Exhaust Emission Controls Available to Reduce Emissions
from
Nonroad Diesel Engines

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Manufacturers of Emission Controls Association
1660 L Street, NW • Suite 1100 • Washington, DC 20036 • tel: (202) 296-4797 • fax: (202) 331-1388
www.meca.org

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Introduction

A wide variety of nonroad diesel engines are in-use today, ranging from agricultural tractors, to construction and mining equipment, to forklift trucks used for materials handling. The engines used to power these vehicles can be relatively small, in the range of <75 horsepower, or as large as >750 hp. The duty cycles of nonroad vehicles also vary considerably, with some applications being relatively steady state (e.g., agricultural tractors) and others being transient in nature (e.g., nonroad haulage trucks).

The use of exhaust emission control technology for nonroad diesel engines is not new. For well over twenty five years, nonroad diesel engines in vehicles in the construction, mining, and materials handling industries have been equipped with exhaust emission control technology – initially with diesel oxidation catalysts (DOCs) followed later by particulate filter systems (DPFs). Worldwide, over 250,000 nonroad vehicles and equipment have been equipped with exhaust emission control technology. The technology has provided important pollution reductions and has demonstrated excellent durability both as original equipment and as retrofit technology. Recently, selective catalytic reduction (SCR) for NOx emission control has also been used in select nonroad diesel engine applications including marine vessels and locomotives.

As states look for new ways to achieve the National Ambient Air Quality Standards (NAAQS) for both particulate matter (PM) and ozone, exhaust emission control of nonroad diesel engines is critical. Engine design improvements combined with exhaust emission control technology offer great potential for significantly reducing emissions from nonroad diesel engines. Generally, the technologies, such as DPFs and NOx adsorbers, and integration strategies being developed to meet the 2007 and 2010 heavy-duty onroad diesel engine standards can be applied to nonroad diesel engines and vehicles. Also, SCR, widely used on stationary engines, will be a NOx control option, as will exhaust gas recirculation (EGR) technology.

Smaller engines, typically less than 75 hp, present special challenges in that they will need on-highway type fueling systems to employ the same technologies being developed for highway vehicles. Specifically, the capability to modulate between lean and rich operation will be needed to employ NOx adsorber catalysts. Therefore, either the capability to have in-cylinder post fuel injection or supplemental in-exhaust fuel addition systems will need to be developed for these engines. Also, in order to employ SCR for NOx control, these engines will need to be equipped with appropriate electronic control units and urea injection systems. Employing PM filters on these engines will also require that the necessary technology be employed to ensure that filter regeneration is achieved. While these challenges exist, they can be addressed. For example, options already exist for filter regeneration for small engines as is discussed below. Furthermore, DOCs can be readily applied to these engines to significantly reduce emissions today.

Today's nonroad diesel engines are characterized by relatively high engine-out emissions. An important part of the emission control system approach will be to reduce engine-out emissions to enable exhaust emission control to be effectively employed and to make the truly clean nonroad engine a reality. A systems approach combining the best in engine and emission control technology is being successfully applied in other mobile source applications and can certainly be utilized in reducing emissions from nonroad diesel engines. As is the case with onroad diesel engine emission control, diesel fuel containing <15 ppm sulfur is absolutely essential to maximize the control and operating capabilities of exhaust emission control technologies.

As noted above, although challenges exist in reducing emissions from nonroad diesel engines, the technologies – both engine based and exhaust emission control technologies – exist today and continue to rapidly develop. These technologies in combination with low (<15 ppm) sulfur diesel fuel and appropriate system integration strategies can be used to significantly reduce emissions from nonroad diesel engines. It will be the transference of these technologies and the integration strategies being developed to enable onroad engines to meet the upcoming 2007 requirements to the nonroad sector that will enable nonroad diesel engines to operate clean.

This paper was prepared to summarize the experience with emission control technologies on nonroad diesel engines. The control capabilities, as well as the operating experience with the technologies in various applications, are highlighted. Also, the opportunities and challenges for the reduction of emissions from future nonroad diesel engines are reviewed.

Description of Diesel Exhaust Emission Control Technologies Options for Nonroad Diesel Engines

Several exhaust emission control technologies are and will be available to substantially reduce emissions from nonroad diesel engines. These include diesel particulate filters (DPFs), diesel oxidation catalysts (DOCs), lean NOx catalysts, NOx adsorbers, and selective catalytic reduction (SCR). Crankcase emissions can also be controlled from nonroad diesel engines.

Diesel Particulate Filters (DPFs)

As the name implies, diesel particulate filters remove particulate matter in diesel exhaust by filtering exhaust from the engine. They can be installed on nonroad vehicles and equipment 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”. Both exhaust gas temperature and diesel fuel sulfur level have to be taken into consideration.

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 prescribed 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, including: ceramic and silicon carbide materials, fiber wound cartridges, knitted silica fiber coils, ceramic foam, wire mesh, sintered metal substrates, 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 backpressure, 2) improve the radial flow of oxidation in the filter during regeneration, and 3) improve the mechanical strength of filter designs.

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 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 adsorbs on 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.

- *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. This unburned fuel can then be oxidized in the particulate filter to combust accumulated particulate matter.

