Reducing Emissions from Diesel Vehicles & Equipment:

A VTrans Demonstration

Vermont Agency of Transportation

March 2008

VTrans Working to Get You There
Vermont Agency of Transportation

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16. Abstract

In an effort to further their own knowledge and experience with diesel retrofits, VTrans initiated a project to reduce emissions focused on both on- and off-road diesel trucks and equipment. A fleet inventory was compiled to determine the most appropriate trucks and equipment for retrofit. Installing the Diesel Oxidation Catalyst retrofits, (DOC's) generally required about two hours and was reasonably straightforward, without the need for any specialized tools.

In-use emission testing was also performed on several of the DOC-equipped trucks by the VT Air Pollution Control Division (APCD). The emission testing program evaluated performance under real-world conditions and was able to determine emission reductions of CO, HC, and PM. Overall results of the program indicate that the DOC's performed consistently with EPA published verification data.

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About VTrans

VTrans' mission is to provide for the movement of people and commerce in a safe, reliable, cost-effective, and environmentally responsible manner. To achieve this mission VTrans has embraced four key concepts: Safety, Excellence, Planning and Preservation. The underlying goals of these concepts are:

SAFETY: Make safety a critical component in the development, implementation, and maintenance of the transportation system.

EXCELLENCE: Cultivate and continually pursue excellence in financial stewardship, performance accountability, and customer service.

PLANNING: Optimize the future movement of people and goods through corridor management, environmental stewardship, balanced modal alternatives, and sustainable financing.

PRESERVATION: Protect the state's investment in its transportation system.

Acknowledgements

Completing a diesel retrofit project that introduces new technologies to a fleet requires the cooperation of many individuals and in this case across several state agencies. M.J. Bradley & Associates would like to recognize the various people that helped this project succeed.

Looking at ways to reduce diesel emissions, the Agency of Transportation Materials & Research Section undertook a Research, Development, and Technology Transfer project to evaluate exhaust after treatment technology on trucks and equipment in house prior to asking contractors to use these same technologies. John Narowski and Jennifer Fitch were instrumental at getting this project off the drawing board and provided valuable input throughout the deployment.

Ms. Gina Campoli was crucial towards maintaining a balance between the project sponsors, (Materials & Research Section), the day-to-day operators (Operations Division), and other interested agencies both with Vermont (Agency of Natural Resources) and other Northeast States. She provided continued support and guidance throughout as well as much needed internal coordination among different project advocates.

Realizing the emission benefits would not have been possible without the enthusiastic support of the VTrans Operations Divisions. Chief among those that helped bring this project to fruition were Ken Valentine and Dave Thurber. Mr. Thurber was responsible for coordinating the fleet inventory and scheduling so that the retrofits occurred in a timely manner without impacting the ability of VTrans to serve the public. Personnel that assisted during installation and evaluation are Eric Kipp, Bob Fowler, Dennis Reid, Jeff Hebb, Mike Hill, Darby Merrihew, Jerry Comstock, Rob Sylvester, Norm Couture, Rod Morin, and Mark Dindo.

The Air Pollution Control Division of the Vermont Department of Environmental Conservation, provided considerable assistance throughout the project, not only by evaluating the technology's emissions reduction performance under real-world conditions, but also by providing input during the project design and technology procurement phases. Specifically, David Love, Harold Garabedian, and Tom Moye, along with technical and equipment assistance from Aaron Pulaski of the New York State DEC, were invaluable in conducting the technology evaluations that will be used to inform future policy objectives.

Finally, putting together the various aspects of a retrofit project, such as supporting the fleet evaluation, technology procurement, installation, and documentation took the effort of a number of M.J. Bradley & Associates staff, including project manager Paul Moynihan, Tom Balon, Dana Lowell, Lauren Wilensky, Todd Danos, and Dave Seamonds.

Contents

Acronym List

APCD	Vermont Air Pollution Control Division
BAT	Best Available Technology
CARB	California Air Resources Board
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECM	Electronic Control Module
EPA	U.S. Environmental Protection Agency
FTF	Flow through Filter
Hp	Horsepower
ICC	Independent Catalytic Converter
LSD	Low Sulfur Diesel
NMHC	Non-Methane Hydrocarbons
NOx	Nitrogen Oxides
PM	Particulate Matter
PM_{10}	Particulate Matter < 10 microns
$PM_{2.5}$	Particulate Matter < 2.5 microns
ppm	Parts per Million
RFP	Request for Proposal
ULSD	Ultra Low Sulfur Diesel
VTrans	Vermont Agency of Transportation

Executive Summary

In an effort to further their own knowledge and experience with diesel retrofits, VTrans initiated a project to reduce emissions focused on both on- and off-road diesel trucks and equipment. A primary outcome of the project is the desire to inform VTrans policy makers and the interested public about diesel oxidation catalyst (DOC) retrofits. Specific objectives of the project were to:

1. *Gain experience with procurement, installation, maintenance and operation of pollution control technologies for both on- and off-road diesel-powered equipment.*
2. *Evaluate the performance of DOCs and identify potential problems, hidden costs, unforeseen complications and additional benefits from the use of this type of retrofit technology.*
3. *Help identify best management practices to be proposed and adopted by VTrans in its operations and standard contract specifications.*

A fleet inventory was compiled to determine the most appropriate trucks and equipment for retrofit and a request for proposals was solicited from emission control technology vendors. After award, individual trucks and equipment were further evaluated to verify if the vendor's product would fit in the available space and with minimal exhaust reconfiguration. After the final list of retrofits was established, an order was placed. In total, from initial fleet survey to retrofit took longer than originally anticipated at more than 6 months, although once a final order was initiated, delivery occurred in approximately 8 – 10 weeks.

Installing the DOCs generally required about two hours and was reasonably straightforward, without the need for any specialized tools. Once the emission control devices were installed, they were well received by VTrans personnel and after more than six months in service, received no negative feedback.

In-use emission testing was also performed on several of the DOC-equipped trucks by the VT Air Pollution Control Division (APCD). The emission testing program evaluated performance under real-world conditions and was able to determine emission reductions of CO, HC and PM. Overall results of the program indicate that the DOCs performed consistently with EPA published verification data.

Concluding the retrofit program, best management practice recommendations were developed, including:

- Investigate continued deployment of DOCs for on-road trucks in the VTrans fleet.
- Encourage retrofit with devices that replace the existing muffler.
- Build upon limited VTrans experience and other regional programs to deploy DOCs on construction and off-road equipment in the VTrans fleet.
- Implement contracting mechanisms to deploy DOCs on state-funded highway and construction projects.
- Coordinate voluntary or mandatory retrofit initiatives with regional partners.

CHAPTER 1 Introduction: *Why Retrofit?*

VTrans initiated this project with the overall goal of obtaining information and experience regarding the use of diesel oxidation catalyst (DOC) emissions control retrofit technology in order to inform VTrans policy makers and the interested public about this technology. Additionally, this goal was driven by three objectives:

1. *Gain experience with procurement, installation, maintenance and operation of pollution control technologies for both on- and off-road diesel-powered equipment.*
2. *Evaluate the performance of DOCs and identify potential problems, hidden costs, unforeseen complications and additional benefits from the use of this type of retrofit technology.*
3. *Help identify best management practices to be proposed and adopted by VTrans in its operations and standard contract specifications.*

Diesel truck and equipment engine retrofits focus on reducing diesel PM pollution in order to protect the health of nearby workers and citizens.

For nearly four decades, focused efforts have been underway to reduce emissions from mobile sources, both on-road trucks and non-road equipment and engines. While most of the early efforts centered on the on-road gasoline cars, significant efforts have been enacted over the past 15-20 years to reduce emissions from heavy-duty diesel trucks, and non-road diesel engines. In addition to gaseous pollutants such as nitrogen oxides (NOx) and non-methane hydrocarbons (NMHC), the Environmental Protection Agency (EPA) has implemented more stringent emission standards for particulate matter (PM) emissions in a phased approach, taking into account the state of technology at the time.

What is PM

PM is a generic term used to describe a combination of diverse liquid and solid substances that come from both man-made and natural sources. Diesel PM is generally composed of a carbon soot core with other materials adsorbed on the surface, including hydrocarbons, toxics, metals, and sulfates. Very small PM particles can be easily inhaled and pose a significant health risk to humans. Reducing PM pollution from all sources, including diesel engines, will be beneficial for the local community, as well as for workers that are in close proximity to diesel exhaust.

PM is often classified according to how large the particles are, with the two primary classifications PM_{10} (average particle diameter less than 10 microns)

Illustration – What is Diesel PM

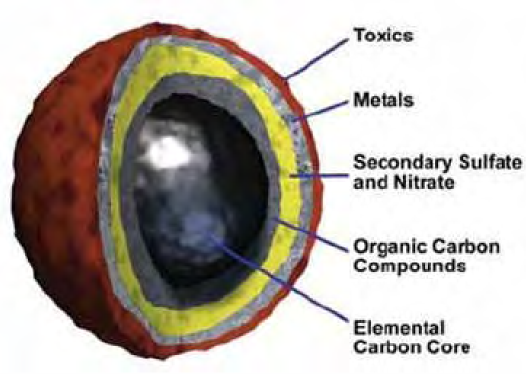
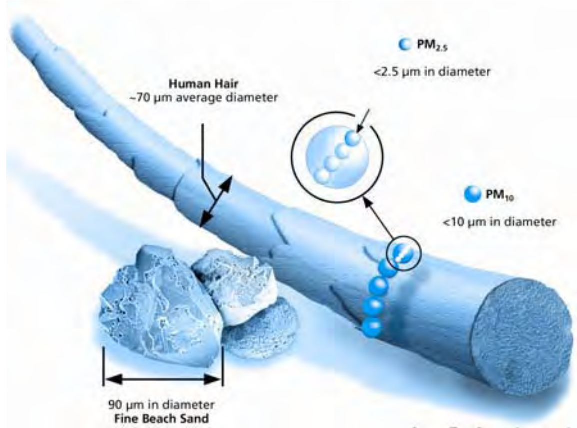


Image Courtesy Clean Air Task Force: "Diesel and Health in America: The Lingering Threat", February 2005.

and $PM_{2.5}$ (average particle diameter less than 2.5 microns); the smaller $PM_{2.5}$ particles are a sub-set of PM_{10} particles. The PM produced by diesel engines is typically composed mostly of very small particles, with greater than 97 percent of diesel PM mass $PM_{2.5}$.

A typical human hair, at about 70 microns, is nearly 30 times wider than a $PM_{2.5}$ particle. $PM_{2.5}$ presents a serious human health risk because the particles are small enough to pass through the nose and throat and lodge deep within the lungs when inhaled. The smallest particles may also enter the bloodstream directly through the lungs.

Diesel Particulate Matter (PM) Size Compared to Human Hair and Beach Sand



Courtesy of US EPA Office of Research & Development

Health Effects of Diesel PM

A person's exposure to diesel $PM_{2.5}$ is referred to as either short-term (from a few hours to several days), or long-term (from one to many years). An individual's frequency and magnitude of exposure, as well as their general state of health and age, all influence the effects of breathing diesel $PM_{2.5}$. Children are at increased risk from PM exposure because their lungs are still developing, they breathe more rapidly than adults, and they are generally more active than adults.

Short-term exposure is most harmful for people with existing health problems and can exacerbate existing lung disease; cause asthma attacks, coughing and acute bronchitis; increase the severity of asthma attacks; and may increase susceptibility to respiratory infections. Short-term PM exposure has also been linked to heart attacks and arrhythmias in people with existing heart disease.

Long-term exposure to PM occurs over a number of years and results from living or working in environments where there is sustained exposure to PM. This kind of long-term exposure has been associated with various pulmonary and cardiovascular disease such as reduced lung function, the development of chronic bronchitis and cardiovascular diseases[1] and even premature death.

