Case Studies of Construction Equipment Diesel Retrofit Projects

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1.0 Introduction

Diesel engines provide important fuel economy and durability advantages for large heavy-duty trucks, buses, and nonroad equipment. Although they are often the power plant of choice for heavy-duty applications, they have the disadvantage of emitting significant amounts of particulate matter (PM) and oxides of nitrogen (NOx), and lesser amounts of hydrocarbon (HC), carbon monoxide (CO) and toxic air pollutants.

Due to the lag in emission control regulations until 1996, diesel engines used in construction equipment are typically more polluting than those used for normal highway applications. It is estimated that 47 percent of mobile source diesel PM emissions nationwide comes from nonroad diesels and 25 percent of mobile source NOx comes from nonroad diesels. The reduction of diesel emissions from construction equipment has the potential to significantly improve air quality for those who live or work in or adjacent to construction sites. With the approval of the U.S. EPA Clean Air Nonroad Diesel Rule (see www.epa.gov/nonroad-diesel/2004fr.htm) that is scheduled for implementation in 2008-2015 timeframe, diesel emissions reduction from nonroad engines will occur through the use of advanced diesel engine technology, ultra-low sulfur diesel fuel (15 ppm S max.), and advanced diesel exhaust emission control technology such as diesel particulate filters (DPFs) for reducing PM emissions, and selective catalytic reduction (SCR) systems and NOx adsorber catalysts for reducing NOx emissions. These EPA Tier 4 emission standards for nonroad engines will apply to diesel engines used in most kinds of construction, agricultural, and industrial equipment. Technologies for complying with the Tier 4 nonroad diesel regulations will flow from the experience gained in complying with EPA's 2007-2010 heavy-duty highway diesel program (see www.epa.gov/OMSWWW/diesel.htm). However, due to the long operating lives of these diesel engines, it will take decades for older, "dirtier" nonroad diesel engines to be replaced with the mandated, newer "cleaner" engines. Given the health and environmental concerns associated with diesel engines and because the nonroad engines make up a significant percentage of diesel pollution emitted, there is an increasing interest in retrofitting the older nonroad diesel engines.

The case studies discussed in this paper focuses on those projects that have been completed, are in progress, or have received funding for retrofitting diesel-powered construction equipment with emission control technology. Many of the projects highlight the feasibility of installing verified onroad technologies on construction equipment and relate some of the lessons learned that may assist others in planning new construction equipment retrofit projects. The limited range of experience with retrofits on construction equipment summarized in this report also serves to point out the need for expanding the range of verified retrofit technology options for nonroad diesel applications in general, and construction equipment in particular. This paper focuses on technology-based strategies and, where available, provides information on the specific type of technology installed on the type of construction equipment and the emission reduction that was achieved. For more detailed descriptions of available emission control technologies that can be retrofit on existing onroad and nonroad diesel engines, please see MECA's white paper, *Retrofitting Emission Controls On Diesel-Powered Vehicles* (see www.meca.org or the MECA diesel retrofit web site: www.dieselretrofit.org).

2.0 Completed or Current Projects

2.1 The Central Artery/Tunnel (CA/T) Project, Boston, MA

The Central Artery/Tunnel (CA/T) Project, also known as the "Big Dig", is a major highway construction project designed to reduce traffic congestion and improve mobility in central Boston. The project requires the use of heavy-duty construction equipment in a concentrated area. Under a Clean Air Construction Initiative Program, 25 percent of long-term nonroad diesel equipment used in constructing the CA/T Project has been retrofitted with advanced pollution control devices, with more than 200 pieces of equipment retrofitted.

The construction equipments were retrofitted with diesel oxidation catalysts (DOCs) over diesel particulate filters (DPFs) because of the reduction in hydrocarbon (HC) associated with diesel odors and carbon monoxide (CO) and PM_{10} provided by DOC, the ease of installation and maintenance, and the cost of a DOC compared to DPF that allowed more pieces of equipment to be retrofitted with the available funds. In addition to retrofitting with emission control devices, the project included assigning staging zones for waiting trucks and limiting idling to not more than five minutes. The construction equipment was also refueled with ultra-low sulfur diesel (ULSD) and emulsified diesel fuels.

Equipment retrofitted with DOCs includes:

- Nichi, Caterpillar, SIC, Terex, and JLG lifts
- Mantis cranes
- John Deere and Caterpillar dozers
- Cradel excavators

The model years of the equipment ranged from 1994 to 2000, with most of the equipment being 1999 or 2000 model year. According to the contractors, the equipment retrofitted with DOCs has not experienced any adverse operational problems, such as loss of power or additional fuel consumption. During the pilot program, the Environment Canada used a portable emission-testing device and several DOCs will be removed and sent to Environment Canada for emission testing in subsequent evaluations.

To date, preliminary estimates from 2000-2004 of area-wide emission reductions from the retrofitted equipment indicate a reduction of approximately:

- 36 tons/year of CO,
- 12 tons/year of HC, and
- 3 tons/year of PM

More information on this project can be found at: www.massturnpike.com/bigdig/background/airpollution.html.

