Retrofitting Emission Controls On Diesel-Powered Vehicles

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Executive Summary

Diesel engines are important power systems for onroad and offroad vehicles. These reliable, fuel-efficient, high torque engines power many of the world's heavy-duty trucks, buses, and nonroad vehicles. While diesel engines have many advantages, they have the disadvantage of emitting significant amounts of particulate matter (PM) and the 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 the air pollution from diesel engines. Through their efforts, cost-effective retrofit technologies have been developed to reduce harmful emissions. In the mining, materials handling and trucking industries, in urban bus fleets, ports, construction and freight, diesel retrofit technologies have demonstrated their ability to significantly reduce unwanted emissions at reasonable costs 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. 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. (Note: As new information becomes available, this document will be updated.)

Available Control Technologies

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

- Diesel oxidation catalysts (DOC)
- Diesel particulate filters (DPF)
- 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 (LNC)

The retrofit of oxidation catalysts on diesel engines has been taking place for well over twenty years in the nonroad vehicle sector. Over 250,000 oxidation catalysts have been installed in underground mining and materials handling equipment. With nearly universal application, oxidation catalysts have been retrofitted on over 750,000 on-road and off-road vehicles worldwide. Oxidation catalysts installed on engines running 500 ppm or less sulfur fuel have achieved total particulate matter reductions of 20 to 50 percent, hydrocarbon reductions of 60 to 90 percent (including those HC species considered toxic), and significant reductions of carbon monoxide, smoke, and odor.

The number of vehicles retrofitted, the number of programs, and the interest in new programs for diesel particulate filters (DPF) has grown significantly over the past few years with more than 200,000 DPFs installed as retrofits to date in a variety of world markets. Today, second and third generation retrofit filter systems can reduce PM emissions by 80 to more than 90 percent. The majority of these installed retrofit DPF systems make use of high efficiency, ceramic wall-flow filters.

Flow-through filter technology is a relatively new method for reducing diesel PM emissions. Flow-through filters can employ catalyzed metal wire mesh structures or tortuous flow, metal foil-based substrates with sintered metal sheets to reduce diesel PM. Technologies verified to date employ catalysts and/or fuel-borne catalysts to oxidize soot. This technology is expected to be more widely applicable than high efficiency filters because it is much less likely to plug under unfavorable conditions. Flow-through filters are capable of achieving PM reduction of about 30 to 75 percent.

Recently, exhaust gas recirculation (EGR) and lean NOx catalysts have been retrofitted on heavy-duty diesel vehicles. EGR is capable of achieving about a 40 percent reduction in NOx emissions. EGR retrofits are being introduced in the U.S, with approximately 1,000 engines retrofitted with low-pressure EGR systems. Low-pressure 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 percent reduction in NOx emissions. This technology is more effective when a supplemental hydrocarbon reductant 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 infrastructure and can be used to retrofit older engines. 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 onroad diesel engine applications. This particular system combines a lean NOx catalyst with a DPF to reduce NOx emissions by 25 percent and PM emissions by more than 85 percent.

Selective catalytic reduction (SCR), using urea as a reducing agent, has also been installed on diesel-powered vehicles. SCR is capable of reducing NOx emissions from 75 to 90 percent while simultaneously reducing HC emissions up to 80 percent and PM emissions by 20 to 30 percent. SCR has been installed on heavy-duty trucks, 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. Numerous demonstration projects intended to commercialize retrofit SCR systems for vehicles in the U.S. are underway at this time.

Emission control systems which combine catalysts, filters, and engine adjustments and components are also available and can be used for retrofit on diesel vehicles. One such technology has demonstrated over a 40 percent NOx reduction while maintaining very low particulate emissions. The system uses ceramic engine coatings combined with fuel injection timing retard and an oxidation catalyst and has been approved under the U.S. EPA's urban bus rebuild/retrofit program. Another example is a cerium-based fuel-borne catalyst filter system in combination with EGR. A third system which provides substantial PM emission reductions and has been approved by the U.S. EPA under the Agency's urban rebuild/retrofit program employs a proprietary cam shaft in combination with an oxidation catalyst.

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; and
- training and education needs of vehicle operators and 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 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 taken place or 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., seven 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.

Conclusion

Although diesel emissions from mobile sources have raised health and welfare concerns, a number of effective control strategies exist or are being developed that can greatly reduce the emissions from diesel-powered vehicles. Retrofit technologies including DOC, DPF, EGR, lean

NOx catalysts, and SCR have been successfully demonstrated on both onroad and nonroad 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 nonroad equipment. They are often the power plant of choice for heavy-duty applications. 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.

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. 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.

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 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.

In addition to the undesirable health affects associated with diesel exhaust, diesel emissions also adversely impact 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 from diesel engines.

Despite health and environmental concerns, the diesel engine remains a popular means of powering trucks, buses and other heavy equipment. Most buses and heavy-duty trucks are powered by diesel engines for good reasons. 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.

