Sub-Rank"	Benefits	Drawbacks	Suppliers **AV**: ARB Verified **EV**: EPA Verified
SCR + DPF	A	50-80%	80-90%	1. M2 = C 2. M3 = C 3. M4 = A+	1. Most effective, commercially available NOx-and PM-reduction technology. 2. Earmarked as NOx-reduction strategy for on-highway OEM 2010 (most likely with the catalytic combustion of fuel design DPF).	1. High system unit, installation and variable (urea) cost. 2. Complex – requires either pre-installation engine mapping and/or unproven NOx feedback to ensure correct urea dosing. 3. Significant maintenance requirements. 4. Limited commercially available product for mobile-source applications, to-date. 5. EGT-dependent for peak efficiency (SCR); EGT-dependent for regeneration (DPF).	Extengine/Argillon Miratech/HUG CCA
Lean NOx Cat + DPF (a.k.a.., LNC)	B	25%	80-90%	1. M2 = C 2. M3 = C 3. M4 = B+	1. Less effective than SCR+DPF, but commercially available NOx-and PM-reduction technology. 2. "Self-operating" – requires no urea replenishing, for example.	1. Comparatively poor NOx performance when compared with SCR 2. 5-8% fuel economy penalty. 3. viewed as interim solution until SCR or NOx-Adsorbers become commercialized.	Cleaire (AV)

Technology	Rank ('M1')	NOx Reduction	PM Reduction	Equipment "Sub-Rank"	Benefits	Drawbacks	Suppliers **AV**: ARB Verified **EV**: EPA Verified
Engine Repower	B	Varies, depending upon "Tier" of engine being replaced (see Tables 13 & 14, below) Varies, depending upon engine "Tier" replaced		1. M2 = B 2. M3 = B 3. M4 = B Assumes all these equipment types have electronic FIE. Replacing older, mechanical FIE-equipped machines with electronic FIE increases installation complexity to the point where some mechanical-to-electronic replacements may not be feasible.	1. Full engine manufacturer warranty is attractive to many fleets. 2. Frequently cost-effective, especially for NOx-reduction. 3. May present the only option for some non-road applications (such as locomotives and some vessels such as tugboats.) due to lack of aftertreatment options. 4. No unique maintenance requirements – "just like the engine that was replaced." 5. Depending on the "Tier" installed, may result in fuel economy improvement, especially if replacing mechanical FIE w/electronic FIE.	1. High unit cost. 2. High installation cost. 3. Some mechanical FIE engines, may not be replaceable with electronic FIE engines. 4. Depending on the Tier engine being replaced, new, higher Tier engine may only yield modest NOx, or PM reductions.	OEMs
Engine Rebuild (kits)	B	Varies depending upon "Tier" of engine being rebuild		M2 = B M3 = B M4 = B	1. Minimal additional cost to fleet operator 2. Provides renewed engine warranty; comfort to the fleet owner	1. Limited availability of engines and applications 2. Compliance issues	OEMs

Technology	Rank ('M1')	NOx Reduction	PM Reduction	Equipment "Sub-Rank"	Benefits	Drawbacks	Suppliers **AV**: ARB Verified **EV**: EPA Verified
EGR + DPF	C	40%	80-90%	1. M2 = C- 2. M3 = D 3. M4 = C+	1. Less effective than SCR+DPF, more effective tan LNCs, and commercially available NOx-and PM-reduction technology. 2. "Self-operating – requires no urea replenishing, for example.	1. High unit cost. 2. High, complex installation cost. 3. Complex operation 4. Requites engine dyno engine mapping. 5. DPF is EGT dependent for regeneration 6. DPF requires periodic ash cleaning. 7. Requires use of ULSD 8. 3-5% fuel economy penalty 9. EGR process whereby exhaust gas (with some water and impurities) is re-introduced back into the combustion process, may compromise engine durability and warranties. 10. Only suitable for medium and smaller engines (< 250 hp). 11. Not suitable for engines operated at high loads for prolonged time periods.	STT Emtec/JMI (AV)

Technology	Rank ('M1')	NOx Reduction	PM Reduction	Equipment "Sub-Rank"	Benefits	Drawbacks	Suppliers **AV**: ARB Verified **EV**: EPA Verified
SCR + Active DPF	C	50-80%	80-90%	1. M2 = D 2. M3 = D 3. M4 = C+	1. Potentially the most effective, NOx and PM-reduction technology, when commercially available. 2. Earmarked as NOx-reduction strategy for on-highway OEM 2010. 3. EGT-independent.	1. Very complex and expensive system. 2. Available only in prototype stage.	Extengine (under development)

Table 4-12. Recommended Fuels and Additives Technologies

Technology	Rank ('M1')	NOx Reduction	PM Reduction	Equipment "Sub-Rank"	Benefits	Drawbacks	Suppliers **AV**: ARB Verified **EV**: EPA Verified
Non-Metallic additives/FBCs	B	0-7%	0-10%	Applicable to all engines.	1. Modest, NOx and PM reductions. 2. Requires no engine or vehicle modifications. 3. Requires no infrastructure (such as for urea-SCR or CNG). 4. No apparent increase other pollutants – criteria or unregulated. 5. Non-toxic (unlike metal-based additives). 6. May be used in conjunction with DPFs and other aftertreatment devices. 7. Fungible with diesel of any sulfur content. 8. 3-5% fuel economy improvement.	1. Small NOx and PM reductions; difficult to quantify. 2. Labor intensive – tanks must be filled (though quantities are small). 3. Continual replenishment incurs variable cost for fleets. 4. Compliance issues – reliance on humans to replenish tanks, or install automatic filler (either on-board vehicle or at centrally fuelling tank, incurring additional costs. 5. Awaiting verification. 6. May increase NMHC+CO. 7. May deteriorate fuel properties (e.g., stability)	Biofriendly (TxLED) GTAT

Technology	Rank ('M1')	NOx Reduction	PM Reduction	Equipment "Sub-Rank"	Benefits	Drawbacks	Suppliers **AV**: ARB Verified **EV**: EPA Verified
Biodiesel	B	0 to -4% (for B20)	10-15% (for B20)	Using ASTM 6751 quality blends, up to B20 is acceptable in most engines.	1. Reduces PM, CO, HC 2. Various blends available: B20 is 20% biodiesel, 80% diesel. 3. Verified for trucks. 4. Requires no engine or vehicle modifications. 5. Requires no infrastructure (such as for urea-SCR or CNG). 6. Improves lubricity. 7. Manufacturing from US stocks may reduce foreign energy dependency.	1. May increase NOx 2. Higher freezing temperature – not recommend for cold weather operation (esp. >B20 blends). 3. Needs to meet ASTM specs 4. Care needed for transport and storage.	(EV), various manufacturers
E-Diesel	C	1.6%	20%	Applicable to all engines; low flash point precludes use in marine applications (safety/fire concerns).	1. Modest NOx and PM reductions (values at left from 9/03 ARB verification). 2. Requires no engine or vehicle modifications. 3. Requires no infrastructure (such as for urea-SCR or CNG). 4. No apparent increase other pollutants – criteria or unregulated. 5. Non-toxic (unlike metal-based additives). 6. May be used in conjunction with DPFs and other aftertreatment devices. 7. Fungible with diesel of any sulfur content.	1. Lowering of flash point increased fuel volatility and compromises safety. 2. Diminished physical and chemical properties when compared to conventional diesel: a. Lower lubricity. b. Lower cetane number. c. Lower flash point. d. Lower viscosity.	O_2 Diesel (AV)