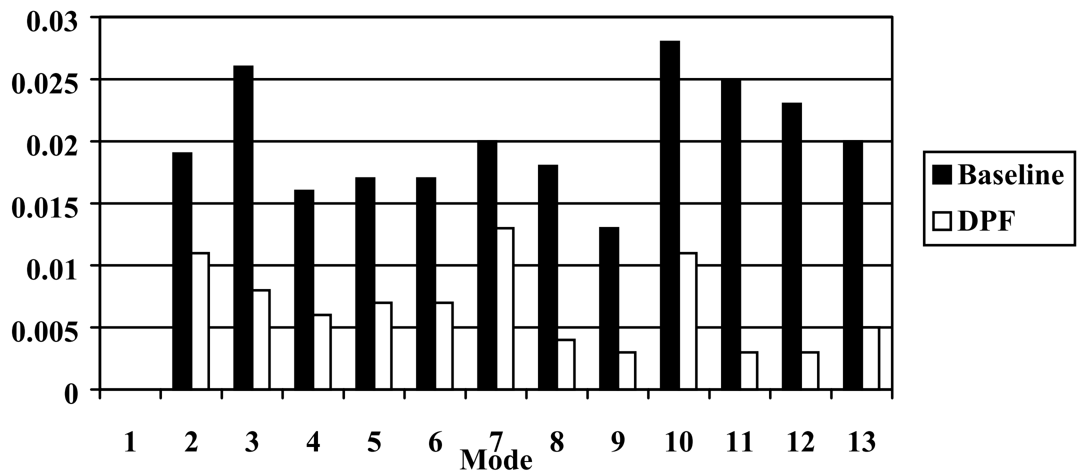
- *On-board fuel burners or electrical heaters*. Fuel burners or electrical heaters upstream of the filter can provide sufficient exhaust temperatures to ignite accumulated particulate matter and regenerate the filter.

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

Sulfur affects filter performance by inhibiting the performance of catalytic materials upstream of or on the filter. This phenomenon not only adversely affects the ability to reduce emissions, but also adversely impacts the capability of these filters to regenerate – there is a direct trade-off between sulfur levels in the fuel and the ability to achieve regeneration. Sulfur also competes with chemical reactions intended to reduce pollutant emissions and creates particulate matter through catalytic sulfate formation. The availability of very low, <15 ppm sulfur fuel will enable these filters to be designed for improved PM filter regeneration and emission control performance, as well as to minimize any increase in sulfate emissions. Indeed, diesel fuel containing <15 ppm sulfur is required to ensure maximum emission control performance on the broadest range of diesel nonroad engines possible.

Emissions control performance of DPFs is well established. While most emission testing has been performed on transient test cycles where PM reductions in excess of 90 percent have been demonstrated time and time again, steady state test data also exists as shown in Figure 1 (Reference 1). This testing was performed using fuel containing 54 ppm sulfur.

Figure 1. 13-Mode Steady-State DPF Control Performance (g/bhp-hr)



As can been seen the control performance of catalyst-based DPFs is affected adversely by even 54 ppm sulfur in the fuel for some operating modes due to the formation of H_2SO_4. The use of lower (e.g., <15 ppm) sulfur fuel is essential to achieving the greater PM control efficiencies that will be needed to achieve truly low emission levels in nonroad engine applications. In fact, in a joint government industry research program aimed to investigate the effects of diesel fuel sulfur content on emissions from heavy-duty diesel engines, two different diesel particulate filters were evaluated for their PM emission control performance with fuels containing different fuel sulfur levels on the steady-state 13 mode OICA test cycle (Reference 2). When testing with 3-ppm sulfur fuel both filter systems achieved a 95 percent PM emission reduction.

Another advantage of the use of DPFs on diesel-powered nonroad engines is their ability to dramatically reduce toxic HC emissions. The capability of two separate catalyst-based DPF systems to reduce 18 distinct polyaromatic hydrocarbons (PAHs) has also been evaluated (Reference 1). On average, the PAHs were reduced by 89 and 84 percent, respectively. The testing was performed over the U.S. Federal Test Procedure (FTP). Although the FTP is a transient test cycle used for motor vehicles, the results would be similar, or better, on a steady state test cycle because of the relatively low load associated with the FTP and corresponding exhaust gas temperatures (the catalyst function of the filter performs better at elevated temperatures). Also, DPFs control in excess of 99 percent of the carbon-based ultrafine particles (SAE Paper 2000-01-0473).

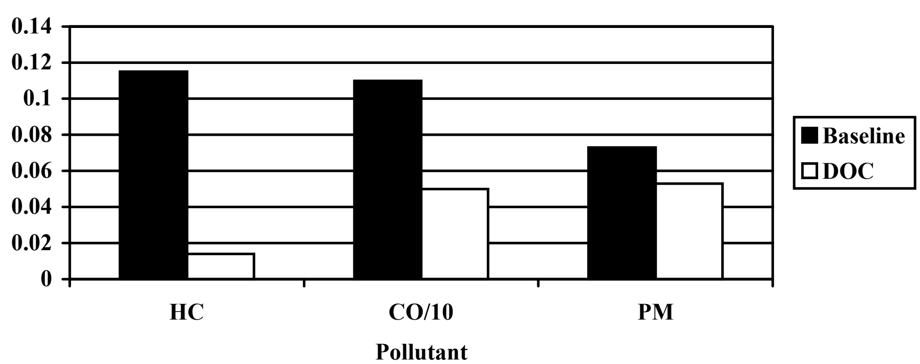
As noted, DPFs are commercially available today. Over 70,000 onroad, heavy-duty vehicles and 400,000 diesel passenger cars have been equipped with the technology. Nevertheless, development work continues to improve the technology focusing on such areas as improving filter design, structural integrity, materials, geometries, as well as improving filter regeneration performance (SAE Papers 2002-01-0322, 2002-01-0325, 2002-01-0323, and 2003-01-0378).

