Retrofitting Emission Controls for Diesel-Powered Vehicles

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EXECUTIVE SUMMARY

Diesel engines are important power systems for on-road and off-road vehicles. These reliable, fuel-efficient, high-torque engines power many of the world's heavy-duty trucks, buses, and off-road vehicles. Diesel engines are easy to repair, inexpensive to operate, and extremely durable. It is common for a diesel engine to last 15-20 years and achieve a one million-mile life. From the standpoint of greenhouse gas emissions, diesel engines can compete with other advanced technologies, like hybrid electric vehicles, due to a diesel engine's inherent fuel economy relative to conventional spark-ignited, gasoline engines. Diesel-powered vehicles have demonstrated a 30-40% fuel economy advantage over their gasoline counterparts. This translates to about a 20% reduction in CO_2 emissions.

While diesel engines have many advantages, they have the disadvantage of emitting significant amounts of particulate matter (PM) and oxides of nitrogen (NOx) into the atmosphere. Diesel engines also emit toxic air pollutants. Health experts have concluded that pollutants emitted by diesel engines adversely affect human health and contribute to acid rain, ground-level ozone, and reduced visibility. Studies have shown that exposure to diesel exhaust causes lung damage and respiratory problems and there is increasing evidence that diesel emissions may cause cancer in humans.

Companies that manufacture emission controls have responded to the challenge of reducing air pollution from the in-use diesel vehicle fleet by developing a large portfolio of retrofit emission control devices. These cost-effective retrofit technologies were developed to reduce the entire range of regulated and unregulated harmful emissions. Some of these devices can significantly reduce the number of ultrafine particles that have been receiving much attention in recent years from both health experts and the regulatory communities.[1,2] In both the on-road and off-road sectors, diesel retrofit technologies have demonstrated their ability to significantly reduce unwanted emissions at reasonable cost without jeopardizing vehicle performance.

Interest in diesel retrofit from the U.S. Environmental Protection Agency (EPA), the California Air Resource Board (ARB), and international entities has grown. ARB has established a mandatory retrofit program for most in-use diesel-powered vehicles in the state as part of its Diesel Risk Reduction Plan (DRRP). The U.S. EPA has established a voluntary program with state and federal funding under its National Clean Diesel Campaign. Both agencies require retrofit devices to complete a rigorous verification program to ensure that the devices meet strict performance and durability requirements. The Manufacturers of Emission Controls Association (MECA) has received many inquiries regarding the installation of emission controls on existing diesel engines. Inquiries have included requests for technical information, information on past retrofit experiences, the types of retrofit control technologies available, the suitability of a given technology to a particular application, and the emission reductions that can be achieved. This document has been prepared to supplement information already made available by MECA on emission control technologies.

Available Control Technologies

Today, viable emission control technologies exist to reduce exhaust emissions from existing diesel vehicles. The major retrofit technologies are listed below. Retrofit technologies designed to control particulate matter (PM) include:

- Diesel oxidation catalysts (DOCs)
- Diesel particulate filters (DPFs)
- Flow through filters (FTFs)
- Closed crankcase ventilation (CCV)

Retrofit technologies designed to control oxides of nitrogen (NOx) include:

- Exhaust gas recirculation (EGR)
- Selective catalytic reduction (SCR)
- Lean NOx catalysts (LNCs or HC-SCR)
- Lean NOx traps (LNTs)

The retrofit of oxidation catalysts on diesel engines has been taking place for well over twenty years in the off-road vehicle sector. Over 300,000 oxidation catalysts have been installed in underground mining and materials handling equipment. With nearly universal application, oxidation catalysts have been retrofitted on millions of on-road and off-road vehicles worldwide. And tens of millions of these devices are operating as first-fit, original equipment (OE) on new vehicles. Oxidation catalysts installed on engines running 500 ppm or less sulfur fuel have achieved total particulate matter reductions of 20 to 50%, hydrocarbon reductions of 60 to 90% (including those HC species considered toxic), and significant reductions of carbon monoxide, smoke, and odor.

The number of vehicles retrofitted with high efficiency, wall-flow diesel particulate filters (DPF) has grown significantly over the past few years. Over 300,000 on-road and off-road heavy-duty engines worldwide have been retrofitted with passively or actively regenerated DPFs, with more than 100,000 DPF retrofits installed on diesel engines in the U.S. since 2001. In addition, millions of new passenger cars have been equipped with DPFs in Europe since mid-2000. Significant investments in DPF production capacity have been made and will be expanded in the future to ensure that DPF demands for both new vehicles and retrofit applications in North America can be met. The operating and durability performance of DPFs has been very impressive. For example, a growing number of on-road DPF-equipped heavy-duty vehicles have been successfully operating for millions of miles. Today, second and third generation retrofit filter systems can reduce PM emissions from 85% to more than 90%. The majority of these installed retrofit DPF systems make use of high efficiency, ceramic wall-flow filters. Since 2007, every new diesel vehicle sold in the U.S. or Canada has been equipped with a high efficiency DPF as required by the U.S. EPA's 2007/2010 highway heavy-duty emission regulation. This represents more than three million new trucks operating on DPFs mostly in the U.S. In 2010, new highway trucks were required to reduce NOx emissions by 90% relative to pre-2007 requirements and have been equipped with NOx control technologies such as lean NOx trap catalysts, urea SCR, and high-flow EGR systems. Urea SCR has established itself as the preferred NOx reduction technology for on-road and off-road vehicles and engines.

Flow-through filter (FTF) technology or partial filters employ catalyzed metal wire mesh structures, tortuous flow, metal foil-based substrates with sintered metal sheets, or specially designed ceramic filters to reduce diesel PM. These partial filter technologies have employed catalysts and/or fuel-borne catalysts to oxidize soot. This technology has been applied on older, dirtier engines because it is much less likely to plug (compared to wall flow filters) and most often does not require ash cleaning. Flow-through filters are capable of achieving PM reduction of about 30 to 75%, as well as trapping the sub-micron, ultrafine particles capable of penetrating deep into the lungs. FTFs can be catalyzed to offer co-benefits of reducing HC, CO, and toxics of up to 80-90%.

The Association for Emissions Control by Catalyst (AECC) conducted test programs for particle size and number on light-duty and heavy-duty vehicles using the procedures outlined in the European Particle Measurement Program (PMP). The results of the testing demonstrated the efficiency of wall-flow filters to reduce engine out particle number by three orders of magnitude at a filtration efficiency of 99.9%.[3]

The recent focus on climate change and global warming has sparked a discussion of the global warming potential of black carbon.   Black carbon is a major component of PM emissions from fossil fuel-burning sources and has a significant net atmospheric warming effect by enhancing the absorption of sunlight. Since black carbon particles only remain airborne for weeks at most compared to carbon dioxide, which can remain in the atmosphere for more than a century, removing black carbon has an immediate benefit to both global warming and public health.

Black carbon from diesel engines can be significantly reduced through emission control technology that is already commercially available. High-efficiency DPFs on new and existing diesel engines provide nearly 99.9% reductions of black carbon emissions. During the regeneration of DPFs, captured carbon is oxidized to CO_2, but this filter regeneration still results in a net climate change benefit since the global warming potential of black carbon has been estimated to be up to 4500 times higher than that of CO_2 on a per gram of emission basis.

As emission requirements have incorporated the need for NOx reductions as well as PM from the in-use diesel fleet, manufacturers have developed integrated PM + NOx retrofit technologies. Exhaust gas recirculation (EGR) and lean NOx catalysts combined with DPFs have been retrofitted on heavy-duty diesel vehicles. EGR is capable of achieving about a 40% reduction in NOx emissions. EGR retrofits have seen limited application in the U.S, with approximately 1,000 engines retrofitted with EGR systems that also include a DPF. Retrofit EGR systems have also found a significant market penetration in Hong Kong, with over 450 systems installed.

Lean NOx catalyst (LNC) technology can achieve a 10 to 40% reduction in NOx emissions. This technology is more effective when a supplemental hydrocarbon reductant, such as diesel fuel, is injected into the exhaust stream. The hydrocarbons facilitate the conversion of NOx to nitrogen and water vapor over the catalyst. LNC technology is attractive because the technology does not require any core engine modifications or additional reductant fluid such as diesel exhaust fluid (DEF or urea). Lean NOx catalysts can be combined with DPFs or DOCs to provide both NOx and PM reductions. One such system has been verified by ARB for a large variety of on-road and off-road diesel engine applications. This particular system combines a lean NOx catalyst with a DPF to reduce NOx emissions by 25 to 40% and PM emissions by more than 85%.

Selective catalytic reduction (SCR) systems, using diesel exhaust fluid (DEF) as a reducing agent, have been installed on millions of new diesel-powered trucks in the U.S., Europe, and Japan. A variety of new U.S. and European diesel passenger cars are also being sold with SCR control technologies. Manufacturers are also offering SCR technologies in China for compliance with China's National 4 regulations (equivalent to Euro IV). Several manufacturers are demonstrating the same technology in combination with a DPF to retrofit on-road and off-road engines. SCR is capable of reducing NOx emissions from 70 to 90% while simultaneously reducing HC emissions up to 80% and PM emissions by 20 to 30%. In combination with a DPF, the PM reductions can be increased to over 85%. SCR has been installed on heavy-duty trucks, off-road equipment, marine vessels and locomotives. SCR is frequently applied to stationary diesel engines to achieve large NOx reductions in steady-state operations. SCR systems retrofitted on line-haul trucks in Europe operated successfully over an extended period where mileage accumulations exceeded several hundred thousand miles. SCR technology, available on new trucks in late 2009, has been selected by new truck manufacturers as the technology of choice to meet the U.S. EPA 2007/2010 on-highway regulation.

Diesel Retrofit Programs

Although technologies exist to reduce emissions from in-use diesel engines, care must be exercised to plan and implement a retrofit program to ensure that air quality benefits are realized. Successful implementation and operation of a diesel retrofit program depends on a number of elements.

The program should define:

- which vehicles are suitable for retrofit
- the appropriate emission control technology for each vehicle
- the emission reductions that are desired or required
- fuel quality needs (e.g., sulfur level; ideally, ULSD should be used)
- operational and maintenance requirements
- training and education needs of vehicle operators and the public

Factors that influence vehicle selection include, application, duty cycle, exhaust temperature and vehicle maintenance. Knowing this information will help in the selection of an appropriate technology for the vehicle. For optimum results the engine of a vehicle should be rebuilt to the manufacturer's specifications before a catalyst, filter system, or other emission control device is installed.

Along with California's Diesel Risk Reduction Plan and U.S. EPA's Voluntary Diesel Retrofit Program, retrofit programs have been initiated worldwide, including those in Hong Kong, Japan, Sweden, United Kingdom, Switzerland, Korea, Mexico, and other countries throughout the world. In the U.S., six regional collaboratives have been formed to bring together public and private funding and interests in reducing emissions from all diesel engines currently operating in these regions.

Although diesel emissions from mobile sources have raised health and welfare concerns, a number of effective control strategies exist or are being developed that are cost-effective and can greatly reduce emissions from existing diesel-powered vehicles while deferring the expenses of buying a new vehicle or equipment. Retrofit technologies, including DOCs, DPFs, FTFs, EGR, lean NOx catalysts, and SCR, have been successfully commercialized and/or demonstrated on both on-road and off-road vehicles. These technologies can greatly reduce particulate matter, oxides of nitrogen, and other harmful pollutants from diesel exhaust.

1.0 INTRODUCTION

Diesel engines provide important fuel economy and durability advantages for large heavy-duty trucks, buses, and off-road equipment. They are often the power plant of choice for heavy-duty applications due to their high torque at low engine speeds or rpm. While they have many advantages, they also have the disadvantage of emitting significant amounts of particulate matter (PM) and the oxides of nitrogen (NOx) and lesser amounts of hydrocarbon (HC), carbon monoxide (CO) and toxic air pollutants.

Particles emitted from diesel engines are small – in most cases less than 2.5 microns in diameter. The particles are complex consisting of an uncombusted carbon core, adsorbed hydrocarbons from engine oil and diesel fuel, adsorbed sulfates, water, and inorganic materials such as those produced by engine wear. Because of their extremely small size and composition, the particles emitted by diesel engines have raised many health concerns. Health experts have expressed concern that diesel PM may contribute to or aggravate chronic lung diseases such as asthma, bronchitis, and emphysema.[4]

There is growing evidence that exposure to diesel PM may increase the risk of cancer in humans. As early as 1988, the International Agency for Research on Cancer (IARC) concluded that diesel particulate is probably carcinogenic to humans. In June 2012 IARC changed their designation for diesel exhaust from probable to a known carcinogen to humans. The term "carcinogen" is used by the IARC to denote an agent that is capable of increasing the incidence of malignant tumors. In August 1998, California's Air Resources Board identified PM emissions from diesel-fueled engines as a toxic air contaminant. In 2000, the U.S. EPA declared diesel PM to be a "likely human carcinogen." A recent report, "Diesel and Health in America: The Lingering Threat," issued in February 2005 by the Clean Air Task Force, reviews the health impacts of diesel particulate emissions in the U.S. This report states that fine particulate pollution from diesel engines shortens the lives of nearly 21,000 people in the U.S. every year, with health-related damage from diesel PM estimated to total $139 billion in 2010. There is evidence that suggests that the health threat of diesel exhaust may be exacerbated within those industries in closest proximity to it such as trucking and construction.[5,6]

In addition to the direct health impacts of particulate matter, the carbonaceous component of PM often referred to as black carbon has been found to be a significant contributor to the atmospheric warming effect by enhancing the absorption of sunlight. The global warming potential of black carbon has been estimated to be up to 4500 times higher than that of CO_2 on a per gram of emission basis. This warming impact is enhanced when PM is deposited on snow in the arctic reducing its reflectivity and accelerating sea level rise. Since black carbon particles only remain airborne for weeks at most compared to carbon dioxide, which can remain in the atmosphere for more than a century, removing black carbon from diesel exhaust has an immediate benefit to both global warming and public health.