Technology	**Rank ('M1')**	**NOx Reduction**	**PM Reduction**	**Equipment "Sub-Rank"**	**Benefits**	**Drawbacks**	**Suppliers** **AV**: ARB Verified **EV**: EPA Verified
Water Emulsions	C	10-20%	15-60%	Should not be used in older engines (older than 1998).	1. Good compromise solution for modest, but consistent NOx and PM reductions. 2. EPA and ARB verified for dockside ports and construction equipment, and trucks. 3. Requires no engine or vehicle modifications. 4. Requires no infrastructure (such as for urea-SCR or CNG). 5. No apparent increase other pollutants – criteria or unregulated.	Reduces engine power Increases fuel consumption Availability issues. Cold weather operation and storage issues (water freezes!). Stability -- special fuel storage requirements (needs periodic in-tank mixing). Potential engine durability issues with older (pre-1994) engines. Incremental cost increase over diesel fuel. Not accepted by may users/fleets Increases HC and potentially other, no-regulated emissions	Lubrizol (EV) Aquazole (AV)

Technology	**Rank ('M1')**	**NOx Reduction**	**PM Reduction**	**Equipment "Sub-Rank"**	**Benefits**	**Drawbacks**	**Suppliers** **AV**: ARB Verified **EV**: EPA Verified
Metallic additives/FBCs	D	Some modest reductions reported, but not documented		Applicable to all engines	1. Some, though undocumented, NOx and PM reductions. 2. Requires no engine or vehicle modifications. 3. Requires no infrastructure (such as for urea-SCR or CNG). 4. Typically used to promote DPF regeneration at lower EGTs. 5. Fungible with diesel of any sulfur content. 6. Some (though undocumented) fuel economy improvement. 7. 2-5% fuel economy benefit.	1. Toxicity concerns (trace atmospheric metals). 2. Undocumented NOx and PM reductions. 3. Labor intensive – tanks must be filled (though quantities are small). 4. Continual replenishment incurs variable cost for fleets. 5. Compliance issues – reliance on humans to replenish tanks, or install automatic filler (either on-board vehicle or at centrally fuelling tank, incurring additional costs.	CDTI (EV only in conjunction with DOC and flow through wire mesh filter).

Table 4-13. Idle Reduction Technologies

Technology	Rank ('M1')	Comments	Suppliers
Automatic engine shut-down systems	B	Limited availability for non-road engines Strategy compatible with passive DPF systems	ZTR Control Systems TAS Cummins
Battery powered cabin heating and air conditioning devices	C	Availability generally limited to highway truck and locomotive engines.	Autotherm Bergstrom Safer Corporation
Diesel driven heating systems	C		Kim Hotstart Automotive Climate Control Espar Teleflex Webasto
Auxiliary power units/generator sets	D		EcoTrans Technologies Aux Generators Frigette Thermo King Pony Pack

The following two tables provide Tier 1-3 (Table 4-14) and Tier 4 EPA emission standards. The respective NOx/PM emission limits allow estimation of the emission reductions when using engine repower or rebuild technologies.

Table 4-14. EPA Non-road Engine Emission Standards, Tiers 1 – 3, g/kWh

Rated Power (kW)	Tier	Model Year	NOx	HC	NMHC + NOx	CO	PM
kW<8 hp<11	Tier 1	2000	—	—	10.5	8.0	1.0
	Tier 2	2005	—	—	7.5	8.0	0.80
8≤kW<19 11≤hp<25	Tier 1	2000	—	—	9.5	6.6	0.80
	Tier 2	2005	—	—	7.5	6.6	0.80
19≤kW<37 25≤hp<50	Tier 1	1999	—	—	9.5	5.5	0.80
	Tier 2	2004	—	—	7.5	5.5	0.60
37≤kW<75 50≤hp<100	Tier 1	1998	9.2	—	—	—	—
	Tier 2	2004	—	—	7.5	5.0	0.40
	Tier 3	2008	—	—	4.7	5.0	
75≤kW<130 100≤hp<175	Tier 1	1997	9.2	—	—	—	—
	Tier 2	2003	—	—	6.6	5.0	0.30
	Tier 3	2007	—	—	4.0	5.0	
130≤kW<225 175≤hp<300	Tier 1	1996	9.2	1.3	—	11.4	0.54
	Tier 2	2003	—	—	6.6	3.5	0.20
	Tier 3	2006	—	—	4.0	3.5	
225≤kW<450 300≤hp<600	Tier 1	1996	9.2	1.3	—	11.4	0.54
	Tier 2	2001	—	—	6.4	3.5	0.20
	Tier 3	2006	—	—	4.0	3.5	
450≤kW ≤560	Tier 1	1996	9.2	1.3	—	11.4	0.54

Rated Power (kW)	Tier	Model Year	NOx	HC	NMHC + NOx	CO	PM
	Tier 2	2002	—	—	6.4	3.5	0.20
	Tier 3	2006	—	—	4.0	3.5	
kW>560 hp>750	Tier 1	2000	9.2	1.3	—	11.4	0.54
	Tier 2	2006	—	—	6.4	3.5	0.20

Table 4-15. EPA Non-road Engine Emission Standards, Tier 4, g/kWh

Rated Power	Model Year	PM	NOx
hp < 25	2008	0.40	-
25 ≤ hp < 75	2013	0.03	4.7
75 ≤ hp < 175	2012-2014	0.03	0.40
175 ≤ hp < 750	2011-2013	0.02	0.40
hp > 750	2011-2014	0.02	0.40

5.0 DIESEL ENGINE USE IN THE FUTURE

This section is intended to assess the future of diesel use and emissions in the off road sector by considering the use of new technologies that may impact diesel use, existing and future local, state, and federal regulations, and the potential growth of areas in which diesel technologies are used in New York State. Current technology and regulations form the basis for the following discussion, but any predictions about the evolution of diesel use are qualitative and largely speculative.

Many influences will affect future diesel development, and the following forces are likely to be important drivers:

- engine technology developments
- control strategy evolution
- regulatory initiatives
- economic or market growth
- public stakeholder influences

These forces are synergistic, interact in complex ways, and can vary dramatically depending on unforeseen circumstances. For example, §5.5 describes how implementation of ULSD and best available technology (BAT) regulations in NYC had their origins in the September 11, 2001 terrorist attacks.

5.1 ENGINE TECHNOLOGY DEVELOPMENTS

5.1.1 Diesel Engine Technologies

Common trends in modern diesel engines include:

- High fuel injection pressures for improved fuel atomization and dispersal in the cylinder. For instance, 2007 Volvo engines feature fuel injection pressures of 35,000 psig (241 MPa).
- Advanced fuel injection systems, such as common rail injection or advanced unit injectors, with multiple fuel injections per stroke.
- Exhaust gas recirculation, with increased EGR rates in 2007 engines.
- Variable geometry turbochargers. Dual-stage turbochargers will be increasingly used to provide high boost pressures.

In addition to these "conventional" approaches, advanced combustion regimes are being introduced to the diesel engine. An example is the Clean Diesel Combustion (CDC) concept introduced by the EPA and being further developed in cooperation with International, Ford, and other industrial partners. The CDC engine uses massive EGR rates to produce ultra low NOx without the need for aftertreatment, and without compromising engine efficiency. To maintain the high EGR rates, the engine requires an advanced charge air system with very high boost pressures. The concept still produces relatively high PM emissions, making PM aftertreatment necessary.

Further engine technology development is necessary in order to meet future emission challenges, especially those related to NOx control, while maintaining or improving efficiency. Several problems exist with the various NOx aftertreatment technologies. It is likely that the 2010 emission standards can only be met if NOx aftertreatment is combined with advanced combustion concepts, as well as with the continuing use of EGR.

Homogeneous charge compression ignition (HCCI) has been attracting considerable attention as a potential emission control technology for both heavy- and light-duty diesel engine applications. Diesel engines form PM (soot) and NOx under varying flame temperatures and excess air ratios as shown in Figure 5-1[34]. The various types of HCCI move the combustion process away from the soot and NOx formation zones, contrary to the conventional diesel combustion regime, shown as “Today’s Technology” in the figure. HCCI, partial HCCI, low temperature combustion (LTC, roughly corresponding to the DCCS zone in the chart) and other premixed combustion modes are being extensively researched by engine manufacturers, research institutes, and academia. About 150 SAE technical papers were published on HCCI related topics in 2005.