In addition, EPA has identified diesel $PM_{2.5}$ as a probable carcinogen due to the demonstrated link between long-term exposure and increased risk of death from lung cancer. The agency has also designated many of the hydrocarbons in diesel PM (e.g., benzene and formaldehyde) as toxic hazardous air pollutants and/or carcinogens.

PM Regulations

EPA recognizes that heavy-duty vehicles are noteworthy contributors to poor air quality in many areas of the country, and that concerted efforts to clean them up will provide significant benefits. Controlling emissions from heavy-duty diesel engines has been a particular EPA focus. Over the last 20 years EPA has enacted a series of regulations, for

[1] American Heart Association, *American Heart Association Scientific Statement: Air Pollution is Serious Cardiovascular Risk,* June 1, 2004.

both on- and off-road diesel engines, that require new engines to be lower-emitting. The result is that on-road engines today are 96 percent cleaner than ones produced 15 years ago, while off-road engines are approximately 50 percent cleaner.

Although new engines are cleaner, there are still a significant number of older engines in use. Because of the long useful life of these diesel engines in both on- and off-road applications these older engines can benefit from a diesel PM-targeted retrofit strategy to lower in-use emissions. To date the only retrofit programs other than those targeted to urban buses have been voluntary; many are being spearheaded by federal, state, and local agencies similar to VTrans.

Reducing Diesel PM In-Use

What Can Be Done?

Diesel PM reduction strategies fall into one of four general categories as listed below:

1. *Reduce Idling:* Decrease engine idling to reduce emissions and save fuel.
2. *Replace/Repower/Rebuild:* Retire vehicles or engines "early," and replace them with new, cleaner engines, or rebuild and upgrade engines to incorporate cleaner technologies.
3. *Retrofit:* Install retrofit equipment or a muffler replacement device to reduce emissions. These include diesel oxidation catalysts (DOCs), Flow Through Filters (FTFs), and diesel particulate filters (DPFs), which are discussed in Chapter 2.
4. *Refuel:* Use a cleaner diesel fuel.

These strategies take advantage of some of the same technologies used to make new diesel engines cleaner, including changes in the diesel engine itself as well as the use of catalytic after treatment devices added to the tailpipe. Except for retrofitting, these are the same approaches that have been taken to clean up gasoline-powered cars and light trucks.

Methods for implementing these strategies include grant programs, enforcement programs, regulations, voluntary initiatives, as well as contract and permit requirements. Many municipalities and states, including VTrans, are currently exploring methods to require contractors on state and/or federally funded projects to reduce in-use diesel emissions through retrofit or engine upgrade/replacement programs. In Connecticut, the DOT successfully implemented a contract-based diesel PM reduction strategy for contractors' diesel equipment and trucks.

What Has Been Done

A great number of retrofit projects have been implemented throughout the U.S., mostly on a voluntary basis, and many states are currently considering efforts to require diesel PM emission reduction retrofits for select categories of vehicles. Following is a non-exhaustive description of some programs that have occurred in the wider region around Vermont.

<u>Legislative Initiatives</u>

In September of 2005 New Jersey passed N.J.A.C. 7:27-14. This law prevents diesel-powered motor vehicles from idling for more than 3 consecutive minutes, and includes, stiff penalties for non-compliance. This law also requires all school buses in New Jersey, public and private, to be fitted with closed crankcase controls. This technology prevents exhaust emissions from entering the bus cabin, where children could breathe it in. The law also states that owners of transit buses, garbage trucks, and on/off road construction vehicles must provide the state with retrofit Compliance Plans. These Compliance Plans detail how each diesel vehicle will be retrofitted and with what technology. Installation of retrofit equipment will be phased in over a ten-year period. The cost for each retrofit is being reimbursed.

On December 22, 2003, New York City adopted Local Law 77. This law mandates the use of Ultra Low Sulfur Diesel (ULSD) fuel and best available technology (BAT) to reduce emissions from off-road equipment used in city construction. This law requires ULSD fuel and BAT to be used for heavy-duty diesel equipment above 50 horsepower that are used on all city-funded construction contracts. The law's requirements were phased in starting in June of 2004. It first applied to projects in lower Manhattan and later expanded to include all projects city-wide by December 2004. This law is in effect for equipment owned, leased and operated by any city agency.

Real World Deployments

The Port Authority of New York and New Jersey implemented advanced diesel particulate emission controls on construction equipment at the World Trade Center. The initiative began prior to Local Law 77, and started with the retrofit of two Caterpillar 966G front end loaders with DPF. At the same time a fuel switch to ULSD was implemented for the retrofit vehicles. As a follow-on to the project, the Port Authority developed policies that require all contractors using diesel-powered equipment at the World Trade Center site to use best available PM emission controls.

Boston's Central Artery/Tunnel project was under construction for over 15 years beginning in 1991. Construction required the continuous use of several hundred pieces of construction equipment for excavation, underpinning, roadway and tunnel construction, and street surfacing. To minimize the impact of this equipment on the air quality of surrounding Boston neighborhoods, the project sponsor, the Massachusetts Turnpike Authority, in collaboration with other government and private organizations, implemented a construction equipment retrofit program beginning in 1998. This was the first large-scale construction equipment retrofit program undertaken, and by the time the Big Dig was complete over 200 pieces of construction equipment had been retrofitted with DOCs.

Begun in 2002, the New Haven Harbor Corridor Crossing Improvement Program is a major road project along seven miles of the I-95 corridor in southern Connecticut. The project sponsor, the Connecticut Department of Transportation, began planning for construction equipment retrofits in October 2000, one year before the first contract was bid. The Connecticut Clean Air Construction Initiative was developed with the participation of the Connecticut Construction Industries Association and other groups. Under this program contractors were required to either retrofit their equipment with DOCs or use alternative clean fuels. These requirements were put into the contract bid specifications so that contractors could plan for the costs and include them in their bids.

To date all contractors have chosen the retrofit option. Six different contractors have already installed DOCs on nearly 100 pieces of equipment used on the project with retrofit costs for individual pieces of equipment ranging from $800 to $2,000.

VTrans Diesel PM Reduction

Beginning in 2005, VTrans undertook a small scale retrofit project focused on on-road plow trucks and off-road equipment engines. Consistent with other regional retrofit programs, a number of technologies/fuels that could reduce diesel PM emissions were considered. VTrans ultimately chose to implement DOC technology because it could provide the largest number of retrofits given the available funding. A VTrans priority was to compare retrofit performance on a significant number of trucks.

Project completion was delayed due to procurement difficulties and extended delivery schedules from the manufacturer. Further discussion about the procurement process is included in Chapter 3.

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CHAPTER 2 Emission Control Options

This section discusses the retrofit options available to reduce diesel PM emissions.

A primary concern for anyone contemplating an emissions reduction program is the effectiveness and robustness of the various commercial products on the market. A primary resource for evaluating manufacturer emissions reduction claims are the Technology Verification Programs operated by the EPA and California Air resources Board (CARB).

Verification Programs

In order to provide standardized information on the effectiveness of various retrofit technologies and alternative diesel fuels, EPA and CARB operate emission reduction verification programs. For PM, the EPA program evaluates both fuel and after treatment options, while the CARB program focuses on after treatment devices. Retrofit device and fuel manufacturers who seek verification for their technologies must submit test results from standardized emissions tests, along with information on the limitations and special requirements of the technology (e.g., minimum required sulfur level of the fuel).

In the EPA program manufacturers must verify a product or technology for each of a number of different engine families and report the actual emissions reductions achieved for nitrogen oxides (NOx), particulate matter (PM), volatile organic compounds (VOC), and carbon monoxide (CO).

The CARB verification program separates verified technologies into three levels, based on emissions reduction effectiveness for PM, and reports the level that a product falls into rather than actual PM reductions. The CARB categories include Level 1 (PM reduction of 25% or greater), Level 2 (PM reduction of 50% or greater), and Level 3 (PM reduction of 85% or greater). In the case of technologies that also reduce NOx, the actual NOx control-effectiveness is reported, provided that it exceeds a minimum level.

Although EPA and CARB have slightly different verification requirements, EPA will accept as verified retrofit technologies and fuels that are verified under the CARB program.

EPA and/or CARB have verified a number of commercial products for each of the retrofit technologies discussed here. A current list of the verified devices is provided in Appendix A. Technologies are listed for both on-road and off-road engines. For any changes to this list, please see EPA and CARB's websites, also listed in Appendix A.

Warranties

As a condition of verification any retrofit device verified by CARB must be warranted by the manufacturer to be free of defects and to continue to reduce emissions for the minimum periods shown in the table below. EPA-verified products do not have a mandated minimum warranty period, and warranties may vary by manufacturer. For construction equipment the warranty period is likely to be stated in years and hours of operation. Some products may carry a base warranty of one year.

Minimum Warranty Period for CARB-Verified Retrofit Devices	
Engine Size	*Warranty Period*
On-Road Engines	
70 < hp ≤170, GVWR ≤ 19,500 lb	5 yrs / 60,000 miles
> 170 – 250 hp, 19,500 < GVWR ≤ 33,000 lb	5 yrs / 100,000 miles
> 250 hp, GVWR > 33,000 lb	5 yrs / 150,000 miles
> 250 hp, GVWR > 33,000 lb AND Truck drives > 100,000 miles/yr AND Odometer reads < 300,000 miles at installation	5 yrs / 60,000 miles
Non-Road Engines	
< 25 hp	3 yrs / 1,600 hrs
25 – 50 hp	4 yrs / 2,600 hrs
> 50 hp	5 yrs / 4,200 hrs

Diesel Fuel & Retrofits

To some extent the attributes of the fuel being used in a vehicle dictates which after treatment technologies can be used for a retrofit program. The use of ultra-low sulfur diesel (ULSD) with less than 50 parts per million (ppm) sulfur is necessary when a vehicle is retrofit with a passive DPF. When retrofitting with a DOC, an FTF, or an active DPF standard low sulfur diesel (LSD), with up to 500 ppm sulfur, can be used, although using ULSD in conjunction with these devices provides even more of a benefit.

Current EPA regulations implemented in 2006 require that virtually all fuel sold for on-road vehicles be ULSD, with no more than 15 ppm sulfur, and that virtually all fuel sold for off-road construction equipment be LSD with no more than 500 ppm sulfur. Therefore all on-road vehicles are currently using fuel that will allow for retrofit with any PM-reduction device, including a passive DPF.

Most off-road equipment is likely to be using LSD, and may require a switch to a lower sulfur fuel if retrofit with a passive DPF. Any other type of PM-reduction device can be retrofit on off-road equipment without requiring a new fuel.

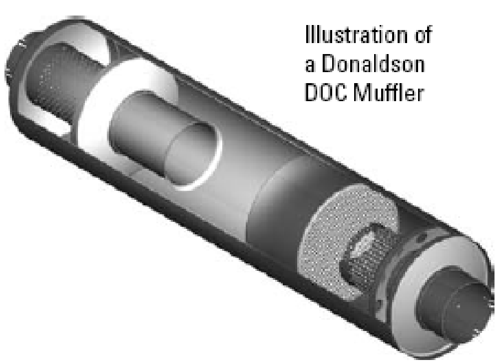
It may be possible to retrofit some off-road equipment with a passive DPF without switching fuels. This is because much of the off-road fuel currently being sold is likely to contain much less sulfur than the maximum 500 ppm allowed by law. This is because the reality of the fuel supply chain limits the number of different types of diesel available. The current distillate supply chain in the Northeast was set up to handle the two grades of fuel that have been used for the last 13^{+} years – the 500 ppm sulfur fuel once used in on-road vehicles and the 3,000 ppm sulfur fuel formerly used in off-road diesel equipment and still used for residential heating. This supply system most likely cannot handle a third grade of fuel (i.e., 15 ppm ULSD) without significant investments by fuel suppliers. Therefore, it is likely that there will be only two real fuel choices – ULSD and heating oil – and that most, if not all, of the off-road LSD fuel sold will actually be "off-spec" on-road ULSD (i.e., 15 ppm fuel that has been contaminated by 3,000 ppm heating fuel in the supply chain). Much of this off-spec ULSD sold as off-road LSD may have quite low sulfur levels (less than 50 ppm) and therefore may be acceptable for use with a passive DPF.