Diesel Oxidation Catalysts (DOCs)

Diesel oxidation catalyst is a technology that is available today and could be readily applied to virtually the entire range of nonroad engine applications. Over 250,000 nonroad vehicles and equipment including mining vehicles, skid steer loaders, forklift trucks, construction vehicles and stationary engines, as well as, over 35,000,000 diesel passenger cars have been equipped with the technology.

The principle behind a diesel oxidation catalyst for the control of emissions from a diesel engine is that the catalyst causes chemical reactions without being changed or consumed. An emission control catalyst system consists of a steel housing, whose size is dependent on the size of the engine for which it is being used, that contains a metal or ceramic structure, which acts as a catalyst support or substrate. There are no moving parts, just acres of interior surfaces on the substrate coated with either base or precious catalytic metals such as platinum group metals. Catalysts transform pollutants into harmless gases by causing chemical reactions in the exhaust stream. Diesel oxidation catalysts serve to reduce PM, CO, HC, and toxic HC emissions. PM emissions are reduced by the chemical transformation of the soluble organic fraction (SOF) to carbon dioxide and water. DOCs can reduce total PM emissions by up to 50 percent depending on the amount of SOF in the PM and the amount of sulfur in the fuel. Figure 2 highlights the emissions control performance of a DOC as measured over the heavy-duty engine FTP with fuel containing 368-ppm sulfur (Reference 1). Even with the high sulfur content used, a 27 percent reduction in PM was achieved on the MY 1998 engine.

Figure 2. DOC Performance (g/bhp-hr)



Like catalyst-based DPFs, oxidation catalysts are effective in controlling toxic HC emissions. The control capabilities of two DOCs were evaluated for 18 distinct PAHs (Reference 1). Reductions in excess of 50 percent are readily achieved with reductions approaching 70 percent possible. Similar or better results can be expected on steady-state test cycles for the reasons mentioned above for catalyst-based DPFs.

Diesel oxidation catalysts are virtually maintenance-free. Periodic inspection to ensure that cell plugging is not occurring is advisable. Cell plugging, if it occurs at all, would be limited to those situations such as engine malfunction (e.g., a faulty injector or two) or where there is prolonged idle in cold ambient temperatures (e.g., multi-day idling in Alaska). On-board diagnostic techniques like backpressure monitoring can be used to alert the operator in these rare instances when plugging might occur and the catalysts can easily be removed, cleaned and reinstalled.

Like diesel particulate filters, diesel oxidation catalysts are also affected by sulfur. 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), which was introduced in 1993 throughout the U.S., has facilitated the application of catalyst technology to diesel-powered vehicles. Very low fuel sulfur (<15 ppm) would further enhance the control capabilities of DOCs.

NOx Adsorber Catalysts

NOx adsorber catalysts are currently being used commercially in light-duty gasoline direct injection (GDI) engines. This technology is also undergoing extensive research and development in anticipation of the U.S. 2007 on-road heavy-duty diesel engine regulations and to help significantly reduce NOx emissions from light-duty diesel vehicles. The progress in developing and optimizing this technology has been extremely impressive.

NOx adsorbers act to store NOx emissions during lean engine operation and release the stored NOx by periodically creating a rich exhaust environment by either engine operation or the injection of a reductant in the exhaust stream. When released the NOx is converted to N_2 by a three-way catalytic reaction. In the laboratory, NOx adsorbers have demonstrated the ability to control up to 90 percent or more of the engine out NOx emissions over a broad temperature range as shown in Figure 3. Also, excellent progress has been made in improving the thermal durability of NOx adsorbers as illustrated in Figure 4. A Toyota vehicle equipped with a combined NOx adsorber/PM filter system came close to meeting the EPA Tier 2, bin 5 emission standards with a low-mileage emission system. A 60-vehicle fleet equipped with Toyota's combined NOx adsorber/PM filter technology is now undergoing road testing in Europe. A HDE NOx/PM system tested at EPA's laboratory achieved emission levels below the 2007 HDE emission standards of 0.2g/bhp-hr NOx and 0.01 g/bhp-hr PM using low mileage emission components.

The current focus of NOx adsorber technology development and optimization is on: 1) expanding the operating temperature window in which the technology will perform, 2) improving the thermal durability of the technology, 3) improving the desulfurization methods and performance, and 4) improving system packaging and integration. While NOx adsorber catalysts are not currently available for nonroad diesel engines, NOx adsorber and the associated engine technologies will be available for use on nonroad diesel engines in the future. The incorporation of on-highway type fueling systems will allow for the use of NOx adsorber technology on the smaller engines as well.