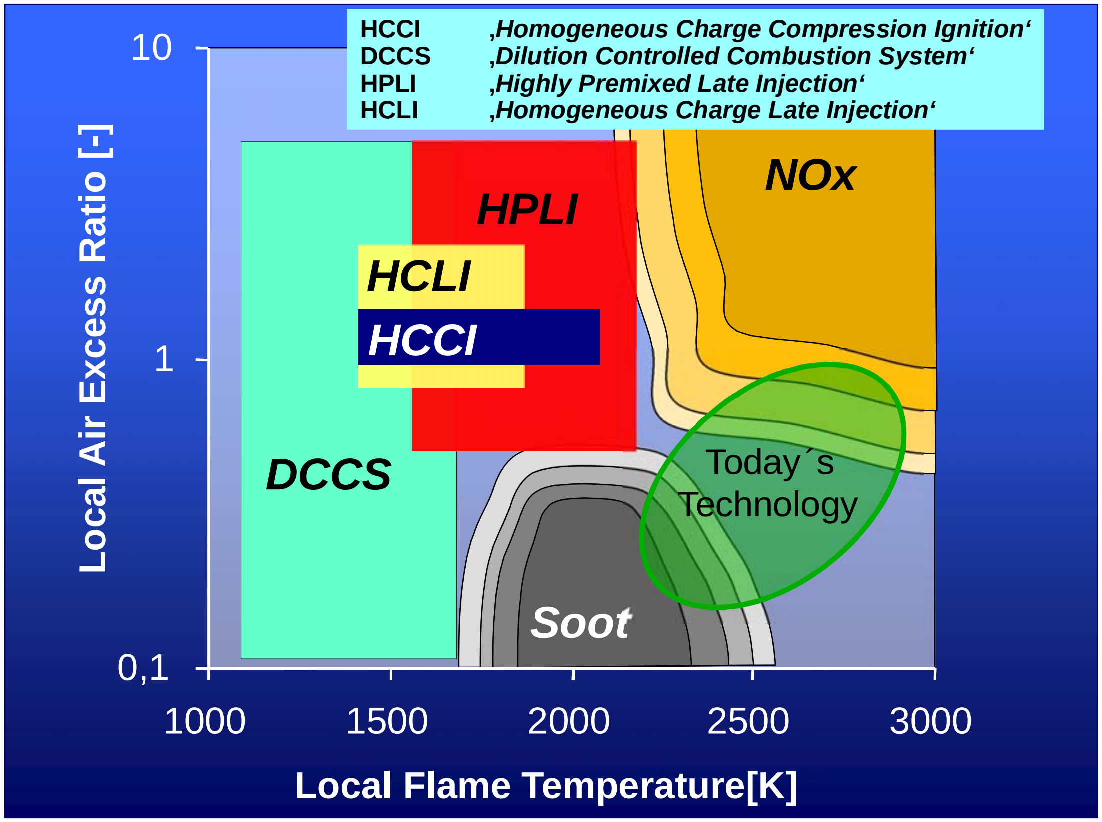

Figure 5-1. Soot and NOx Formation Zones and Combustion Regimes

HCCI combustion could allow for ultra low NOx and PM emissions through engine control means, without the need for particulate filters, NOx aftertreatment, or other costly hardware. The effect of HCCI on engine efficiency and fuel economy remains uncertain, but developers have been aiming at efficiencies at least matching that of today's diesel engines. On the negative side, HCCI produces relatively high CO and HC emissions at low exhaust temperatures. Therefore, heated DOC systems may be necessary in HCCI engines.

HCCI is difficult to control at high engine loads. While full-load HCCI combustion has been reported in laboratory engines, many challenges remain before it can be commercialized. A more likely approach, especially in the near-term, is the so called "mixed-mode" diesel engine, operating in the HCCI mode at low loads, and switching to conventional diesel combustion at higher loads. Development of a mixed-mode fuel injector for such engines has been reported by Caterpillar. It is probable that mixed-mode combustion will be widely used in 2010 highway truck and bus engines.

Premixed diesel combustion will likely play a role in 2007 engines. Partially premixed combustion may be in use in some currently available engines. For example, Caterpillar's "ACERT" engines feature an intake valve actuator. It can be speculated that this variable valve actuation technology allows for early opening of the intake port and results in a partially premixed charge. Variable valve actuation, as indicated by the presence of an actuator, seems to be also featured in Euro IV truck engines by Volvo. Technical details are not available because manufacturers consider their engine designs to be trade secrets.

5.1.2 Gasoline Engine Influences

The reasons for choosing diesel or gasoline engines for motive are varied and subject to debate. The choice of diesel engines for light-duty highway vehicles may depend partly on fuel cost. In Europe, diesel penetration ranges from between 20 - 80 % of the fleet depending on country, while in the US it is approximately 2 - 3 %, except for the medium-duty pickup, van, and "work-truck" market, which is about 30 % diesel-powered. England has the smallest price differential between gasoline and diesel fuel and has the correspondingly lowest penetration of diesel-powered light-duty vehicles (at approximately 20 %). By contrast, diesel fuel in Austria is much less expensive than gasoline, and the corresponding light duty diesel penetration is approximately 80 %. The fuel pricing structure in the US is currently inverted with respect to Europe. Lack of interest in diesel-powered vehicles, with their significantly higher initial purchase price, is exacerbated by diesel fuel costs of $0.20 to $0.40 per gallon more than gasoline.

The heavy-duty diesel market is entirely different from the light-duty consumer world. While fuel cost differentials are a factor, they are substantially superseded by a number of other issues specific to on-highway vehicle or nonroad machine applications. Diesel-powered machines in on-highway and nonroad construction sectors are purchased to perform specific tasks that are difficult for their heavy-duty gasoline counterparts (if they existed) to perform. Heavy-duty gasoline vehicles and equipment do not possess the power or torque rise (for pulling large loads or lifting material on a construction site, for example) that an equivalently sized diesel vehicle or machine possesses. Providing an equivalent gasoline-powered vehicle would require a larger unit, with an engine of significantly larger displacement than the diesel it would replace, just to attain equivalent power. The gasoline engine's far less broad torque curve, necessary to provide peak power over a large speed and load range, implies that the power source is unsuited for the heavy-duty on-highway and nonroad industry.

The anticipated increased complexity and cost of emission systems in future diesel truck engines, however, has sparked some interest in developing gasoline fueled engines. A research consortium to develop a heavy-duty gasoline engine has been started by the Southwest Research Institute. In order to become a commercially viable option, the gasoline engines would have to show thermal efficiency and fuel economy similar to that of the diesel engine. This would likely require turbocharging, which in turn could cause problems with NOx emission control. The feasibility of this concept largely depends on the cost and fuel economy of 2010 heavy-duty diesel engines, which remains uncertain.

One argument for potential consideration of gasoline engines for the construction industry involves smaller pieces of equipment at approximately 100 hp or less. It is true that smaller gasoline-powered pieces of equipment could be designed to achieve nearly the same operational characteristics of their diesel counterparts. The engines, however, would likely be physically larger. This is because the diesel engine is more thermodynamically efficient, and a gasoline replacement engine would typically have a larger displacement.

The operational issues that make diesel attractive to construction fleets are important. The diminished safety of the gasoline engine (gasoline is a far more volatile fuel than diesel and can explode much more readily), the diminished reliability, and reduced durability of current gasoline engines will affect purchase decisions. The Otto cycle (gasoline, spark-ignition) thermodynamic efficiency is about 30 % less than the Diesel cycle, and this translates into significantly poorer fuel economy. This is an important consideration in the construction industry, for example, where the two largest expenditures for fleets are fuel and labor. The need for two fuel streams for a gasoline and diesel fleet (necessitating two on-site fueling tanks or separate gasoline and diesel trucks for equipment re-fueling) can also affect fleet purchase decisions.

In the end, it is unlikely that gasoline-powered pieces of equipment, regardless of size, will find their way into the New York or national construction markets. Furthermore, the Tier 4 nonroad emissions standards, discussed in §5.3, have comparatively lenient NOx requirements for nonroad engines less than 75 hp. This presents less of a barrier to achieving Tier 4 standards for these smaller engines. Among the smallest Tier 4 nonroad engines (between 25 and 50 hp), some displacement of diesel with gasoline may occur because of the PM emission standards. The incremental cost of fitting DPFs on small engines may be sufficiently high to encourage a switch to gasoline units which would not require such aftertreatment.