A number of countries worldwide have established significantly lower exhaust emission limits for new diesel engines that will be phased in over the 2005 through 2015 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 Available Retrofit Controls

Several types of emission control systems can be installed on a diesel vehicle. This section provides information on the available diesel retrofit controls, including descriptions of their operating characteristics, control capabilities, operating experience, and costs. A summary table of available diesel retrofit technologies is provided in Appendix A.

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.

Diesel particulate filters (DPFs) have also been retrofitted to existing vehicles. Diesel particulate filters 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, the portion of the particulate that some health experts believe may be the PM component of greatest concern. Particulate filters can be designed to control up to 90 percent or more of the toxic HCs emitted by a diesel engine. Catalytic exhaust control and particulate filter technologies have been shown to decrease the levels of polyaromatic hydrocarbons, nitro-polyaromatic hydrocarbons, and the mutagenic activity of diesel PM.

More recently, *exhaust gas recirculation (EGR)* and *lean NOx catalysts* have been retrofitted on heavy-duty diesel vehicles. EGR is capable of achieving a 40 percent reduction in NOx emissions or more. Lean NOx catalysts have demonstrated NOx reductions of 10 to 40 percent.

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 30 to 50 percent.

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.

Emulsified diesel fuel is a blended mixture of diesel fuel, water, and other additives that reduces emissions of PM and NOx. Emulsified diesel can be used in any diesel engine, but some reduction in power and fuel economy is expected due to the fact that the addition of water reduces the energy content of the fuel. Emulsified diesel can reduce emissions of NOx by about 10 to 20 percent and PM by about 50 to 60 percent.

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 at 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.

In some cases, oxidation catalyst and filter technologies can be combined with engine management techniques, e.g., injection timing retard and exhaust gas recirculation (EGR) or with ceramic engine coatings or other technologies, to provide significant control of both particulate and NOx.

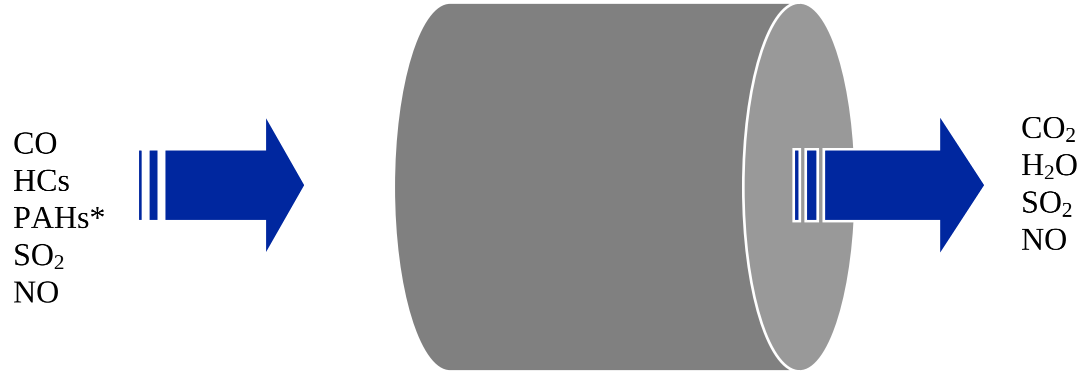
2.1 Diesel Oxidation Catalysts

The diesel oxidation catalyst (DOC) has become a leading retrofit control strategy in both the onroad and nonroad 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 250,000 off-road vehicles around the world for over 30 years. Over 1.5 million oxidation catalysts have been installed on new heavy-duty highway trucks since 1994 in the U.S. These systems have operated trouble free for hundreds of thousands of miles. Oxidation catalysts have been retrofitted on over 750,000 on-road and off-road vehicles worldwide. 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.

2.1.1 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. 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.



* Polyaromatic hydrocarbons

Figure 1. Diagram of a Diesel Oxidation Catalyst

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.

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. More information on U.S. EPA verified diesel technology is available at: www.epa.gov/otaq/retrofit/retroverifiedlist.htm and information on ARB verified technology is available at: www.arb.ca.gov/diesel/verdev/verdev.htm.

2.1.2 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 counted as 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 increasing 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 is being rolled out across the U.S. and Canada during 2006 as part of EPA's and Environment Canada's 2007-2010 highway diesel engine emissions program (see www.epa.gov/otaq/diesel.htm).

Currently, diesel fuel for nonroad engines contains about 3,000 ppm sulfur. Starting in 2007, EPA's 2004 Tier 4 Non-Road Diesel Rule sets a 500 ppm limit for sulfur on diesel fuel produced for nonroad engines, locomotives, and marine applications. The rule also sets a subsequent limit of 15 ppm sulfur (ultra-low sulfur diesel) for nonroad fuel by 2010 and by 2012 for locomotive and marine applications. The availability of these fuels will allow nonroad engines to fully take advantage of catalyst technology for both original equipment and retrofit applications.