Low sulfur diesel fuel – <15 ppm sulfur – is absolutely essential to commercializing NOx adsorber systems that can function effectively for both onroad and nonroad diesel engine applications. At higher sulfur levels, a NOx adsorber quickly becomes ineffective as the sulfur attaches to the sites meant to "trap" the NOx. The sulfur remains attached to these sites until high temperature, rich conditions, which are not characteristic to normal diesel engine operation, are met. Also, while a sulfur regeneration mode or desulfurization cycle will need to be employed in any case, the frequency of desulfurization must be kept to a minimum to avoid substantial fuel economy penalties and perhaps a degradation of the NOx adsorber performance that, in turn, will require an even more frequent desulfurization. As the sulfur level increases, the frequency, as well as the severity, of reservations needed increases.

Figure 3. Improvements in NOx Control Efficiency

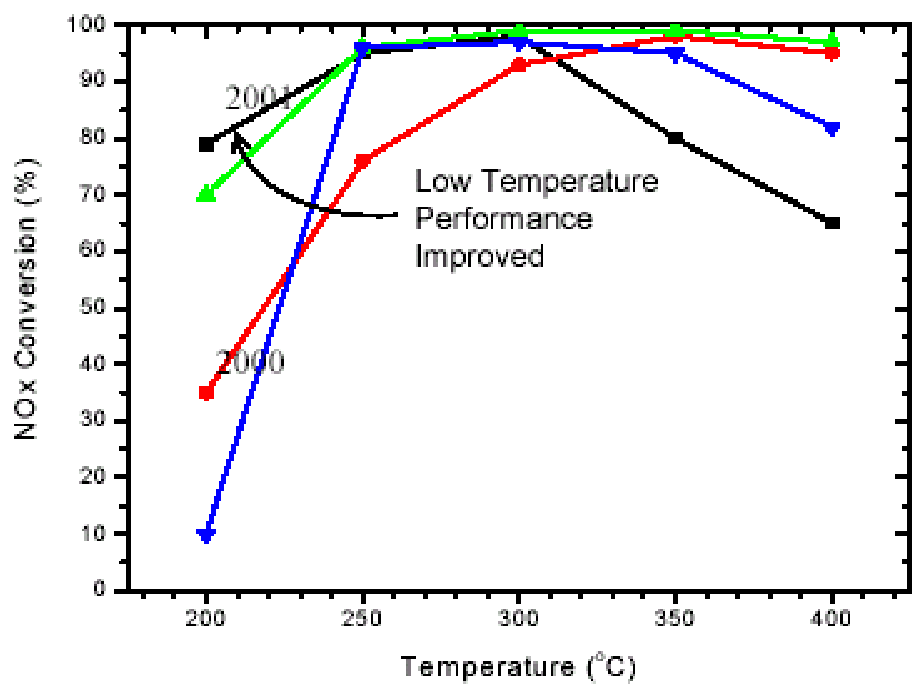
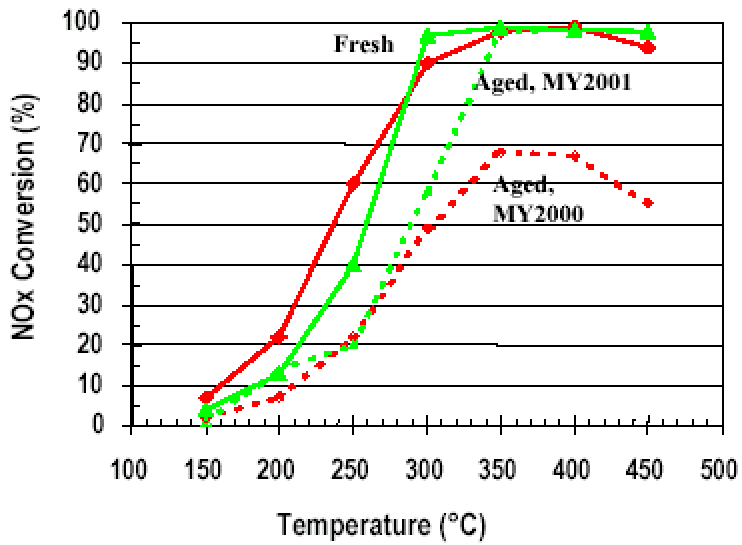


Figure 4. Improvements in Thermal Durability



Selective Catalytic Reduction

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 engines provides simultaneous reductions of NOx, PM, and HC emissions.

Like an oxidation catalyst, the catalyst in an SCR system allows chemical reactions to take place that would not take place during normal engine operation. Again, like an oxidation catalyst, the SCR catalyst enables chemical reactions without being consumed itself. Unlike an oxidation catalyst, however, a SCR system needs a chemical reagent, a reductant, to convert nitrogen oxides to molecular nitrogen and oxygen in the exhaust stream. The reductant is typically urea or ammonia (NH_3). The reductant is added at a rate calculated from an algorithm that estimates the amount of NOx present in the exhaust stream. The algorithm relates NOx emissions to engine operating conditions, for example engine revolutions per minute (rpm) and load. As exhaust gases and reductant pass over the SCR catalyst, chemical reactions occur that reduce NOx emissions 65 to in excess of 90 percent and, where an oxidation function is included, reduce HC emissions from 30 to 90 percent and PM emissions from 15 to 50 percent. In addition, toxic HC emissions reductions can be achieved if an oxidation component is incorporated into the catalyst. In these instances, reductions similar to a DOC will be achieved. Like all catalyst-based emission control technologies, SCR performance is enhanced by the use of low sulfur fuel.