Diesel Oxidation Catalysts

A DOC can be used on virtually any diesel engine, and will produce significant emissions benefits. A DOC can reduce VOC and CO emissions in the range of 20 – 75 percent and PM emissions by 25 percent or more.[2]

A DOC contains a flow-through metal or ceramic core whose flow channels are coated with a precious metal catalyst such as platinum. This catalyst core is packaged into a metal container similar in size and shape to an exhaust muffler. The exhaust gas must pass through the device and the catalyst promotes the oxidation of unburned PM, VOC, and CO, producing carbon dioxide (CO_2) and water.

Typical Diesel Oxidation Catalyst



Courtesy of Donaldson, Inc

[2] For all technologies the reported range of emissions reductions is from test results reported under the EPA and CARB Technology Verification Programs. See Appendix A for a list of currently verified devices.

Fuel Requirements

DOCs can be used in applications with either ULSD or LSD fuel, and any impact on fuel economy is typically negligible.

Installation

Some DOCs are designed as a straight replacement for the vehicle's existing muffler, with the catalyst and a resonator packaged into the same container. Others include only the catalyst core and are designed to be installed in addition to the existing muffler/resonator. Either way, retrofit installation is generally straightforward and takes only a few hours. Space constraints on some vehicles or equipment would be the only impediment to installation, as typically the DOC is slightly larger than the muffler it replaces.

Maintenance

DOCs require virtually no on-going maintenance after installation, and because DOCs are typically packaged in stainless steel, as opposed to a standard steel muffler, they usually last for five years or more. For many operators a retrofit DOC will be the last muffler ever purchased for their truck or equipment.

Costs

For a typical construction engine with less than 250 hp, a DOC ranges from $800 to $3,500, including installation. In general the larger the engine the more expensive the DOC will be. DOCs are usually some of the most cost-effective retrofit devices available – judging by the amount of money it costs to install and maintain them in relation to the emission benefits gained – and are a very good retrofit option for trucks and equipment that have a duty cycle that make them unsuitable for a DPF.

Limitations

There are very few limitations with respect to using DOCs. Very old engines (older than model year 1990), and engines that consume excessive amounts of lubricating oil, may not be good candidates for retrofitting because high oil levels in the exhaust could cause the flow channels of the DOC catalyst core to plug with PM. Virtually all other engines can be retrofit with a DOC.

Flow-Through Filters

FTFs can be used on a wide variety of trucks and equipment engines and provide even greater emissions benefits than a DOC. An FTF can reduce VOC and CO emissions by 50 – 89 percent and PM emissions by approximately 50 percent.

An FTF includes a flow-through catalyst core and is very similar to a DOC, but it uses a different type of core material to hold the catalyst. Different manufacturers use wire mesh, wire fleece, or sintered metal cores, all coated with a precious metal catalyst and packaged into a metal container similar to those used to package a DOC.

As in a DOC, the catalyst promotes the oxidation of unburned PM, VOCs, and CO in the exhaust passing through the device, producing CO_2 and water. Because of how the core material is manufactured and configured, individual PM particles typically have greater opportunity for contact with a catalyst site than in a standard DOC, so that an FTF eliminates more PM than a DOC.

Typical Flow Through Filter

Courtesy of Fleetguard Emissions Solutions

Installation

As with a DOC, retrofit installation is generally straightforward and takes only a few hours. Most FTFs are designed to replace a vehicle's existing muffler and include a resonator in the package with the catalyst core. While an FTF often is the same size as the vehicle's existing muffler it may weigh a bit more and require additional or more robust mounting hardware. Space constraints on some equipment would be the only impediment to installation.

Fuel Requirements

Like DOCs, FTFs can operate on both ULSD and LSD fuel.

Maintenance

FTFs usually require virtually no on-going maintenance after installation. Similar to a DOC, FTFs are usually packaged in stainless steel, and usually last at five or more years.

Costs

For a typical engine under 250 hp an FTF costs from $3,500 to $5,000, including installation. In general the larger the engine the more expensive the FTF will be.

Limitations

Maintaining a minimum exhaust temperature over the truck or equipment's operating cycle is the only requirement that set FTFs apart from a DOC. Generally, the engine exhaust temperature must be at least 250°C for about 35 percent of the time for an FTF to work consistently. This somewhat limits their application, as not all duty cycles can maintain this type of operating profile, but pre-purchase exhaust temperature data logging under normal conditions, typically a condition required by the device verification, will determine FTF suitability.

See below for a more in-depth discussion of exhaust temperature limitations, which also apply to passive DPFs. Exhaust temperatures do not need to be as high for an FTF to work as they do for a passive DPF to work, so that FTFs are applicable to a wider range of engines.

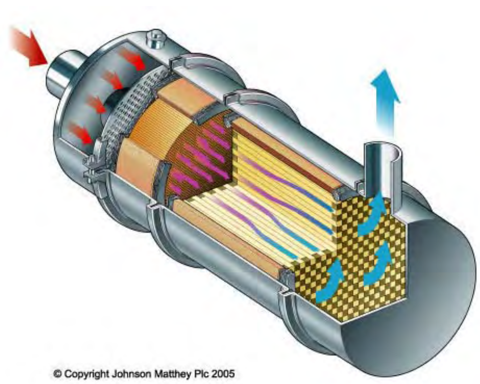
FTFs may also increase fuel use by up to one percent because they slightly increase back-pressure on the engine.

Diesel Particulate Filters

Diesel particulate filters can be either "passive" or "active" devices. A passive DPF works without any additional energy input other than the heat in the exhaust coming from the engine. An active DPF includes a system to add energy to the exhaust to increase its temperature.

A passive DPF can be used on a wide variety of engines, while an active DPF can be used on virtually all diesel engines. Either type of device provides even greater emissions benefits than a DOC or FTF. DPFs, whether passive or active, reduce PM emissions by 85 percent or more. Passive DPFs that incorporate a catalyst also reduce VOC and CO emissions by 60 – 90 percent, while non-catalyzed active DPFs will reduce CO and VOC emissions by approximately 10 and 20 percent, respectively.

Typical Passive Diesel Particulate Filter



Courtesy of Johnson Matthey, Inc

Passive DPFs

The two types of DPFs share some components but also have significant differences. A passive DPF combines an oxidation catalyst with a porous ceramic, sintered metal, or silicon carbide filter in a metal container similar to an exhaust muffler.

There are several variations on the design. Some passive DPFs have a separate flow-through catalyst core (essentially a DOC) in a series with an uncatalyzed filter, while others use a filter with the catalyst applied directly to it. Either way, passive DPFs sit in the exhaust stream of the vehicle like a typical muffler.

The gaseous components of the exhaust pass through the porous walls of the filter section, while the solid PM particles are physically trapped in the filter walls. The catalyst promotes oxidation of the trapped PM at temperatures typical of diesel exhaust, which then exits the filter as gaseous CO_2 and water. The catalyst also oxidizes gaseous VOC and CO in the exhaust like a typical DOC or FTF.

A passive DPF requires a minimum exhaust temperature of 250 – 290°C for approximately 35 percent of the time to oxidize the collected PM in the filter. This is easily achievable for many on-road engines, but certain engines and duty cycles may not have sufficient exhaust temperature to use a passive DPF effectively. In general passive

DPFs can be used for duty cycles in which the diesel engine operates for a majority of the time under high loads.

Active DPFs

An active DPF also uses a porous filter to physically remove PM from diesel exhaust. Like a passive DPF, the active DPF may employ a catalyst coating on the filter to lower the temperature at which the collected PM will oxidize out of the filter. However, in order to accommodate a wider range of duty cycles an active DPF also incorporates an "active" system to raise the temperature inside the filter.

The most common method used to raise the filter's temperature is to inject additional diesel fuel into the exhaust stream, downstream of the engine but in front of the filter. As this fuel burns it raises the exhaust temperature.

There is also at least one verified device commercially available for diesel engines, which combines a "bare" uncatalyzed filter on the vehicle with an electric heating element.[3] While the vehicle is operating the filter continually collects PM. At night the user must plug the heating element into a power outlet, which uses electricity to create enough heat to burn all of the collected PM out of the filter in a few hours.

Because they incorporate a method to increase the exhaust temperature as required, or otherwise burn off collected soot, active DPF systems can be used on a much wider range of engines and duty cycles.

Fuel Requirements

Passive DPFs require diesel fuel with less than 50 ppm sulfur, and the current ULSD required by EPA to be used in on-road trucks allows them to be considered for virtually all on-road engines. Using fuel with low sulfur levels is important because higher levels of fuel sulfur reduce the oxidation efficiency of collected PM and can result in filter plugging. Active DPF systems that inject diesel fuel into the exhaust generally do not have fuel sulfur restrictions and can be used with LSD with as much as 500 ppm sulfur.

Installation

Installation of both passive and active DPFs is relatively straightforward and usually takes four to eight hours per vehicle. Active DPF systems take longer to install than passive systems because they include more equipment.

Electrically-regenerated active DPF systems typically require access to a 208/240 volt 20 amp electrical outlet for each vehicle, for daily regeneration of the filter.

DPFs, both active and passive, are often slightly larger than the vehicle's existing muffler and may weigh significantly more. Additional or more robust mounting hardware is nearly always required. Space constraints on some vehicles would be the only impediment to installation.

Maintenance

Ash, consisting of non-combustible components of lubricating oil, collects in the DPF filter over time, creating a need to periodically clean the DPF. Approximately once every 12 to 24 months, depending on the use of the truck or equipment, the filter must be removed from the vehicle and cleaned. This cleaning requires a special machine and can often be done by the engine manufacturer's service representative or another third party for a fee expected to be in the range of $200 - $400 per filter. The devices are often designed with the

[3] This is the HUSS FS-MK.

filter section connected to inlet and outlet sections with band clamps, for easy removal of only the filter section for cleaning. This can be done in as little as half an hour. Depending upon the availability of spare filter sections and/or how quickly a service representative can clean the filter, the original muffler may need to be installed while the DPF is being cleaned to minimize the amount of truck down time. Alternatively, if the maintenance schedule is optimized, the truck can combine maintenance events so that while the filter is being cleaned work can be done on other systems.

Since both passive and active DPFs are always packaged in stainless steel cans installed devices usually last five or more years. Similar to stainless steel DOCs and FTFs, a retrofit DPF will generally be the last 'muffler' that needs to be purchased for a truck.

Costs

For a typical engine with less than 250 hp, costs range from $8,500 to $10,000, for a passive DPF and $14,000 to $20,000 for an active DPF including installation. As with other retrofit devices the larger the engine the more expensive the device typically is.

Active DPFs that use electric regeneration must be plugged in for up to five hours per vehicle per day, during which time they will consume approximately 15 kilowatt-hours of electricity. [4] At this rate, filter regeneration is estimated to cost on the order of $1 - $2 per day.

Limitations

Passive DPFs will not work on all engines. The more PM the engine produces the larger the filter and catalyst must be to work continuously without plugging. For some very old engines (older than model year 1990) it may not be practical to retrofit with a passive DPF, due to cost issues and space constraints.

Certain engines and duty cycles may also not have sufficient exhaust temperature to use a passive DPF effectively. In particular, lightly loaded duty cycles may not be appropriate for passive DPFs. Evaluation of the exhaust temperature profile for the engine/duty cycle is recommended before passive DPFs are installed on a vehicle type for the first time and is typically a requirement of the device verification.