2.1.3 Operating Experience

Oxidation catalysts can play a significant role in removing particulate and smoke from existing diesel engines and, as noted above, can be used in combination with engine management techniques to control NOx emissions. Oxidation catalysts have been retrofitted on over 750,000 on-road and off-road vehicles worldwide. Retrofitting oxidation catalysts on existing diesel engines is relatively straightforward. For example, in many applications the oxidation catalyst can be retrofitted as a muffler replacement. Indeed, many of the catalysts used on nonroad vehicles are retrofits.

On the nonroad side, oxidation catalysts have been retrofitted to diesel vehicles for over 30 years with over 250,000 installations having been completed to date. A significant percentage of these units have been equipped to mining and materials handling vehicles, but construction equipment, marine vessels and other types of nonroad engines have been retrofitted as well. PM emissions as well as CO and HC emission reductions are targeted in the the mining and materials handling industries for occupational health concerns. Typically, these systems operate trouble free for several thousand operating hours and are normally replaced only when an engine undergoes a rebuild.

2.1.4 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. Installations typically take less than 2 hours.

Nonroad diesel equipment is characterized by widely varying horsepower (hp) ratings. Retrofit control technologies have been installed on vehicles with horsepower ratings under 50 hp to vehicles powered by engines in excess of 2,000 hp. Both muffler replacement catalyst and in-line units have been installed.

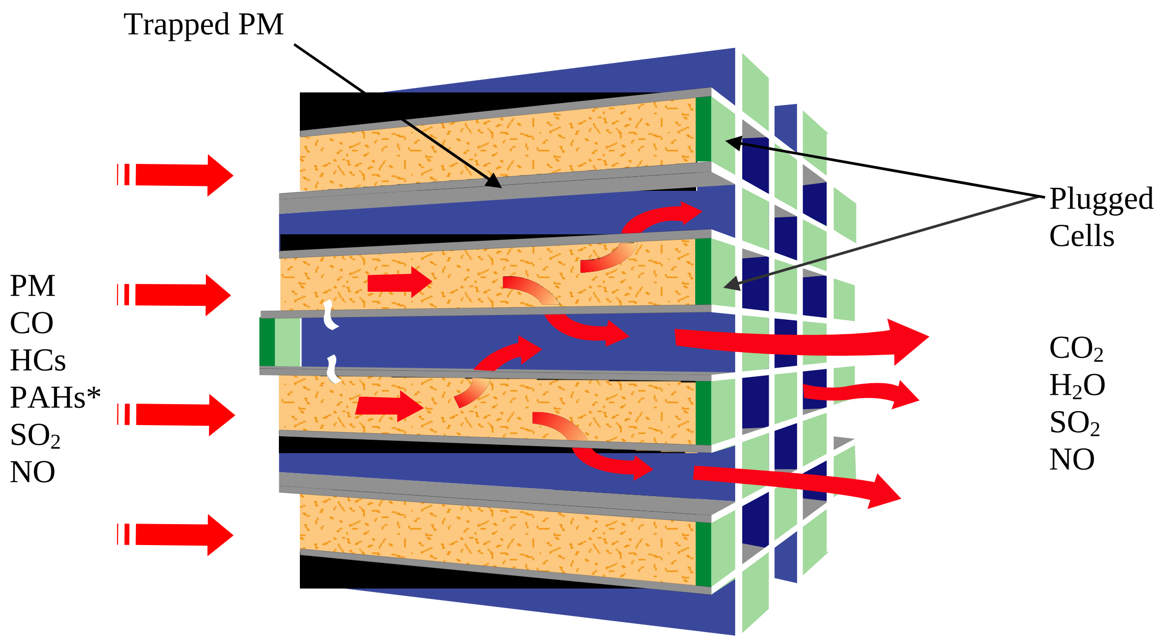
2.2 Diesel Particulate Filters

2.2.1 Operating Characteristics and Performance

As the name implies, diesel particulate filters remove particulate matter in diesel exhaust by filtering exhaust from the engine. They can be installed on 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." Filters that regenerate in this fashion cannot be used in all situations.

In some nonroad 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.

Filter Material. A number of filter materials have been used in diesel particulate filters including: ceramic and silicon carbide materials, 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. Filter efficiency has rarely been a problem with the filter materials listed above, but work has continued to: 1) optimize filter efficiency and minimize back pressure, 2) improve the radial flow of oxidation in the filter during regeneration, and 3) improve the mechanical strength of filter designs. Figure 2 provides a diagram of a typical high-efficiency, wall-flow filter system. High-efficiency, wall-flow filters have demonstrated the ability to reduce diesel particulate emissions by more than 90 percent in retrofit applications.