5.1.3 Other Technologies

Such fuels as compressed natural gas (CNG) or liquid propane gas (LPG) will likely continue to be used in their respective niche markets. It is not believed they will pose a significant competition to diesel, especially because advanced diesel technology is often cleaner than CNG or LPG engines.

Hydrogen fuel cell powerplants are currently in early stages of development, targeting primarily passenger cars. Their usage in mobile nonroad machinery in the near-to-medium term is unlikely.

Internal combustion engines, both diesel and gasoline, will be increasingly used in hybrid electric powertrains. In heavy-duty vehicles, where diesel is the preferred type of engine, hybrids have already made their entry into the urban bus market. According to a recent National Renewable Energy

Laboratories study[35] which evaluated urban buses in New York City, Orion VII / BAE hybrids showed the best fuel economy, lowest fuel cost, lowest maintenance costs, and highest reliability when compared with CNG and conventional diesel buses.

In nonroad applications, electric hybrid switch locomotives have been developed and commercialized by RailPower Technologies ("Green Goat"; see <http://www.railpower.com/products_hl_ggseries.html>). Development of an electric hybrid tug boat has also been reported[36] and non-road vehicles which use hydraulic regenerative braking (hydraulic hybrid) are coming to market[37]. This work indicates that hybrid designs may be feasible in construction applications, but on-highway, railroad switching, and certain marine developments are more likely. This is because many commercial vehicle fleets operate over well-characterized routes and potential cost savings can be calculated more accurately than for construction equipment.

5.2 CONTROL STRATEGY EVOLUTION

Control strategies have evolved both as part of OEM initiatives to control their own engine emissions and as aftermarket or retrofit systems developed by other concerns. The balance between these two forces is likely to change, based on the OEM market history and the more intimate connections that are developing between the engine and various control technologies.

5.2.1 OEM Market History

Diesel oxidation catalysts were the first emission control strategies introduced on new diesel engines by Volkswagen in 1989 on a voluntary basis. They became a standard component on European diesel passenger cars since the introduction of the Euro 2 emission standards in the mid-1990's.

In the US, the use of DOC for highway heavy-duty engines was triggered in 1994, when the EPA introduced a PM emission standard of 0.1 g/bhp-hr for trucks and 0.05 g/bhp-hr for buses. Diesel oxidation catalysts were introduced on several truck and bus engines in order to meet that PM standard. The use of catalysts on US heavy-duty engines, however, had been steadily decreasing, as the 0.1 g/bhp-hr PM standard could be achieved in more advanced, electronically controlled engines without the use of aftertreatment devices. The reduction of PM emission was the only purpose of the DOC; no reductions of gaseous HC or CO were necessary under the 1994 regulations. Certain heavy-duty engines are again using DOCs to meet the 2004 emission standards, such as the Caterpillar ACERT engines.

Mercedes introduced PDPFs in the mid-1980's on passenger cars sold in California, but these were soon abandoned due to technical problems. Peugeot re-introduced the DPF in 2000 in France. The Peugeot system has utilized fuel additives and engine management strategy to support active regeneration. Since 2004 and 2005, DPFs have been increasingly introduced by German and other European car manufacturers. Under the proposed Euro 5 emission regulation, all cars are expected to require DPFs in the 2008 - 2009 time frame. All new DPF systems currently introduced in Europe utilize catalyzed filter technology (with active regeneration support), as opposed to fuel additive regeneration.

Nissan Diesel (Japan) introduced the first urea-SCR systems on mobile engines in 2004 and DaimlerChrysler (Germany) began using them in January 2005. By February 2006, DaimlerChrysler had sold 10,000 SCR equipped trucks.

5.2.2 Future OEM Systems

The US 2007 - 2010 emission standards will force the use of advanced aftertreatment systems on all heavy-duty truck and bus engines. The 2007 engines will be fitted with catalyzed DPFs with active regeneration support. The filters will be able to regenerate passively during high engine load operation. During light load operation, when the exhaust temperature is insufficient to support passive regeneration, active regeneration is triggered by the engine control unit. The exhaust temperature is increased by injection of diesel fuel (in general, a combination of in-cylinder and exhaust injection) followed by oxidation over a catalyst positioned upstream of the filter. This strategy obviously involves a certain fuel economy penalty, due to the extra consumption of fuel for regeneration, as well as the increased pressure drop over the DPF. Engine manufacturers expect the 2007 engines to have similar fuel economy to the current engines, as the DPF fuel economy penalty would be offset by engine efficiency gains in other areas (combustion design, reduction of parasitic loads, etc.).

In the long term, US Department of Energy funded research is aiming at a 60 % thermal efficiency target in the heavy-duty diesel engine, by incorporating additional technologies such as exhaust heat recovery. The increased thermal efficiency would more than compensate for fuel penalties associated with aftertreatment, creating prospects for ultra clean diesel engines which would also be more fuel efficient.

The emission control strategy for 2010 engines still remains somewhat uncertain. The 2010 engines will continue to use the DPF system, most likely in combination with some form of NOx aftertreatment. The NOx adsorber technology, once envisioned by the EPA, has never achieved the necessary emission durability. It appears that urea-SCR, despite urea supply, infrastructure, and regulatory compliance issues, is the only NOx aftertreatment option that is sufficiently mature to allow for commercial deployment in 2010.

The impact of the DPF plus SCR package on engine performance and fuel economy is difficult to predict. In the current Euro IV / V engines with urea-SCR systems, the engines are calibrated for advanced injection timing, high NOx (9-10 g/kWh) and low PM output (no DPF), resulting in about 5 % fuel economy improvement. Urea solutions, consumed at a rate of about 5 % relative to diesel fuel, presents an added operational cost in SCR engines. However, because the price of urea is only about 50 - 60 % of the price of diesel fuel, operators of urea-SCR engines enjoy an overall operating cost benefit. Unfortunately, the Euro IV / V SCR strategy is only possible at relatively relaxed NOx requirements. Note that the Euro V NOx limit is 2 g/kWh. To meet the US 2010 NOx limit of 0.2 g/bhp-hr, a combination of low engine-out emissions (using in-cylinder techniques and EGR) and SCR will be necessary. Therefore, fuel economy improvement through advanced injection timing calibration alone is unlikely.

Similar aftertreatment technologies, such as DPF followed by DPF + NOx aftertreatment, are anticipated in US nonroad engines as the Tier 4 standards are phased-in over the 2011 - 2014 period. Tier 4 engines above 25 hp are likely to require DPFs while those above 75 hp will require NOx aftertreatment.

Diesel aftertreatment technologies past 2010 - 2015 are open to speculation, depending on the progress in novel combustion technologies. For instance, if full HCCI combustion becomes feasible, both the DPF and urea-SCR technologies will become redundant, and the DOC (possibly in a heated version) would become the major aftertreatment strategy.

5.2.3 Future of the Retrofit Market

The aftermarket for retrofit technologies dates back to the 1970's when the first DOCs were introduced in underground mining applications. The first aftermarket DPFs were introduced in the late 1980's, also in underground mines.

The size of the engine emission control aftermarket for both diesel and spark-ignition engines remained very limited through the 1980's, but gradually reached some tens of millions of dollars per annum in the 1990's. This allowed the formation of several small size suppliers who specialized in small volume, often custom designed control systems. There were no barriers for entry for small start-up suppliers, as no formal product performance criteria existed.

In the late 1990's, a number of diesel retrofit programs had been established in the US and in other parts of the world. Most of these programs also introduced formal performance criteria and testing requirements for the retrofit emission control strategies, such as the California and the EPA verification programs. More larger companies entered the market as the economic incentive grew bigger, and the equipment verification requirements created higher barriers for smaller, less well-capitalized players.