2.2 I-95 New Haven Harbor Crossing Corridor Improvement Program, New Haven, CT

As part of the Connecticut's Clean Air Construction Initiative, the I-95 New Haven Harbor Crossing Corridor Improvement Program, also known as the Q-Bridge Project, has successfully installed DOCs on approximately 70 pieces of construction equipment. The construction contractors have also volunteered to use low sulfur diesel (500 ppm sulfur) on all of their nonroad equipments. The Initiative was established to protect workers and residents from harmful construction emissions along a populated corridor. The contractors are required to implement the following:

- Install emissions control devices on nonroad diesel-powered construction equipment with engine horsepower ratings of 60 hp and above, that are on the project or assigned to the contract for more than 30 days;
- Truck staging zones will be established for diesel-powered vehicles to wait to load or unload;
- Idling is limited to three minutes for delivery and dump trucks and other diesel-powered equipment, with some exception;
- All work must be conducted to ensure that no harmful effects are caused to adjacent sensitive areas;
- Diesel-powered engines must be located away from fresh air intakes, air conditioners, and windows.

The construction began in 2003 and is scheduled to be completed in 2013. All contractors and sub-contractors are required to participate in the Connecticut Clean Air Construction Initiative by the ConnDOT. As bid by each contractor, the costs of purchasing DOCs and/or using clean fuels were included in the overall contract cost. Thus far, all the contractors have decided to install DOCs instead of using clean fuels, such as emulsified diesel fuel. More information on this project can be found at: www.i95newhaven.com/poverview/environ_init.asp.

2.3 Dan Ryan Expressway Road Construction Project

The Illinois Department of Transportation (IDOT) implemented a pollution reduction initiative on the reconstruction project of the Dan Ryan Expressway that runs through the middle of the south side of Chicago. Through this project, all heavy construction equipment on the Dan Ryan project will be either retrofitted with emissions control device or will use ULSD fuel (15 ppm sulfur). IDOT has also implemented idling limits and dust controls to reduce air emissions from construction activities. An estimated 290 pieces of construction equipment in use on the Dan Ryan project will have emissions control device or will use ULSD. Funded in part through a grant of $60,000 from U.S. EPA, these emissions control strategies are a contract requirement for equipment operating on the Dan Ryan project. The focus of this project is on reduced idling, with contractors required to establish truck staging areas while waiting to load or unload, and the idle time is limited to no more than 5 minutes. The Illinois Tollway Authority has also adopted IDOT's Initiative and is requiring the use of either ULSD fuel or retrofitting heavy construction equipment on the reconstruction and widening projects along several highways. The project is estimated for completion in August 2007. More information on this project can be found at: www.danryanexpressway.com.

2.4 New York City Local Law No. 77

New York City Local Law No. 77 was signed into law on December 22, 2003 and requires the phase-in use of ULSD and best available technology (BAT) for emission control in all diesel-powered nonroad vehicles used in city construction projects. It applies to all diesel nonroad vehicles with an engine rated at 50 hp or greater that is owned by, operated by or on behalf of, or leased by a city agency. From December 19, 2005 on, any solicitation for a public works contract less than $2 million must specify that the contractors use Best Available Technology (BAT), but this schedule has been delayed. The Commissioner of the New York City Department of Environmental Protection will update the list of approved technology at least every six months, and includes those technologies verified by EPA or ARB. The requirements of Local Law No. 77 are enforced with penalties for those contractors that violate the provisions of the law, such as civil fine between $1,000 and 10,000 plus twice the amount of money saved by the contractor failing to comply with the requirements. More information on Local Law No. 77 can be found at: www.nyccouncil.info/pdf_files/bills/law03077.pdf.

2.5 WTC Diesel Emissions Reduction Project

The 7 WTC Diesel Emissions Reduction Project is a national model for demonstrating clean construction by using ULSD and retrofit nonroad, heavy-duty diesel construction equipment with DOCs or DPFs. The WTC Diesel Emissions Reduction Project is the first public/private initiative in New York construction market focused on reducing emissions from heavy-duty diesel construction equipment that was initiated by Clean Air Communities (CAC). The project plan calls for immediate use of ULSD fuel for selected equipment on-site and the phase-in of retrofit technologies on equipment owned by participating contractors or sub-contractors working at the 7 WTC site. CAC provides technical support and funding to construction contractors working at 7 WTC to implement ULSD fuel and to retrofit selected equipment. Funding has also been provided to construction corporations and transit fleets operating in the vicinity of 7 WTC in partnership with the Battery Park City Authority. The CAC project will retrofit 8 pieces of construction equipment at the WTC site and 10 pieces of equipment will use the ULSD fuel. More information on this project can be found at: www.cleanaircommunities.org/projects/wtc.html.