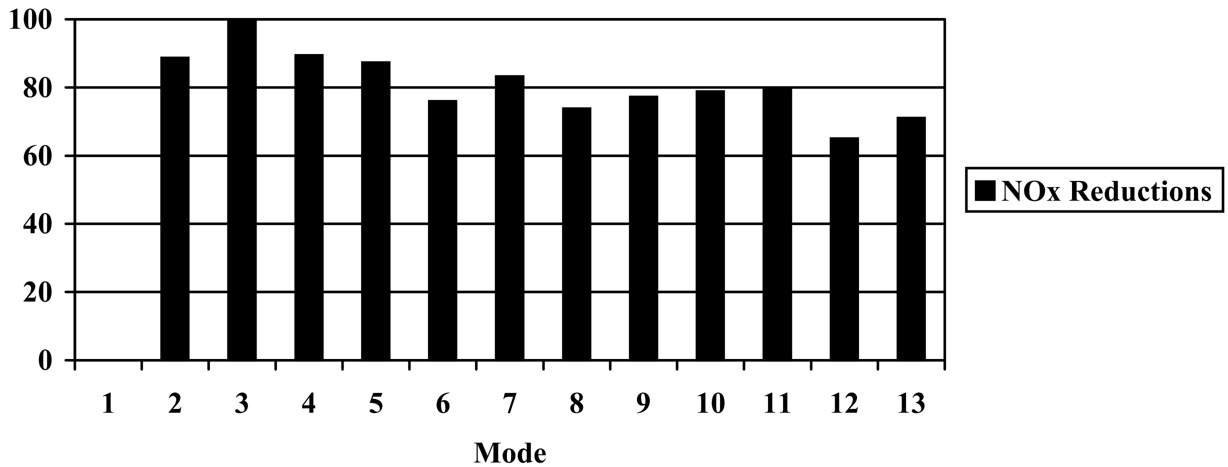
Both precious metal and base metal catalysts have been used in SCR systems. Base metal catalysts, typically vanadium and titanium, are used for exhaust gas temperatures between 450°F and 800°F. For higher temperatures (675°F to 1100°F), zeolite catalysts may be used. Precious metal SCR catalysts are useful for low temperatures (350°F to 550°F). In order to apply

SCR technology over the full range of nonroad engine applications and accompanying engine operating temperature windows, both types of catalysts likely will be utilized. SCR catalysts will benefit from the use of low sulfur fuel in terms of improved performance and minimizing sulfate formation when precious metals are used.

The control capabilities of SCR have also been evaluated (Reference 1). The NOx control performance is shown in Figure 5. As can be seen, NOx reductions ranged from approximately 65 percent in mode 12 to almost 100 percent in mode 3. Overall, a NOx reduction in excess of 80 percent was achieved.

Commercial application of SCR in the nonroad sector to date has been primarily on large marine and locomotive engines where the reductant can readily be stored onboard. The captive nature of many applications for nonroad diesel equipment makes more widespread use of this technology feasible in that the infrastructure requirements to ensure reductant availability can be more easily addressed than in the on-road highway sector.

Figure 5. 13-Mode SCR NOx Control Performance (% reduction)



Lean NOx Catalysts

Lean NOx catalyst systems have also been used on diesel engines. Some lean NOx catalysts rely on the injection of a small amount of diesel fuel or other reductant into the exhaust. The fuel or other hydrocarbon reductant serves as a reducing agent for the catalytic conversion of NOx to N_2. Other systems operate passively at reduced NOx conversion rates. The catalyst substrate is a porous material often made of zeolite. The substrate provides 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. A hydrocarbon/NOx ratio of up to 6/1 is needed to achieve good NOx reductions. Since the fuel used to reduce NOx does not produce mechanical energy, lean NOx catalysts typically operate with a fuel penalty of about 3 percent. Currently, peak NOx conversion efficiencies typically are around 10 to 20 percent.

Two types of lean NOx catalyst formulations have emerged: a low temperature catalyst based on platinum and a high temperature catalyst utilizing base metals, usually copper. Each catalyst is capable of controlling NOx over a narrow temperature range. Combining high and low temperature lean NOx catalyst systems broadens the temperature range over which they convert NOx making them more suitable for practical applications.

Like all catalyst-based emission control technologies, the use of low sulfur diesel fuel enhances the performance of lean NOx catalysts. It also ensures that sulfate production is minimized allowing for maximum PM emissions control.

Crankcase Emission Control

Today, in most turbocharged diesel engines, the crankcase breather is vented to the atmosphere often using a downward directed draft tube to prevent fouling of the turbocharger and the resultant maintenance. While a rudimentary filter is often installed on the crankcase breather (the vent for the oil reservoir), a substantial amount of particulate matter is released to the atmosphere. For diesel engines used in motor vehicle applications, emissions through the breather may exceed 0.7 g/bhp-hr during idle conditions on recent model year engines.

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 have the capability to eliminate crankcase emissions.

Factors to Be Considered When Applying Exhaust Emission Control Technology to Nonroad Engines

When equipping a nonroad vehicle with an exhaust emission control system, several items must be considered. These include:

- pollutant being controlled,
- exhaust gas temperatures and backpressure, and
- vehicle integration.