At this time, we are entering the peak years of the diesel retrofit market. Heavy-duty engines manufactured today are still not equipped with advanced aftertreatment. Once on the road they immediately become a potential retrofit target. After 2007 (and 2011 - 13 in nonroad engines), new engines will be fitted with DPFs by the OEMs. Thus, the pool of engines that can be retrofitted will be limited to the increasingly older and smaller population of in-use engines, causing a gradual decline of the aftermarket. A new replacement part market, analogous to oil and air filters for automobiles, may emerge. However, independent aftermarket suppliers will have to compete with OEM replacement parts, and this may present a significant barrier for smaller size suppliers.

In summary, the increasing OEM integration of diesel aftertreatment will eventually lead to a decline of the retrofit market. Small suppliers who depend on aftermarket sales must increasingly build business with OEMs in order to continue growth. A potential fit exists between those suppliers and the smaller nonroad engine manufacturers who face sizeable technological challenges in meeting the Tier 4 standards.

5.3 REGULATORY INITIATIVES

5.3.1 Federal On-highway Engine Regulations

Emission regulations have become a major force driving the development of diesel engine technology since the 1990's. The United States was the first country to introduce diesel emission standards, and the US regulations have generally remained the most stringent in the world. Since late 1990's, increasingly more stringent standards have also been introduced in the EU and Japan (JP). Today's and future EU and JP standards match the stringency of US regulations in PM emission limits, but tend to remain more relaxed in controlling NOx.

The most challenging diesel emission regulation for new heavy-duty truck and bus engines are the US 2007-2010 standards, with the following emission limits:

- PM: 0.01 g/bhp-hr
- NOx: 0.2 g/bhp-hr
- non-methane hydrocarbons (NMHC): 0.14 g/bhp-hr

The above PM emission limit applies to all model year (MY) 2007 on-highway engines. The NOx limit will be phased in on 50 % of 2007 - 2009 MY engines (manufacturer's fleet average basis) with full compliance in 2010. All engine manufacturers have elected to meet the 50 % phase-in requirement by certifying all of their 2007 - 2009 MY engines to a NOx level corresponding to 50 % of the current (2004) requirements. As a result, all 2007 - 2009 engines are expected to have NOx emissions of less than about 1.2 g/bhp-hr.

The 2007 emission standards will be met through the use of DPFs and EGR, as discussed below. The 2007 emission limits are considered feasible, and manufacturers are in an advanced stage of testing 2007 trucks with their fleet customers.

The 2010 standards present more technical challenges due to the extremely stringent 0.2 g/bhp-hr NOx limit. The most promising current technology for meeting the 0.2 g limit is a combination of advanced combustion techniques, EGR, and urea SCR. However, urea availability (infrastructure) and compliance issues are currently being discussed between the EPA and engine manufacturers.

5.3.2 Federal Nonroad Engine Regulations

Emission regulations for nonroad engines are typically delayed relative to on-highway engines. The non-road equivalent of the 2007-2010 standards, which are believed to require similar engine and emission technologies, are the Tier 4 emission standards summarized in Table 5-1.

Table 5-1. Tier 4 Emission Standards

Engine Power	Year	CO	NMHC	NMHC+NO_x	NO_x	PM
kW < 8 (hp < 11)	2008	8.0 (6.0)	-	7.5 (5.6)	-	0.4[a] (0.3)
8 ≤ kW < 19 (11 ≤ hp < 25)	2008	6.6 (4.9)	-	7.5 (5.6)	-	0.4 (0.3)
19 ≤ kW < 37 (25 ≤ hp < 50)	2008	5.5 (4.1)	-	7.5 (5.6)	-	0.3 (0.22)
	2013	5.5 (4.1)	-	4.7 (3.5)	-	**0.03 (0.022)**
37 ≤ kW < 56 (50 ≤ hp < 75)	2008	5.0 (3.7)	-	4.7 (3.5)	-	0.3[b] (0.22)
	2013	5.0 (3.7)	-	4.7 (3.5)	-	**0.03 (0.022)**
56 ≤ kW < 130 (75 ≤ hp < 175)	2012-2014[c]	5.0 (3.7)	0.19 (0.14)	-	**0.40 (0.30)**	**0.02 (0.015)**
130 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)	2011-2014[d]	3.5 (2.6)	0.19 (0.14)	-	**0.40 (0.30)**	**0.02 (0.015)**

Bold typeface standards will likely require aftertreatment technologies for achievement.
[a]Hand-startable, air-cooled, DI engines may be certified to Tier 2 standards through 2009 and to an optional PM standard of 0.6 g/kWh starting in 2010
[b]0.4 g/kWh (Tier 2) if manufacturer complies with the 0.03 g/kWh standard from 2012
[c]PM and CO: full compliance from 2012. NOx and HC: Two options. Option 1, if banked Tier 2 credits used: 50% of engines must comply in 2012-2013; Option 2, if no Tier 2 credits claimed: 25% engines must comply in 2012-2014, with full compliance from 31 December, 2014
[d]PM and CO: full compliance from 2011; NOx and HC: 50% engines must comply in 2011-2013

The 0.03 g/kWh PM limits are believed to require the use of DPFs on new nonroad engines and the 0.40 g/kWh NOx limits will likely require aftertreatment. Ultra-low PM-emitting engines larger than 50 hp will be required from 2011 - 2013, depending on the engine power. Ultra-low NOx-emitting engines larger than 75 hp will be required from 2014. After those dates, the major PM or NOx emission contributors will be older in-use engines and small Tier 4 engines (which will not require PM or NOx aftertreatment).

The Tier 4 standards are not applicable to locomotive and marine engines. In 2004, the EPA issued an Advance Notice of Proposed Rulemaking, indicating that aftertreatment-forcing standards for both locomotives and marine engines would be proposed in 2005. However, the rulemaking has been delayed, and no proposal has been published yet.

5.3.3 Federal, State, and Local Initiatives

The EPA operates a "Voluntary Diesel Retrofit Program" designed to encourage public and private fleet owners to reduce emissions from existing equipment. The EPA Office of Transportation and Air Quality facilitates the introduction of innovative emission reduction technologies through a performance verification program. The verified technology list serves as a resource from which diesel equipment owners and operators can choose aftermarket technologies with proven effectiveness. The list is available at <www.epa.gov/otaq/retrofit/retroverifiedlist.htm>.

The Northeast Diesel Collaborative, at <www.northeastdiesel.org>, was established in 2005 by the Northeast States for Coordinated Air Use Management (NESCAUM). The collaborative's mission is to create partnerships, initiate pilot projects, voluntary, and mandatory emissions reduction programs which target on-highway, construction, marine, and rail applications. Initiatives include:

- retrofitting, retiring, and replacing polluting engines
- electrifying truck stops to enable truckers to shut down their engines
- creating and enforcing measures to reduce engine idling
- requiring clean diesel in contracts
- promoting cleaner fuels
- offering workshops and producing toolkits for key sectors and stakeholders
- measuring and assessing program effectiveness

State-level programs outside of New York include the Texas Emissions Reduction Plan which has, in the past, funded grants to fleets for technology demonstrations, research and development programs, and emission reduction incentives. A list of projects is available from <www.tceq.state.tx.us/implementation/air/temp/hot.html>. Other Texas state-level programs are described at <www.tercairquality.org> and <www.tercairquality.org/NTRD>.

The California Air Resources Board operates a technology performance verification program which is similar to EPA's. This program supports California's Diesel Risk Reduction Plan, which concentrates on PM emissions. A list of California-verified technologies is available at <http://www.arb.ca.gov/diesel/verdev/currentlyverifiedtech.htm>.