In order to investigate diesel emission reduction from nonroad construction equipment at the World Trade Center, the Port of Authority of New York and New Jersey initiated a project designed to investigate the use of emission reduction strategies for several pieces of equipment with focus on PM reduction. The construction equipment selected for the project included two Caterpillar 966G wheel loaders and one Caterpillar 2,000 kW generator. First of the emission reduction strategy was to switch the fuel to ultra low sulfur diesel (ULSD) fuel and then the wheel loaders were retrofitted with DPFs. DPFs installed for the project utilized passive regeneration technology. Caterpillar, Inc. installed the DPF into the wheel loader exhaust system with a complete retrofit replacement kit that is a direct replacement for the original muffler. Because it was determined that the generator was unsuitable candidate for a DPF due to the lack of sufficient exhaust temperature, no emissions test was conducted on the generator. To quantify the emission reduction achieved with the ULSD and DPF, portable emission monitoring systems (PEMS) were installed on the wheel loaders. Two independent portable systems were installed simultaneously because no one system can provide the emission measurement metrics requested by the Port Authority: 1) the Clean Air Technologies International Montana system, and 2) the Environment Canada DOES2 system. Emission testing on the wheel loaders was performed to determine reduction efficiency performance of deploying ULSD and a DPF with ULSD against onroad diesel fuel. Emission testing was performed over a two-week period. The two loaders, TG-22 and TG-25 were exercised through a complete testing sequence one at a time. The following testing sequence was used:

- DPF and ULSD;
- OEM muffler and ULSD; and
- OEM muffler and on-road diesel fuel

The tests were run for each configuration until a minimum of three acceptable test runs were established. The test results are as follows:

PM Emissions Result

Significant PM emission reductions were documented as a result of implementing ULSD and installing DPFs. Both of the portable emissions monitoring systems found PM emission reduction in the 15 to 20 percent range when just ULSD was used and greater than 90 percent reduction when ULSD was combined with a DPF.

Table 1. PM Emission Test Results

Fuel	Retrofit Technology	Environment Canada PEMS		CATI PEMS	
		g/gal	% reduction	g/gal	% reduction
On-road diesel	None	3.964	---	1.551	---
ULSD	None	3.464	12.6	1.289	16.9
ULSD	DPF	0.100	97.5	0.011	99.3

CO Emissions Result

Significant CO emission reductions were observed during this program when the DPF was employed.

Table 2. CO Emission Test Results

Fuel	Retrofit Technology	Environment Canada PEMS		CATI PEMS	
		g/gal	% reduction	g/gal	% reduction
On-road diesel	None	25.64	---	25.23	---
ULSD	None	22.98	10.4	24.84	1.5
ULSD	DPF	3.43	86.6	2.15	91.5

HC Emissions Result

Results from switching from onroad diesel to ULSD alone indicate a net increase in HC emissions. However, a 97 percent reduction is achieved by switching to ULSD and using the DPF.

Table 3. HC Emission Test Results

Fuel	Retrofit Technology	Environment Canada PEMS	
		g/gal	% reduction
On-road diesel	None	1.26	---
ULSD	None	1.93	-52.7
ULSD	DPF	0.03	97.4

Note: Because the CATI Montana system is not equipped with a heated sample line, the HC total mass and real-time data is considered anecdotal and is not presented.

NOx Emissions Result

The program as developed by the Port Authority did not target NOx reductions, and the emission test results indicate approximately 16 percent reduction as a result of switching fuels and between about 20 to 30 percent by using the DPF. Applications of DPFs is not expected to impact NOx emissions and the results reported here may be related to engine backpressure effects associated with operations utilizing a DPF.

Table 4. NOx Emission Test Result

Fuel	Retrofit Technology	Environment Canada PEMS		CATI PEMS	
		g/gal	% reduction	g/gal	% reduction
On-road diesel	None	100.0	---	123.0	---
ULSD	None	84.5	15.6	103.7	15.7
ULSD	DPF	80.4	19.7	87.93	28.5

CO_2 Emissions Result

The test results show that there was little difference in CO_2 results between fuel/retrofit technology configurations. The reductions shown are partially attributable to the differences in hydrogen and carbon content of the two fuels.

Table 5. CO_2 Emission Test Result

Fuel	Retrofit Technology	Environment Canada PEMS		CATI PEMS	
		g/gal	% reduction	g/gal	% reduction
On-road diesel	None	10,275	---	11,808	---
ULSD	None	9,714	5.5	11,298	4.3
ULSD	DPF	9,749	5.1	11,340	4.0

More information on this project is available at: www.mjbradley.com/documents/PANYNJ_WTC_Final_Report-09Aug04.pdf.

2.6 LAX Master Plan Program: Community Benefits Agreement

As part of the LAX Master Plan Program, the Community Benefits Agreement provides a range of community benefits and impact mitigations that will be implemented by the Los Angeles World Airports (LAWA). Included in this Agreement is the requirement to retrofit all diesel construction equipment with best available emissions control devices to firstly reduce diesel PM and then NOx secondly. This requirement for retrofit applies to all diesel-powered nonroad equipment, onroad equipment, and stationary diesel engines. The emission control devices must be verified or certified by EPA or ARB for onroad or nonroad vehicles. Additionally, as part of a Demonstration Project, LAWA may allow diesel construction equipment used at a LAX Master Plan Program construction site to be retrofitted with a new emission control device that have not yet been certified or verified by ARB or EPA for use for onroad or nonroad vehicles or engines. LAWA, in consultation with the Coalition Representative and LAWA contractors, must develop processes to determine if a Demonstration Project using a new emission control device is needed, and how the project will be implemented. All emission control device installed on the diesel engines must achieve emission reduction no less than the reduction that could be achieved by an ARB Level 2 device (50-85% PM reduction efficiency). The emission reduction device may not increase the emission of any pollutant above the level that is standard for that engine. In order to determine the best available emission control devices for new technology that may become available in the future, the new emission control devices must meet a cost-effectiveness threshold of $13,600 per ton of NOx reduced. For $PM_{2.5}$ and PM_{10} reduction, any diesel particulate filter, diesel oxidation catalyst, or other technology on EPA or ARB verified list are considered to be cost-effective.