Pollutant Being Controlled

Exhaust emission control on nonroad vehicles was first used in the 1960s to address occupational health concerns and odor in closed working environments like underground mines and warehouses where diesel-powered and propane-powered equipment can be found. For occupational health reasons, the control technologies initially used targeted CO and HC. However, as diesel particulate emissions became recognized as a threat to workers' health, diesel particulate filters, which not only provided for control of CO and HC but also PM emissions, were developed and applied. Also, the ability of DOCs to reduce PM emissions was recognized. Today, technologies exist and are emerging to control CO, HC, PM, and NOx emissions from nonroad diesel vehicles. The application of a number of these control technologies will benefit from the extensive development and commercial experience in both new on-road vehicle and engines and with diesel engine retrofit.

Exhaust Gas Temperatures and Backpressure

An exhaust emission control system's performance is often dependent on exhaust gas temperature. Catalyst performance is mainly a function of temperature. The exhaust gases must be of sufficient temperature for catalyst light-off. The design of the system must take this into account. For example, a diesel particulate filter system which does not use an external heat source to initiate regeneration – a catalyst-based or "passive" DPF – will require exhaust gas temperatures high enough for this process to take place (usually around 300 deg C). The system's design should also minimize exhaust backpressure to eliminate or minimize any potential fuel economy penalties.

Diesel Fuel Properties

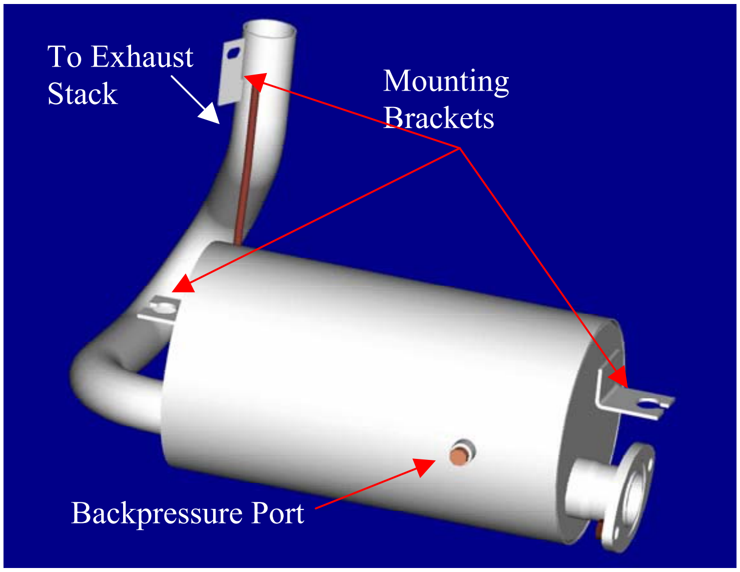
Low sulfur (<15 ppm) diesel fuel needs to be available to ensure that catalyst-based exhaust emission control technologies can be used most effectively. The low sulfur content will ensure that maximum performance and durability are achieved. It also ensures that sulfation does not occur and maximum PM emission reductions are achieved. Also importantly, it ensures that regeneration of catalyst-based DPF systems occurs at the lowest possible temperature ensuring their reliability on a broad range of nonroad diesel vehicles. DOCs have successfully been used to reduce emissions from urban buses with fuel containing up to 500 ppm sulfur under EPA's mandatory rebuild retrofit program where PM emissions reductions in excess 25 percent are being achieved.

In order to apply NOx adsorber technology to nonroad diesel engines, it is imperative that low (<15 ppm) sulfur diesel fuel be available.

Vehicle Integration

Vehicle integration is important from three points of view: 1) to ensure the system is installed at the appropriate place in the exhaust system to provide optimum performance (as discussed above), 2) to ensure the system fits in the available space, and 3) safety. Integrating controls has been successfully accomplished over the years on a variety of nonroad vehicles and equipment. Currently, many of the systems for nonroad vehicles are integrated into a muffler, which is used to replace the standard muffler as illustrated in Figure 6 for a forklift truck.

Figure 6. Schematic of a Muffler Incorporating a DOC for a Forklift Truck

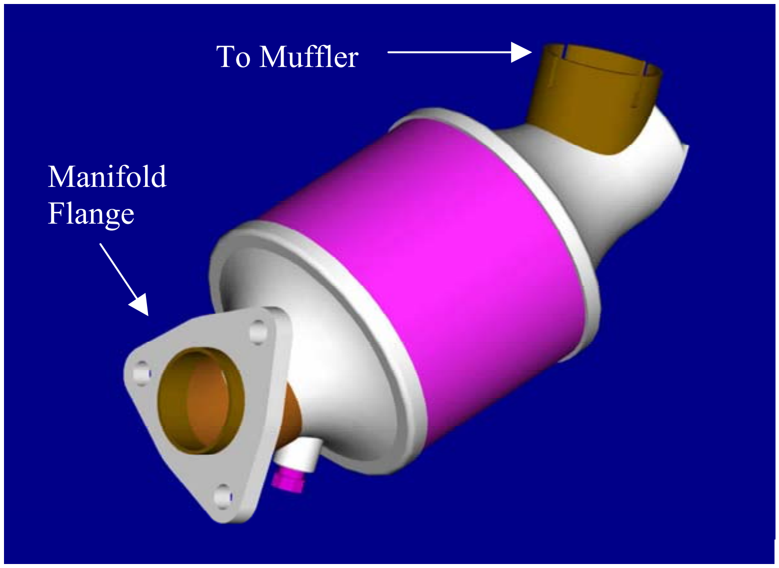


Although sometimes a challenge for existing vehicles where exhaust emission control technology has been retrofitted to the vehicle, past experience has shown that control equipment integration on nonroad vehicles and equipment is not as difficult as many believe. DOCs have also been designed to fit close-coupled to the manifold in the existing engine compartment. Figure 7 is a schematic of one such design also for a forklift truck. The ability to close-couple the technology to the engine manifold can be used to maximize the performance of exhaust emission control technology by taking advantage of the elevated temperatures in this position.