As ash or excess carbon builds up in a DPF filter the backpressure on the engine will rise. Very high engine backpressure can lead to high turbo charger temperatures and progressive engine damage. For this reason all DPFs (both passive and active) should always be used with a backpressure monitoring system that triggers a maintenance light once the backpressure rises above a set threshold. This system consists of a pressure transducer, an electronic control module (ECM), and a maintenance/ warning light mounted in the engine compartment or operator cab. The ECM requires a connection to the vehicle's power system.

Both types of DPF, passive and active, are expected to increase fuel consumption. Passive DPFs may increase fuel use by one to three percent. Active DPF systems that inject diesel fuel into the exhaust as a method of raising exhaust temperature could increase fuel use by up to seven percent, depending on the engine and duty cycle. Electrically regenerated DPFs are expected to produce a small increase in fuel consumption similar to a passive DPF.

[4] Based on manufacturer literature for Cleaire Horizon-M

Comparison of Retrofit Technologies

	DOC	FTF	Passive DPF	Active DPF
PM Reduction	25%	50%	85%	85%
CO, VOC Reduction	20 – 75%	50 – 89%	60 – 90%	Variable*
Cost (< 250 hp)	\$800 – \$3,500	\$3,500 - \$5,000	\$8,500 - \$10,000	\$14,000 - \$20,000
On-going Maintenance & Costs	None	None	Annual filter cleaning Increased fuel use of 1% - 3%	Annual filter cleaning Increased fuel use of up to 7%. If regenerating electrically requires electric infrastructure
Limitations	None	Minimum exhaust temp required	Minimum exhaust temp required < 50 ppm sulfur fuel required	None

** If the filter is catalyzed, reductions will be similar to a passive DPF. With an uncatalyzed filter reductions will be lower.*

CHAPTER 3 VTrans Retrofit

The guiding objectives of this project were to determine what complexity is involved using DOC retrofits to reduce diesel PM emissions, how they operate in the field, and whether purchasing and contracting decisions should encourage their use. This report aims to document the procurement and installation of DOCs and present the knowledge and experience gathered during the project to inform future contracting and purchasing decisions by VTrans.

The project was funded with approximately $25,000 for the purchase of retrofit devices. In order to maximize the number of trucks that could be retrofit, VTrans decided to limit the retrofits to DOC technology only.

Fleet Profile

The first steps in a retrofit program are an evaluation of the target fleet and feasibility determination for the various available technologies. During this phase, the VTrans fleet was evaluated with respect to common engine, chassis and duty cycle combinations. While there are several broad categories of equipment in use at VTrans, the focus for this project was initially limited to plow trucks and construction loaders. Also, in an effort to gain the longest in-service life from the retrofit DOCs, only recent vintage engines were considered for retrofit. The plow trucks were all built by International, but had either a Caterpillar 10-liter/350hp or an International 8.7-liter/275hp engine.

Duty Cycle Evaluation

While DOC technology can be retrofit on nearly all diesel engines with no exhaust temperature limitations, an exhaust temperature data logging exercise was conducted to determine whether other options would be viable for the target trucks and loaders. In general, if the particular make and model of truck or construction equipment has already been retrofitted by someone else there should be no problem retrofitting like vehicles with the same type of device, unless the truck is operated under a very different type of duty cycle (i.e., longer periods of idling, lower average

6-Wheel Dump/Plow Truck

Front-End Loader

engine load). If the make/ model of equipment has never been retrofit, or if there is any question about its duty cycle, exhaust temperature data should be collected prior to committing to an FTF or passive DPF retrofit. For installing a DOC, the vehicle or device manufacturer can determine based on the engine year and size whether a DOC is appropriate. For the VTrans data logging exercise, a representative truck and loader were selected.

The exhaust temperature data logging was conducted during July 2006, and consisted of installing a small, inexpensive, battery-powered data logger and a J-type thermocouple.[5] Due to engine/muffler configurations and space constraints, the location of the exhaust temperature thermocouple varied for each vehicle (e.g., post-muffler for the loader versus post-turbo for the on-road trucks). After installation, the truck or loader was then operated under typical operating conditions. The following charts summarize the exhaust temperature data that was recorded for the trucks and loader.

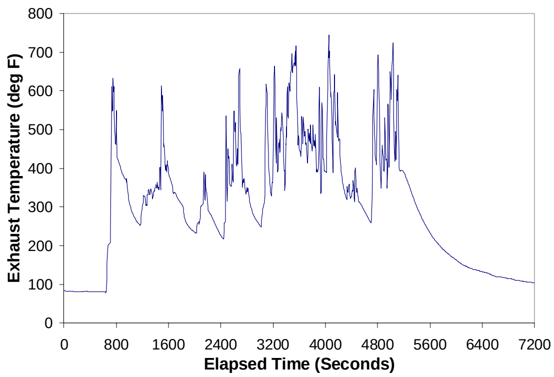
Based on the recorded exhaust temperatures, both the plow trucks and the loaders have marginal exhaust temperature for successful retrofit with an FTF or a passive DPF. To increase the possibility of successful retrofit, an insulated turbo downpipe (e.g., the TempMax™ manufactured by Environmental Solutions Worldwide), or other insulating material such as exhaust wrap can also be installed.

Exhaust Temperature Data Logger & Thermocouple

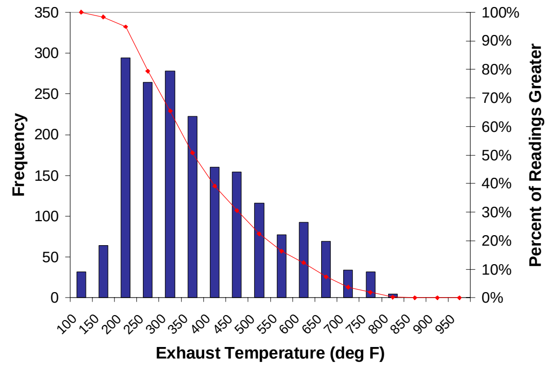
Thermocouple Installation

[5] To install the thermocouple, an exhaust band clamp with a fitting welded to it is installed ideally just before the existing muffler. To accommodate the thermocouple, a one-eighth inch hole is drilled through the fitting into the exhaust pipe. After the thermocouple is installed, the fitting is tightened and the wire from the thermocouple is attached to the data logger. Typically, the data logger is mounted in or on the vehicle in an easily accessible spot.

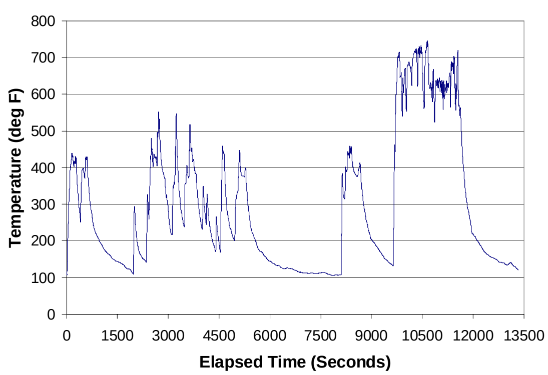
6-Wheel Dump/Plow Truck Real-Time Exhaust Temperature – 2-Hr. Window



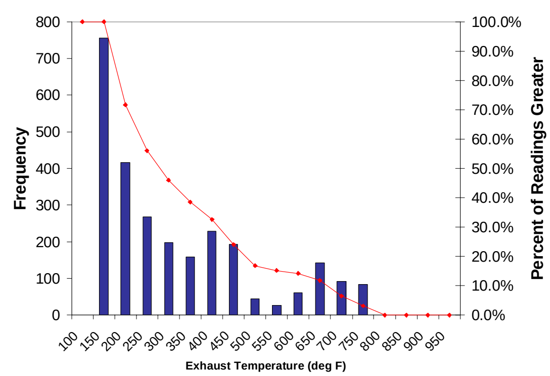
6-Wheel Dump/Plow Truck Exhaust Temperature Distribution



Front End Loader Real-Time Exhaust Temperature – 3+-Hr. Window



Front End Loader Exhaust Temperature Distribution



DOC Procurement

VTrans initiated the procurement process for DOC devices through the State of Vermont purchasing department. A request for proposal (RFP) was advertised and sent to ten individual DOC manufacturers and/or their local representatives. The RFP documents included information about the specific candidate trucks and loaders, including make, model, model year, vehicle identification number, and engine horsepower rating. An RFP was sent to each DOC manufacturer on the then-current list of EPA- and CARB-verified devices.

The RFP limited responses to proven verified technology, expressly stating that installations acting as proof-of-concept would not be considered. However, the RFP did allow for using technology outside of its verified application (e.g., using a DOC verified for an on-road application in a non-road application) as long as minimum warranty requirements were met. In addition to standard State of Vermont contracting requirements, the RFP included several requirements specific to DOC technology and warranty, including:

- The Proposer must furnish all necessary equipment in the form of a retrofit kit (e.g., mounting brackets, exhaust pipes, adapters, clamps, bolts, and heat shield) as well as detailed installation instructions, suitable to enable installation by a qualified mechanic familiar with the vehicle/equipment type, yet unfamiliar with diesel PM emission reduction after treatment retrofit devices. In short, the installation shall be possible by a technician with normal skills using commons tools and no welding shall be required for installation. The proposer must explicitly state whether existing parts from the exhaust system will be used or re-used.
- The after treatment device must be canned in stainless steel.
- The retrofit kit shall include all materials necessary for a successful installation, including mounting brackets, exhaust pipes, adapters, clamps, and bolts as necessary. Mounting brackets and other hardware shall be made of materials appropriate to the intended applications environment.
- The selected Vendor shall provide a product warranty that, at a minimum, meets the warranty provisions of the California Air Resources Board diesel emissions control verification procedure. The specific provisions of this warranty are described in Title 13, California Code of Regulations, Section 2707. The proposer must explicitly state the warranty period and any limitations as part of the bid package. The warranty shall include coverage for consequential damage to the engine or other vehicle/equipment systems caused by the Vendor's technology, as described in the California Code of Regulations, Section 2707, (a)(1)(C).

At the conclusion of the RFP process, only Donaldson responded with a bid. A review of the bid materials indicated that for the on-road trucks, Donaldson has and was proposing an "off-the-shelf" DOC for installation, which was slightly larger than the existing muffler but was suitable for the engines. For the non-road loaders, Donaldson proposed to supply an Independent Catalytic Converter (ICC) that achieves the same emission reduction as a DOC, but does not incorporate any sound reduction qualities and therefore, must be used in conjunction with the existing muffler. At the conclusion of the award negotiation, Donaldson received an award to provide 13 DOCs for on-road trucks at a cost of $1,025 each plus $145 for each installation kit, and 2 ICCs for the non-road application at a price of $800 each plus $47.68 for required installation components (clamps & exhaust pipe reducer accessories).[6]

Typically, once an award is made, DOC and ICCs can be provided by a manufacturer within 90 days, although during this project approximately six months passed from the date of award until delivery of the DOCs and ICCs. A contributing factor to this delay was that although muffler part numbers were provided in the RFP, several of the standard available DOCs from Donaldson did not meet the space limitations and inlet/outlet configurations of the existing trucks. This required additional trucks to be recruited for inclusion into the program and an order was not placed until it was certain that there was a single DOC available to fit all of the on-road trucks. Another contributing factor to this delay was that the ICC would not fit on the loaders. The ICC available for the size engine in the loader was determined to be on the borderline of being too heavy to be mounted in the existing vertical configuration, and space was not available for a horizontal installation. Also, because the ICC must be used in combination with the existing muffler, even if a vertical installation was possible from the weight perspective, the combined height of the ICC and then muffler would exceed the height of the cab, leading to safety concerns from both vehicle height and visibility perspectives. To still meet the goal of deploying a non-road PM reduction strategy, ICCs were installed on two mobile compressor engines used for roadway painting operations.