Recent attention in the health and environmental communities has been focused on ultrafine particulates (UFP) being emitted by diesel engines with and without exhaust emission controls. UFP are typically defined as diesel particles with an average diameter less than 100 nm or 0.1 µm.[7] Some researchers believe that ultrafine particles are more dangerous because of their small size and physical structure allowing them to penetrate into the gas-exchange portion of the lung and subsequently into the blood stream resulting in possible systemic effects.[1,2,8] The extremely high surface area of ultrafine particles provides a favorable support for deposition of volatile toxic compounds that are present in the exhaust upon cooling and dilution in the atmosphere [4] A combination of these two mechanisms provides a pathway by which air toxics such as polycyclic aromatic hydrocarbons (PAHs) can adsorb onto particles and enter the body efficiently increasing the oxidative stress and inflammation within the cells in other organs.[2,4] In this paper we will discuss how diesel exhaust control technologies remediate ultrafine particles.

The NOx emissions from diesel engines also pose a number of health concerns. Once in the atmosphere, the oxides of nitrogen react with volatile organic compounds (VOCs) in the presence of sunlight to form ozone. Ozone is a reactive and corrosive gas that contributes to many respiratory problems. Ozone is particularly harmful to children and the elderly. The American Lung Association (ALA) reported 10,000 to 15,000 hospital admissions and 30,000 to 50,000 emergency room visits in the 1993 and 1994 high ozone season in 13 American cities because of elevated ozone levels. NOx emissions themselves can damage respiratory systems and lower resistance to respiratory infection. As with ozone, children and the elderly are particularly susceptible to NOx emissions. Based on results of health studies and recommendations of its own Clean Air Science Advisory Committee (CASAC), the U.S. EPA is reviewing the National Ambient Air Quality Standard (NAAQS) for ozone to determine if further tightening below the current 0.075 ppm limit is justified. NOx emissions are also a major contributor to the $PM_{2.5}$ inventory when they react in the atmosphere with ammonia and other gases to form nitrate particles as secondary $PM_{2.5}$. Many states develop control strategies for NOx as a way to help them meet their State Implementation Plan (SIP) commitments for attainment of the $PM_{2.5}$ NAAQS.

In addition to the undesirable health affects associated with diesel exhaust, diesel emissions also adversely affect the environment. Diesel particulate emissions soil buildings and impair visibility. Diesel NOx emissions contribute to the problems of acid rain and ground-level ozone. From a quality of life perspective, there is increasing interest in reducing the smoke and odors associated with emissions from diesel engines.

Despite health and environmental concerns, the diesel engine remains a popular means of powering trucks, buses and other heavy equipment. Diesel engines are reliable, fuel efficient, easy to repair and inexpensive to operate. One of the most impressive attributes of the diesel engine is its durability. In heavy-duty trucks, some engines have achieved operating lives of 1,000,000 miles; some engines power city buses for up to 15 to 20 years. Because of the above attributes and better fuel economy and lower CO_2 emissions, diesel engines have also become a significant powertrain for light-duty passenger vehicles in Europe and more recently in the U.S. This has been made possible by the implementation of clean diesel technologies.[9] For examples of how diesel retrofit devices have been successfully applied across the existing diesel fleet, see the MECA retrofit website to find a number of case study reports (www.meca.org/resources/reports).

A number of countries worldwide have established significantly lower exhaust emission limits for new diesel engines that have been and will be phased in over the 2005 through 2020 timeframe. However, due to the very long operating lives of many diesel engines, older uncontrolled diesel vehicles will continue to make up a significant portion of the heavy-duty vehicle fleet in these countries for years to come. Given the health and environmental concerns associated with diesel engines, there is increasing interest to retrofit older, "dirtier" diesel engines while newer, "cleaner" diesel engines enter the marketplace.

2.0 IN-USE DIESEL EMISSION REDUCTION PROGRAMS

Successful diesel retrofit programs are occurring worldwide, including programs by the U.S. EPA, California ARB, the state of New Jersey, New York, Texas, Illinois, New York City, Hong Kong, Japan, South Korea, Mexico, and Sweden. China, Thailand, India and Chile also have experience with retrofit programs.

The U.S. EPA announced the creation of a Voluntary Diesel Retrofit Program for diesel vehicles in 2000. Trucks, buses, and off-road equipment are covered by the program. Under the program, if a state uses a verified retrofit technology, they are eligible to receive State Implementation Plan (SIP) emission reduction credits. EPA established a goal of retrofitting, replacing, or repowering all 20 million in-use diesel engines by 2015. The EPA program includes a protocol for calculating credits, the structure of a verification system for approving retrofit technologies, and in-use testing requirements to ensure that the emission reduction credits claimed are achieved in the field. More information on EPA's Voluntary Diesel Retrofit Program can be found at: www.epa.gov/cleandiesel/.

The Air Resources Board (ARB) identified diesel PM as a toxic air contaminant in August 1998. This action led to the development of the Diesel Risk Reduction Plan (DRRP) to reduce the risk from diesel PM emissions, which was approved by the ARB in September 2000. Identified in the Plan, entitled the "Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel-Fueled Engines and Vehicles," are measures to dramatically reduce emission levels of diesel PM.

The measures fall into three broad categories:

1. more stringent engine exhaust emission standards for new on- and off-road vehicles and equipment;
2. retrofitting existing on-road and off-road engines with devices that will reduce diesel PM by 85 percent or more; and
3. improving and implementing programs that will maintain mandated exhaust emission levels throughout the life of the vehicle or equipment.

The goal is to reduce diesel PM emissions from the state's current 1.2 million on-road, off-road, and stationary diesel engines by 75 percent in 2010 and 85 percent by 2020.

The Plan emphasizes retrofit and in-use controls for existing diesel engines because these engines typically have useful lifetimes in excess of 400,000 miles. A diesel engine is rebuilt, rather than replaced, when it reaches the end of its useful lifetime. Current regulations, except those applying to urban transit buses, allow the engine to be rebuilt to meet the standards in effect at the time of manufacture. To address this problem, the report recommends a large-scale program to retrofit diesel particulate filters, and other feasible technologies, on existing diesel engines.

Since ARB adopted their landmark Diesel Risk Reduction Plan in 2000, the Board has approved regulations that mandate PM and NOx reductions from a variety of existing diesel engines operating in the state. Regulated fleets include; transit buses, other transit fleet vehicles, refuse haulers, stationary engines, portable diesel engines, transportation refrigeration units (TRUs), public and utility fleet vehicles, cargo handling equipment, port trucks, off-road public and private fleets, and private on-road vehicles. The adopted regulations mandate compliance by two primary compliance pathways to achieve specific emission limits that are lowered over time: the fleet can achieve this by meeting a fleet average limit in PM and NOx emissions, or the fleet can apply best available control technology (BACT) to a minimum number of vehicles over a multi-year implementation schedule. If a fleet cannot meet its fleet average targets for a given year, California has set a maximum percentage of retired and retrofit vehicles that must be completed in a given year. The most recent regulations that impact on and off-road private and public fleets focus on PM reductions in the early years of implementation with eventual phase in of NOx reductions. Nearly all on-road medium- and heavy-duty vehicles must have a Level 3 PM filter (85 percent PM reduction or greater) by 2015 and by 2024 be upgraded to meet equivalent 2010 on-highway emission certifications or better.

2.1 Incentives and Retrofit Funding

Because diesel engines can last up to 20 to 30 years or longer, it will take many years before the bulk of the existing diesel engines may be retired and be replaced with diesel engines that meet more stringent emissions standards. Therefore, it is important to provide incentives for these in-use engines to be retrofitted with emission control devices or be replaced. Incentives are an effective way to encourage the use of diesel retrofit control technologies.

Incentives can include:

- a reduction in vehicle registration fees, taxes, or user fees;
- retrofit in lieu of paying smoke inspection violation fines;
- an exemption from roadside smoke inspections;
- an exemption from use restrictions;
- clean diesel awards/publicity for fleet operators who use retrofit control technologies; and
- partial funding by government agencies.

A number of local air quality agencies have adopted regulations that require that vehicles be retrofitted to perform any publicly funded construction project in an urban area.

Retrofit technologies offer a viable means of reducing emissions from trucks, buses, construction equipment and other heavy-duty vehicles, including marine and locomotives that are currently in use. There are enormous health and environmental benefits that can be achieved by implementing diesel retrofit programs. These benefits have been estimated to be $10 or more for every dollar of cost associated with the program. Under current EPA policy, states can take credit for the emission reductions achieved in retrofit programs in their State Implementation Plan (SIP) plans that describes a state's strategy for achieving and maintaining National Ambient Air Quality Standards. Like other SIP strategies, the voluntary measures must be consistent with SIP attainment and Rate of Progress requirements. The emission reductions from retrofit programs must be quantifiable, enforceable, permanent and surplus. EPA policy allows 3 percent of the inventory for each criteria pollutant to meet air quality standards to be from voluntary mobile source emission reduction programs. EPA is encouraging states, local agencies, industries, and environmental organizations to promote EPA's Voluntary Diesel Retrofit Program and to incorporate this program into their SIP.

There are many available sources to fund diesel retrofit projects. Funding sources include federal, state and local programs. Building on the successes of EPA's regulatory and voluntary programs to reduce emissions from diesel engines, EPA created the National Clean Diesel Campaign that includes voluntary sector programs to reduce diesel emissions.

- *Clean School Bus USA.* U.S. EPA initially launched the Clean School Bus USA program in April 2003 with the goal of upgrading the nation's entire school bus fleet (more than 400,000 buses) to low emission buses by 2010. Clean School Bus USA is a public-private environmental partnership that seeks to reduce children's exposure to air pollution from diesel school buses. The program emphasizes three ways to reduce school bus emissions through anti-idling strategies, engine retrofit and clean fuels, and bus replacement. The goal of the program is to reduce both children's exposure to diesel exhaust and the amount of air pollution created by diesel school buses. More information on EPA's Clean School Bus USA program can be found at: www.epa.gov/cleanschoolbus/csb-overview.htm.

- *Clean Construction USA.* Clean Construction USA is a voluntary program that promotes reduction of diesel exhaust emissions from approximately 1.8 million pieces of construction equipment and vehicles used in the U.S. today. The program promotes the use of innovative emissions control technologies and the replacement of old equipment by promoting retrofit incentives and providing technical assistance. Clean Construction USA encourages contractors, owners, and operators of construction equipment to; properly maintain their equipment, retrofit and replace older diesel engines with verified or certified technologies, and use cleaner fuels. More information on EPA's Clean Construction USA program can be found at: www.epa.gov/cleanschoolbus/construct-overview.htm.

- *Clean Ports USA.* Clean Ports USA is a voluntary program that encourages port authorities and terminal operators to retrofit and replace older diesel engines with verified technologies; use cleaner fuels; and to provide economic incentives for ports' contracts with tenants, contractors, and others. More information on EPA's Clean Ports USA program can be found at: www.epa.gov/cleanschoolbus/ports-overview.htm.

- *SmartWay Transport Partnership.* SmartWay Transport Partnership is a voluntary program between EPA and the freight industry to increase energy efficiency and to reduce greenhouse gas emissions. This initiative intends to reduce 33 to 66 million metric tons of CO_2 emissions and up to 200,000 tons of NOx emissions per year by 2012. The three primary components of the program are: creating partnerships, reducing unnecessary engine idling, and increasing the efficiency and use of rail and intermodal operations. More information on EPA's SmartWay Transport Partnership can be found at: www.epa.gov/cleanschoolbus/sw-overview.htm.

In June 2005, the U.S. Senate passed an amendment to the Energy Bill that authorized funding to cut emissions from high-polluting diesel engines. The Diesel Emissions Reduction Act (DERA) of 2005 created a national program to fund the cleanup of all types of diesel-powered vehicles, including trucks, buses, tractors, ships, and trains. The legislation authorizes $200 million per year over five years in grants and loans for states and organizations to clean up existing diesel fleets. Congress re-authorized DERA funding in 2010 for up to $100 million per year for federal budget years 2012 through 2016. Although in the early years of DERA the funding was limited and primarily focused on cleaning up school busses, in 2008 the funding was increased to $49.2 million. In 2009, DERA received a $60 million allocation plus an additional $15 million allocated to California's South Coast and San Joaquin Valley regions. Also, in 2009, DERA received a significant boost in funding of $300 million as part of the American Reinvestment and Recovery Act of 2009 (ARRA). Since 2008, Congress has provided EPA with more than $580 million for its DERA funded projects. EPA has provided reports to Congress in 2009 and 2012 on their DERA program activities (reports available at: www.epa.gov/cleandiesel/publications.htm).