In addition to diesel construction equipment retrofit requirement, all construction equipment used for LAX Master Plan Program must use ultra-low sulfur diesel (ULSD) fuel, provided that there is an adequate supply in the Southern California area. If adequate supply of ULSD is not available, other fuels that do not emit greater emissions of fine PM or NOx than would using ULS, could be used.

Designation of the best available emission control devices will be reassessed annually and LAWA must establish processes to revise these designations and include them into construction bid documents before bidding of new construction phases of the LAX Master Plan Program. LAWA must also ensure that the requirements for installing diesel emission control devices and the use of ULSD are followed by all Airport Contractors, Airport Lessees, and Airport Licensees. Violation of these requirements is subject to a fine of $1,000 per day per violation. Compliance with these requirements will be monitored by an independent third party monitor. Diesel equipment manufactured before 1990 must be retrofitted with DOCs verified by ARB for use on nonroad diesel engines by December 31, 2005. If no verified DOC exists for the particular diesel equipment on or before June 30, 2003, the installation schedule is delayed until ARB can make the appropriate findings to support verification. If ARB verified DPFs are shown to be available and technically feasible, safe, reliable and cost effective for the pre-1990 diesel equipment, it must be retrofitted with the DPF by December 31, 2010. For diesel equipment that is manufactured in or after 1990, verified DPFs or verified DOCs must be installed within 36 months of ARB verification of the technology.

More information on the Community Benefits Agreement is available at: www.laane.org/lax/index.html.

2.7 The Impact of Retrofit Exhaust Control Technologies on Emissions from Heavy-Duty Diesel Construction Equipment (SAE paper no. 1999-01-0110)

The testing program was conducted to study the in-use emissions and duty cycles from five heavy-duty construction vehicles and examine the emission reduction potential of retrofit control technologies on construction equipment, such as DOCs, passive DPF, and active DPF technologies. For this study, the following emissions reduction devices were installed:

- Backhoe was equipped with an active uncatalyzed particulate filter that was designed to operate a full shift and then at the end of the shift, regenerate using in-line electrical burners powered by 220 V shore power. The substrate was a 100 cells/inch^2 cell wall flow filter.
- Volvo front end loader was retrofitted with an oxidation catalyst with substrates in parallel 19 cm diameter and 13 cm length. The catalyst contained 300 cells/inch^2 and had a total volume of 7 liters. The catalyst washcoat contained a proprietary zeolite and the precious metal catalyst is platinum based. The unit was a direct replacement of the stock muffler.
- Caterpillar front end loader was retrofitted with a catalyzed particulate filter 100 cells/inch^2. The washcoat is a proprietary precious metal coating.
- Dump truck was retrofitted with an oxidation catalyst that is 3 cm in diameter. The catalyst contains 300 cells/inch^2 with a proprietary precious metal washcoat. The catalyst was a direct replacement of the stock muffler.
- Bulldozer was retrofitted with an oxidation catalyst specifically designed for this application. It contains 200 cells/inch^2 and has a proprietary precious metal coating.

After conducting the tests on each of the five construction equipments along with baseline emissions tests, it was concluded that:

- Dumptruck, equipped with DOC, showed PM reduction of 17%; however, the conversion of the gaseous emissions was low;
- Backhoe, equipped with active DPF, showed PM reduction of 81%;
- Bulldozer DOC system showed PM reduction of 24%, CO emissions were also significantly reduced while HCs were not reduced;
- Caterpillar wheeled loader, equipped with catalyzed DPF, showed a combination of 97% PM reduction and excellent gaseous control; and
- Volvo wheeled loader, equipped with DOC, showed PM reduction of 52% (during the tests a leak developed in the mass flow controller and made it difficult, if not impossible to determine the absolute emission rates).

This test program confirmed that retrofitting exhaust emission control technologies to nonroad construction equipment is feasible and that real in-use emission reductions can be achieved. Based on the results of this study, retrofitting 200,000 diesel construction equipment with DOCs in the Northeast would reduce PM emissions up to 4,000 tons/year, CO up to 45,000 tons/year, and HCs up to 7,000 tons/year. Retrofitting 200,000 construction equipments with DPFs would reduce PM emissions up to 15,000 tons/year, CO up to 109,000 tons/year, and HCs up to 17,000 tons/year.