After the award was made, other vendors that had received the RFP were canvassed to get a sense as to why they did not respond to the RFP. There were two common concerns expressed by all manufacturers related to (1) the requested quantity and (2) the required warranty terms.

Several manufacturers felt that it was not worth the effort to respond to an RFP for a small number of units, and that for an order of that size they would expect to receive an order on a non-competitive basis. Some manufacturers did not respond because they do not offer a standard warranty that includes the terms required by the RFP, or they do not want to offer such a warranty outside of California [7]. Based on discussion with the vendors it appears that if the warranty provisions of the RFP had been less rigorous more companies would have responded.

Installation, Operation & Maintenance

Installation

Installation of the DOC and the first of the ICCs was reasonably straight-forward, without the need for any specialized tools, and was completed during late summer / early fall 2007. DOC installation required about two

[6] DOC Series 6100, Part No. M111193
ICC Series 6000, Part No. M080563

[7] The warranty terms required in the VTrans RFP are identical to the terms mandated by CARB in their verification program.

hours from removing the existing muffler to completion, including mild modification to some of the new parts as well as existing/re-used components on the truck. Modifications included (1) notch out a small section of the hydraulic hose heat shield so that the hanger could be mounted to the rubber isolator; (2) cut out a small section of the new clamp so that the connection with the rubber isolator could be made; and (3) shorten the solid elbow muffler outlet pipe so that the flex pipe between the horizontal DOC outlet and the vertical stack did not need to be shortened. The following photos illustrate the installation of a DOC on one of the dump/plow trucks.

Truck Ready for Installation

Old Muffler (left) – New DOC (right)

DOC Installed

Installation of the ICC on the paint compressor truck required about two hours, somewhat longer than a standard muffler replacement, because of the tight clearances and the need to install exhaust pipe expanders/reducers to go from the existing 3” exhaust pipe diameter to the 3.5” inlet and outlet of the ICC. Because of the limited space available on the rear deck of the compressor truck, there were two locations initially identified for mounting the ICC. The first involved relocating the muffler from its original location to a spot beyond the ICC and mounting the ICC vertically. The second would mount the ICC horizontally on top of the engine cabinet just after the muffler. Mounting in either position requires use of isolated brackets to minimize vibration and for the horizontal installation, provide adequate support for the approximately 30-pound device.

Compressor Truck

Compressor Engine ICC Horizontal Mount Option

During installation, VTrans personnel chose a vertical installation to optimize exhaust temperature going through the ICC by putting it as close to the engine as possible. This required relocating the muffler to the top of the engine cabinet. Moving the muffler involved adding several short lengths of exhaust pipe to accommodate the transition into and out of the ICC and again into and out of the muffler. In addition, as can be seen in the "ICC Installed" photo, two clamps were used to attach the ICC to the side of the engine cabinet to adequately support the weight.

Compressor Engine – Existing Muffler

Compressor Engine – ICC Installed

Compressor Engine – Relocated Muffler

Operations and Maintenance

DOCs do not require any on-going annual maintenance, and the possibility of failure usually lies not with the DOC, but with the engine (e.g., excess lube oil consumption fouling or plugging the catalyst). To date, with approximately six months of in-service operation, VTrans personnel report no impacts to daily operation or ongoing maintenance schedules. In a limited survey of dump/plow truck drivers, there were no negative comments and the drivers indicated there was no noticeable change in vehicle performance as a result of installing the DOC.

Perhaps the most positive comment received about the dump/plow trucks is from VTrans maintenance workers. Several remarked that there was a noticeable difference in the lack of diesel smell associated with the trucks as they were brought into the garage for maintenance.

The mechanics had the same general comment about the compressor engines and one VTrans worker that operates the paint spray equipment on the back of the compressor truck indicated he is very pleased with the new ICC. This worker sits at the rear of the compressor truck and operates the line-painting equipment as the truck travels along at very low speeds. He was happy because he no longer smells the diesel exhaust where he sits at the rear of the truck.

> *With the DOC, there is much less smell to the diesels when we bring them into the garage to work on them.*
>
> **– VTrans Mechanic**

Emission Testing

To assess the emission reduction performance of the DOCs, the VT APCD performed an in-use emission testing program. The program evaluated performance under real-world conditions and using two sets of analyzers, one before and one after the DOC, was able to determine emission reductions of CO, HC and PM. Overall results of the program indicate that the DOCs performed consistently with EPA published verification data. The results of the emission testing are provided in Appendix B.

Best Management Recommendations

Approximately six months of operation has resulted in only positive comments from the operators and mechanics. Mid-way through the winter, temperatures throughout Vermont have certainly been seasonable, with the 90-day median temperature slightly below freezing.[8] Through the several winter storms of the season and the cold stretches of January and early February 2008, operation of the trucks with DOCs was uneventful.

Based on these experiences, several best management practices are recommended.

1. Investigate continued deployment of DOC or other PM-targeted emission control devices for on-road trucks in the VTrans fleet.
2. Encourage retrofit with a device that replaces the existing muffler, such as a DOC, rather than requiring a separate emission control device and muffler.

[8] **Source: National Weather Service 90-Day Temperature Analysis data available at http://www.cpc.ncep.noaa.gov/products/tanal/ninetyday.html**

Following this path generally simplifies the installation.

3. Build upon limited VTrans experience and greater experiences in Boston with the Big Dig and Connecticut with the Q-Bridge project to deploy DOC technology on construction and off-road equipment in the VTrans fleet.

4. Implement contracting mechanisms to deploy DOC and/or other PM-targeted emission control devices for on- and off-road trucks and equipment used on state-funded highway and construction projects.

5. Coordinate voluntary or mandatory retrofit initiatives with regional partners throughout the Northeast to streamline retrofit requirements with similar programs.

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APPENDIX A: Currently Verified Retrofit Technologies

EPA Technology Verification Program

Manuf.	Name	Tech	Applicability	Reductions (%)			
				PM	CO	NOx	HC
Caterpillar	Catalyzed Converter/ Muffler (CCM)	DOC	Highway, heavy-heavy and medium-heavy duty, 4 cycle, non-EGR, model year 1998 - 2003, turbocharged or naturally aspirated engines	20	20	n/a	40
Caterpillar	Diesel Particulate Filter	DPF	Off-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
Caterpillar	Emissions Upgrade Group	DOC + Engine mods	Caterpillar model 3306 diesel engines for off-road applications with model years from 1988 to 1995 with mechanical direct fuel injection	15	3	27	61
Clean Diesel Technologies	Platinum Plus Purifier System	DOC + Fuel Borne Catalyst	Highway, medium-heavy- and heavy heavy-duty, 4 cycle, model year 1988 - 2003, turbocharged or naturally aspirated engines	25-50	16-50	0-5	40-50
Clean Diesel Technologies	Platinum Plus Wire Mesh Filter System	FTF + Fuel Borne Catalyst	Highway, medium heavy-duty, 4 cycle, model year 1991 - 2003, non-EGR, turbocharged or naturally aspirated engines	55-76	50-66	0-9	75-89

Manuf.	Name	Tech	Applicability	Reductions (%)			
				PM	CO	NOx	HC
Cummins Emission Solutions	Cummins Emission Solutions & Cummins Filtration DOC + CCV	DOC + closed crank case filter	Highway, heavy-heavy and medium-heavy duty, 4 cycle non-EGR, model year 1991 - 2003, turbocharged or naturally aspirated engines	30	50	n/a	74
Donaldson	Series 6000 + Spiracle	DOC + closed crank case filter	Highway, heavy heavy- and medium heavy-duty, 4 cycle, non-EGR, model year 1991 - 2003, turbocharged or naturally aspirated engines	25-33	13-23	n/a	50-52
Donaldson	Series 6100	DOC	Highway, heavy heavy- and medium heavy-duty, 4 cycle, non-EGR, model year 1991 - 2003, turbocharged or naturally aspirated engines	20-26	38-41	n/a	49-66
Donaldson	Series 6100 + Spiracle	DOC + closed crank case filter	Highway, heavy-heavy- and medium heavy-duty, 4 cycle, non-EGR, model year 1991 - 2003, turbocharged or naturally aspirated engines	28-32	31-34	n/a	42
Engelhard	DPX	DPF	Highway, heavy-duty, 4 cycle, model year 1994 - 2002, turbocharged or naturally aspirated engines	60	60	n/a	60
Engelhard	CMX Catalyst Muffler	DOC	Highway, heavy-duty, 2 cycle and 4 cycle engines	20	40	n/a	50

Manuf.	Name	Tech	Applicability	Reductions (%)			
				PM	CO	NOx	HC
Engine Control Systems	Purifilter	DPF	Highway, heavy and medium heavy-duty; Urban Bus; 4 cycle; model years 1994 - 2003; turbocharged or naturally aspirated; non-EGR engines	90	75	n/a	85
Engine Control Systems	AZ Purimuffler	DOC + closed crank case filter	Highway, heavy-duty, 4 cycle, mechanically or electronically injected, turbocharged or naturally aspirated, originally manufactured from 1991 through 2004 engines	40	60	n/a	75
Engine Control Systems	AZ Purimuffler	DOC	Highway, medium heavy-duty, 4 cycle, model years 1991 - 2003 Cummins and Navistar/International engines originally manufactured with no after treatment, turbocharged or naturally aspirated, non-EGR engines	40	40	n/a	70
Engine Control Systems	AZ Purimuffler	DOC	Highway, heavy heavy-duty, 4 cycle, model years 1991 - 1993 Cummins engines originally manufactured without exhaust after treatment, turbocharged or naturally aspirated, non-EGR engines	35	40	n/a	70
Engine Control Systems	AZ Purimuffler	DOC	Highway, heavy duty, 2 cycle engines	20	40	n/a	50

Manuf.	Name	Tech	Applicability	Reductions (%)			
				PM	CO	NOx	HC
Engine Control Systems	AZ Purimuffler	DOC	Highway, heavy duty, 4 cycle engines	20	40	n/a	50
International Truck & Engine Corp.	Green Diesel Technology	DOC + Engine mods	Highway, light heavy-duty, 4 cycle, Navistar/International engines, model years 1999 - 2003 in the following families: XNVXHO444ANA YNVXHO444ANB 1NVXHO444ANB 2NVXHO444ANB 3NVXHO444ANB	0-10	10-20	25	50
Johnson Matthey	CCRT	DPF	Highway, heavy-duty, urban bus, 4 cycle, non-EGR model year 1994 - 2006, turbocharged or naturally aspirated engines.	90	85	n/a	95
Johnson Matthey	CRT	DPF	Highway, heavy-duty, 4 cycle, model year 1994 - 2006, turbocharged or naturally aspirated engines	90	85	n/a	95
Johnson Matthey	CEM™ Catalytic Exhaust Muffler	DOC	Highway, 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	DOC	Highway, heavy-duty, 2 cycle engines	20	40	n/a	50
Lubrizol	PuriNOx	Emul-sified Diesel Fuel	Highway & Non-road, heavy-duty, 2 & 4 cycle	16-58	-35 to 33	9 - 20	-30 to -120

Manuf.	Name	Tech	Applicability	Reductions (%)			
				PM	CO	NOx	HC
Paceco Corporation	MES	DPF	Pre-1996 off-road, 4-cycle, heavy-duty diesel engines in the 225 - 450 kW (NR7) power range in electrical generation applications	39	90	n/a	95
PUREM	PMF Green-Tec	DPF	Highway, medium-heavy duty up to 280 hp, 4 cycle, non-EGR, model year 1998-2003, turbocharged or naturally aspirated engines	90	85	n/a	90
Various	B20 Biodiesel	Biodiesel Fuel	Highway, heavy-duty, 2 & 4 cycle	9	21	n/a	10
Various	B5 Biodiesel	Biodiesel Fuel	Highway, heavy-duty, 2 & 4 cycle	2	5	n/a	2
Various	Cetane Enhancer	Fuel Additive	Highway, heavy-duty, 4 cycle, non-EGR-equipped engines	n/a	n/a	0 - 5	n/a