California has adopted several funding programs to support the many regulations aimed at cleaning up the in-use diesel fleet under the DRRP. The Carl Moyer Program is a statewide program that is designed to promote diesel emission reductions through grants for both the private and public sector. The program funds, overseen by ARB, are used to offset the incremental costs of cleaner than required heavy-duty vehicles and equipment. Categories eligible for funding of replacement, repowering, or retrofits under the Moyer Program include, on-road motor vehicles (GVWR >14,000 lbs), off-road equipment (> 50 hp), marine vessels, locomotives, stationary agricultural pump engines, forklifts, airport ground support equipment, and heavy-duty auxiliary power units. The Moyer program provides approximately $140 million per year of incentive funds to help defray the costs of cleaning up in-use vehicles that provide early or excess emission reductions relative to reductions required by ARB regulations. To qualify for Moyer funding, the vehicle must be cleaned up at least three years prior to any regulation goes into effect for that vehicle category. Funds are awarded on a competitive basis based on the cost-effectiveness of the project. For more information on the Moyer program, go to: www.arb.ca.gov/msprog/moyer/moyer.htm.

Certain areas in the state of Texas are in non-attainment with respect to the ozone NAAQS and therefore the Texas Commission on Environmental Quality has established the Texas Emission Reduction Plan (TERP) to address NOx emissions from a variety of sources. The TERP consists of several voluntary financial incentives and other assistance programs. Categories eligible for funding under TERP include, on-road motor vehicles, off-road equipment, marine vessels, locomotives, stationary agricultural pump engines, forklifts, airport ground support equipment, and heavy-duty auxiliary power units. For more on funding available through TERP, go to: www.tceq.state.tx.us/implementation/air/terp/.

2.2 Retrofit Device Verification Programs

There are two verification programs for retrofit technology in North America, the California Diesel Risk Reduction Plan and the U.S. EPA Voluntary Retrofit Program. The verification process strives to provide confidence in performance and durability of retrofit, diesel emission control systems. To accomplish this, each verification process tests candidate technologies under standard protocols to demonstrate the level of emission reduction, tests the technology in actual applications in the field over a minimum durability period, and monitors the performance of the technology over its full useful life via in-use compliance testing. Technologies that have successfully passed the verification process are included in a list of verified technology providers. If a technology fails to meet the in-use testing criteria specified in the verification program, it is removed from the list. This list serves as a guide to vehicle or fleet owners in the process of trying to meet state or local emission regulations or that are interested in voluntarily reducing emissions from their on-road or off-road vehicles. There has been some attempt at reciprocity between the ARB and EPA verification programs; however, they maintain independence in many respects. The same set of emission data can be submitted to both programs; however, each reserves the right to request additional testing to demonstrate applicability for the requested engine families. More information on U.S. EPA verified diesel technologies is available at: www.epa.gov/cleandiesel/verification/. More information on ARB verified technologies is available at: www.arb.ca.gov/diesel/verdev/verdev.htm.

ARB finalized a "Retrofit Verification Procedure" to verify the performance of diesel retrofit technologies used in California on June 11, 2003 and the amendments to the procedures were adopted in 2004, 2008, 2009, and 2012. The procedures specify the testing and other requirements (including mandatory minimum retrofit equipment warranty requirements) a manufacturer must meet to have a retrofit device verified in California. The procedures allow companies to verify technologies that achieve different PM and NOx reduction levels. In California, PM reduction technologies are divided into three categories: Level 1 verified technologies must reduce PM emissions from 25 to less than 50%; Level 2 technologies 50 to less than 85%; and Level 3 technologies 85% and above. A PM technology can be verified to less than 25% (Level 0) as long as it reduces NOx emissions by at least 25%. NOx control technologies are broken out into 5 categories or Marks in 15% bands of NOx reduction: Mark 1 starts at 25-39%, Mark 2 covers 40-54%, Mark 3 is 55-69%, Mark 4 from 70-84%, and Mark 5 represents anything above 85% NOx reduction. An emission control technology must reduce NOx or PM emissions by at least 25% in order to be verified. As of January 1, 2009, verified retrofit systems in both the ARB and EPA programs have had to limit incremental NO_2 emissions to no more than 20% of the baseline, engine-out NOx levels. Verified retrofit technologies that meet the 20% incremental NO_2 limit were given a "Plus" designation (e.g., Level 3 +) by ARB. Technologies not able to meet the NO_2 requirement were removed from the verified list until they demonstrated compliance with this portion of the regulation. For more information on ARB's retrofit verification procedures, go to: www.arb.ca.gov/diesel/verdev/verdev.htm.

3.0 AVAILABLE RETROFIT CONTROLS

A number of emission control systems that can be installed on a diesel vehicle are summarized below and further discussed in this section.

Diesel oxidation catalysts (DOCs) installed on a vehicle's exhaust system can reduce total PM by as much as 25 to over 50 percent, depending on the composition of the PM being emitted. Diesel oxidation catalysts can also reduce smoke emissions from older vehicles and virtually eliminate the obnoxious odors associated with diesel exhaust. Oxidation catalysts can reduce more than 90 percent of the CO and HC emissions and more than 70 percent of the toxic hydrocarbon emissions in diesel exhaust.

Wall-flow diesel particulate filters (DPFs) have been widely retrofitted on on- and off-road in-use diesel vehicles. DPFs can achieve up to and, in some cases, greater than a 90 percent reduction in PM. Filters are extremely effective in controlling the carbon fraction of the particulate known as black carbon. Black carbon has been identified as a significant contributor to global warming with a CO_2 equivalence estimated to be hundreds if not thousands of times that of carbon dioxide. DPFs are also the most effective devices to control emissions of ultrafine particles emitted from diesel engines. Particulate filters can be combined with a DOC or directly catalyzed to control up to 90 percent or more of the toxic HCs emitted by a diesel engine. The DPFs incorporating a catalyst function have been shown to decrease the levels of polyaromatic hydrocarbons, nitro-polyaromatic hydrocarbons, and the mutagenic activity of diesel PM.

Flow-through or partial filters are a relatively new method for reducing diesel PM emissions. Flow-through filters employ catalyzed metal wire mesh structures, tortuous flow, metal foil-based substrates with sintered metal sheets, or specially designed ceramic filters to reduce diesel PM. Flow-through filters are capable of achieving PM reduction of about 30 to 75 percent, depending on the engine operating characteristics. Because of their open structure, these devices are less prone to plugging and may be more suited to older diesel engines with higher engine-out PM levels.

Exhaust gas recirculation (EGR) systems have been retrofitted on heavy-duty diesel vehicles. EGR is capable of achieving a 40 percent reduction in NOx emissions or more.

Selective catalytic reduction (SCR) using urea as a reducing agent has been shown to be effective in reducing NOx emissions by up to 90 percent while simultaneously reducing HC emissions by 50 to 90 percent and PM emissions by 20 to 30 percent.

Lean NOx Catalysts or HC-SCR have been installed on heavy-duty on-road and off-road vehicles in combination with a DPF and are capable of achieving from 25-40 percent NOx reduction. These devices rely on the use of on-board diesel fuel from the vehicle as the reducing agent.

Lean NOx Trap Storage Catalysts (LNT) have been successfully used on new light and medium-duty vehicles with over 80 percent NOx conversion. An experimental retrofit LNT system using syngas to regenerate the trap was demonstrated on medium duty trucks.

Closed crankcase ventilation technology can be retrofitted on turbocharged diesel engines to eliminate crankcase emissions. For model years 1994 to 2006 heavy-duty diesel engines, crankcase PM emissions reductions provided by crankcase emission control technologies range from 0.01 g/bhp-hr to 0.04 g/bhp-hr.

Biodiesel is produced by reacting vegetable or animal fat with methanol or ethanol to produce a lower-viscosity fuel that is similar in physical characteristics to diesel. Biodiesel can be blended into petroleum-based diesel fuel at any ratio, but is most commonly blended up to 20 percent, called B20. Pure biodiesel is called B100. Typical emission benefits of B20 include a 10 percent decrease in CO, up to a 15 percent decrease in PM emissions, a 20 percent decrease in sulfate emissions, and a 10 percent decrease in HC emissions. Under higher load operating conditions, biodiesel blends have been shown to slightly increase NOx emissions. In most cases biodiesel blends up to B20 can be used in combination with the above exhaust control devices to achieve co-reductions of emissions. Vehicle owners should check with their device manufacturer prior to using biodiesel in combination with retrofit devices. Particular attention to the quality of biodiesel with respect to impurities and other performance standards is critical to proper performance of the engine as well as compatibility with the retrofit exhaust control device. Retrofit device manufacturers recommend only the use of biodiesel blends made from B100 that meets the ASTM specification D6751.

3.1 Diesel Oxidation Catalysts

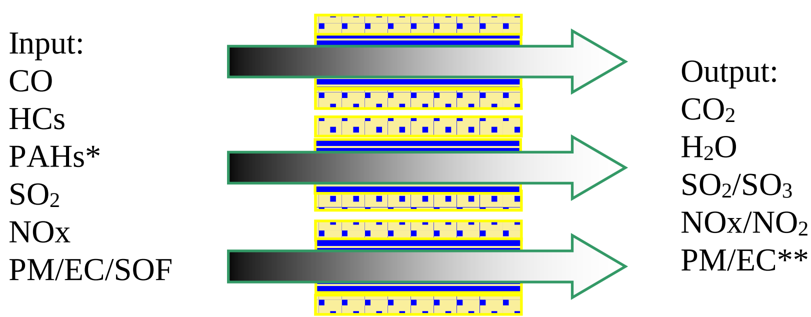
The diesel oxidation catalyst (DOC) is a leading retrofit control strategy in both the on-road and off-road sectors throughout the world, reducing not only PM emissions but also CO and HC emissions. Using oxidation catalysts on diesel-powered vehicles is not a new concept. Oxidation catalysts have been installed on over 300,000 off-road vehicles around the world with applications going back over 30 years. Millions of oxidation catalysts have been installed on new heavy-duty highway trucks since 1994 in the U.S. These systems have operated trouble free for millions of miles. Oxidation catalysts have been retrofitted on millions of on-road and off-road vehicles worldwide. The popularity of DOCs is due to their flexibility and reliability. Because they are a completely passive, flow through device, they can be retrofitted on a wide range of applications as long as the exhaust temperatures remain above approximately 150 ºC.

Oxidation catalysts can be used not only with conventional diesel fuel, but have also been shown effective with biodiesel and emulsified diesel fuels, ethanol/diesel blends and other alternative diesel fuels.

3.1.1 Operating Characteristics and Control Capabilities

In most applications, a diesel oxidation catalyst consists of a stainless steel canister that contains a honeycomb structure called a substrate or catalyst support. There are no moving parts, just large amounts of interior surface area. The interior surfaces are coated with catalytic metals such as platinum or palladium. It is called an oxidation catalyst because the device converts exhaust gas pollutants into harmless gases by means of chemical oxidation. In the case of diesel exhaust, the catalyst oxidizes CO, HCs, and the liquid hydrocarbons adsorbed on carbon particles to CO_2 and water. In the field of mobile source emission control, liquid hydrocarbons adsorbed on the carbon particles in engine exhaust are referred to as the soluble organic fraction (SOF) – the soluble part of the particulate matter in the exhaust. Diesel oxidation catalysts are efficient at converting the soluble organic fraction of diesel particulate matter into carbon dioxide and water. A conceptual diagram of a diesel oxidation catalyst is shown in Figure 1.

The level of total particulate reduction is influenced in part by the percentage of SOF in the particulate. For example, a Society of Automotive Engineers (SAE) Technical Paper (SAE No. 900600) reported that oxidation catalysts could reduce the SOF of the particulate by 90 percent under certain operating conditions, and could reduce total particulate emissions by up to 40 to 50 percent. Reductions of 20 to 35 percent are typical of newer model year engines. Destruction of the SOF is important since this portion of the particulate emissions contains numerous chemical pollutants that are of particular concern to health experts. DOCs do not generally oxidize or reduce the elemental carbon or black carbon constituents of diesel PM.



* Polyaromatic hydrocarbons or other toxic hydrocarbon species
** Elemental carbon

Figure 1. Diagram of a diesel oxidation catalyst

Oxidation catalysts have proven effective at reducing particulate and smoke emissions on older vehicles. Under the U.S. EPA's urban bus rebuild/retrofit program, five manufacturers certified diesel oxidation catalysts as providing at least a 25 percent reduction in PM emissions for in-use urban buses. Certification data also indicates that oxidation catalysts achieve substantial reductions in CO and HC emissions. Currently, under the ARB and EPA retrofit technology verification processes, several technology manufacturers have verified diesel oxidation catalysts as providing at least a 25 percent reduction in PM emissions.