Both the states of New Jersey and Connecticut have ongoing diesel emissions reduction initiatives that would mandate use of control technologies and ULSD for select on-highway and nonroad vehicles. New Jersey's Diesel Risk Reduction Legislation, embodied in bills A3182 and SCR113, mandates retrofit deployment for:

- school buses that are publicly or privately owned (16,470 vehicles)
- garbage trucks that are publicly or privately owned and used in public contracts (2,180 vehicles)
- NJ Transit buses (1,993 vehicles)
- privately owned transit buses (7,588 vehicles)
- publicly owned on-road and non-road vehicles (2,138 vehicles)

New Jersey will require use of ULSD for all non-road vehicles as of January 15, 2007, if the outcome of a public hearing, conducted by NJ Department of Environmental Protection (DEP) in July 2006, indicates that there is sufficient supply. Approximately 800 tons of PM reductions will be achieved over the next four years if this early phase takes effect. The state's January, 2007 ULSD requirement is more stringent than the federal mandate which does not require use of this fuel in the nonroad sector until 2010.

In addition to this mandatory program, NJ DEP has formed a series of sector-specific workgroups and conducted a number of stakeholder workshops. The groups were asked to develop a menu of diesel control strategies to be submitted to NJ DEP as they develop the State Implementation Plan for PM2.5 and ozone. The results for all four workgroups were published in October of 2005[38] and recommended a series of voluntary programs that would essentially be layered over the mandatory program, outlined above.

Connecticut's Clean Diesel Plan, through Senate Bill 920, directs the Commissioner of Environmental Protection, through CT DEP, to develop a Connecticut Diesel Emission Reduction Strategy that will recommend programs, policies and legislation for achieving reductions of diesel PM consistent with reduction targets in the Connecticut Climate Change Action Plan 2005. The impetus for the legislation emanated from Environment Northeast, a regional environmental group. The recommendations were submitted to the Governor's Office for review in January 2006.

At the local level, New York City's LL77 mandates USLD and "best available technology" for controlling emissions on construction equipment used on behalf of the City. Section 5.5 discusses this statute and its history.

Also at the local level, NESCAUM, for example, is involved with initiatives such as a NYC Department of Sanitation DPF retrofit program which started in 2002.

5.3.4 <u>Harmonization of Standards</u>

Engine and equipment manufacturers have been calling on the environmental regulatory authorities in the US and worldwide to harmonize engine emission testing requirements and emission standards. Such harmonized requirements would make it possible to supply virtually the same engine models to different markets, thus minimizing the cost of engine development and regulatory emission approvals.

California has had the right to establish its own emission standards, which can be different from the federal EPA requirements. Other states can either adopt the California standards or adhere to the federal regulations. Traditionally, California emission requirements for passenger cars (currently LEV II) have been more stringent than those by the EPA (currently Tier 2). California has also adopted greenhouse gas (GHG) emission standards from passenger cars, but the regulation is currently being challenged in court by the auto industry. GHG emissions are not currently regulated under the EPA requirements.

In heavy-duty vehicles, however, the California and EPA 2007 - 2010 truck and bus engine emission standards are virtually identical. California and federal emission standards for nonroad engines are also well-harmonized. The federal Clean Air Act Amendments (CAAA) of 1990 preempt California's authority to control emissions from new farm and construction equipment under 175 hp [CAA Section 209(e)(1)(A)] and require California to receive authorization from the federal EPA for controls over other nonroad sources [CAA Section 209 (e)(2)(A)]. Therefore, the same Tier 1 - 4 nonroad emission standards have applied federally and in California.

Worldwide emission standards for highway engines are not currently harmonized. One of the reasons is the lack of worldwide test cycles for light- and heavy-duty vehicles. Work on the development of such cycles is ongoing under the auspices of the United Nations Economic Commission for Europe Working Party on Pollution and Energy (UNECE GRPE) with the participation of US regulatory agencies.

Another important reason for the lack of harmonization are differences in policy in regards to GHG emissions between the EU and US authorities. At the US federal level, there is a reluctance to regulate GHG emissions, and priority is given to voluntary programs. In the EU, GHG emissions became one of the key environmental issues as the Union assumed a worldwide leadership role in controlling climate change. GHG emissions from passenger cars are currently controlled through voluntary agreements between the European Commission and automakers, but will likely become subject to mandatory regulation in the future.

The disconnect between EU and US NOx standards is likely to continue. The EU has chosen dieselization of the passenger car fleet as one method to control transportation GHG emissions, so the corresponding NOx limits are more relaxed than in the US. Very tight NOx standards would likely cause the gasoline auto population to rise, which would also cause CO2 emissions to rise, contrary to EU goals.

Some modifications of the stringent US NOx limits may occur, however, because recent research is at odds with established policies that rely on NOx control to reduce ground-level ozone. A phenomenon, known as the weekend ozone effect, has been discovered in southern California. Heavy-duty diesel traffic, due to its significant contribution to the NOx emission inventory, has been suspected to be one of the most important sources of smog. Ambient measurements have shown, however, that the highest levels of ozone occur during weekends, at times when heavy-duty diesel traffic volumes are decreased. Current theories are that the increased ozone levels on weekends are due to reduced NOx emissions[39]. Lowering ambient NOx concentrations in southern California may be actually counterproductive to controlling ozone concentrations.

The highest level of emission standard harmonization exists in mobile nonroad engines. As mentioned above, standards for that engine category have been harmonized between the EPA and California. Some common approaches were taken in the US the Tier 1 / 2 standards and the EU Stage I / II regulation. In 2004, the EU adopted Stage III / IV emission standards for nonroad engines which are harmonized to a large degree (in terms of both emission limits and timing) with the US Tier 3 / 4 regulations. The test cycles for nonroad engines, including the existing steady-state cycle and the new, Tier 4 Non-Road Transient Cycle are harmonized between the US and the EU. At this time, Japanese nonroad emission standards remain different from those in the US and EU, and long term requirements, similar to the US Tier 4 or EU Stage IV regulations, have not yet been adopted in Japan.

5.4 ECONOMIC OR MARKET FORCES

Over the past two or more decades, construction throughout the nation has steadily increased with New York City and New York State being no exception. An aging infrastructure has prompted renewed bridge, road and tunnel construction for public-sector projects, while renewed commercial and consumer demand has spurred development of commercial office space, condominiums and other types of what the construction industry terms “vertical construction.” Adding to this rather predictable growth is that arising from unforeseen events, such as the aftermath of the terrorist attacks on September 11, 2001, that has precipitated a rapid rise in construction in lower Manhattan. Taken together, these infrastructure requirements, market forces, and unpredictable events bode well for the future economic good health of the construction industry. While quantitative construction market predictions are beyond the scope of this work, the trend points to vigorous construction activity in both the City and the State.

Within the context of this expansion are a number of "specialty projects" that promote increased use of diesel-powered nonroad machines. The harbor deepening project at the Port Authority of New York and New Jersey (PANYNJ) is one example of the numerous port expansion projects throughout the US that require use of diesel machines, in this case rather old, high-emitting dredging machines in close proximity to communities and businesses. The PANYNJ recently completed a rail line into their Staten Island Terminal and is contemplating additional rail lines. These projects will require construction equipment. Finally, other "specialty projects" such as the NYC DEP's numerous infrastructure projects like the Croton Water Filtration Plant in the Van Courtland Park area of the Bronx, the South Ferry Terminal Construction in Lower Manhattan and the Fifty-Ninth Street Tunneling Project for the New York City Water Board, all point to steady, and perhaps increasing, use of diesel-powered construction equipment in New York City.

On the State level, a myriad of NY State Thruway construction projects, either under study, in the construction process or scheduled for future construction, are a snapshot of considerable statewide construction activity. They include the Albany and Buffalo Corridor Studies, the I-84 / I-87 Interchange Project, the Thruway Reconstruction Project between interchanges 23 and 24, and the Tappan Zee Bridge Deck replacement that is expected to begin this summer and be completed by the fall of 2008.

Inter-modal options using rail, highway, and marine applications, such as the promotion of short-haul shipping on the Hudson River to reduce highway congestion, are receiving increased attention as alternatives to traditional land-based routes. Ferry activity in New York harbor, which increased substantially to transport commuters after 9/11, is regarded as a long-term viable alternative to passenger automobile commuter traffic, while oceangoing ship traffic encompassing both commercial and passenger cruise lines shows no signs of abating. Finally, increased sensitivity regarding inherent inefficiencies in truck traffic supporting ports has prompted renewed interest in development of a rail infrastructure for the ports, such as that just competed in Staten Island, as noted above.