* Polyaromatic hydrocarbons

Figure 2. Diagram of a Wall-Flow Diesel Particulate Filter

In the figure, particulate-laden exhaust enters the filter from the left. Because the cells of the filter are capped at the downstream end, exhaust cannot exit the cell directly. Instead, exhaust gas passes through the porous walls of the filter cells (thus the wall-flow filter designation). In the process, particulate matter is deposited on the upstream side of the cell wall. Cleaned exhaust gas exits the filter to the right.

Regeneration. 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 upstream oxidation catalyst. In this technique, an oxidation catalyst is 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. 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. Throttling the air intake to one or more of the engine cylinders can increase the exhaust temperature and facilitate filter regeneration.

- Post top-dead-center (TDC) fuel injection. Injecting 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. This unburned fuel can then be oxidized in the particulate filter to combust accumulated particulate matter.

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

- Off-board electrical heaters. Off-board regeneration stations combust trapped particulate matter by blowing hot air through the filter system.

The experience with catalyzed filters indicates that there is a virtually complete reduction in odor and in the soluble organic fraction of the particulate, but 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. Ultra-low sulfur diesel fuel (15 ppm sulfur maximum) is now available in the U.S. and has greatly facilitated these efforts.

In some situations, installation 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 either the U.S. EPA or 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. Concerning maintenance of the filter system itself, manufacturers are designing systems to minimize maintenance requirements during the useful life of the vehicle. In some cases, accumulated lubricating oil ash may have to be periodically removed, however. Manufacturers provide the end-user with appropriate removal procedures. 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 diesel retrofit website at: www.dieselretrofit.org.

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.

2.2.2 The 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.

2.2.3 Operating Experience

Limited 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 200,000 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 80 to greater than 90 percent.

In Europe, 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 1,000,000 filter-equipped cars sold since that first introduction. No performance or maintenance issues have been reported in Europe with passenger car DPFs. Peugeot (PSA) was the first manufacturer to introduce DPF system for European diesel cars in 2000. Other European automobile manufacturers, such as Audi, Fiat, Ford, VW, BMW, and Mercedes, are now offering DPF systems based 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. More recently in the summer of 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 is claimed to be the cleanest operating diesel bus fleet in the world. Transit fleets in many large cities in Europe and the U.S. have now been retrofit with diesel particulate filters.

Beginning with the 2007 model year, all heavy-duty highway diesel engines sold in the U.S. will be equipped with diesel particulate filters as part of EPA's 2007-2010 highway diesel engine emission program. Diesel particulate filters are also now standard equipment on new highway diesel engines sold in Japan.

Diesel particulate filters have been installed on nonroad equipment since 1986. Over 20,000 active and passive systems have been installed on nonroad applications as either original equipment or as a retrofit worldwide. Some nonroad filter systems have been operated for over 15,000 hours or over 5 years and are still in use. Examples of nonroad equipment equipped with filters include: mining equipment, construction equipment, material-handling equipment such as forklift trucks, street sweepers and utility vehicles. Germany, Austria and Switzerland have established mandatory filter requirements for underground mining equipment.

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 75 to 90 percent and PM reductions greater than 90 percent. 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 using a particulate filter can reduce NOx emissions from 10 to 25 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).

2.2.4 Costs

High-efficiency, passive filters for diesel retrofit applications are currently being sold for about $7,000 to $10,000 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. 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 than passive retrofit filter options due to the added complexity needed to achieve controlled regenerations with active technology options such as burners, diesel fuel injection over a DOC, or electrical heaters.

2.3 Flow-Through Filters or Partial Diesel Particulate Filters

2.3.1 Operating Characteristics and Performance

Flow-through filter technology is a relatively new method for reducing diesel PM emissions. Flow-through filters employ catalyzed metal wire mesh structures or tortuous flow, metal foil-based substrates with sintered metal sheets to reduce diesel PM. Technologies verified to date employ catalysts and/or fuel-borne catalysts to oxidize diesel soot as the exhaust flows through these more turbulent flow devices. This technology is expected to be more widely applicable than high efficiency filters because it is much less likely to plug under unfavorable conditions such as high engine-out PM emissions. Flow-through filters are capable of achieving PM reduction of about 30 to 75 percent.

2.3.2 Operating Experience

A flow-through filter based on a tortuous metal foil substrate that contains sintered metal foil sheets is currently offered in Europe as a retrofit technology for a range of late-model diesel passenger cars. This metal foil-based filter is offered by one engine manufacturer in Europe on a family of new heavy-duty diesel engines. A similar flow-through metal filter substrate has recently been verified as a Level 2 technology by ARB with PM reduction of greater than or equal to 50 percent. Catalyzed wire mesh flow-through filter retrofit technologies have also been verified by both ARB and EPA for a range of onroad engine applications. Thus far, there have been limited commercial use of retrofit flow-though filters but there is an increasing interest in this technology due to its ability to significantly reduce PM emissions from older, "dirtier" diesel engines.