3.1.2. Impact of Sulfur in Diesel Fuel on Catalyst Technologies

The sulfur content of diesel fuel is critical to applying catalyst technology. Catalysts used to oxidize the SOF of the particulate can also oxidize sulfur dioxide to form sulfates, which is considered part of the particulate. This reaction is not only dependent on the level of sulfur in the fuel, but also the temperature of the exhaust gases. Catalyst formulations have been developed which selectively oxidize the SOF while minimizing oxidation of the sulfur dioxide. However, the lower the sulfur content in the fuel, the greater the opportunity to maximize the effectiveness of oxidation catalyst technology for both better total control of PM and greater control of toxic HCs. Lower sulfur fuel (500 ppm sulfur; 0.05% wt), which was introduced in 1993 throughout the U.S., facilitated the application of catalyst technology to diesel-powered vehicles. Now, the availability of ultra-low sulfur diesel (ULSD) fuel (15 ppm sulfur; 0.0015% wt) in the U.S. and Canada allows for further enhancements of catalyst performance for retrofit applications. Ultra-low sulfur diesel fuel was rolled out across the U.S. and Canada in the latter part of 2006 as part of EPA's and Environment Canada's 2007-2010 highway diesel engine emissions program (see: www.epa.gov/otaq/highway-diesel/index.htm).

EPA's 2004 Tier 4 Non-Road Diesel Rule for off-road engines, locomotives, and marine applications set a limit of 15 ppm sulfur (ultra-low sulfur diesel) for off-road fuel by 2010 and by 2012 for locomotive and marine applications. The availability of these fuels allows off-road engines to fully take advantage of catalyst technology for both original equipment and retrofit applications similar to the experience already available for on-road vehicles.

3.1.3 Operating Experience

Oxidation catalysts can play a significant role in removing particulate and smoke from existing diesel engines and can be used in combination with engine management techniques and NOx catalysts to control NOx emissions. Oxidation catalysts have been retrofitted on millions of on-road and off-road vehicles worldwide. Retrofitting oxidation catalysts on existing diesel engines is relatively straightforward. An oxidation catalyst will function effectively at exhaust temperatures above about 150 ºC. In many applications the oxidation catalyst can be retrofitted as a muffler replacement. Indeed, many of the catalysts used on off-road vehicles are retrofits.

In off-road applications, oxidation catalysts have been retrofitted to diesel vehicles for over 30 years with over 300,000 installations having been completed to date. A significant percentage of these units have been equipped on mining and materials handling vehicles, but construction equipment, marine vessels and other types of off-road engines have been retrofitted as well. PM emissions as well as CO and HC emission reductions are targeted in the mining and materials handling industries for occupational health concerns. Typically these systems operate trouble free for thousands of operating hours and are normally replaced only when an engine undergoes a rebuild.

3.1.4 Costs

Diesel oxidation catalysts are estimated to cost from $500 to $2,000 per catalyst depending on engine size, sales volume and whether the installation is a muffler replacement or an in-line installation. These cost estimates are derived from current applications on typical highway diesel engine applications. Many systems are designed to replace the original muffler on the vehicle and, as such, not only provide emission control but also provide the appropriate level of noise attenuation. In most cases, oxidation catalysts are easy to install with installations typically taking less than 2 hours.

Off-road diesel equipment is characterized by widely varying horsepower (hp) ratings. Retrofit control technologies have been installed on vehicles with engine horsepower ratings under 50 hp to over 2,000 hp.

3.2 Diesel Particulate Filters

As the name implies, diesel particulate filters (DPFs) remove particulate matter in diesel exhaust by filtering exhaust from the engine. This can be accomplished via two primary ways. The most common is the use of a wall-flow filter as shown in Figure 2 where a porous honeycomb structure is used having alternating channels plugged at opposite ends. This effectively forces the exhaust gases containing the particles through the cell walls causing the particles to be filtered and deposited on the inside wall of the channel as the cleaned exhaust exits to the right of the diagram. Wall-flow filters have the highest level of filtration efficiency (>90 percent) for particles, including ultrafine particles. The filtration efficiency of these wall-flow ceramic filters can be reduced by removing some of the channel plugs from the substrate. The other mode of particle filtration is accomplished by using catalyzed metal wire mesh structures or tortuous flow, metal foil-based substrates with sintered metal sheets as shown in Figure 3.

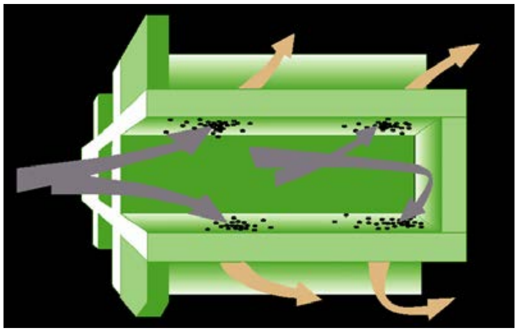


Figure 2. Schematic of a ceramic wall-flow diesel particulate filter

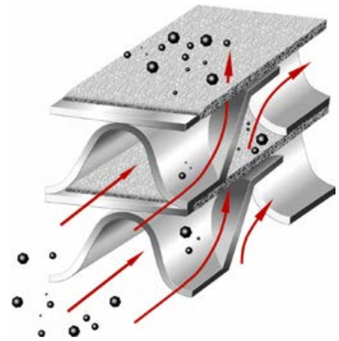


Figure 3. Schematic of a metal flow-through filter

In this particular design, the corrugated foil channels contain perturbations that force a portion of the exhaust upwards through the metal mesh effectively trapping the particles. This type of filter is known as a partial or flow-through filter and exhibits filtration efficiencies in the range of 50-80 percent. Both filter designs will be detailed in later sections.

3.2.1 Operating Characteristics and Performance of Wall-Flow Filters

Diesel particulate filters can be installed on either vehicles or stationary diesel engines. Since a filter can fill up over time, engineers that design filter systems must provide a means of burning off or removing accumulated particulate matter. A convenient means of disposing of accumulated particulate matter is to burn or oxidize it on the filter when exhaust temperatures are adequate. By burning off trapped material, the filter is cleaned or "regenerated." Soot combustion is facilitated at lower temperatures by the use of catalyst coatings applied to the filter surfaces. Filters that regenerate in this fashion cannot be used in all situations because they require exhaust temperatures above around 250 ºC for a minimum amount of their operating time.

In some off-road mining applications, disposable filter systems have been used. A disposable filter is sized to collect particulate for a working shift or some other predetermined period of time. After a prescribe amount of time or when backpressure limits are approached, the filter is removed and cleaned or discarded. To ensure proper operation, filter systems are designed for the particular vehicle and vehicle application.

A number of filter materials have been used in diesel particulate filters. Wall-flow filter substrates are available from ceramic materials such as, cordierite, mullite, aluminum titanate and silicon carbide. Other filter designs have employed fiber wound cartridges, knitted silica fiber coils, ceramic foam, wire mesh, sintered metal structures, and temperature resistant paper in the case of disposable filters. Collection efficiencies of these filters range from 50 to over 90 percent. Filter materials capture particulate matter by interception, impaction and diffusion. Work has continued to: 1) optimize filter efficiency and minimize back pressure, 2) improve the radial flow of oxidation in the filter during regeneration, 3) improve the mechanical strength of filter designs, and 4) increase the ash storage capacity of the filter. Technological developments in DPF design include advancements in cell shape and cell wall porosity optimization aimed at minimizing engine backpressure and extending the interval between filter service. Advances such as higher pore volume, increased pore connectivity along with thinner web designs facilitate catalyst coating while maintaining longer times between soot regeneration events.

Many techniques can be used to regenerate a diesel particulate filter. Some of these techniques are used together in the same filter system to achieve efficient regeneration. Both on- and off-board regeneration systems exist. The major regeneration techniques are listed below.

- Catalyst-based regeneration using a catalyst applied to the surfaces of the filter. A base metal or precious metal coating applied to the surface of the filter reduces the ignition temperature necessary to oxidize accumulated particulate matter.

- Catalyst-based regeneration using an oxidation catalyst placed upstream of the filter to facilitate oxidation of nitric oxide (NO) to nitrogen dioxide (NO_2). The nitrogen dioxide reacts with the collected particulate, substantially reducing the temperature required to regenerate the filter.

- Fuel-borne catalysts reduce the temperature required for ignition of trapped particulate matter. These can be used in conjunction with both passive and active filter systems.

- Air-intake throttling to one or more of the engine cylinders can increase the exhaust temperature and facilitate filter regeneration.

- Post top-dead-center (TDC) fuel injection of small amounts of fuel in the cylinders of a diesel engine after pistons have reached TDC introduces a small amount of unburned fuel in the engine's exhaust gases. Fuel can also be injected into the exhaust pipe ahead of the filter. This unburned fuel can then be oxidized in the particulate filter to combust accumulated particulate matter.

- On-board fuel burners or electrical heaters upstream of the filter can provide sufficient exhaust temperatures to ignite the accumulated particulate matter and regenerate the filter.

- Off-board electrical heaters can be applied to combust trapped particulate matter by blowing hot air through the filter element while removed from the vehicle.

Retrofit filter devices that rely on external sources of heat such as a burner or electrical heater to regenerate and burn off the soot are referred to as active filters. In one design a hybrid system has been verified that combines passive regeneration with a catalyzed filter element and an electrically heated active system in one unit to extend the operating period between forced regenerations.

The experience with catalyzed filters indicates that there is a virtually complete reduction in odor and in the soluble organic fraction of the particulate. Catalyzed wall-flow filters achieve over 90 percent reduction in HC and CO in addition to PM reductions of over 90 percent. Some catalysts may increase sulfate emissions. Companies utilizing these catalysts to provide regeneration for their filters have modified catalyst formulations to reduce sulfates emissions to acceptable levels. At least one retrofit DPF manufacturer is developing a DPF that is regenerated at temperatures as low as 200 ºC by introducing a synthetic gas mixture of H_2 and CO (syngas) into the exhaust upstream of the DPF to combust the soot. This allows the application of this system to low temperature duty cycle operations and facilitates regeneration during idle and start-stop city driving.

Some installations of a filter system on a vehicle may cause a very slight fuel economy penalty. This fuel penalty is due to the backpressure of the filter system. As noted above, some filter regeneration methods involve the use of fuel burners and to the extent those methods are used, there will be an additional fuel economy penalty. Many filter systems, however, have been optimized to minimize, or nearly eliminate, any noticeable fuel economy penalty. Experience in the New York City Transit program and in the San Diego school bus program has shown that fuel penalties for filters are zero or less than one percent. During the required retrofit technology verification protocols established by the U.S. EPA and the California ARB, fuel penalties have been documented at about 1 percent for high efficiency filter systems.

Filter systems do not appear to cause any additional engine wear or affect vehicle maintenance. Filters require periodic cleaning as part of their regularly scheduled maintenance. In addition to elemental and organic carbon, diesel PM also entrains within the particles metallic elemental impurities from the fuel or additives in engine lubricating oil. As PM soot is regenerated in the filter, the carbonaceous component of the soot is combusted and burned; however, a minute amount of incombustible inorganic ash is left behind in the filter. After many regeneration events, this ash builds up in the filter and results in increasing backpressure of the system. Eventually a maintenance indicator light signals that the filter should be cleaned to remove the ash. Manufacturers are designing systems to minimize maintenance requirements during the useful life of the vehicle. Manufacturers provide the end-user with appropriate cleaning procedures or recommended facilities that perform filter cleaning. More information on filter maintenance can be found in MECA's technical document, "Diesel Particulate Filter Maintenance: Current Practices and Experience" available on MECA's website at: www.meca.org/diesel-retrofit/resources.[10]

Filter systems have been designed so that vehicle drivability is not affected, or at least effects can be minimized, most notably by limiting exhaust backpressure. Diesel particulate filter systems, which replace mufflers in retrofit applications, have achieved sound attenuation equal to a standard muffler.

3.2.2 Impact of Sulfur in Diesel Fuel on Diesel Particulate Filters

Sulfur in diesel fuel significantly affects the reliability, durability, and emissions performance of catalyst-based DPFs. Sulfur affects filter performance by inhibiting the performance of catalytic materials upstream of or on the filter. Sulfur also competes with chemical reactions intended to reduce pollutant emissions and creates particulate matter through catalytic sulfate formation. Catalyst-based diesel particulate filter technology works best when fuel sulfur levels are less than 15 ppm. In general, the less sulfur in the fuel, the better the technology performs. The use of ultra-low sulfur diesel fuel (15 ppm sulfur maximum) greatly facilitates filter regeneration at lower temperatures in passive DPF devices. The performance of uncatalyzed filters, such as those used in many actively regenerated devices, is not affected by fuel sulfur.

3.2.3 Operating Experience

Diesel particulate filter retrofit demonstration programs began in the 1980s and continued in the early 1990s. The number of vehicles retrofitted, the number of programs and the interest in new programs has grown significantly over the past few years with more than 300,000 DPFs installed as retrofits to date in a variety of world markets. Today, second and third generation high-efficiency filter systems can reduce PM emissions from 85 to greater than 90 percent.