2.8 Demonstration Projects for Diesel Particulate Filter Technologies on Existing Off-Road Heavy-Duty Construction Equipment

The South Coast Air Quality Management District (SCAQMD) and California ARB jointly initiated a project to evaluate the durability and effectiveness of passive DPF technology installed on existing nonroad diesel construction equipment. The focus of the project was the installation of 21 PM filters onto 15 diesel engines that are used on 12 heavy-duty construction vehicles. The demonstration study comprised of engineering and retrofitting the construction equipment and monitoring their operation for a period of one year. The effectiveness and durability of the filters and their installation hardware were measured and laboratory dynamometer emission testing under various steady-state and transient conditions was also conducted. The Los Angeles County Sanitation District (LACSD) provided six vehicles (scrapers and dozers) that were fueled with ULSD fuel and two scrapers and two dozers were also operated as control vehicles to provide baseline information for fuel economy, oil consumption, and reliability performance against the vehicles retrofitted with the DPFs. C.W. Poss Construction, Inc. (Poss) also provided six vehicles (scrapers and dozers) as the study vehicles but did not operate any control vehicles. Two different manufacturers provided the DPFs for the construction equipment.

Vehicles and DPFs used:

- LACSD vehicles: 1996 vintage 657 E scrapers, and 2000 vintage D9 dozers
- Poss vehicles: Caterpillar 651 B scrapers and Caterpillar 824/825/834 series dozers manufactured between 1971 and 1983
- DPFs from supplier A: 20”x15” filters for all applications, except for one 15”x15” used on an 825C dozer with a Caterpillar 3406 engine
- DPFs from supplier B: 20”x15” filters on most applications

The final equipment selections are as follows:

- A total of 12 vehicles were retrofitted in the study: 6 with DPFs from supplier A and 6 with DPFs from supplier B; with 6 of the test vehicles located at LACSD and 6 at Poss
- A total of 15 engines were retrofitted: 8 with DPFs from supplier A and 7 with DPFs from supplier B; with 9 located at LACSD and 6 at Poss
- A total of 21 filters were involved in the program: 12 from supplier A and 9 from supplier B; with 12 located at LACSD and 9 located at Poss

After operating these construction equipments with DPFs for a period of one year, filters from suppliers A and B were tested at the West Virginia University (WVU) Engines and Emissions Research Laboratory. Dynamometer tests on a Caterpillar engine using both transient and 8-mode steady-state duty cycles were conducted. The test showed that DPFs from both suppliers were highly effective in reducing PM emission on the dynamometer tests. Both pre- and post-demonstration testing by WVU on the filter from supplier B showed more than 98 percent PM emissions reduction. Pre-demonstration test of the filter from supplier A showed greater than 98 percent PM emissions reduction, while the post-demonstration testing showed approximately 91 percent PM emission reduction. None of the filters from suppliers A and B affected the levels of total NOx significantly, while the traps greatly reduced the levels of HC and CO emissions (about 79 and 65 percent for the filter from supplier A, respectively, and 93 and 97 percent for the filter from supplier B, respectively).

Table 6. Post-Demonstration Dynamometer Emissions Test Results

Emission Type	Fuel Type	8-mode Weighted Average (g/bhp-hr)	Transient Cycle (g/bhp-hr)	% Reduction vs. ECD1 Baseline (Transient Test)
PM	ECD1 Baseline	0.17	0.33	0%
	EDC1-Supplier B	0.01	0.00	>99%
	EDC1-Supplier A	0.01	0.03	90.9%
NOx	ECD1 Baseline	6.52	6.40	0%
	EDC1-Supplier B	6.14	6.05	5.5%
	EDC1-Supplier A	5.96	5.96	6.9%
HC	ECD1 Baseline	0.12	0.30	0%
	EDC1-Supplier B	0	0	>99%
	EDC1-Supplier A	0	0	>99%
CO	ECD1 Baseline	1.31	2.10	0%
	EDC1-Supplier B	0.24	0.16	92.4%
	EDC1-Supplier A	0.03	0.21	90.0%

In evaluating the durability and reliability of the filters, filters from supplier B at LACSD initially performed well, but backpressure began to rise on all units equipped with the larger filters within 400 to 500 hours of operation. Inspection of the filter showed that the ceramic trap elements had “shifted” out of the canister on all of the larger units. These systems were replaced or re-canned. Since then, new filters with new banding design have accumulated approximately 1,000 hours of operation and the original filters that were re-canned using new banding design have accumulated approximately 2,500 hours. The filters from supplier B performed well on 1996 vintage and newer diesel engines, but were deemed incompatible with the 1970s vintage Poss diesel engines. The filters from supplier A showed excellent durability and reliability throughout the demonstration period with only one failure on a D9 dozer at LACSD. In this failure, the ceramic filter inside the canning shifted and was broken up, causing excessive backpressure and loss of power.

Although basic DPF performance was validated for use on heavy-duty diesel construction equipment, many challenges still remain with installing and mounting large DPFs on large construction equipment. These challenges are compounded by the fact that higher horsepower engines like those tested in this program required two very large filter sizes to handle the high-volume exhaust flow of the engines.

2.9 Reliability of DPF-Systems: Experience with 6000 Applications of the Swiss Retrofit Fleet (SAE paper no. 2004-01-0076)

In 2000, the occupational health agencies of Switzerland (Suva) declared that DPFs are essential for underground workplaces. The environmental agencies of the Swiss federal government (BUWAL) followed in mid-2002 with the Ordinance on Protecting Air Quality at Construction Sites (BauRLL) all over Switzerland. DPFs were first retrofitted onto large public construction sites, with emphasis on air quality in tunnel projects and their associated labor intensive activities. As of 2003, approximately 6,500 construction equipment have been retrofitted with DPFs. This study was conducted to evaluate the filtration quality of VERT-Test compliant traps in both their new state and after 2,000 operating hours. The report examined trap failures, their causes and prevention based on information from manufacturers, retrofitters, and independent inspections.