The above list of verified technologies was updated on December 28, 2007. Please see the most current list at:

http://www.epa.gov/otaq/retrofit/verif-list.htm

California Air Resources Board Technology Verification Program

Manuf.	Product Name	Technology Type	Reduction		Applicability
			PM	NOx	
Level 3: Minimum 85% PM Reduction					
Cleaire	Horizon	DPF (active)	85%	N/A	Most on-road engines through 2006 model year; 15 ppm sulfur diesel; CARB diesel. Conditionally verified for off-road engines.
Cleaire	Longview	Lean NOx Catalyst + DPF	85%	25%	1993-2003 model year on-road; 15 ppm sulfur diesel.
Clean Air Systems	PERMIT	DPF	85%	N/A	Stationary emergency and prime generators; 15 ppm sulfur diesel.
Donaldson	DPM	DPF	85%	N/A.	1993-2004 on-road; 15 ppm sulfur diesel.
EGR Technologies LLC	CleanAIR System	DPF+EGR	85%	50%	Conditional verification for stationary prime and emergency standby generator sets and pumps ≤ 600 hp and ≤ 0.4 g/bhp-hr PM
Engine Control System	Purifilter (low load)	DPF	85%	N/A	1994-2003 on-road; 15 ppm sulfur diesel
Engine Control System	Purifilter (high load)	DPF	85%	N/A	1994-2003 on-road; 15 ppm sulfur diesel
Engine Control System	Combifilter	DPF	85%	N/A	1996-2007 off-road; 15 ppm sulfur diesel; CARB diesel
HUSS Umwelttechnik	FS-MK	DPF (active)	85%	N/A	Most on-road and off-road diesel engines through 2006 model year.
International Truck & Engine Corporation	DPX	DPF	85%	N/A.	1994-2003 on-road Navistar (International); 15 ppm sulfur diesel.
Johnson Matthey	CRT	DPF	85%	N/A.	Stationary emergency and prime generators. Conditionally verified for stationary pumps.

Manuf.	Product Name	Technology Type	Reduction		Applicability
			PM	NOx	
Johnson Matthey	EGRT	DPF+EGR	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.
MIRATECH Corporation	combiKat	DPF	85%	N/A	Stationary emergency and prime generators with a PM emission rate of 0.2 g/bhp-hr or less.
Süd-Chemie Inc	EnviCat	DPF	85%	N/A	Stationary prime and emergency standby generators and pumps; 15 ppm sulfur diesel.
Level 2: Minimum 85% PM Reduction					
Donaldson	DFM DMF	Flow Through Filter	50%	N/A	1991-2002 on-road; 15 ppm sulfur diesel.
Lubrizol	PuriNOx	Emulsified Fuel	50%	15%	1988-2003 on-road.
Environmental Solutions Worldwide	Particulate Reactor	Flow Through Filter	50%	N/A	Select model years 1991-1997
Engine Control System	AZ Purimuffler/ Purifier	DOC + Alt Fuel	50%	20%	1996-2002 off-road; PuriNOx
Thermo King	PDPF	Flow through filter	50%	N/A	1985 -1998 Isuzu D201 transport refrigeration unit engines; 15 ppm sulfur diesel
Rypos	ADPF	DPF (active)	50%	N/A	1996-2002 stationary engines; CARB diesel.
Level 1: Minimum 25% PM Reduction					
Donaldson	DCM 6000	DOC	25%	N/A	1988-1990 on-road; 15 ppm sulfur diesel; CARB diesel.
Donaldson	DCM 6000 + Spiracle	DOC + crankcase filter	25%	N/A	1988-2002 on-road; 15 ppm sulfur diesel; CARB diesel.
Donaldson	DCM 6100 + Spiracle	DOC + crankcase filter	25%	N/A	1991-2002; CARB diesel.

Manuf.	Product Name	Technology Type	Reduction		Applicability
			PM	NOx	
Donaldson	DCM 6100	DOC	25%	N/A	1994-2002; 15 ppm sulfur diesel.
Donaldson	DCM 6000 + Spiracle (off-road)	DOC + crankcase filter	25%	N/A	Off-road port equipment; 15 ppm sulfur diesel; CARB diesel.
Extengine	ADEC	DOC + SCR	25%	80%	1991-1995 Cummins 5.9 liter off-road; 150-200 hp; 15 ppm sulfur diesel or CARB diesel.
Engine Control System	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 HHD certain model Cummins and DDC; 15 ppm sulfur.
Engine Control System	AZ Purifier & Purimuffler	DOC	25%	N/A	1996-2002 off-road; 15 ppm sulfur diesel.
Paceco Corporation	Mitsu Engineering and Shipbuilding Diesel Particulate Filter	DPF	25%	N/A	Pre-1996 model year or Tier 1, 2, or 3 certified off-road diesel engines on rubber-tired gantry cranes.
Vycon	Regen System	Hybrid flywheel energy storage system	25%	30%	Pre-1996 model year or Tier 1, 2, or 3 certified off-road diesel engines on rubber tired gantry cranes; CARB diesel < 15 ppm S or biodiesel blend

The above list of verified technologies was updated on December 28, 2007. Please see the most current list at:

http://www.arb.ca.gov/diesel/verdev/vt/cvt.htm

APPENDIX B: VT APCD Emission Testing

APPENDIX B: VT ANR Emissions Testing

Purpose

To conduct an in-use emissions testing program with VTrans on-highway and non-road heavy-duty diesel-powered engines to evaluate the emissions reduction performance of EPA-verified diesel oxidation catalyst (DOC) technology under real-world conditions.

Vehicles and Equipment

- 2003 International 7400 truck w/ 275 hp 530 Caterpillar I6/8.7L diesel engine typically used in snow-plowing and other state highway maintenance operations (Figure 1)
  - Operated on ultra-low sulfur diesel (ULSD) fuel during emissions testing

Figure 1 - VTrans highway maintenance truck

- 2002 Sullair 185 DUQ JD Compressor w/ 40 hp John Deere PowerTech I4/4.5L diesel generator typically used in state roadway painting operations (Figure 2)
  - Operated on ULSD with a 5% biodiesel (B5) blend during emissions testing

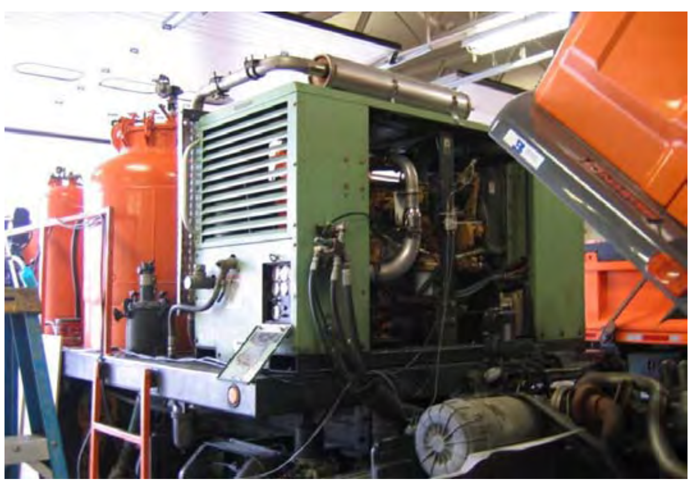

Figure 2 - VTrans mobile compressor engine

Emissions Test Equipment

- Two sets* of OEM 2100 Universal "Montana" Portable Emissions Monitoring Systems (PEMS) manufactured by Clean Air Technologies, Inc. (Figure 3)
    - Laser light-scattering technology for measurement of particulate matter (PM) emissions
        - Pre-DOC PM concentrations measured via laminar flow element inserted into sample port in exhaust line upstream of DOC (Figure 4)
        - Post-DOC concentrations measured via sample probe in exhaust stack (Figure 5)
    - Non-dispersive infrared (NDIR) gas analyzer for measurement of total hydrocarbon (THC) and carbon monoxide (CO) emissions
        - Pre-DOC THC and CO concentrations measured via sample port installed in exhaust line upstream of DOC (Figure 4)
        - Post-DOC THC and CO concentrations measured via sample probe in exhaust stack (Figure 5)

** one before and one after the DOCs*

Figure 3 – Pre- and post-DOC PEMS unit

Figure 4 – Sample ports for pre-DOC measurements

Figure 5 - Probes for post-DOC measurements

- Onboard computer (Figure 6)
- Engine diagnostic scanner to monitor critical engine operating parameters via the engine control module (ECM) diagnostic link (note: sensor array device used in place of diagnostic scanner for mechanically-controlled compressor engine)
- Global positioning system (GPS) used for tracking on-highway vehicle speed

Figure 6 – PEMS onboard computer display

Test Procedure

- Test cycle for 2003 International highway maintenance truck
  - ANR staff, in consultation with VTrans District 3 Operations Division staff, developed a test route representative of typical state highway maintenance truck operation (Table 1).
  - A map of the test route in Rutland, VT (Figure 7).
  - A drive trace for the highway maintenance truck generated by an onboard GPS unit during the emissions test cycle (Figure 8).

Route	***Distance***
Leave VTrans District 3 parking lot	0.1 miles
Turn left onto rural road	0.2 miles
Turn right onto Rt. 7 S	3.8 miles
Turn right onto Rt. 4 W	5.7 miles
Make U-turn onto Rt. 4 E	5.7 miles
Turn left onto Rt. 7 N	3.8 miles
Turn left onto rural road	0.2 miles
Turn right into VTrans District 3 parking lot	0.1 miles
	19.6 mi. total

Table 1 – Description of test route with distances traveled by VTrans highway maintenance truck

Figure 7 - Map of test route for VTrans highway maintenance truck

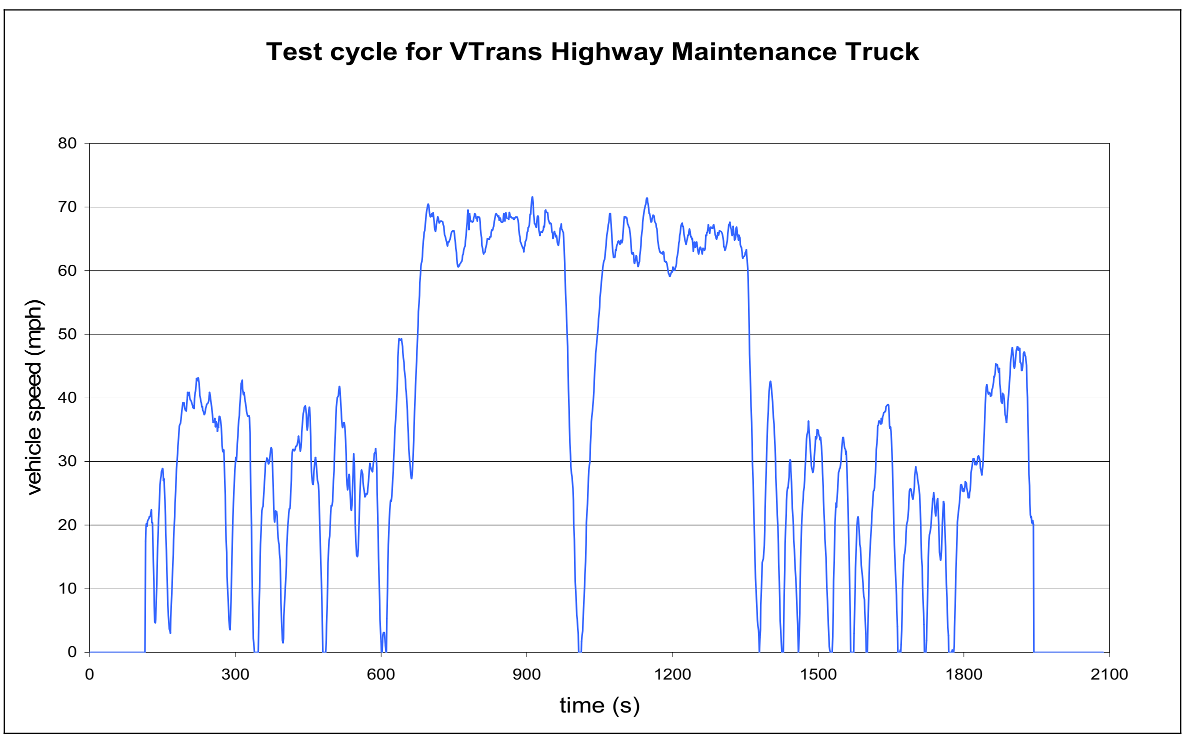

Figure 8 – Vehicle speed for VTrans highway maintenance truck

- Test cycle for 2002 John Deere mobile compressor engine
  - ANR staff, in consultation with VTrans District 6 Operations Division staff, developed a test cycle for the mobile compressor engine representative of typical state roadway painting operation (Table 2).
  - Engine speed in rpm for the mobile compressor engine during the emissions test cycle (Figure 9).