5.5 PUBLIC STAKEHOLDER INFLUENCES

5.5.1 Forces behind New York City's Local Law 77

LL77 was born from a confluence of factors both foreseen and unplanned. Much of the awareness of a diesel PM problem at the City level came from EPA's intensifying focus on fine PM exposure, air quality, and local health effects in regions of forecasted PM non-attainment, and from the cleanup and subsequent construction after the terrorist attacks on the World Trade Center on September 11, 2001. With considerable diesel-powered equipment on the site for the massive debris removal and reconstruction effort, EPA monitoring showed highly elevated levels of PM. In the height of the recovery, with over 200 pieces of diesel-powered construction equipment on-site, the emissions profile of this fleet was estimated to be equivalent to that from over 660 unregulated transit buses circling the same site, twelve hours per day.

In an effort to ameliorate this condition, a seminal pilot program was initiated at the reconstruction of Seven World Trade Center, a smaller, sixty-story building that was the first slated for complete rebuilding in the months following the attacks. Under the program, varied types of construction equipment were retrofitted with different types of diesel emissions control devices (including DOCs, ADPFs, and a FTF) to gauge the feasibility of deployment of these types of devices in subsequent, larger scale projects. The success and public awareness of Seven World Trade Center, in addition to growing pressure about addressing the local air quality problem in lower Manhattan, led to consideration of mandatory requirements for diesel emissions mitigation on NYC municipal construction projects. This was the genesis of LL77.

The City Council passed and Mayor Bloomberg approved LL77 in December, 2003. The law amends the city administrative code of New York by requiring that any diesel powered nonroad vehicle 50 horsepower or greater, owned by, operated by or on behalf of, or leased by a City agency, be powered by ULSD and utilize the “best available technology” (BAT) for reducing pollutant emissions. The law requires that any solicitation for a public works contract and any contract entered into as a result from such a solicitation include performance based specifications requiring that all contractors use ULSD and BAT.

In July, 2005, NYC DEP issued its final rulemaking, promulgating LL77 under Chapter 14 of Title 15 of the Rules of the City of New York, requiring the use of ULSD and emissions control technologies for both nonroad vehicles used in city construction and all municipally owned nonroad vehicles regardless of whether they are being utilized on an active construction site. The rulemaking set forth the initial determinations by the DEP Commissioner as to what constitutes BAT for purposes of compliance with city administrative codes, provides a method for BAT selection, and defines a waiver procedure whereby applicants may request a BAT exemption for safety concerns or unavailability of BAT technologies.

An important component of LL77 requires a technologically-based analysis and assessment of emission reduction technologies. Towards this end, the law initially requires the DEP Commissioner to make and periodically publish determinations as to which technologies constitute BAT, and to update such determinations no earlier than once every six months. In establishing BAT, the DEP Commissioner is instructed to make determinations based primarily on PM emissions reduction and secondarily on NOx reductions. Verified technology lists from the US EPA and California ARB for on-highway and nonroad vehicles can form the basis of BAT determinations. The Commissioner may also select non-verified technologies as are deemed appropriate.

The Croton Water Filtration Project, referenced above, is the first construction project to employ LL77 precepts. A second phase, construction of two water connection tunnels, will commence in 2009 and also adhere to LL77 requirements. Other communities, such as White Plains, are also considering their own version of LL77, and a bill pending in the Massachusetts State Legislature mirrors LL77.

5.5.2 Current Political Climate for Retrofits in New York

Much of the formulation of LL77 emanated from state and regional awareness of the growing concern over emissions from diesel engines. For example the Croton Water Filtration Plant construction project, a multi-million dollar city initiative, incorporates a community outreach component, the Croton Facilities Monitoring Committee, that is actively engaged in dialogue with the City regarding construction and the diesel emissions reduction components of the project.

The introduction of LL77 has generated considerable interest in diesel emission reductions from environmental and community groups, political leaders, and industry and health professionals. County laws that follow the LL77 precepts have passed through the Westchester and Rockland legislatures. Spurred by reports regarding the toxicity of PM, including official classification by ARB and EPA, groups have a heightened awareness of diesel-powered activity in their community. This has precipitated renewed activity by Environmental Defense and the Natural Resources Defense Council among others, on a national level and by numerous local and regional groups.

5.6 CONCLUSION

Diesel-powered equipment use in New York will continue to grow, linked primarily to the growth in construction activity for nonroad machines and commercial activity in the transportation sector. Diesel technology will continue to evolve, driven both by regulatory actions and the potential for greater efficiency. Developments are likely to be incremental because of the need to thoroughly prove a new technology’s performance before introducing it to such long-lived equipment. HCCI, other advanced engine technologies, electric hybrid, hydraulic hybrid, self-shifting transmission, and other drive train technologies could represent significant portions of the fleet by 2020 because they will be able to consume less fuel and produce fewer emissions while performing the same work.

Emissions per unit will continue to decrease as Tier III and IV regulations are implemented and as older equipment drops out of the fleet. The differences between the 2002 baseline and 2009 projections, as presented in §2.0, provide indications of future trends. Total emissions are also likely to drop as more state and local authorities mandate use of ULSD and various control technologies, but all such changes will take time to develop because of the existing fleet’s durability.

More local initiatives can be expected due to grassroots efforts such as those described in connection with LL77. This could lead to patchwork regulations and implementations, but many state and city governments may see this as the only alternative in the face of federal government inaction, especially with respect to emissions from the legacy fleet.

The retrofit and aftermarket business will change considerably as control technologies become more intimately connected to engines and drive trains. At this time, many control strategies are still in the development or beta testing stage. The technologies are maturing, however, and they will begin to consistently differentiate into classes which are appropriate to the engine size and service. The suite of technologies that designers will consider for railroad locomotives, for example, will routinely be quite different than those considered for large rubber-tired loaders. OEMs are likely to either closely collaborate with control strategy manufacturers or they will designate their own business units for design and building the equipment. Manufacturers who are not connected with OEMs will probably migrate to the replacement parts market.

In conclusion, both regulatory and economic forces are driving diesel science and technology development. The resulting incremental changes will make the 2020 fleet very different from today's.

6.0 DEMONSTRATION PROGRAM TEST MATRIX

The ultimate goal of NYSERDA's Non-Road Clean Diesel Program is to demonstrate and evaluate the feasibility and performance of suitable commercially available emission control technologies on high-priority non-road equipment, using in-use field testing approaches. An important aspect of the program's design is to evaluate diesel equipment and emission control technology combinations that will provide the state with the highest potential for air quality improvements in conjunction with the lowest energy, economic, and operational impacts. This implies that high priority equipment types, such as those with large populations or high emission rates, should be paired with effective, feasible control strategies.

Current program funding will allow for field demonstration of approximately 15 non-road diesel equipment and emission control technology combinations in NYS. Considering the non-road diesel inventories presented in Section 2.0, high priority sectors and equipment types were identified and ranked in Section 3.0. Section 4.0 describes the control strategies and technologies that are currently available and feasible for use on non-road diesel equipment, and provides a ranking of the control strategies for several categories of equipment.

6.1 PRIORITY EQUIPMENT FOR FIELD DEMONSTRATIONS

As discussed in Section 3.0, there are various methods of evaluating the emissions and equipment inventory data to determine which equipment types, sizes, and ages should be the priority equipment selected for evaluation in a field demonstration program. However, for the most part, when looking at these various procedures for evaluating the non-road diesel sector, a series of equipment types appears consistently near the top of various rankings (Section 3.2). As discussed in Section 3.0, analysts evaluated the impacts of non-road diesel equipment types directly using the following criteria:

- total PM emissions;
- total NOx emissions;
- population and activity;
- normalized NOx emissions (lb/unit);
- normalized PM emissions (lb/unit); and
- combined weighted rankings.