In Europe, new vehicles equipped with diesel particulate filters are being offered commercially. Filters were introduced on new diesel passenger cars in Europe in mid-2000, with more than 5,000,000 filter-equipped cars sold since that first introduction. Peugeot (PSA) was the first manufacturer to introduce a DPF system for European diesel cars in 2000. All European automobile manufacturers, including Audi, Fiat, Ford, VW, BMW, and Mercedes, are now offering DPF systems based either on the PSA system and the use of fuel-borne catalysts, or catalyzed filter systems that do not employ a fuel-borne catalyst.

Sweden's Environmental Zones program resulted in the commercial introduction of diesel particulate filters on urban buses. More than 4,000 buses have been equipped with passive filter systems in Sweden. Some of these buses have accumulated more than 250,000 miles of service. Transit fleets in many large cities in Europe and the U.S. have now been retrofit with diesel particulate filters.

Since 2007, every new heavy-duty, on-road diesel vehicle sold in the U.S. or Canada has been equipped with a high-efficiency diesel particulate filter to comply with the U.S. EPA's 2007/2010 highway emission regulation. This represents over 3 million new trucks operating on DPFs mostly in the U.S. Starting with Euro VI-compliant heavy-duty engines, all new heavy-duty highway diesel engines available in Europe include a high-efficiency diesel particulate filter. Diesel particulate filters are also standard equipment on new highway diesel engines sold in Japan.

Diesel particulate filters have been installed on off-road equipment since 1986. Tens of thousands of active and passive systems have been installed on off-road applications as either original equipment or as retrofits worldwide. Some off-road filter systems have operated for over 15,000 hours or over 5 years and are still in use. Examples of off-road equipped vehicles with filters include mining equipment, construction equipment, material-handling equipment, forklift trucks, street sweepers and utility vehicles. Germany, Austria and Switzerland have established mandatory filter requirements for construction equipment used in tunneling projects. High efficiency filter retrofit technologies for these European off-road applications are verified using the VERT verification protocols. [11]

Diesel particulate filters can be combined with exhaust gas recirculation (EGR), NOx adsorber catalysts or selective catalytic reduction (SCR) to achieve significant NOx and PM reductions. Engines retrofit with low pressure EGR and a DPF can achieve NOx reductions of over 40 percent and PM reductions of greater than 90 percent. Engines equipped with SCR and a filter can achieve NOx reductions of 70 to 90 percent and PM reductions greater than 90 percent. In 2004 Volvo Bus launched a fleet of new diesel buses operating along the west coast of Sweden equipped with catalyst-based DPFs for controlling diesel PM combined with selective catalytic reduction (SCR) systems using urea as the reducing agent to control NOx emissions. This bus fleet was claimed to be the cleanest operating diesel bus fleet in the world at that time. Essentially all Euro VI-compliant and U.S. EPA 2010-compliant new heavy-duty highway diesel engines are now available with DPF+SCR systems. Combined NOx and PM reductions can also be achieved by recalibrating the engine to minimize NOx while using a filter to capture increased PM emissions. A lean NOx catalyst added to an exhaust system in combination with a particulate filter has been verified in California to reduce NOx emissions from 25 to 40 percent using diesel fuel as the reductant for NOx (NOx performance of such a lean NOx catalyst is generally strongly tied to the fuel reductant use and reductant dosing strategy).

3.2.4 Costs

High-efficiency, passive filters for diesel retrofit applications are currently being sold for about \$10,000 to \$16,000 each. Prices vary depending on the size of the engine being retrofit, the sales volume (the number of vehicles being retrofit), the amount of particulate matter emitted by the engine, the emission target that must be achieved, the regeneration method, and other factors. Cost can also be impacted by the amount of application engineering that is required for example on specialized off-road equipment. While passive filters rely solely on exhaust gas temperature to regenerate soot that accumulates during operation, actively regenerated, high-efficiency filter retrofit systems are generally more expensive (\$15,000 - \$30,000) due to the added complexity needed to achieve controlled regenerations with active technology such as burners, diesel fuel injection over a DOC, or electrical heaters.

3.3 Flow-Through or Partial Diesel Particulate Filters

3.3.1 Operating Characteristics and Performance of Partial Filters

Flow-through filters employ catalyzed metal wire mesh structures, tortuous flow, metal foil-based substrates with sintered metal sheets, or specially designed ceramic filters to reduce diesel PM. These technologies generally employ catalysts and/or fuel-borne catalysts to oxidize diesel soot as the exhaust flows through these more turbulent flow devices. This passive soot regeneration mechanism requires sufficient exhaust temperatures to ensure captured soot is burned at regular intervals. This technology is less likely to plug under unfavorable conditions such as high engine-out PM emissions compared to wall-flow filters. Lack of appropriate regeneration of captured soot in partial filters can result in bypassing of exhaust flow with little or no soot removal. Flow-through filters are capable of achieving PM reduction of about 30 to 75 percent. An example of a flow-through filter and a detailed cartoon of the channel are shown in Figure 4. The surfaces of this type of filters can be catalyzed to facilitate regeneration of the soot or an uncatalyzed filter can be combined with an upstream DOC to accomplish soot regeneration. The incorporation of a catalyst in either of these two ways offers co-benefits of 50-90 percent reduction of hydrocarbons and carbon monoxide in addition to the PM reductions as shown in Figure 5. The data were generated on an engine dynamometer operating on a hot FTP cycle. The aged system represents 3600 hours of field aging on a 1993 refuse hauler.[12]

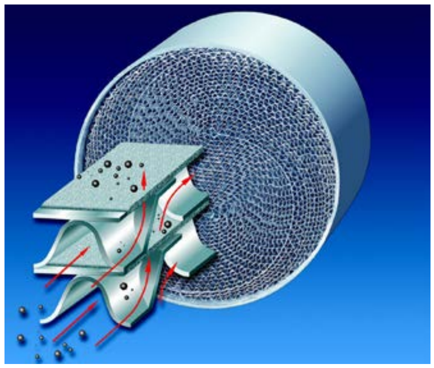


Figure 4. Metal partial filter

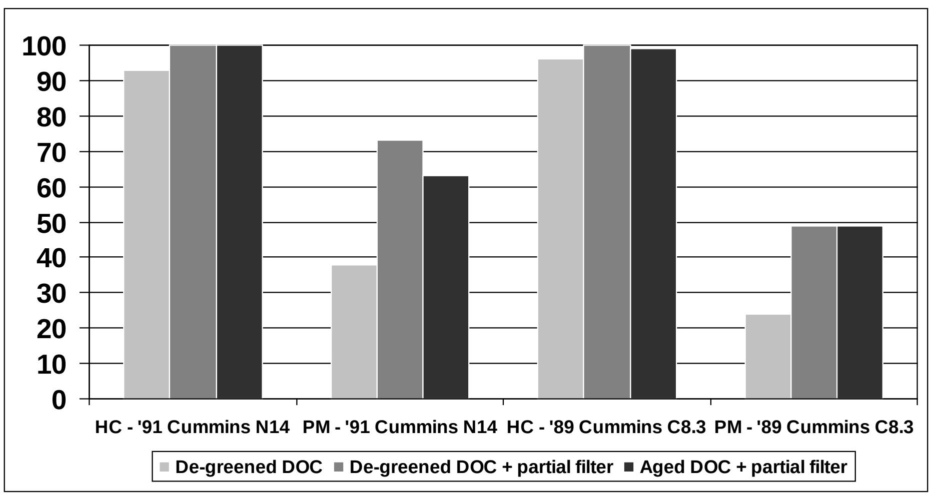


Figure 5. DOC + retrofit partial filter performance

3.3.2 Operating Experience

A few original equipment manufacturers (OEM) in Europe have employed high level EGR and flow-through filters to comply with emission standards for some light-duty and heavy-duty applications. A similar flow-through metal filter substrate has also been used in retrofit applications with PM reduction of greater than or equal to 50 percent. Catalyzed, wire mesh flow-through filter retrofit technologies have also been used for a range of on-road engine applications. Another feature of partial filters is that due to their flow through design they may not require cleaning in some applications with lower soot load.

3.3.3 Costs

Flow-through, partial filters for diesel retrofit applications are currently being sold for about $5,000 to $7,000 each. Prices vary depending on the size of the engine being retrofit, the sales volume (the number of vehicles being retrofit), the amount of particulate matter emitted by the engine, the emission target that must be achieved and other factors. Cost can also be impacted by the amount of application engineering that is required for example on specialized off-road equipment.

3.4 Exhaust Gas Recirculation (EGR)

Retrofitting exhaust gas recirculation on a diesel engine offers an effective means of reducing NOx emissions from the engine. Both low-pressure and high-pressure EGR systems exist but low-pressure EGR is used for retrofit applications because it does not require engine modifications.

3.4.1 Operating Characteristics and Control Capabilities

As the name implies, EGR involves recirculating a portion of the engine's exhaust back to the charger inlet or intake manifold, in the case of a naturally aspirated engines. In most systems, an intercooler lowers the temperature of the recirculated gases. The cooled recirculated gases, which have a higher heat capacity than air and contain less oxygen than air, lower combustion temperature in the engine, thus inhibiting NOx formation. Diesel particulate filters are always used with a low-pressure EGR system to ensure that large amounts of particulate matter are not recirculated to the engine. EGR systems are capable of achieving NOx reductions of more than 40 percent. A schematic of a low-pressure EGR+DPF retrofit system is shown in Figure 6.

3.4.2 Operating Experience

Over 2,000 EGR systems have been installed on bus engines in Europe and Hong Kong. EGR retrofit systems have been installed in the U.S on solid waste collection vehicles, buses, and some city-owned vehicles. Technology demonstration programs have been conducted in Houston, TX and Los Angeles, CA. ARB verified one low-pressure EGR system for a limited range of on-road applications. It employs a low-pressure EGR loop and a DPF to achieve 85 percent reduction in PM and 40 percent reduction in NOx.

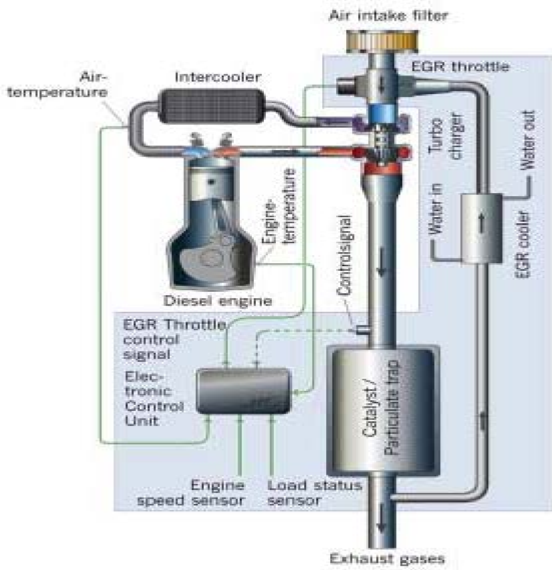


Figure 6. Low pressure exhaust gas recirculation (EGR) + DPF

3.4.3 Costs

The cost of retrofitting a low pressure EGR system on a typical bus or truck engine is about $18,000 to $20,000, which includes the diesel particulate filter.

3.5 Selective Catalytic Reduction

Controlling NOx emissions from a diesel engine is inherently difficult because diesel engines are designed to run lean. It is difficult to chemically reduce NOx to molecular nitrogen in the oxygen-rich environment of diesel exhaust. The conversion of NOx to molecular nitrogen in the exhaust stream requires a reductant (NH_3, HC, CO or H_2) and under typical engine operating conditions, sufficient quantities of reductant are not present to facilitate the conversion of NOx to nitrogen.

SCR has been used to control NOx emissions from stationary sources for over 30 years. More recently, it has been applied to mobile sources including trucks, marine vessels, and locomotives. Applying SCR to diesel-powered vehicles provides simultaneous reductions of NOx, PM, and HC emissions.

3.5.1 Operating Characteristics and Control Capabilities

An SCR system uses a metallic or ceramic wash-coated catalyzed substrate, or a homogeneously extruded catalyst and a chemical reductant, like ammonia, to convert nitrogen oxides to molecular nitrogen and oxygen in oxygen-rich exhaust streams like those encountered with diesel engines. In mobile source applications, an aqueous urea solution or diesel exhaust fluid (DEF) is usually the preferred reductant source. The urea solution is injected into the exhaust stream upstream of the SCR. The heat from the exhaust and mixing hydrolyzes the urea to ammonia and CO_2. In some cases ammonia has been used as the reductant in mobile source retrofit applications. The reductant is added at a rate calculated by an algorithm that estimates the amount of NOx present in the exhaust stream. The algorithm relates NOx emissions to engine parameters such as engine revolutions per minute (rpm), exhaust temperature, backpressure and load. As exhaust and reductant pass over the SCR catalyst, chemical reactions occur that reduce NOx emissions to nitrogen and oxygen. A typical layout for a retrofit SCR system for a highway vehicle is shown in Figure 7. In this system a DPF is followed by an SCR catalyst for combined reductions of both diesel PM and NOx.