Even on very small engines, exhaust emission controls can be successfully integrated. Two examples of this having been accomplished in the past are 1) the successful design and installation of over 15 million catalysts worldwide on small motorcycles and mopeds, and 2) the installation of catalyst technology on lawn and garden equipment such as chainsaws, trimmers, and lawn mowers in the U.S. and Europe. The same type of innovations in design and packaging can be applied to even the smallest-sized nonroad diesel engines.

DPFs have also been successfully integrated onto nonroad vehicles. Figure 8 shows a small forklift truck equipped with a diesel particulate filter system that is regenerated using off-vehicle power. The system includes not only the filter, but also a heater element and appropriate wiring to allow the vehicle to be plugged into an electrical regeneration station. Operator visibility was not impaired. Similarly, DPFs have been installed on large vehicles. Figure 9 depicts a locomotive grader equipped with a catalyst-based DPF that regenerates passively. The engine size required that four filters in series be used. As can be seen, the installation accomplished while successfully insuring operator visibility with the filter installed on top of the existing muffler and inline with the existing exhaust stack.

Figure 7. A Close-Coupled DOC for a Forklift Truck

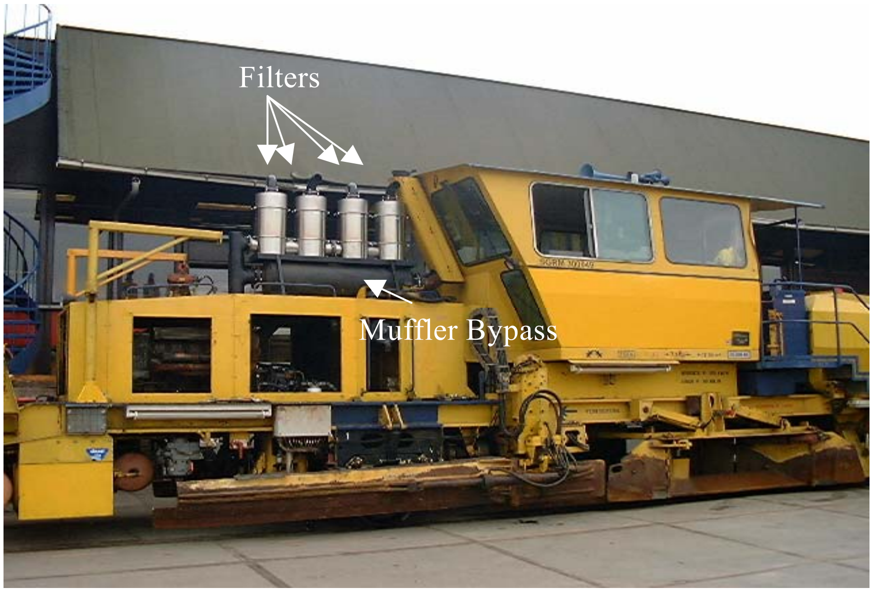


Also, exhaust emission control technology can be designed and integrated on to vehicles to address special operating concerns and environments. For example, where equipment is used in explosive operating environments, such as underground coal mines, emission control technology has been designed to meet special surface temperature requirements. Also, exhaust emission control technologies can and have been installed on vehicles so as not to impair operator visibility.

The examples highlighted above illustrate the feasibility of integrating retrofit exhaust emission control technology onto nonroad vehicles. Integration at the time of manufacture will afford considerable additional opportunities to further simplify and optimize the installation of emission control technology.

Figure 8. A DPF System on a Small Forklift Truck

Figure 9. A Locomotive Grader Equipped with a DPF



An important aspect of vehicle integration is to ensure that the vibration associated with the operation of nonroad vehicles can be withstood to ensure that the systems are indeed durable. A testament to the fact that this can be achieved is the fact that the systems have been used in underground mining applications for years with DOCs having been in service for the life of the vehicle and DPFs having been installed on equipment that has operated for over 15,000 hours in rugged work environments and still provided effective emission reduction performance. SCR systems have also proven durable in nonroad applications.

In a joint government/industry program (Reference 3), an underground field evaluation of diesel particulate filters was undertaken both to determine the effectiveness of DPFs to reduce underground miner workers' exposure to diesel emissions and to learn how to ensure that the technology could be used effectively in a rugged underground environment. Part of the demonstration was to evaluate durability. Two catalyst-based filters were operated in an underground mine for over 4,000 hours and returned to Environment Canada's emissions testing laboratory to determine the filters' performance. The testing was performed over an 8-mode steady state test cycle on a Detroit Diesel Series 50 engine. Their performance was then compared to a new unused filter provided by the same manufacturer. The two filters returned from the mine site averaged a PM emission of 0.01 g/bhp-hr – the same level of control achieved from the new filter. This result confirmed that the two filters having been installed in the mine had undergone very little – if any – deterioration.