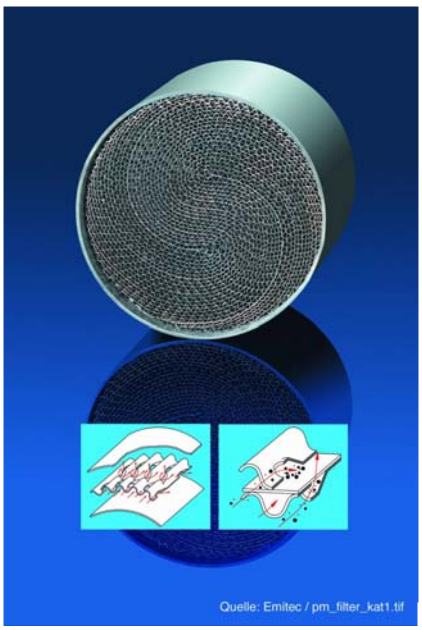


Figure 3. Various Types of Flow-Through Filters (Sintered Metal Sheets and Wire Mesh)

2.4 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.

2.4.1 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 4.

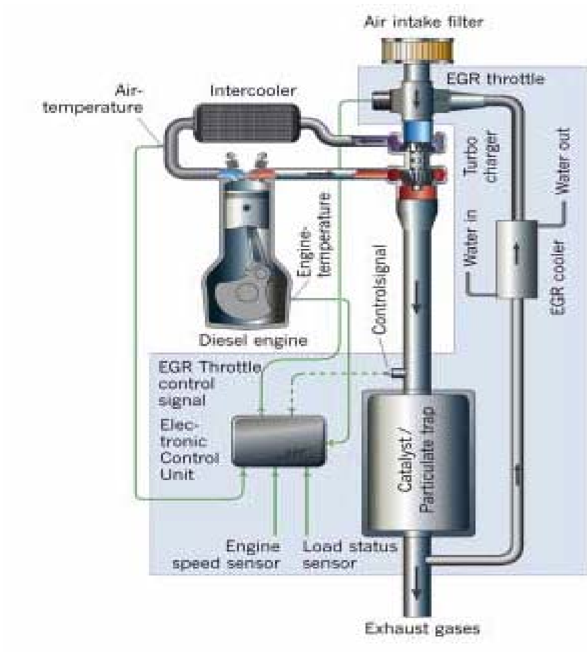


Figure 4. Low Pressure Exhaust Gas Recirculation (EGR) + DPF

2.4.2 Operating Experience

Over 2,000 EGR systems have been installed on bus engines in Europe and Hong Kong. EGR retrofit systems are now being 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. Additional demonstration programs are also underway in the San Francisco Bay area; Sacramento, CA; Los Angeles, CA; and Washington DC. ARB has verified one low-pressure EGR system for a limited range of onroad applications. It employs EGR and a DPF to achieve 85 percent reduction in PM and 40 percent reduction in NOx.

2.4.3 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.

2.5 Selective Catalytic Reduction (SCR)

SCR has been used to control NOx emissions from stationary sources for over 15 years. More recently, it has been applied to select mobile sources including trucks, marine vessels, and locomotives. Applying SCR to diesel-powered vehicles provides simultaneous reductions of NOx, PM, and HC emissions.

2.5.1 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 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 is usually the preferred reductant. 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. A typical layout for a retrofit SCR system for highway vehicle is shown in Figure 5. In this system a DPF is followed by an SCR catalyst for combined reductions of both diesel PM and NOx.

Open loop SCR systems can reduce NOx emissions from 75 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 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, however. SCR catalysts may also be combined with DOCs or DPFs for additional reductions of PM 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.

2.5.2 Operating Experience

SCR is currently being used on both onroad and nonroad engines or vehicles. Applications include trucks, marine vessels and locomotives. Over 100 mobile SCR retrofit systems have been operational in U.S. since 1995 and several hundred SCR retrofit systems have been installed in Europe on highway trucks. Some vehicles have been operated for over 350,000 miles. Many engine manufacturers are now offering SCR systems on new highway heavy-duty engines sold in Europe to comply with the European Union’s Euro 4 or Euro 5 heavy-duty engine emission requirements. One engine manufacturer has already sold more than 10,000 new, SCR-equipped trucks in Europe that use a urea-based reductant.

SCR systems have also been installed on marine vessels and locomotives. 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. Most recently one of the Staten Island ferries operating between Staten Island and Manhattan has been retrofit with an SCR system in the U.S.

2.5.3 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 $12,000 with a DOC to $20,000 with a DPF per vehicle. As more SCR retrofit systems become verified through either the ARB or EPA verification programs, better estimates for system cost will become available.