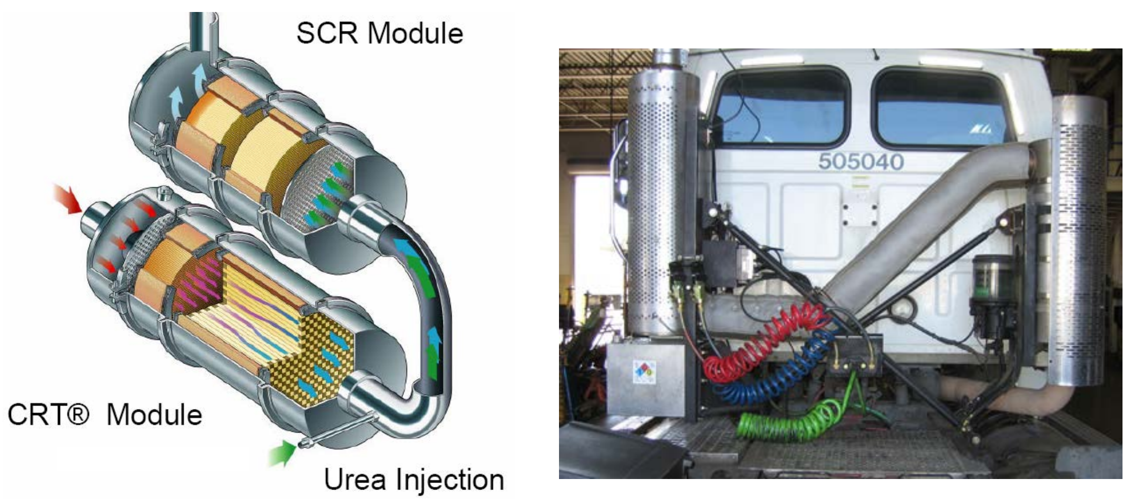


Figure 7. Selective catalytic reduction + DPF system

Open loop SCR systems can reduce NOx emissions from 70 to 90 percent. Closed loop systems on stationary engines can achieve NOx reductions of greater than 95 percent. SCR systems reduce HC emissions up to 80 percent and PM emissions 20 to 30 percent. They also reduce the characteristic odor caused by hydrocarbons in the exhaust produced by a diesel engine and diesel smoke. Like all catalyst-based emission control technologies, SCR performance is enhanced by the use of low sulfur fuel. Low sulfur fuel is not a requirement for many SCR catalyst formulations. SCR catalysts may also be combined with DOCs or DPFs for additional reductions of PM, HC and CO emissions. Combinations of DPFs and SCR generally require the use of ultra-low sulfur diesel to achieve the highest combined reductions of both PM and NOx.

Application of SCR to vehicles and equipment with transient operating conditions offers special challenges and it may not be appropriate for all vehicle applications. Care must be taken to design a SCR system for the specific vehicle or equipment application involved. For more technical information on the operation of SCR catalysts, please review MECA's white paper on "Emission Control Technologies for Diesel Engines" at: www.meca.org/resources/reports.

3.5.2 Operating Experience

SCR is currently being used on both on-road and off-road engines or vehicles. Applications include trucks, marine vessels and locomotives. In 2005, SCR using a urea-based reductant was introduced on a large number of on-road diesel heavy-duty engines to help meet the Euro 4 or Euro 5 heavy-duty NOx emission standards. There are now hundreds of thousands of SCR-equipped trucks operating in Europe. SCR has been identified by the majority of engine manufacturers as their chosen strategy for complying with 2009 or 2010 on-road heavy-duty diesel engine emission standards in both the U.S. and Japan. Several auto manufacturers have also developed and commercialized SCR systems for light-duty diesel vehicles that are being sold in California and across the U.S. Major heavy-duty engine manufacturers completed millions of miles of durability demonstrations on U.S. 2010 and Euro VI technology diesel engines employing SCR and DPF emission control technologies. In OEM applications, where manufacturers have control over engine calibrations, SCR systems have been reported to deliver a 5-7 percent fuel savings. A number of on-road diesel demonstrations have been done with combination SCR+DPF retrofit systems (e.g., more than 50 such systems were run in California on utility vehicles, transit buses, trash trucks and on-highway Class 8 trucks). In some of these applications these SCR + DPF equipped retrofit systems have achieved over 80 percent NOx reduction. There are hundreds of SCR + DPF retrofit devices operating on medium and heavy-duty on-road vehicles in Europe.

SCR systems have also been installed on a variety of off-road diesel engines, including engines used on agricultural equipment, construction equipment, marine vessels and locomotives. SCR systems have been included on a large number of off-road engines certified to either the U.S. Tier 4 or Euro Stage IV emission standards. Significant numbers of marine vessels have been equipped with SCR including auto ferries, transport ships, cruise ships, and military vessels. The marine engines range from approximately 1250 hp to almost 10,000 hp and the installations have been in operation since the early to mid-1990s. Two of the Staten Island ferries operating between Staten Island and Manhattan has been retrofit with an SCR system in the U.S.

Due to the sensitivity of SCR catalysts to poisoning by impurities that may be introduced through the use of low purity urea, such as that designed for agricultural purposes, it is imperative that only high purity DEF be used that is specifically designed for urea-SCR NOx control systems. DEF is specifically made for use in SCR systems by meeting strict purity requirements. Manufacturers of retrofit SCR devices recommend the use of only API (American Petroleum Institute) certified DEF as identified by the symbol in Figure 8 on the packaging.

Figure 8. Certified DEF identification logo

3.5.3 Costs

SCR systems are an emerging retrofit technology option. Retrofit system costs are currently limited but will vary depending on the size of the diesel engine that is being retrofitted. Retrofit SCR costs are expected to range from about $18,000 with a DOC to $30,000 with a DPF per vehicle.

3.6 Lean NOx Catalysts

3.6.1 Operating Characteristics and Control Capabilities

A lean NOx catalyst often includes a porous material made of zeolite (a micro-porous material with a highly ordered channel structure), along with either a precious metal or base metal catalyst. The zeolites provide microscopic sites that are fuel/hydrocarbon rich where reduction reactions can take place. Some lean NOx catalyst systems inject a small amount of diesel fuel or other reductant into the exhaust upstream of the catalyst. The fuel or other hydrocarbon reductant serves as a reducing agent for the catalytic conversion of NOx to N_2. Other systems operate passively without any added reductant at reduced NOx conversion rates. Without the added fuel and catalyst, reduction reactions that convert NOx to N_2 would not take place because of excess oxygen present in the exhaust. Lean NOx catalysts are sometimes referred to as hydrocarbon SCR (HC-SCR) catalysts due to their characteristic selective reduction of NOx. Peak NOx conversion efficiencies are typically around 25 to 40 percent (at reasonable levels of diesel fuel consumption). Higher NOx conversion efficiencies have been observed on specially designed HC-SCR catalysts that employ an ethanol-based reductant.

3.6.2 Operating Experience

There are thousands of lean NOx catalyst diesel retrofit systems in service in the U.S. Lean NOx catalyst technology has been utilized in passenger car applications in Europe and a retrofit system combined with a Level 3+ DPF has been verified by the California ARB (25 percent NOx control) for a range of on-highway applications. A version of this technology has been verified for some off-road applications at a combined 40 percent NOx reduction level and

>85 percent PM reduction. The ARB-verified retrofit technology combines a lean NOx catalyst upstream of a DPF for combined reduction of NOx and PM using controlled injection of diesel fuel upstream of the lean NOx catalyst. This retrofit technology is also being demonstrated and commercialized for a variety of off-road applications, including agricultural pumps, and portable engines, and can also be used to reduce emissions from marine and locomotive diesel engines.

3.6.3 Costs

The cost of retrofitting a combined lean NOx catalyst + DPF system on a typical bus or truck engine is about $15,000 to $20,000, which includes the diesel particulate filter. A retrofit lean NOx catalyst + DPF system that utilizes controlled injection of diesel fuel as the reductant is shown in Figure 9.

Figure 9. Lean NOx catalyst + DPF retrofit system

3.7 NOx Adsorber Catalysts

NOx adsorber catalysts, also referred to as lean NOx traps (LNT) or NOx storage catalysts, provide another catalytic pathway for reducing NOx in an oxygen rich exhaust stream.

3.7.1 Operating Characteristics and Performance

NOx adsorber technology removes NOx in a lean (i.e., oxygen rich) exhaust environment via a series of storage and release mechanisms. The mechanism involves:

1. Catalytically oxidizing NO to NO_2 over a precious metal catalyst.

2. Storing NO_2 on an adjacent alkaline earth oxide trapping site as a nitrate.

3. The stored NOx is then periodically removed in a two-step regeneration process by temporarily inducing a rich exhaust condition followed by reduction to nitrogen by a process similar to the conventional three-way catalyst reaction.

As discussed above, under normal lean diesel engine operation, the NOx adsorber stores the NOx emissions. In order to reduce the trapped NOx to nitrogen, called the NOx regeneration cycle, the catalyst must be exposed periodically to a short (a few seconds) rich exhaust environment. In OEM applications, the engine may be operated rich periodically by a change in calibration such as intake throttling, EGR or post-combustion fuel injection into the cylinder.[9] In retrofit applications, the rich spike must be introduced post-combustion by injecting fuel into the exhaust stream ahead of the catalyst. Because LNTs require brief periods of rich operation to regenerate, this results in a small fuel economy penalty and a corresponding increase in CO_2 emissions. At least one manufacturer has demonstrated a retrofit device that includes a Level 3 DPF combined with a LNT to achieve both PM and NOx reduction. One unique feature of this system as shown in Figure 10 is that it incorporates a non-catalytic syngas generator that uses diesel fuel to generate a synthetic gas mixture of H_2 and CO on board the vehicle that is used to regenerate both the LNT and DPF at lower temperatures. This lower temperature regeneration capability minimizes the deterioration of the LNT catalyst and facilitates use of the device in low temperature duty cycle applications. LNT and DPF regeneration temperatures as low as 200^{o}C have been demonstrated.

LNT systems on OEM applications have demonstrated conversion efficiency of up to 90 percent over a broad temperature range. The NOx efficiency can be directly impacted by changing the lean/rich modulation of the cycle. LNTs can achieve even higher NOx reduction (>90 percent) when regenerated with on-board generated hydrogen via a fuel reforming reaction over an appropriate catalyst. NOx adsorber technology offers potential for providing a high level of NOx reduction across a wide range of operating conditions (temperature and NOx concentration) which are consistent with the diversity in engine-out exhaust levels associated with medium and heavy-duty diesel applications.

The same compounds that are used to store NOx are even more effective at storing sulfur as sulfates, and, therefore, NOx adsorbers require ultra-low sulfur diesel fuel. The durability of LNTs is linked directly to sulfur removal by regeneration and is a major aspect of technology development. Sulfur must be removed from the trap by periodic high temperature excursions under reducing conditions, a procedure called “DeSOx”. The DeSOx regeneration temperatures are typically around 700^{o}C and require about 15 to 20 minutes to be completed.

3.7.2 Operating Experience of NOx Adsorber Technology

NOx adsorber technology has made significant progress in performance and durability. It has been commercialized on a Volkswagen light-duty diesel passenger car and a Dodge Ram medium-duty diesel pick-up truck meeting EPA’s 2010 on-highway emission standards. These OEM installed devices effectively reduce NOx by over 80 percent.

NOx adsorber technology is also being applied to gasoline vehicles powered by gasoline direct injection (GDI) engines and the results are impressive. In fact, a number of vehicle manufacturers have commercially introduced NOx adsorber catalysts on some of their models powered by lean-burn gasoline engines in both Europe and Japan. While the application of NOx adsorber technology to diesel engines offers different challenges than gasoline applications, the experience being gained in gasoline applications is an important compliment to NOx adsorber technology developments for diesel engines.