Operating Mode	***Time***
Engine start and warm-up cycle	1 minute
Charging compressor	2 minutes
Painting	5 minutes
Draining tanks (simultaneous for all 3 tanks)	2 minutes
Reloading tanks (simultaneous for all 3 tanks)	5 minutes
Charging compressor	2 minutes
Painting	5 minutes
Engine shutdown	5 minutes
Engine restart and warm-up cycle	1 minute
Charging compressor	2 minutes
Painting	5 minutes
Engine shutdown	
	35 min. total

Table 2 – Description of test cycle for VTrans mobile compressor engine

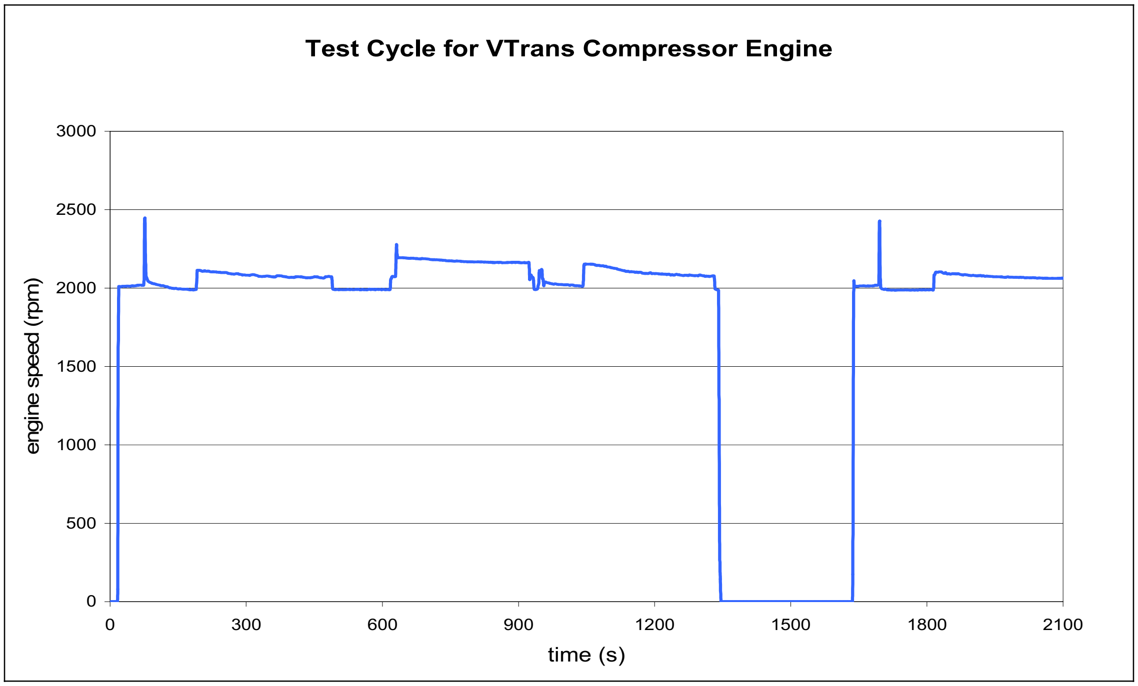

Figure 9 – Engine speed for VTrans mobile compressor engine

Test Results

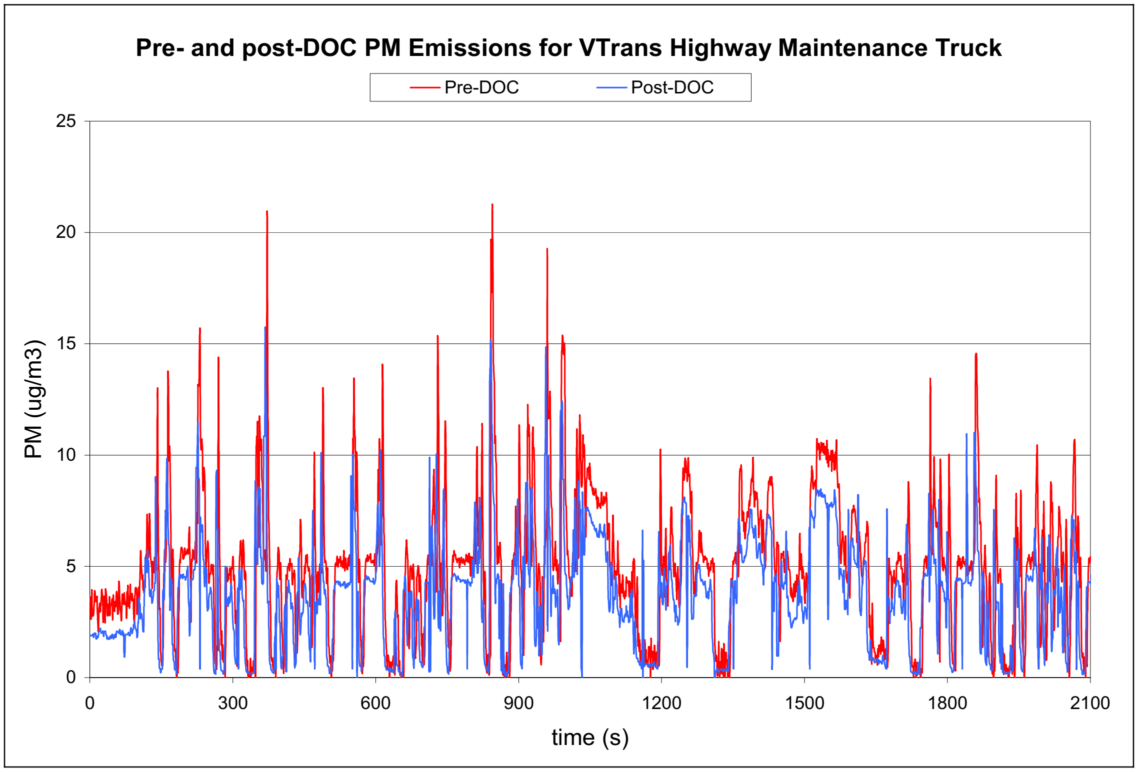

Figure 10 – PM emissions reductions for DOC-equipped VTrans highway maintenance truck

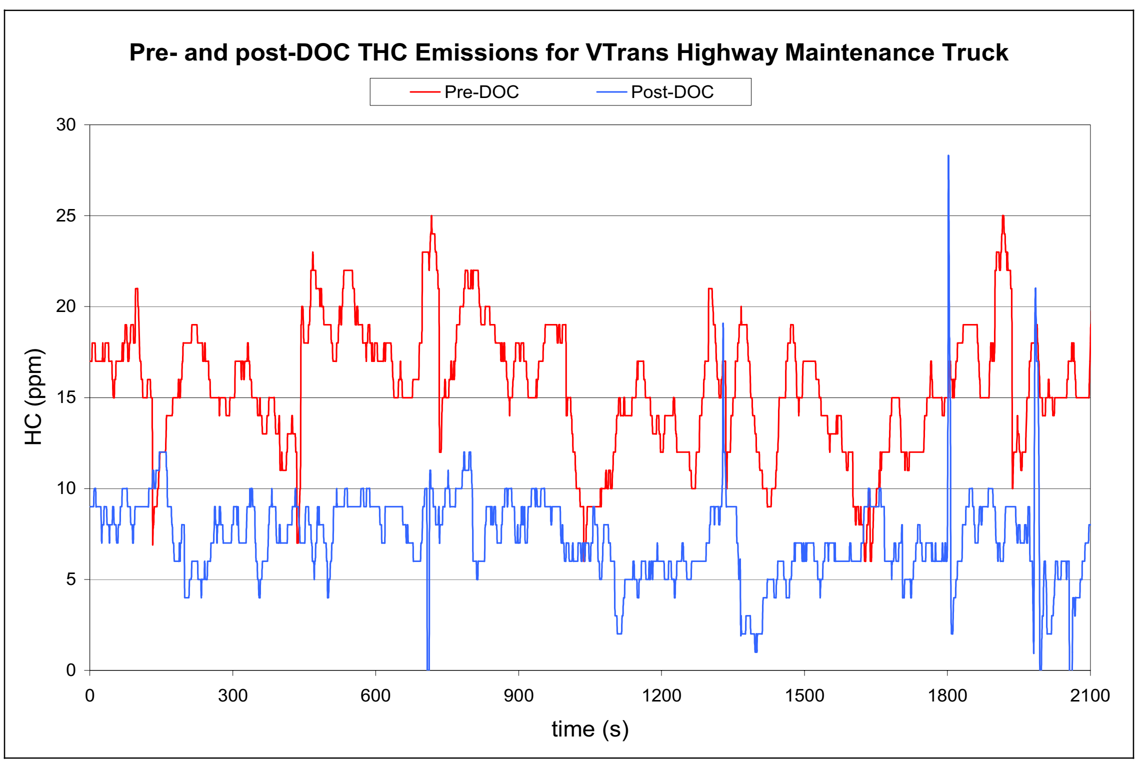

Figure 11 – THC emissions reductions for DOC-equipped VTrans highway maintenance truck