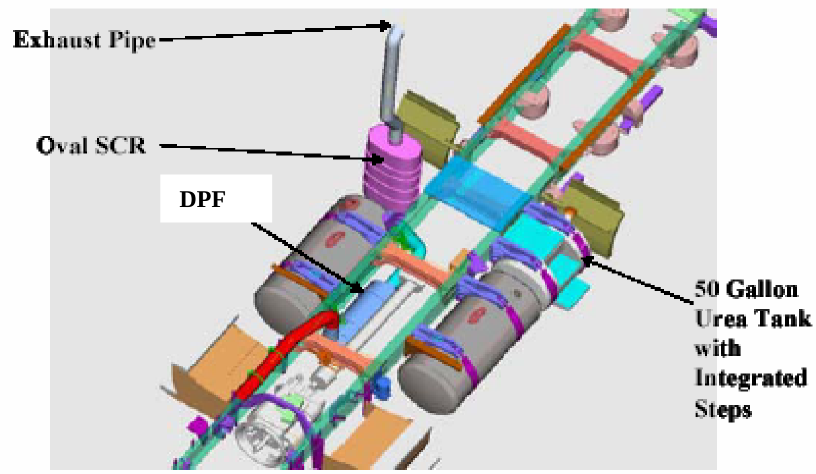


Figure 5. Selective Catalytic Reduction + DPF System

2.6 Lean NOx Catalysts

2.6.1 Operating Characteristics and Control Capabilities

Controlling NOx emissions from a diesel engine is inherently difficult because diesel engines are designed to run lean. In the oxygen-rich environment of diesel exhaust, it is difficult to chemically reduce NOx to molecular nitrogen. The conversion of NOx to molecular nitrogen in the exhaust stream requires a reductant (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.

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. 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. 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. Currently, peak NOx conversion efficiencies typically are around 10 to 30 percent (at reasonable levels of diesel fuel reductant consumption).

2.6.2 Operating Experience

There are more than 1000 lean NOx catalyst-based diesel retrofit systems in service in the U.S. Lean NOx catalyst technology has been utilized in passenger car applications in Europe and has been verified by the California ARB (25 percent NOx control) for a range of highway engine retrofit applications. 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 nonroad retrofit applications, including heavy-duty earthmoving equipment, agricultural pumps, and portable engines, and can also be used to reduce emissions from marine and locomotive diesel engines.

2.6.3 Cost

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 6.

Figure 6. Lean NOx Catalyst + DPF Retrofit System

2.7 Closed Crankcase Ventilation

2.7.1 Operating Characteristics and Control Capabilities

Today, in most 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 on recent model year engines. For 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.

One solution to this 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. These systems greatly reduce crankcase emissions. Figure 7 shows a schematic of a closed crankcase ventilation system.

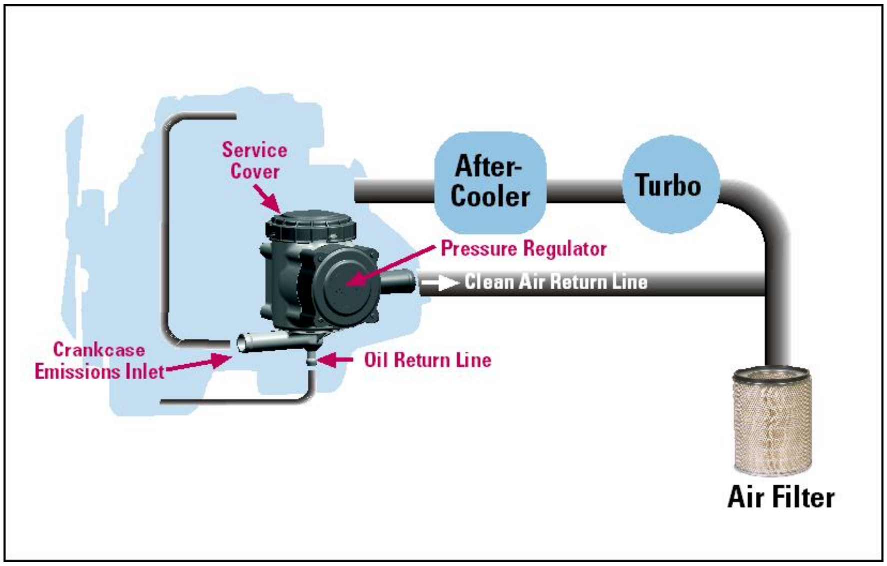


Figure 7. Crankcase Emission Control System

2.7.2 Operating Experience

Crankcase emission control is currently being used in Europe 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. 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. The U.S. EPA's 2007 highway diesel rule and Tier 4 regulations for nonroad diesel engines require that engine manufacturers employ crankcase emission controls on all new diesel engines.

2.7.3 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.