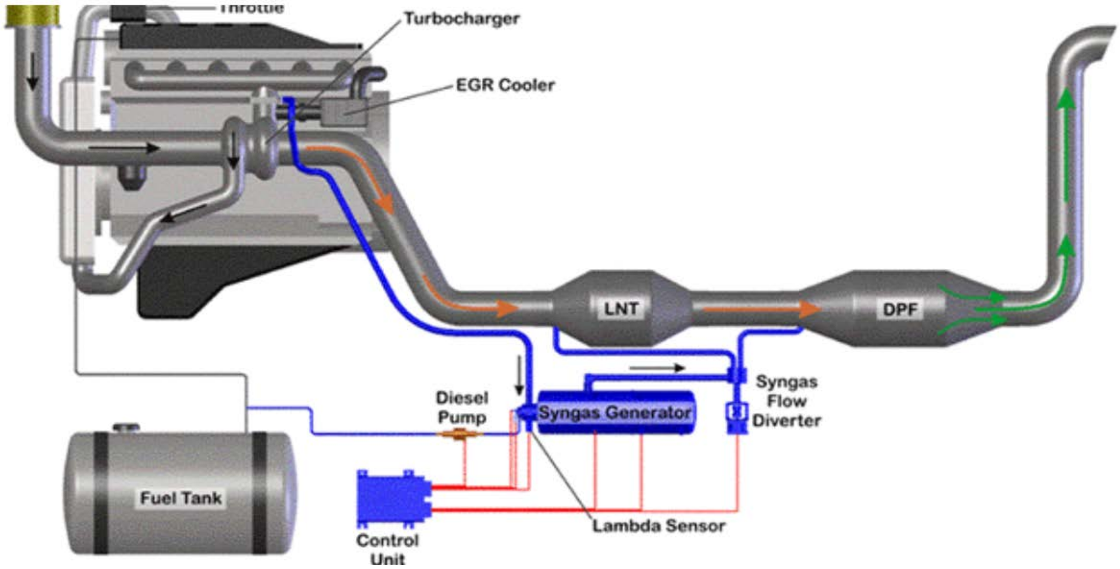


Figure 10. Experimental DPF-LNT retrofit technology utilizing a syngas generator

3.8 Closed Crankcase Ventilation

Crankcase PM is generated by the combination of rapidly moving engine parts in the crankcase, exhaust bypass, and lubricating oil. This process leads to fine atomized particles of predominantly atomized engine oil combined with exhaust components. In applications such as school buses, crankcase PM has been identified as the major source of particulates found in the passenger cabin of these vehicles. Numerous studies of retrofit controls on school buses have concluded that crankcase controls alone or in combination with other exhaust PM controls offer positive benefits to reducing the PM inside and around school busses. [13, 14, 15]

3.8.1 Operating Characteristics and Control Capabilities

Today, in most pre-2007 MY turbocharged, aftercooled diesel engines, the crankcase breather is vented to the atmosphere often using a downward directed draft tube. While a rudimentary filter is often installed on the crankcase breather, substantial amount of particulate matter is released to the atmosphere. Emissions through the breather may exceed 0.7 g/bhp-hr during idle conditions. For U.S. MY 1994 to 2006 heavy-duty diesel engines, crankcase PM emissions reductions provided by crankcase emission control technologies range from 0.01 g/bhp-hr to 0.04 g/bhp-hr or up to 25 percent of the tailpipe emission standards. For diesel vehicles that are equipped with a Level 3 DPF, the crankcase emissions can be as high as twice the tailpipe PM emissions. If one considers the total PM (crankcase + tailpipe PM) coming from the vehicle, in vehicles equipped with a DPF, the crankcase PM can represent as much as 70-80 percent of the total PM. The U.S. EPA recognized the significant contribution of crankcase PM when developing its 2007/2010 on-highway diesel emission standards. All 2007 and newer highway diesel vehicles and Tier 4 off-road vehicles must account for crankcase PM as part of the total PM emissions to meet the overall vehicle PM limits. Some manufacturers are meeting the requirements by using closed crankcase ventilation (CCV) filter devices identical to those verified by EPA for in-use diesel engines. These filters capture virtually 100 percent of the PM coming from the crankcase. EPA allows verified CCV devices to be used as a stand-alone retrofit technology or in combination with other verified retrofit exhaust control devices.

One solution to the crankcase emissions problem is the use of a multi-stage filter designed to collect, coalesce, and return the emitted lube oil to the engine's sump. Filtered gases are returned to the intake system, balancing the differential pressures involved. Typical systems consist of a filter housing, a pressure regulator, a pressure relief valve and an oil check valve. Figure 11 shows a schematic of a closed crankcase ventilation system.

3.8.2 Operating Experience

Crankcase emission control is currently being used in Europe and the U.S. on new highway diesel engines and in the U.S. on retrofit applications. Closed crankcase filter systems have been successfully retrofit on a variety of highway vehicles including school buses, transit buses, and trucks. MECA sales survey of retrofit devices indicate that thousands of retrofit closed crankcase devices have been installed on heavy-duty in-use vehicles. Retrofit crankcase emission control systems can be combined with DOCs or DPFs to reduce PM emissions associated with both the ventilation of the crankcase and the tailpipe.

3.8.3 Cost

The cost of retrofitting a crankcase emission control system on a typical bus or truck engine is between \$450 and \$700. Filter elements associated with these crankcase emission control systems need to be replaced at normal oil change intervals.

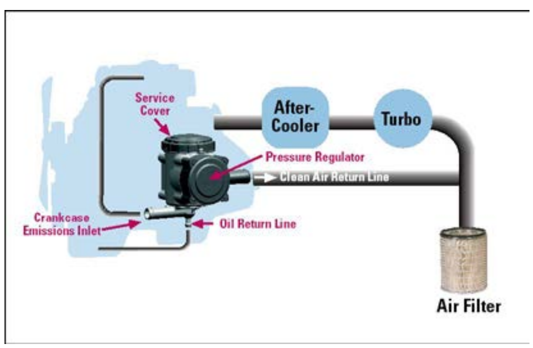


Figure 11. Crankcase emission control system

4.0 OPERATING A DIESEL RETROFIT EMISSION CONTROL PROGRAM

The successful operation of a diesel emission retrofit control program depends on a number of elements. The program should define:

- which vehicles are suitable for retrofit;
- the appropriate emission control technology for each vehicle;
- the emission reductions that are desired or required;
- fuel quality needs (e.g. percent sulfur);
- operational and maintenance requirements; and
- training and education needs of vehicle operators and maintenance personnel.

4.1 Vehicle Selection

Although in theory retrofit control technologies can be applied to any appropriate vehicle or engine, it may be easier to administer and control a program by targeting vehicle fleets. Some examples of captive fleets include urban bus fleets, school buses, privately-owned delivery fleets, publicly- and privately-owned construction equipment, publicly-owned diesel-powered vehicles, utility fleets, and construction equipment at a given construction site. The advantage of targeting these vehicles is that they are often centrally fueled and are typically maintained in a more controlled fashion. In addition, training of operators and maintenance personnel is more easily achieved.

4.2 Retrofit Control Technology Selection

A variety of retrofit control technologies is available for use in a retrofit program as discussed in Section 2.0. The technologies should be selected based on desired reductions in diesel emissions, cost, and applicability.

As outlined in the following sections, different technologies afford varying degrees of emissions reductions. Some technologies target PM emissions alone, while others target not only PM emissions but emissions of CO and HC as well. Other technologies or technologies in combination with engine management strategies can also provide reductions in NOx emissions together with PM. Different technologies can also result in different levels of control. Some retrofit devices can offer very high emission reductions in a limited range of applications whereas more modest reductions may be offered by other technologies with broader application. The applicability of the different retrofit options is also an important consideration. Some technologies can be universally applied, such as diesel oxidation catalysts, while others may be application specific, such as a diesel particulate filter system that may require a certain exhaust gas temperature to regenerate the filter.

It is also important to ensure that the emissions reductions expected are in fact achieved in use. A retrofit technology provider to a retrofit program should provide data to substantiate the claimed reductions. This data should have been generated from a recognized test facility over a recognized test cycle, e.g., U.S., European certification cycles, or other local test requirements.

The ability of the technology to provide emissions reductions over time should also be demonstrated. Both the U.S. EPA's and California ARB retrofit technology verification programs have these requirements (see Section 2.1).

Other factors such as retrofit technology costs, installation constraints, maintenance requirements, and warranty terms can also play a role in the retrofit technology decision.

4.3 Education and Training

Key elements of a diesel emissions retrofit control program are education and training. Both public and operator education on the benefits of, and needs for, a retrofit control program enhances the success and acceptance of the program.

Both vehicle operators and maintenance personnel should be trained on operating and maintenance requirements of retrofit devices. For example, special lubricating oil requirements should be defined if necessary.

5.0 TECHNICAL ISSUES TO BE CONSIDERED WHEN RETROFITTING EMISSION CONTROLS

When retrofitting emission control technologies to existing vehicles, several factors should be considered.

These factors include:

- fuel quality (ideally, 15 ppm maximum sulfur fuel should be used),
- the vehicle and engine application, and
- vehicle maintenance.

These factors will influence the selection of an appropriate emission control technology. The emission reduction target or the emission reduction desired for a specific pollutant may also play an important role in technology selection. For optimum results, the existing engine should be rebuilt to manufacturer's specifications before the emission control system is installed. MECA has available retrofit project pre-installation checklists for retrofit DPF applications on on-road, off-road, and stationary diesel engines. These pre-installation checklists provide a list of issues that need to be addressed in determining the applicability of a retrofit filter on an older engine. These checklists are available at: www.meca.org/diesel-retrofit/resources.

5.1 Fuel Quality

Care must be taken to match the retrofit control technology to the quality of the fuel that is available. For catalyst systems, the system design should minimize the formation of sulfate. This can be addressed by ensuring the use of low or ultra-low sulfur fuel or by placing the catalyst in the exhaust system where the temperature of the gases can be used to minimize sulfation but still achieve emission reductions. This may require knowledge of the vehicle's duty cycle and experience of what has been successfully accomplished in past retrofit programs.

In general, diesel fuel with low sulfur content (500 ppm sulfur or less) is recommended for retrofit programs to broaden the range of available retrofit technologies. For diesel particulate filter retrofits, even lower sulfur fuel (<15 ppm sulfur) is recommended to maximize the emissions reductions. All catalyst-based emission control technologies benefit significantly from the use of ultra-low sulfur fuel.

5.2 Importance of Vehicle Maintenance

Exhaust emission controls are not a substitute for a well maintained and operated diesel engine. Engines equipped with retrofit control technologies should receive routine maintenance just as other engines would. Particular attention must be given to fuel injectors and turbochargers to insure they are operating properly. With particularly dirty engines, periodic cleaning of a DOC or SCR catalyst might be needed. Diesel oxidation and SCR catalysts employing larger cell densities, e.g. 50 to 200 cells per square inch (cpsi), can considerably minimize the risk of plugging and fouling. For engines equipped with DPFs, backpressure should be monitored using monitoring equipment supplied with the DPF. If backpressures become excessively high, the filter should be cleaned according to the procedures specified by the filter supplier.[10] Retrofit technologies like closed crankcase filters and low pressure EGR systems have regular maintenance requirements specified by the technology provider. Retrofit systems should be regularly inspected to ensure that exhaust installation hardware remains in good condition. Inspections should include checking for warning lights on the backpressure monitor, inspecting the mounting brackets for looseness or damage, checking for signs of soot on the inside of the exhaust pipe and inspecting backpressure sensor tubing for any signs of condensation. Fleet vehicles are often excellent candidates for retrofit because organizations that operate fleets often have strong preventative maintenance programs in place.

Once installed, the importance of proper engine maintenance cannot be overemphasized for the durability and long term performance of the vehicle and a retrofit filter. Regular maintenance becomes critical once a DPF is installed because the presence of smoke in the exhaust can no longer be used as an indicator of engine operation problems. High smoke opacity could be a sign of excessive oil consumption or a bad fuel injector, both of which result in high engine-out PM that may lead to plugging of the filter. Once a DPF is installed in the exhaust system, it will capture the PM and mask any signs of high smoke. A recommended regular maintenance practice is to have an opacity-based check of the engine-out exhaust, each time a filter is removed for cleaning. An opacity test is an inexpensive, simple measurement that should be an integral part of a proactive preventative maintenance program. The SAE standard, J1667, provides a recommended practice for performing an exhaust opacity measurement. Performing an annual, engine-out opacity measurement is a way for fleets to actively monitor the condition of their engines and perform the necessary maintenance to keep their equipment functioning within the engine manufacturers recommended guidelines and minimize the chance of filter plugging. This will have the added co-benefit of better performance and longer engine life.

5.3 Matching a Retrofit Technology to an Engine and Vehicle Application

When deciding whether to retrofit an in-use diesel-powered vehicle with a control technology, several factors must be considered, including:

- engine size and backpressure specification,
- engine duty-cycle and resultant exhaust gas temperatures,
- fuel sulfur level (<15 ppm sulfur fuel should be used),
- desired emission reductions, and
- vehicle integration and safety.

All of these items should be discussed with the technology provider.

The size of the engine combined with its backpressure specification will allow the technology provider to size the retrofit control technology insuring appropriate performance while not adversely affecting vehicle operation.

The duty cycle and resultant exhaust gas temperatures are important for both catalyst and filter technologies. The performance of a catalyst is dependent on temperature and it is essential for filter manufacturers, whose system relies on the exhaust gas temperature for regeneration, to know what these temperatures will be during normal vehicle operations. Data logging of vehicles or engines under consideration for retrofit is commonly used to determine exhaust gas temperatures associated with in-service duty cycles. The exhaust temperature information can then be used to select an appropriate retrofit technology option. Proper matching of retrofit technologies with appropriate applications is a critical step in ensuring the success of a retrofit program. Exhaust temperatures are determined by installing a thermocouple into the exhaust of the vehicle connected to a small temperature recording device called a data logger. The vehicle should be operated over its normal duty cycle for 3-4 days to obtain at least 24 hours of engine operation. This information will help the installer or device manufacturer determine the retrofit device best suited for the vehicle and application since some retrofit devices have specific duty cycle requirements. It is important that exhaust temperatures be rechecked if the duty cycle of a vehicle changes from when it was initially data logged to insure that the retrofit technology is still appropriate for the application and working properly.

Integration of a retrofit control technology on to a vehicle is also an important part of the application engineering process. Wide ranges of integration techniques are available to a retrofit control system design engineer including muffler replacement, in-line installation, and other techniques. Once a device is installed on a vehicle, it may be equipped with a temperature and back pressure monitoring device. This unit can be mounted inside the cab or engine compartment to record the operating conditions of the device and insure that it is operating properly. It will also alert the operator when the filter needs to be regenerated and if ash cleaning of the filter is required.