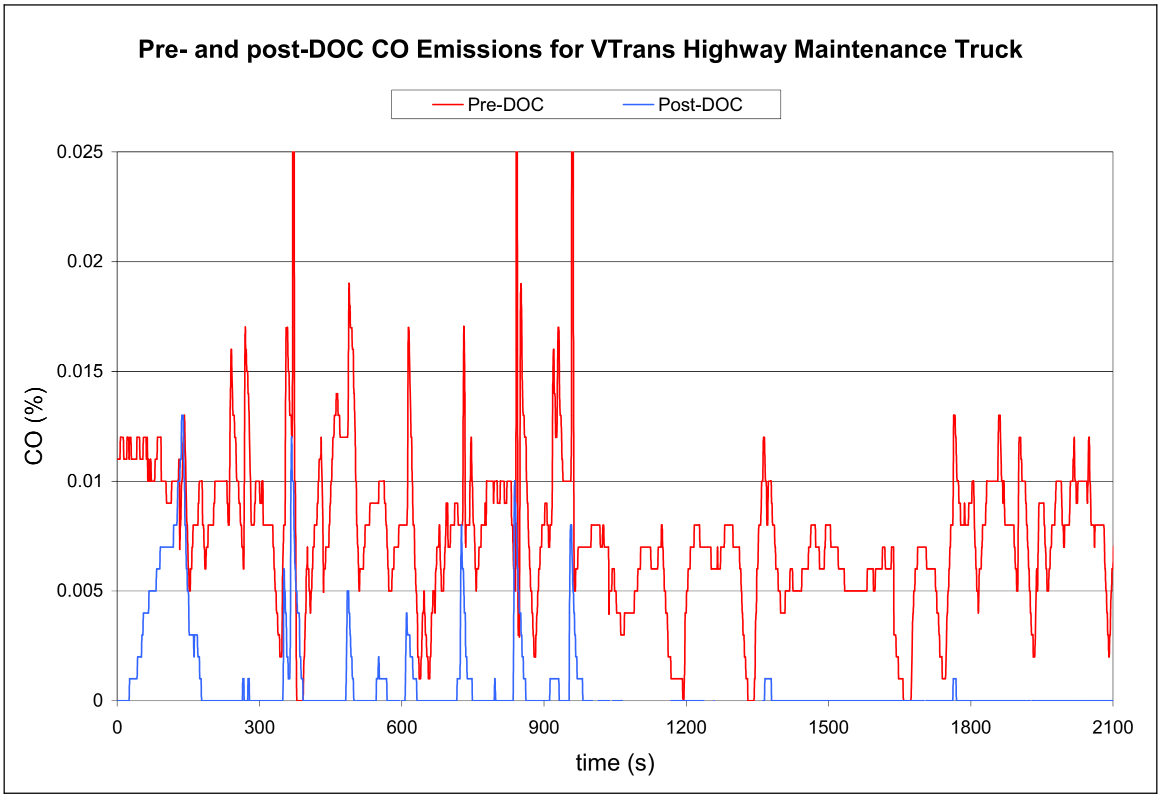

Figure 12 – CO emissions reductions for DOC-equipped VTrans highway maintenance truck

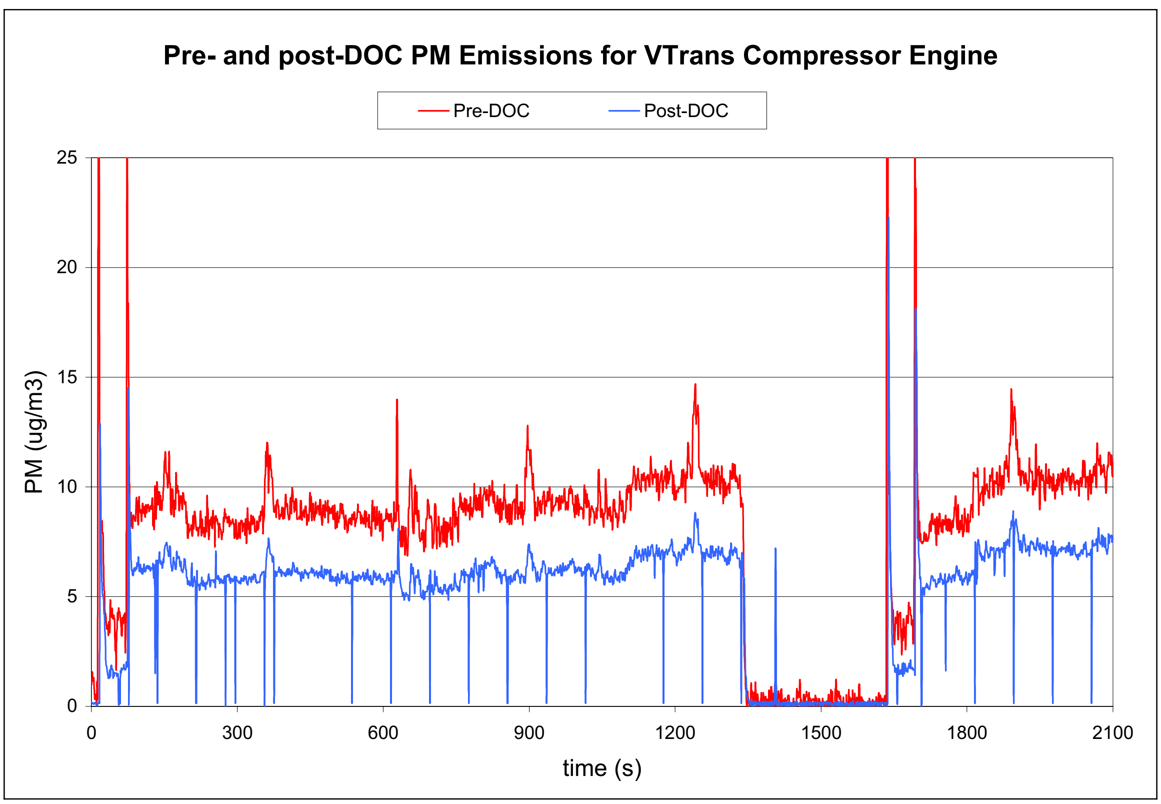

Figure 13 – PM emissions reductions for DOC-equipped VTrans mobile compressor engine

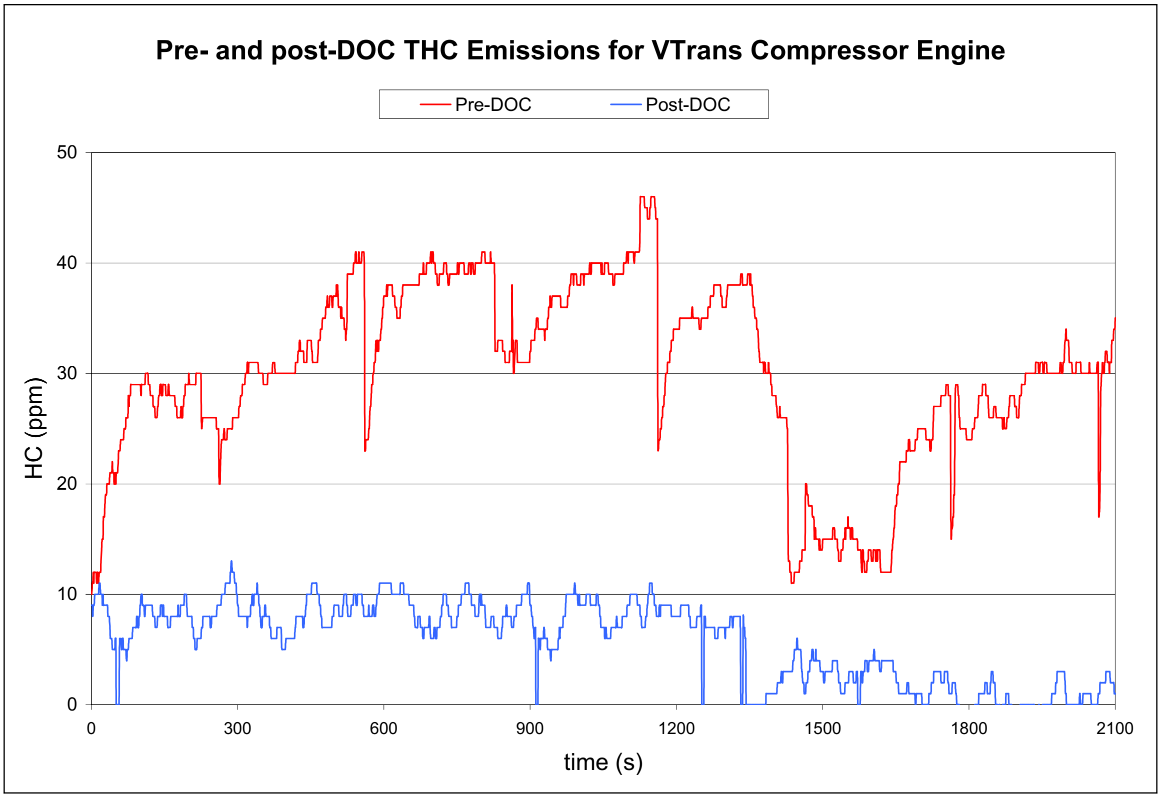

Figure 14 – THC emissions reductions for DOC-equipped VTrans mobile compressor engine

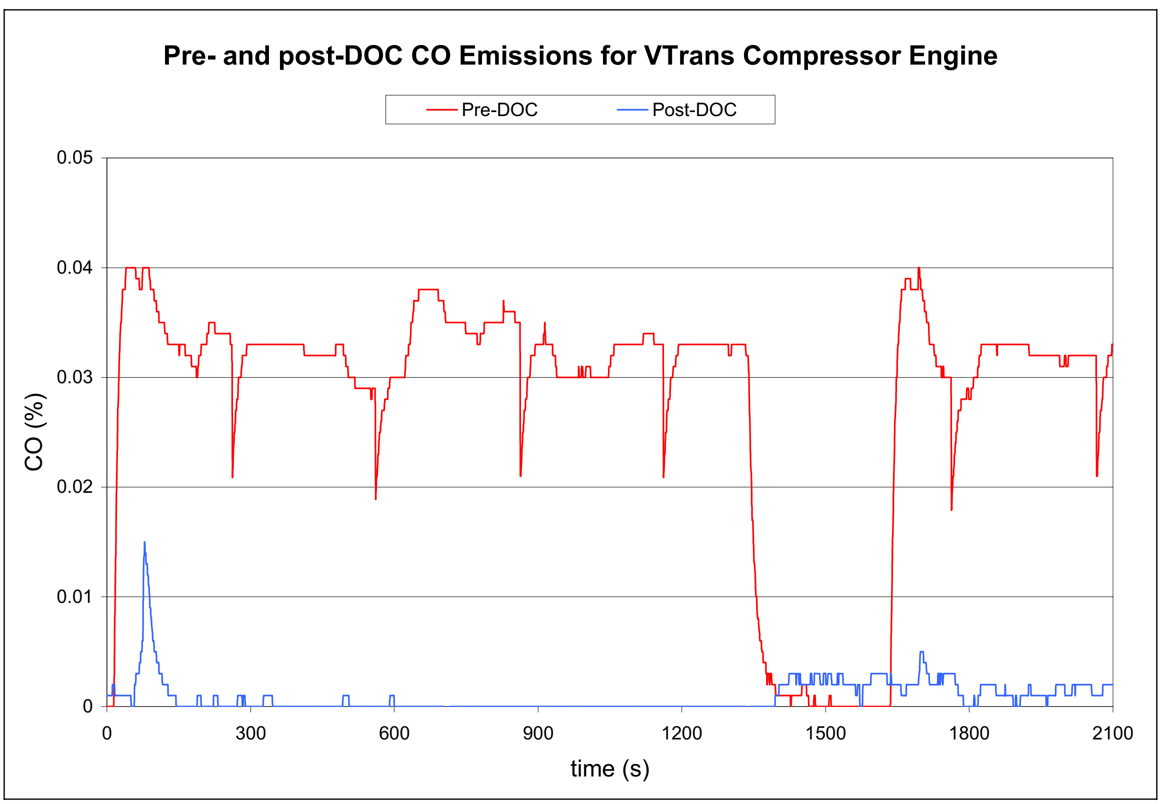

Figure 15 – CO emissions reductions for DOC-equipped VTrans mobile compressor engine

Conclusions

- The analysis of these data serve as an evaluation of 'real world' performance of DOC technology for on-highway and non-road heavy-duty diesel powered engines.
    - 2003 International highway maintenance truck:
        - DOC reduced emissions by
            - 25% for PM
            - 59% for THC
            - 93% for CO
        - DOC performance measurements were consistent with published EPA retrofit verification data.
    - 2002 John Deere mobile compressor engine:
        - DOC reduced emissions by
            - 34% for PM
            - 82% for THC
            - 97% for CO
        - DOC performance measurements were consistent with published EPA retrofit verification data.

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