The fact that exhaust emission control technologies have been used for many years in nonroad applications and proven to be durable attests to the fact the technologies can withstand the dust and moisture associated with many of the nonroad environments where the technologies have been used.

Experience with Exhaust Emission Control Technologies on Diesel-Powered Nonroad Vehicles and Equipment

Experience with exhaust emission control technologies on nonroad diesel engines and vehicles include diesel particulate filters, oxidation catalysts, and selective catalytic reduction.

Diesel Particulate Filters

Both "active" and "passive" DPFs have been used on diesel-powered nonroad vehicles in a wide variety of applications including:

- mining and tunneling,
- materials handling,
- construction.

Diesel particulate filters have been installed on nonroad equipment since 1986 including mining and construction vehicles, skid steer loaders, forklift trucks, large stationary engines, and others. Over 20,000 active and passive systems have been installed 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. Germany, Austria and Switzerland have established mandatory filter requirements for underground mining and tunneling equipment.

DPFs have been used on engines rated at several hundred horsepower, but also on smaller engines under 75 horsepower with tens of thousands systems having been installed on forklift trucks primarily in Europe since the early 1990s. In fact, filter systems are now being installed by the original equipment manufacturers. Many of the systems on the smaller engines are regenerated actively either offboard or onboard with electrical burners because of the low exhaust gas temperatures associated with the vehicle's operation.

Diesel Oxidation Catalysts

In the nonroad sector, oxidation catalysts have been installed on diesel vehicles 1986 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 and other types of nonroad equipment have been equipped as well. The technology has been used on engines >75 hp and engines >750 hp. PM emissions, as well as CO and HC emission reductions, are targeted in these 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.

Selective Catalytic Reduction

SCR systems have also been installed on marine vessels and locomotives. Over 20 marine vessels have been equipped with SCR. 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. Recently, the Swedish company SCA Graphic Paper announced it will equip its fleet of vessels with SCR technology to reduce NOx emissions by 90 percent.

Reducing Emissions from Nonroad Diesel Engines – Opportunities and Challenges

Applying exhaust emission control technology to future nonroad engines offers many very good opportunities, but also some challenges exist.

For all exhaust control technologies, reducing engine-out emissions will be an important step in controlling emissions from nonroad diesel vehicles and equipment. Many of the engine advances that either have been developed or are being developed for onroad highway vehicles should be readily transferable to similarly sized nonroad engines. Smaller diesel engines will need to employ improved fuel systems and achieve better oil consumption characteristics.

Diesel Particulate Filters

DPFs are proven to provide very high emissions reductions and to be durable. The technology as it exists today is applicable to many nonroad applications already. However, to make it applicable to all nonroad applications, active regeneration technology will be required. The types of regeneration technologies and strategies being developed for onroad vehicles will likely be used in the nonroad sector. Also, as noted above, other regeneration strategies have been successfully applied to nonroad engine applications. Other areas being investigated to facilitate the use of DPFs on nonroad diesel vehicles include improved catalyst formulations and size reduction.

Diesel Oxidation Catalysts

Like DPFs, DOCs are a proven technology. They can be applied to all nonroad diesel engine applications today to provide low cost emissions control. Although, currently, DOCs provide only modest PM emission reductions, improved substrate and catalyst formulations may provide higher reductions in the future. The availability of <15 ppm sulfur diesel fuel will further enhance the emission control performance of DOCs.

NOx Adsorbers

The fundamental concept behind NOx adsorber technology is applicable to all diesel engines. The technology also provides very high reductions in NOx emissions. In order for the technology to be used in nonroad applications, the engine controls required to modulate diesel engines between rich and lean operation and to allow for desulfurization will need to be applied to nonroad engines. Again, this technology will be transferable to nonroad diesel engines. Improved catalyst formulations and size reduction are being developed by manufacturers for onroad vehicle applications. These advances would also facilitate the use on NOx adsorbers in the nonroad sector.

Selective Catalytic Reduction

In order for SCR to find widespread use on nonroad vehicles, appropriate injection hardware and control algorithms need to be developed. These are engineering challenges that can be addressed.

Lean NOx Catalysts

Lean NOx catalysts can be used on all nonroad diesel engines for modest NOx emissions reductions.

Crankcase Emission Control

Technology exists to control crankcase emissions from all nonroad, turbocharged diesel engines.

Conclusion

A wide variety of vehicle compatible exhaust emission control systems have been used in nonroad vehicles for over thirty years. The technologies have evolved from targeting just CO and HC emissions to systems that also reduce PM and NOx emissions. Technologies such as DPFs and NOx adsorbers are currently being developed and optimized for onroad HDDEs and the experience gained will facilitate the application of these technologies to nonroad diesel engines. Special challenges exist in applying some technologies to the smaller nonroad diesel engines, but these are engineering challenges that with time can be addressed. The prospects for significantly reducing emissions from nonroad vehicles and equipment in the years ahead are excellent and exhaust emission controls can and will play an important role. Low (<15 ppm) sulfur diesel fuel will be required to ensure high performance, reliable, and durable operation of all catalyst-based exhaust emission control technologies.

References

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