Safety is an important consideration when integrating a device on a vehicle. The safety aspects that must be considered include thermal hazards to operators, high temperatures in close proximity to fuel and hydraulic lines and any visibility impacts on the safe operation of the vehicle or equipment. This is particularly true in off-road applications where visibility to the front, sides and sometimes rear of the vehicle must be addressed. High temperature and thermal contact issues are often addressed by locating the device out of the way of an operator's access or by appropriate shielding of the device to prevent contact burns. To minimize the impact on visibility, a manufacturer will try to locate the device outside the field of view of the operator. For on-road applications the device is often installed in place of the OEM muffler either behind the cab or under the vehicle.

For off-road equipment with smaller displacement engines, the device may be located under the hood in place of the OEM muffler. This may not be possible with larger horsepower engines in which case a location that minimizes the impact on visibility and operator safety should be identified. It is important that the discussion surrounding the safety implications of vehicle-device integration be discussed between the operator, vehicle owner, installer and device manufacturer. In some cases a cardboard or stainless steel box mock-up of the device has been built and placed on the vehicle in the location being considered to determine the visibility impact. Several standards offer visibility guidelines for off-road equipment. These include the International Standards Organization ISO 5006 and a similar standard issued by the Society of Automotive Engineers, SAE J1091. Both use a similar approach for assessing the visibility impact from the operator's position as projected on to a circle of 12 meter radius around the vehicle. The ISO 5006 standard also provides for the use of mirrors or cameras to mitigate visibility issues. California's Office of Occupational Safety and Health (referred to as Cal-OSHA) finalized retrofit safety/visibility requirements for construction equipment in 2011. These Cal-OSHA requirements are available at: www.dir.ca.gov/title8/1591.html.

6.0 RETROFIT FILTER RELIABILITY

The wide spread acceptance of high efficiency, wall-flow particulate filter technology and numerous published test results speak to the performance and effectiveness of this technology in diesel engine applications. Recent references are provided here concerning the reliability of diesel retrofit filters.

MECA has aggregated California retrofit filter warranty claim information provided by our members. The warranty information represents passive Level 3 retrofit filter warranty claim information from several MECA member manufacturers as a percentage of sales over three years: 2010-2012. The numbers are consistent with ARB's findings that filter-related warranty claims are only about 0.6 percent of total retrofit sales in California. Most claims are associated with accessories and electronic components of the device rather than the filter element itself. These claims may include monitors, thermocouples, wiring, brackets etc. In general, the total claims for active devices tend to be slightly higher due to the larger number of components making up actively regenerated retrofit filters. Warranty claims are most often related to early filter plugging due to increased engine-out PM for a number of possible reasons such as: a significant change in the duty cycle from that used in the retrofit preassessment of the vehicle, worn injectors, leaky turbocharger seals, EGR valve failure or charge air cooler leaks, among others. In most cases, following up the necessary repairs by instituting a manufacturer recommended maintenance schedule on the engine has prevented a reoccurrence of the problems with the filter or the engine. Because retrofits applications are pre-assessed and designed with a specific application and worst case duty-cycle in mind, prior to device selection and installation, they deliver reliable operation provided that good engine and device maintenance practices are followed and the vehicle is operated in a way that is similar to the way it was datalogged.

A 2003 survey of 3,848 construction retrofit DPF installations from 2001 to 2003 in Europe found a failure rate of only 1-2 percent, after some early issues were addressed.[16] The root causes of these failures included poor filter cleaning and poor engine maintenance practices, as well as, ignoring of warning alarms by the operators. The latter problem is often observed by retrofit technology manufacturers and can be easily diagnosed from the data captured on the retrofit filter device monitor. In some cases device monitor records have shown that the trucks continued to operate for days or weeks after an alarm was triggered. Other published retrofit experience can be found in a number of technical papers published by the Society of Automotive Engineers (SAE). The experience in these papers involved hundreds of diverse on-road vehicle types operated over millions of miles over a period of several years. These programs had prescribed maintenance practices and there were few issues with devices observed beyond an occasional failed bracket. In one such program, half of the New York City bus fleet was retrofitted with DPFs and the other half was used as a control population.[17,18] Each fleet of vehicles represented several hundred municipal buses. After a year of normal operation, with proper maintenance, they observed no statistical difference in down time between buses equipped with DPFs and those that were not. At the conclusion of the program, the city decided to retrofit the remainder of the buses in its fleet with DPFs. There are many such examples of real-world demonstrations that support the performance and durability of DPFs provided that engines and devices are properly maintained.

7.0 CONCLUSION

- Diesel emissions from mobile sources have raised health and welfare concerns, but a number of retrofit technologies exist or are being developed that can greatly reduce emissions from diesel-powered vehicles.

- Reductions of black carbon from diesel PM offers an added benefit to reducing climate change due to its high global warming potential estimated to be up to 4500 times higher than that of CO_2 on a per gram of emission basis.

- Diesel oxidation catalysts, diesel particulate filters, exhaust gas recirculation, lean NOx catalysts, lean NOx traps, selective catalytic reduction, and crankcase emissions control, have been successfully retrofitted on on-road and off-road vehicles. These technologies offer opportunities to reduce large amounts of particulate and NOx emissions and other pollutants as well, including toxic HCs.

- Diesel oxidation catalysts can reduce particulate matter emissions from 20 to 50 percent, carbon monoxide and hydrocarbons (including toxic emissions) greater than 90 percent, and substantially reduce smoke and odor from diesel engines. Fuel sulfur levels below 500 ppm (0.05% wt) are recommended. Lower sulfur levels improve the emission control performance of an oxidation catalyst.

- Diesel particulate filter technology can reduce harmful particulate emissions by over 90 percent, reduce carbon monoxide and hydrocarbons (including toxic emissions) by over 85 percent, and significantly reduce smoke. For catalyst-based diesel particulate filters, ultra-low sulfur diesel fuel (<15 ppm sulfur) is recommended for maximum efficiency and durability.

- Both oxidation catalysts and particulate filters can be used in conjunction with biodiesel, EGR and engine management techniques to reduce diesel particulate and NOx emissions.

- Selective catalytic reduction can substantially and simultaneously reduce NOx, PM, and HC emissions.

- Lean NOx catalysts have been combined with filter systems to provide NOx reductions of 25 to 40 percent over engine-out emissions.

- When selecting a retrofit control technology, it is important to ensure that the technology is compatible with the duty cycle of the vehicle and the desired emissions reductions.

- Properly maintained vehicles and engines ensure retrofit emission control technologies will perform optimally. End users also need to follow maintenance procedures specified by the retrofit technology supplier to ensure continued performance of the retrofit device.

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APPENDICES

Appendix A – List of Available Diesel Retrofit Technologies

Technology	Emission Reductions			Costs	Fuel Requirements	EPA/ARB Verified Products Available for On-Road/Nonroad?	Additional Information
	HC	PM	NOx				
Diesel oxidation catalyst (DOC)	50-90%	25-50%	--	$500 to $2,000	500 ppm sulfur	Yes/Yes	DOCs have an established record in the highway sector and are gaining in nonroad applications. Sulfur in fuel can impede the effectiveness of DOCs; therefore, the devices require fuels with sulfur levels of 500 ppm or lower. DOCs can be combined with other retrofit technologies for additional PM reductions and/or NOx reductions.
Diesel particulate filter (DPF)	50-95%	>85%	--	passive DPF: $8,000 to $16,000; active DPF: $15,000 to $30,000	CB-DPF – ULSD; active, non-CB-DPF – 500 ppm	Yes/Yes	DPFs use either passive or active regeneration systems to oxidize the PM in the filters. Passive filters require higher operating temperature to work properly. Filters require some maintenance. Not an ideal strategy for engines that burn high amounts of lube oil. DPFs can be combined with NOx retrofit technologies for NOx reductions.
Flow-through filter (FTF)	50-95%	30->60%	--	$5,000 to $7,000	500 ppm sulfur	Yes/No	The filtration efficiency of a flow-through filter is lower than that of a DPF, but is much less likely to plug under unfavorable conditions, such as high engine-out PM emissions and low exhaust temperatures.
Lean NOx catalyst (LNC) with a DPF	--	>85%	5-30%	$15,000 to $20,000	ULSD	Yes/No	Verified LNCs are always paired with a DPF or a DOC.
Selective catalytic reduction (SCR)	80%	20-30%	80%	$18,000 (with DOC) to $30,000 (with DPF)	500 ppm sulfur	Yes/Yes	Commonly used in stationary applications. SCR systems require periodic refilling of an ammonia or urea tank. Often used in conjunction with a DOC or DPF to reduce PM emissions.
Exhaust gas recirculation (EGR) with a DPF	--	>85%	40-50%	$18,000 to $20,000	ULSD	Yes/No	Both low-pressure and high-pressure EGR systems exist, but low-pressure EGR is used for retrofit applications because it does not require engine modifications. The feasibility of low-pressure EGR is more of an issue with nonroad equipment than on-road equipment (i.e., more difficult to cool the exhaust).
Closed crankcase ventilation (CCV)	--	5-10%	--	$450 to $700	500 ppm	Yes/Yes	Usually paired with a DOC or DPF. CCVs require a regular change of the disposable filter (i.e., at every oil change).

Notes:

- Costs are based on on-road experience.
- See current EPA and ARB verified technology lists at: www.epa.gov/cleandiesel/verification/verif-list.htm and www.arb.ca.gov/diesel/verdev/vt/cvt.htm, respectively.

Appendix B – Links to Diesel Retrofit Programs

In conjunction with state and local governments, public interest groups, and industry partners, the U.S. EPA's National Clean Diesel Campaign (www.epa.gov/cleandiesel/) has established a goal of reducing emissions from the over 20 million diesel engines in the existing fleet by 2014. As a result, across the United States, diesel retrofit programs and demonstration projects have grown significantly over the past several years. These programs and projects demonstrate the applicability and feasibility of U.S. EPA and/or California Air Resources Board verified (or certified) pollution reduction retrofit technologies and fuels for both on-road and off-road vehicles and equipment.

In March 2006, the U.S. EPA released a report on diesel retrofit technology application and program implementation experience in the U.S. since 2000. The report, "Diesel Retrofit Technology and Program Experience," identifies over 220 retrofit projects throughout the U.S. The report is designed to serve both as a reference tool on diesel retrofit technologies and programs in the U.S. and to document valuable lessons learned from the projects. The report is available on-line at: www.epa.gov/cleandiesel/publications.htm.

Other resources for information on diesel retrofit projects in the U.S. are EPA's clean diesel collaborative groups. EPA has partnered with leaders from state and local governments, the private sector, and environmental/health groups across the U.S. to form these diesel collaboratives with the aim of leveraging resources and expertise to reduce diesel emissions from in-use vehicles. These collaboratives keep track of past, current, and upcoming diesel retrofit programs/demonstration projects in their respective regions.

Below are links to the seven clean diesel collaboratives in the U.S.:

- Blue Skyways Collaborative: www.blueskyways.org
- Mid-Atlantic Diesel Collaborative: www.dieselmidatlantic.org
- Midwest Clean Diesel Initiative: www.epa.gov/midwestcleandiesel/index.html
- Northeast Diesel Collaborative: www.northeastdiesel.org
- Rocky Mountain Clean Diesel Collaborative: www2.epa.gov/region8/rocky-mountain-clean-diesel-collaborative
- Southeast Diesel Collaborative: www.southeastdiesel.org
- West Coast Collaborative: www.westcoastcollaborative.org

There are many successful diesel retrofit programs and demonstration projects currently ongoing in other parts of the world as well, including:

Asia

- Beijing, China: yosemite.epa.gov/opa/admpress.nsf/4d84d5d9a719de8c85257018005467c2/40a1cf46ebdcb7e4852570b50062e270!OpenDocument
- Bangkok, Thailand: cleanairinitiative.org/portal/node/3494
- Hong Kong: cleanairinitiative.org/portal/node/3495

- Pune, India: cleanairinitiative.org/portal/node/852
- South Korea: eng.me.go.kr/eng/file/readDownloadFile.do;jsessionid=ektFx1ML9qZWDxIo0e6hGaJxEspx36IBHSn9GdRMCMTsrDlL2ssF6LmywB9CfKkV.meweb2vhost_servlet_engine3?fileId=92447&fileSeq=1
- Tokyo, Japan: www.dieselnet.com/standards/jp/tokyofit.html

Europe

- Diesel retrofit regulations: www.dieselretrofit.eu
- Low emission zones: urbanaccessregulations.eu
- Verification of Emission Reduction Technologies (VERT) Association: www.vert-certification.eu

North America

- British Columbia, Canada: www.th.gov.bc.ca/cvse/diesel_retrofit/index.htm
- Ontario, Canada: www.cleanairpartnership.org/schoolbus
- Mexico City, Mexico: cleanairinitiative.org/portal/node/3493

South America

- Santiago, Chile: www.sdc-climateandenvironment.net/document.php?itemID=9396&langID=1