2.8 Emulsified Fuels and Biodiesel

2.8.1 Operating Characteristics and Control Capabilities

An alternative diesel fuel that reduces both PM and NOx emissions is an emulsion of diesel fuel and water. Emulsified diesel fuel is a blended mixture of diesel fuel, water and other additives. The water is suspended in droplets within the fuel, creating a cooling effect in the combustion chamber that decreases NOx emissions. A fuel-water emulsion creates a leaner fuel environment in the engine, lowering PM emissions. Emulsified diesel can be used in any diesel engine, but there is a decrease in power and fuel economy due to the fact that the addition of water reduces fuel energy content. Emulsified fuel can achieve emission reduction of NOx by about 10 to 20 percent and PM by about 50 to 60 percent.

Biodiesel is a domestically produced, renewable fuel that can be manufactured from new and used vegetable oils and animal fats. It is produced by reacting vegetable or animal fats with methanol or ethanol to produce a lower-viscosity fuel that is similar in physical characteristics to diesel, and which can be used neat or blended with petroleum diesel for use in a diesel engine. Biodiesel is commonly blended into petroleum-based fuel at low levels, i.e., 20 percent (B20) or less. Biodiesel can be used in its pure form (B100), but may require certain engine modifications to avoid maintenance and performance problems. Recently ASTM has developed specifications for B100 used as a fuel for mobile sources and specifications are under development for biodiesel blends like B20. Typical emissions 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. In some tests, B20 has shown a slight increase in NOx emissions (about three percent) on some types of existing heavy-duty engines.

2.8.2 Operating Experience

An emulsified diesel + oxidation catalyst system (20 percent to over 40 percent reduction in NOx emissions and a greater than 50 percent reduction in PM emissions) has been verified as a retrofit technology option under both the EPA and ARB verification programs.

B20 has been verified as a retrofit technology option under the U.S. EPA's Voluntary Retrofit Program. There is also growing experience with vehicles operating on biodiesel blends equipped with retrofit technologies like DOCs and DPFs. Retrofit DOCs and DPFs can operate effectively on vehicles using a biodiesel blend fuel up to B20 provided that this biodiesel blend conforms to appropriate biodiesel specifications (e.g., the available ASTM specifications for biodiesel) and that the biodiesel blend meets the fuel sulfur specification required by the retrofit technology supplier for that specific diesel retrofit technology.

2.8.3 Cost

Emulsified diesel costs about $0.20 more per gallon than regular diesel fuel. Biodiesel blends are generally more expensive than conventional highway diesel fuel, but federal tax credits are available for the purchase of biodiesel fuels in the U.S. to help defray these costs.

3.0 Operating a Diesel Retrofit Program

The successful 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. percent sulfur);
- operational and maintenance requirements; and
- training and education needs of vehicle operators and public.

Successful diesel retrofit programs are occurring worldwide, including programs by the U.S. EPA, California ARB, the state of New Jersey, New York City, Hong Kong, Japan, South Korea, Mexico, and Sweden. China, Thailand, India and Chile are also developing retrofit programs. Appendix B provides links to several sources that summarize diesel retrofit programs in the U.S. and other parts of the world.

The Air Resources Board (ARB) identified diesel PM as a toxic air contaminant in August 1998. This action led to development of a plan 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 nonroad vehicles and equipment, continuing the trend towards near-zero PM emissions begun in the late 1980s; 2) retrofitting existing onroad and nonroad 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 onroad, nonroad, 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. An 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 reductions from a variety of existing diesel engines operating in the state including transit buses, other transit fleet vehicles, refuse haulers, stationary engines, portable diesel engines, transportation refrigeration units (TRUs), public and utility fleet vehicles, and cargo handling equipment. Additional regulations will be developed covering nonroad public and private fleets, and private onroad vehicles. The adopted regulations mandate either fleet average reductions in PM emissions and/or the application of best available control technology (BACT) over a multi-year implementation schedule. California has also provided approximately $140 million per year of incentive funds through ARB's Carl Moyer incentive program to help defray the costs of retrofit technology, repowers, or new vehicles that provide early or excess emission reductions relative to reductions required by ARB regulations.

ARB has also established a "Retrofit Verification Procedure" to verify the performance of diesel retrofit technologies used in California. 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 reduction levels. Level 1 verified technologies must reduce PM emissions from 25 to less than 50 percent, Level 2 technologies 50 to less than 85 percent, and Level 3 technologies 85 percent and above. NOx control technologies must achieve a reduction of at least 15 percent. ARB finalized verification procedures became effective on June 11, 2003 and the amendments to the procedures were adopted on February 26, 2004. More recently ARB adopted maximum incremental NO_2 emissions for verified retrofit controls. Starting January 1, 2007, verified retrofit systems must limit incremental NO_2 emissions to no more than 30% of the baseline, engine-out NOx levels. This incremental NO_2 emission limit is further reduced to 20% of baseline NOx emissions on January 1, 2009. Verified retrofit technologies that meet the 2009 20% incremental NO_2 limit early are given a "Plus" designation (e.g., Level 3 Plus). For more information on ARB's retrofit verification procedures , go to: www.arb.ca.gov/diesel/verdev/verdev.htm.