The first reliability test was conducted in October 2000, asking the manufacturers and retrofitters for feedback. Failure rates in this first survey were in the 5 to 6 percent range. A new survey was conducted in October 2003, based mainly on information provided by manufacturers and retrofitters on overall failure rates. This later survey showed an annual failure rate is below 2 percent. Causes of failure include: defective canning; material defects; faulty gluing of the segmented filters and other manufacturing defects causing functional deficiencies; customer's handling accidents; and operational errors such as using high sulfur fuels with catalyzed filters.

The experience with this large retrofitted fleet shows the applicability of DPFs for all types of diesel construction equipment. It also demonstrated that DPFs are technically, operationally, and economically feasible and that there are no major obstacles to large scale retrofitting of DPFs to existing diesel engines.

A database of DPFs verified by VERT for the Swiss diesel retrofit program is available at: www.akpf.org/index.html.

2.10 City of Houston Diesel Field Demonstration Project

In order to address the air pollution contribution from each City of Houston department, the City established a comprehensive Emission Reduction Plan (ERP) in June 2000. The main goal of the ERP is to reduce NOx emission by 50 to 75 percent and $PM_{2.5}$ by at least 25 to 33 percent. Under the Diesel Field Demonstration Project a number of diesel emissions control devices were evaluated in the field on various vehicles and equipment, including construction equipment, during the summer of 2000 through the fall of 2001. The goal of the project was to identify retrofit emission control systems that can achieve 75 percent NOx reductions and at least 25 to 33 percent reduction in fine particulates.

Environment Canada performed the gaseous and particulate exhaust emissions testing on the City of Houston fleet vehicles at Ellington Field, Houston, Texas. A total of 29 units were selected to be representative of the fleet, of which 26 were field tested with emissions control devices. In addition to demonstrating the effectiveness of emissions control devices, the program also evaluated various emulsified diesel fuel formulations. Several manufacturers provided various emissions control technologies to demonstrate the effectiveness of these devices to reduce exhaust emissions. Diesel retrofit technologies evaluated included DOCs, passively regenerated DPFs, and SCR systems. With respect to construction equipment, this project evaluated three different retrofit technology options on a 1992 MY Cummins Gradall G3WD 6BTA 5.9L 190 hp: DOC + emulsified diesel fuel, an SCR system, and a combined DPF + SCR system.

After installation, the vehicle was returned to regular service for a period of time advised by the manufacturer to degreen the device. At the end of this period, emissions testing were performed with the device installed. The following is the summary of results from emissions testing with emissions reduction devices installed:

Table 7. Summary of Emission Testing Results

Vehicle	Technology Installed	% NOx Reduction from baseline	% TPM Reduction from baseline
Gradall G3WD	DOC + Emulsified Diesel	34.8	76.3
Gradall G3WD	SCR	78.2	26.7
Gradall G3WD	DPF + SCR	84.0	91.9

More information on this project is available at: www.arb.ca.gov/msprog/ordiesel/Documents/houston_demo_project.pdf.

As a result of the field demonstration program described above, SCR was selected as one of the technologies to be used on City fleet equipment. This City of Houston Fleet Retrofit project involves retrofitting 33 rubber tire excavators with SCR and one SCR system was installed on a 2003 model year dump truck. In addition, the City has retrofitted about 30 to 40 nonroad engines such as backhoes and water pumps with DOCs. This program will include emission testing at the University of Houston's testing facility with chassis dynamometer to quantify the emission reductions achieved with the retrofit technologies. This project is funded by the Texas Council on Environmental Quality (TCEQ) with Texas Emission Reduction Program (TERP) funds and the Houston-Galveston Area Council with Congestion Mitigation and Air Quality (CMAQ) funds in the amount of $500,000 for the SCR systems.
The vehicles and equipments that were retrofitted include:

- Gradall rubber-tire excavators powered by 1994 to 2000 MY Cummins 5.9L 190 hp engines
- 2003 MY dump truck powered by a Cummins ISC 315 330 hp engine

As of February 18, 2005, all 33 ditch excavators were equipped with an initial design SCR system and the SCR system will be upgraded to increase the level of emission reduction. The SCR systems that were installed included a DOC and a warning signal to indicate when the ammonia supply was getting low. The SCR system was not verified at the time it was installed on the equipment. However, the Houston program helped to provide data for the eventual ARB verification of the SCR for application on nonroad 1991-1995 Cummins 5.9L from 150-200 hp engines. The SCR systems on the excavators will be upgraded with a SCR system that will include a hybrid DPF used with ULSD to achieve greater PM emission reduction. The SCR systems have been in operation for up to three years and have reported no major problems. For more information on this project, go to Appendix B of the Final Draft of *Diesel Retrofit Technology and Program Experience* report at: www.epa.gov/cleandiesel/publications.htm.