In addition, analysts used several subjective criteria to evaluate equipment and identify those that are recommended as priority equipment types for field demonstrations. These factors include:

- Commonality of equipment types and applications (equipment types operated in similar sectors or duties allow for a streamlined field program with minimal amounts of equipment owners involved).
- Interests of state and local regulators and impacts of regulations and local rules (for example, NYCMA LL77-2003 requires implementation of BAT for diesel construction equipment. This makes construction sector equipment evaluations a priority for the NYCMA).
- Potential control strategies available for specific equipment types (i.e. the potential for physical and economical application of various retrofit devices on skid steer loaders is limited because of their small size and low cost).
- Feasibility of field demonstrations under the existing program (financial, schedule, and other constraints – a single locomotive demonstration may consume a disproportionate amount of the project budget).
- Existing demonstration information and existing demonstration programs (equipment types may be identified for which several existing programs are underway or have been completed to evaluate control strategies, such as the marine sector).

As discussed in Section 3.3, when all of these criteria are evaluated, a list of select equipment consistently rises to the top of the priority list. Several of these equipment types (locomotives, marine, A/C refrigeration units) are downgraded when evaluated for the field demonstration program based on the above subjective criteria. The results of this prioritization process yielded the equipment types identified in Table 3-3 as priority equipment. For the purposes of the field demonstration program, this list provides more equipment options than the current testing will allow. However, the list of recommended equipment for the NYSERDA field demonstration program is easily narrowed down to the following items, all within the construction and mining sector:

Table 6-1. Recommended Equipment types for Field Demonstration

Equipment Type	HP Range
Tractors/Loaders/Backhoes	50 - 175
Rubber Tire Loaders	175 - 600
Excavators	75 - 300
Off-Highway Trucks	1200 - 2000

This group of four construction equipment items is responsible for 24% and 21% of the PM and NOx emissions in NYS, respectively, based on the refined emission inventory. Evaluating and implementing control strategies for this group of equipment will result in the largest benefits to air quality in NYS and the NYCMA. In addition, this group of equipment represents a range of engine sizes that appear in the construction and mining sector. Evaluating the performance of control strategies for these equipment types will provide relevant information regarding the applicability of such control strategies to different equipment types utilizing similar engines (such as a 175-300 hp dozer). However, impacts of equipment duty cycles should always be evaluated to ensure proper application of control strategies.

In addition to these equipment types, there may be interest in limited evaluations of control strategies on small skid steer loaders. Because of their large population, use in a variety of applications and locations, and total emission levels, they are a high priority target. However, the feasibility of controls on these units is limited to inexpensive, simple, and small scale control strategies.

Recommendations for demonstrations should also include recommended model years for evaluation. Since a large portion of the diesel fleet is in service for a very long period, those equipment types that impact emissions the most should be evaluated, as should those that are the most common in today's fleets. Evaluations of the baseline model results and model year runs presented in Section 2.1.8 provide an indication of the model years of equipment that are responsible for the largest percentages of emissions. For the equipment types recommended above, the model year ranges presented in Table 6-2 are the highest priority model years. In addition, the construction equipment survey results for the NYCMA provide an indication of the current population distributions for[3]. These distributions are often different than the NONROAD2004 model predicts. The most prevalent model years based on the survey are also presented in Table 6-2. Recommended model year ranges for equipment for the field demonstration program are also provided in the table.

Table 6-2. Recommended Equipment Model Years for Field Demonstration

Equipment Type	Priority Model Years (emissions)	Most Prevalent Model Years (percentage of surveyed fleet)	Recommended Model Year Ranges for Field Demonstration
Tractors/Loaders/Backhoes	1980 -1997	Pre-1996 (33%) 2003 - 2006 (24%)	1980 – 1996
Rubber Tire Loaders	1993 - 2002	1996 - 1999 (51%)	1996 – 1999
Excavators	1996 - 2002	2003 - 2006 (52%)	1996 – 2006
Off-Highway Trucks	1996 - 1999	2003 - 2006 (42%)	1996 – 1999

Field demonstrations based on the test matrix will provide NYSERDA and the PAG with a representative data set regarding the performance of leading emission control technologies on classes of diesel equipment that have an adverse effect on NYCMA air quality. Specific non-road equipment makes and models will be selected based on the equipment types specified in the matrix, the availability of equipment from participating fleets, and the favorability of logistical issues such as equipment size, location, and control device installation.

Likewise, with control equipment, specific technologies will be selected based on participating vendors, in-kind contributions, control device availability, and control device engineering and installation issues. Specific fleets, construction equipment, technology vendors, and technology types will be selected as part of the field demonstration program.

6.2 RECOMMENDED CONTROL STRATEGIES FOR FIELD DEMONSTRATIONS

Descriptions and analyses of numerous control strategies were provided in Section 4.0. Rankings of control strategies, based on the technical, economic, and operational feasibility, verification status, commercial status, and other factors were also provided. There are various types of control strategies available for evaluation. However, several strategies were identified that should provide the most benefit in terms of air quality impacts, balanced with reasonable costs and minimal other negative impacts such as fuel consumption penalties and additional maintenance or operational requirements. Based on the complete feasibility analysis and sub-rankings of the technologies, the following control strategies were identified as priorities for field demonstrations (Section 4.6).

Primary Strategies (broadly applicable for a range of equipment):

- Diesel Particulate Filters
    - Catalyzed
    - DOC with DPF
    - DOC with CDPF
    - Active DPF using shore power
- SCR with DPF
- Engine Rebuild Kits

Secondary Strategies (most feasible for a narrow spectrum of equipment types, relatively new, or limited emission reductions):

- Automatic Engine Shutdown for Idle Reduction
- Flow-through particulate filters
- Active DPF using vehicle power
- DOC
- Lean NOx catalyst with DPF
- Biodiesel blends (B20 with ULSD)

The primary strategies identified would be broadly applicable to the majority of non-road diesel equipment, including all those of interest described in Section 6.1. The secondary strategies would be applicable to a narrow group of equipment types or sizes (i.e active DPF with vehicle power would be most readily applicable to large diesel electric equipment), are relatively new technologies (flow-through filters), or provide only a small emission reduction, albeit at a reasonable cost, and may be best suited for small, less expensive equipment types (such as DOCs and biodiesel applied to a small skid steer loader).

Detailed descriptions of the feasibility analysis, rankings of strategies for various equipment types and sizes, and benefits, and drawbacks for each technology type, and others, are presented in Section 4.0.

6.3 FIELD DEMONSTRATION PROGRAM TEST MATRIX

To develop a recommended field demonstration program test matrix, the selected high priority equipment identified in Section 6.1 and the recommended control strategies presented in Section 6.2 are combined. The integration of equipment and control strategies is based on the desire of the NYSERDA program to provide information regarding the widest variety of control strategies possible over a selected equipment fleet. Evaluations completed in this manner will provide information regarding various strategies for reducing emissions. The results may then be extrapolated to additional equipment types with similar engines or operating conditions. An evaluation of several different control strategies also provides data that may be utilized to determine best available technology for emission reductions. Selected control strategies are recommended for testing on equipment types and sizes that prove a reasonable, representative application of the technology.

Based on the prioritizations described in this and other sections of the report, the following Field Demonstration Program Test Matrix is suggested.

Table 6-3. Demonstration Program Field Test Matrix

Equipment Type	HP	PM controls							PM & Nox Controls				
		Catalyzed DPF	**DOC+CDPF (CCRT)**	**DOC+DPF (CRT)**	**Active DPF, Vehicle Power**	**Active DPF, shore power**	**Flow-Through Filter / Wire Mesh Filter**	**DOC**	**SCR+DPF**	**Lean NOx Catalyst + DPF (LNC)**	**Engine Rebuild (kits)**	**Idle Reduction**	**Biodiesel**
Tractors / Loaders / Backhoes	75 - 175	✓					✓	✓					✓
Rubber Tire Loaders	300 - 600	✓	✓	✓		✓			✓	✓	✓		
Excavators	100 - 300		✓									✓	
Off-Highway Trucks	1200 - 2000				✓								
Skid Steer Loaders	50 - 100							✓					

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