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 retrofit technology approved under the program, they are eligible to receive State Implementation Plan (SIP) emission reduction credits. EPA has received more than 200,000 retrofit commitments as of January 2006. EPA has set the goal of retrofitting, replacing, or repowering all 11 million in-use diesel engines by 2015. The EPA program sets up a protocol for calculating credits, the structure of a third-party 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/otaq/retrofit/.

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/index.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/diesel/construction.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/diesel/ports.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/smartway/index.htm.

3.1 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 captured 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. Also, training of operators and maintenance personnel is more easily achieved.

3.2 Retrofit Control Technology Selection

A variety of retrofit control technologies are available for use in a retrofit control program as discussed in Section 2.0 (and summarized in the table in Appendix A). The technologies to be used 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.

Different technologies can also result in different levels of control. Some technologies can offer very high 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 control technologies 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. 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. Matching retrofit technologies with appropriate applications is a critical step in ensuring the success of a retrofit program.

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.

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

3.3 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 how a particular retrofit device operates and any special maintenance that may be required. For example, special lubricating oil requirements should be defined if necessary.

3.4 Incentives and Regulations

Incentives can also be used 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.

Retrofit advocates have suggested that retrofitted vehicles be required for 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.

4.0 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 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, 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.

4.1 Fuel Quality

Care must be taken to properly 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 some knowledge of the vehicle's duty cycle but 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 very low sulfur fuel.

4.2 The 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. 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. 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. Fleet vehicles are often excellent candidates for retrofit because organizations that operate fleets often have strong preventative maintenance programs in place.

4.3 Matching a Retrofit Technology to an Engine 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.

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 properly 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.

Fuel sulfur level is important when considering the use of retrofit control technologies as discussed in Section 2.0.

The desired emissions reductions are an important consideration when choosing which retrofit control technology is appropriate. Different reductions in gaseous and particulate emissions are achieved by different retrofit control technologies. The technology chosen should reflect the targeted reductions.

Integration of a retrofit control technology on to a vehicle is also an important factor, but has been successfully accomplished in the past. A wide range of integration techniques are available to a retrofit control system design engineer including muffler replacement, in-line installation, and other techniques.

5.0 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.

- Diesel oxidation catalysts, diesel particulate filters, exhaust gas recirculation, lean NOx catalysts, selective catalytic reduction, crankcase emissions control, emulsified diesel fuel and biodiesel fuel have been successfully retrofitted on onroad and nonroad vehicles and these technologies offer opportunities to greatly 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 and emulsified diesel fuel blends, EGR and engine management techniques to simultaneously reduce diesel particulate and NOx emissions.

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

- Lean NOx catalysts have been combined with filter systems to provide NOx reductions of 10 to 25 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 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.

APPENDICES

Appendix A – Table 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%	--	$7,000 to $10,000	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%	$12,000 (with DOC) to $20,000 (with DPF)	500 ppm sulfur	No/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%	--	~$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/otaq/retrofit/retroverifiedlist.htm and www.arb.ca.gov/diesel/verdev/verdev.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/index.htm) has established a goal of reducing emissions from the over 11 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 the recently-formed diesel collaborative groups. The U.S. 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 diesel collaboratives in the U.S.:

- Blue Skyways Collaborative: epa.gov/region6/6xa/blue_skies_collaborative.htm
- Mid-Atlantic Diesel Collaborative: www.dieselmidatlantic.org/diesel/index.htm
- Midwest Clean Diesel Initiative: www.epa.gov/midwestcleandiesel/projects/index.html
- Northeast Diesel Collaborative: www.northeastdiesel.org/index.htm
- Rocky Mountain Clean Diesel Collaborative: epa.gov/region8/air/rmcdc.html
- Southeast Diesel Collaborative: [web site coming soon]
- West Coast Diesel Collaborative: www.westcoastdiesel.org/projects.htm

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

Asia

- Beijing, China: www.epa.gov/OMS/retrofit/china2.htm
- Bangkok, Thailand: www.cleanairnet.org/baq2004/1527/article-59239.html
- Hong Kong: www.epd.gov.hk/epd/english/environmentinhk/air/prob_solutions/cleaning_air_atroad.html
- South Korea: eng.me.go.kr/docs/news/press_view.html?seq=264

- Tokyo, Japan: www.dieselnet.com/standards/jp/tokyofit.html

Europe

- Sweden: www.dieselnet.com/standards/se/zones.html
- Switzerland: www.umwelt-schweiz.ch/buwal/eng/fachgebiete/fg_luft/quellen/verkehr/diesel/index.html

North America

- Mexico City, Mexico: www.epa.gov/otaq/retrofit/mexico_city.htm
- Ontario, Canada: www.ec.gc.ca/cleanair-airpur/CAOL/canus/great_lakes/c3_e.cfm

South America

- Santiago, Chile: www.state.gov/g/oes/env/tr/2005/55755.htm