2.11 Port of Seattle, Sea-Tac International Airport Project

In order to meet conformity commitment to keep NOx emissions from construction projects to less than 100 tons per year, the Port of Seattle initiated a project to reduce NOx emissions from construction activities at Sea-Tac's Runway Three. In 2002, a pilot program was initiated fueling onroad and nonroad vehicles with ULSD. With the success of the program, all vehicles and equipment used in the construction of Runway Three started being fueled with ULSD in February 2004. The next phase of the project involves retrofitting up to 10 or more nonroad engines with DOCs. For this phase, muffler replacement DOCs, rather than DPFs, are planned because some of the equipments emit high levels of PM. Backpressure monitors will also be installed. For more information on this project, go to Appendix B of the Final Draft of *Diesel Retrofit Technology and Program Experience* report at: www.epa.gov/cleandiesel/publications.htm.

3.0 Funded Projects

3.1 2005 National Clean Diesel Campaign Demonstration Grant Construction Projects

On November 7, 2005, U.S. EPA announced grant awards of more than $1 million to ten grantees to implement projects to demonstrate effective emissions reduction strategies for nonroad equipment and vehicles. The purpose of the grants is to demonstrate a wide variety of technologies such as cleaner fuels, and diesel retrofit devices (DOC, DPF, and engine replacement) for nonroad sector. Below is the list of funded projects:

- *City and County of Denver, Colorado*: The City and County of Denver will install DOCs on diesel alley and street paving fleets operating in low-income and underserved communities. This project has been awarded $125,000.
- *American Lung Association of Hawaii*: The American Lung Association of Hawaii will replace older, dirtier diesel construction equipment engines with newer, cleaner engines to reduce air pollution on Oahu and Kauai. This project has been awarded $135,000.
- *Idaho Department of Environmental Quality (DEQ)*: The Idaho DEQ will install DOCs and closed crankcase ventilation systems on portable diesel generators that power rock crushers and hot mix asphalt plants. This project has been awarded $100,000.
- *Maryland Department of Environment*: The Maryland Department of Environment will install DPFs on front end loaders at landfills in the City of Baltimore. This project has been awarded $50,000.
- *Massachusetts Executive Office of Environmental Affairs*: The Massachusetts Executive Office of Environmental Affairs will retrofit construction equipment with diesel retrofit devices and use ULSD fuel. This project has been awarded $120,000.

- *New York State Energy Research and Development Authority (NYSERDA)*: NYSERDA will retrofit nonroad fleets as part of a research project to identify best available retrofit technologies. This project has been awarded $100,000.
- *Oregon-Columbia Chapter of Associated General Contractors (AGC)*: AGC will install retrofit technologies to diesel equipments used in highway bridge replacement projects and use ULSD fuel. This project has been awarded $120,000.
- *York Technical College*: York Technical College and several local municipalities will retrofit nonroad equipments with DOCs. This project has been awarded $95,040.
- *Wisconsin Department of Natural Resources (DNR)*: Wisconsin DNR will install DOCS on construction equipment and use ULSD fuel. This project has been awarded $100,000.

For more information on the National Clean Diesel Campaign 2005 grants, go to: www.epa.gov/cleandiesel/awarded-grants.htm.

3.2 West Coast Diesel Emissions Reduction Collaborative Construction Projects

East Side Combined Sewer Overflow Project

The City of Portland's Combined Sewer Overflow (CSO) program is the largest public works project in the history of the State of Oregon, comprising three "Big Pipe" projects: the Columbia Slough Consolidation Conduit; the West Side "Big Pipe"; and the East Side "Big Pipe". The East Side CSO Tunnel or "Big Pipe", to begin in 2006, is the final and largest of the projects in Portland's 20-year program. During this five year construction project, approximately 150 diesel powered vehicles will be used for construction. The proposed project plan will require the use of ULSD in all project vehicles, use equipment that comply with EPA Tier 2 requirements for nonroad engines at a minimum and install best available retrofit emission control devices, such as DPF, DOC or wire mesh flow-through filters. The funding for the fuel premium will be paid by the contractor and ultimately the ratepayers in the city, but funding for retrofitting is requested from other sources to realize the full environmental and public health benefits that are available. The project is scheduled to be completed in 2011. More information on this project is available at: www.portlandonline.com/cso.index.cfm?c=31727.

City of Fresno Wastewater Treatment Facility Retrofit Project

City of Fresno, Fleet Management Division has agreed to participate in a demonstration program to retrofit three pieces of nonroad equipment with a diesel retrofit technology currently verified by both EPA and ARB for onroad applications to reduce emissions of PM, NOx, VOC and CO. The equipment to be retrofitted is currently operated daily at a Wastewater Treatment Plant located in southwestern quadrant of the City of Fresno. The equipment will be retrofitted a combined lean NOx catalyst/DPF technology that is currently verified by ARB for PM and NOx reductions on a range of on-road diesel engines. This project will demonstrate the viability of a combined PM/NOx emission reduction technology in nonroad engines. The manufacturer of the retrofit technology will conduct all necessary field engineering work with Cummins West, Inc. and Cleaire will also be responsible for submitting the progress and final reports. The City of Fresno will make the equipments available as well as collect all necessary maintenance and operational data. More information on this project is available at: www.westcoastdiesel.org/projects.htm.

Washington Clean Construction: Feasibility Demonstration for Retrofit of Non-road Equipment Project

In order to reduce toxic air emissions, the Yakima Regional Clean Air Authority (YRCAA) is participating with six local air authorities, the Washington State Department of Ecology (Ecology), and the American Lung Association in a demonstration project to retrofit nonroad diesel equipments. In coordination with local air authorities, Ecology will implement a state-wide program to reduce emissions from diesel-powered construction equipment. The purpose of this demonstration project is to demonstrate to the public and private fleet owners of nonroad, diesel powered equipment, the feasibility of retrofitting these equipment with DOCs without disrupting fleet operations. Approximately 50 vehicles will be retrofitted with federal funding and in-kind contribution. More information on this project is available at: www.westcoastdiesel.org/projects.htm.

Construction Equipment Retrofit Demonstration Project

The Construction Equipment Retrofit Demonstration Project is a joint effort of the Collaborative, the Sacramento Metropolitan Air Quality Management District (SMAQMD), and a retrofit technology manufacturer to retrofit five pieces of heavy construction equipment with emission-reducing device. The demonstration project will then evaluate the viability of the retrofit technologies to reduce PM and, to the extent feasible, NOx, HC, and CO emissions. This project will be funded through a $211,000 grant from EPA and $14,000 from SMAQMD. The goal of the demonstration project is to install emission control devices to five pieces of construction equipment to reduce annual diesel emissions by more than 85 percent for PM, up to 25 percent for NOx, and up to 90 percent for CO. More information on this project is available at:
www.westcoastdiesel.org/grants/files/Construction%20Equipment%20Retrofit%20Fact%20Sheet.pdf.

Oregon Construction Equipment Emissions Reduction Project

The Oregon Environmental Council (OEC) will work with builders, state environmental officials, the City of Portland, and other jurisdictions to reduce construction equipment diesel emissions. Through diesel engine retrofits, cleaner fuels, and idle reduction policies, the project aims to reduce diesel emissions from construction equipment used in the City of Portland by at least 20 percent. After the evaluation of the project results, the project's most efficient methods may be applied to reducing construction equipment emissions along the West Coast. This project will be funded through a $26,000 grant from EPA, and $27,000 from OEC. More information on this project is available at:
www.westcoastdiesel.org/grants/files/OEC_Construction_Reduction_fact%20sheet.pdf.

4.0 Summary

As shown by the above case studies, experience with retrofitting construction equipment with emission control devices is growing. The majority of the retrofit experience in construction equipment projects has been focused on demonstrating the feasibility of applying verified, onroad retrofit emission control technology on construction equipment and quantifying the diesel emission reductions achieved. Many of the projects have been initiated by the state, local, and federal agencies to promote interest in retrofitting construction equipment and facilitate other retrofit projects that may build on the successes and challenges learned from previous projects. Much of the experience with construction equipment retrofit projects has been with DOCs. This stems, in part, from the more universal applicability of diesel oxidation catalysts on existing diesel engines compared to other retrofit technology options. Experience to date with DPFs on in-use construction equipment is more limited due to the fact that the application of DPFs involves more engineering constraints with respect to the duty cycles and engine out emission characteristics of diesel engines used in construction equipment applications. Retrofit DPFs also generally require the use of ultra-low sulfur diesel fuel (ULSD). The availability of ultra-low sulfur diesel fuel for nonroad diesel engines will expand significantly as the rollout of ULSD for highway applications expands nationwide in the second half of 2006. Emerging onroad verified retrofit technologies such as actively regenerated DPFs and flow-through particulate filters should also find application in nonroad diesel engines and provide more options for significant reductions in diesel particulate emissions from construction equipment. Similarly, verified retrofit technologies that provide reductions in NOx emissions, such as lean NOx catalysts and SCR systems, will also migrate into the nonroad sector and see greater attention on construction equipment in the future. The construction equipment segment requires an expanded range of verified retrofit technologies to provide broader application coverage for the range of engines and equipment that are currently a part of the existing fleet.

There is an increased interest in the U.S. for retrofitting diesel construction equipment, largely due to the availability of more federal, state, and local incentive funds that can be used for these projects. One such funding source is the federal DOT/EPA Congestion Mitigation and Air Quality (CMAQ) Program. Funds from the CMAQ program have been used to pay for onroad diesel retrofit projects and now can be used for retrofit projects on nonroad engines used in construction projects in nonattainment or maintenance areas with respect to air quality. The CMAQ funding provides priority for diesel retrofit and other cost-effective emission reduction activities, with funding for the overall program of about $1.4 billion per year through 2009. These CMAQ funds are typically controlled at the state and local level, most often by metropolitan planning organizations. Other significant state sources of funding for construction retrofit projects are available in California through ARB's Carl Moyer incentive funding program (see www.arb.ca.gov/msprog/moyer/moyer.htm) and in Texas through the Texas Emission Reduction Plan (see www.tceq.state.tx.us/implementation/air/terp/). Other states are considering similar funding schemes for incentivizing retrofit projects involving onroad and offroad diesel engines. Through utilization of the available funding sources and building on the lessons learned from previous projects, the retrofit of construction equipment with emission control technology will become more widespread and provide an important tool for reducing emissions from the large number of existing nonroad diesel engines operating in the U.S.