# Emission Control Retrofit of Diesel-Fueled Vehicles

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# Emission Control Retrofit of Diesel-Fueled Vehicles

## EXECUTIVE SUMMARY

Recently, MECA has received numerous inquiries regarding the possibility of retrofitting emission control technologies on existing diesel engines. These inquiries have included requests for technical information, past experience with retrofit, and information on the impact of fuel sulfur on emission control retrofit technologies. This document has been prepared to supplement information already made available by MECA on retrofit control technologies and to summarize our recommendations regarding the issue of sulfur in diesel fuel. As new information becomes available, this document will be updated periodically.

*Available Control Technologies*

Retrofit of diesel oxidation catalysts has been taking place for well over twenty years in the nonroad vehicle sector — in particular, in the underground mining and materials handling industries where over 250,000 catalysts have been installed. In these applications, fuel sulfur levels of 0.25% wt are not uncommon. More recently, over 10,000 oxidation catalysts have been retrofitted to urban bus engines as part of the U.S. Environmental Protection Agency's urban bus rebuild/retrofit program and since 1995, over 1,000 systems have been retrofitted to highway trucks. The State of New Jersey plans to retrofit 10,000 state-owned diesel vehicles with oxidation catalysts and the Central Artery/Tunnel Construction Project in Boston announced plans to equip construction equipment with oxidation catalysts. In these latter applications, fuel sulfur levels under 0.05% wt exist. Oxidation catalyst equipped on an engine fueled with sulfur levels at or below 0.05% sulfur have achieved PM reductions of 20 to 50% for particulate matter (PM), as well as 60% to 90% reductions for hydrocarbons (HC) (including those HC species considered toxic), and carbon monoxide (CO).

Over 1000 buses have been retrofitted with oxidation catalysts in London, England and over 1,500 oxidation catalysts have been retrofitted on trucks and buses in Sweden.

Development and commercialization of a number of second-generation diesel particulate filter systems capable of an 80 percent to greater than 90 percent PM emission reduction are underway. In Europe, diesel vehicles retrofitted with filters are being offered commercially on a limited scale. Sweden's Clean Cities Program has resulted in the commercial introduction of filters on urban buses. Over 3000 buses have been equipped with a passive filter system with some of the buses having accumulated in excess of 250,000 miles. Sweden's very low (<0.005% wt) fuel sulfur levels enable this technology to perform as designed. Diesel particulate filters have also been retrofitted on heavy-duty vehicles in Great Britain, Germany, Finland, Denmark, and France.

Filter retrofit demonstration programs are currently being carried out in South Korea and Taiwan. In Taiwan, hundreds of buses have been equipped with different retrofit technologies including both catalysts and filter systems. Taiwan has plans to expand the demonstration to evaluate thirteen different retrofit technologies on ten buses each with a minimum mileage accumulation of 10,000 km and up to 50,000 km. The buses were initially fueled with diesel fuel containing 0.15% wt sulfur. The sulfur level in the fuel was subsequently reduced to 0.10 %. In Korea, over 200 filter systems were evaluated on truck and buses. The systems were evaluated for 50,000 km on the city buses and 20,000 km on the trucks with 0.3% wt sulfur in the diesel fuel.

Recent work on off-road diesel vehicles in a Swiss tunneling project has shown that retrofitted diesel particulate filters not only substantially reduce PM mass emissions, but also significantly reduce the number of fine particles emitted. Fine particles are suspected to pose serious health concerns as they travel deeper into the lung when inhaled.

Selective catalytic reduction (SCR) using urea as a reducing agent has also been retrofitted to diesel-powered vehicles providing simultaneous reductions of NOx (75 to 90%), HC (50 to 90%), and PM (30 to 50%) emissions. Nonroad diesel engines found on marine vessels and locomotives have also been retrofitted. Currently, over forty diesel engines have been retrofitted with SCR with several highway trucks having operated over 30 months and have accumulated over 200,000 miles.

Air enhancement technologies that have been developed in the last few years. For example, electronic superchargers, have successfully demonstrated simultaneous reductions of PM (20 – 40%), CO (30 – 65%) and visible smoke (25 – 90%). Notably, these systems concurrently improve vehicle performance and have no penalties on fuel efficiency. A stand-alone electronic supercharger has been granted Universal Exemption by the California Air Resources Board for virtually all heavy-duty mechanical unit injection (MUI) diesel engines. The technology is being commercially used in daily operations in refuse trucks, transit buses, line haulers and water tankers in the U.S. and worldwide. In 1998, a 0.10 g/bhp-hr PM kit with a combined electronic supercharger and oxidation catalyst was certified under the EPA's urban bus retrofit/ rebuild program and has so far been retrofitted on more than 250 urban bus engines, accumulating over 5 million miles of operation. In the combined system, the electronic supercharger, which exhibits minimal degradation, enhances the performance of the catalytic converter. The system also reduces visible smoke.

New systems which combine catalyst, filters, air enhancement technologies, and engine adjustments and components also are emerging and can be used for retrofit on diesel vehicles. One such technology has demonstrated over a 40 percent $NO_x$ 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-born catalyst filter system in combination with exhaust gas recirculation (EGR). A third system which provides substantial PM emission reductions and has recently 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.

*Emission Control Retrofit Programs*

Although technological solutions exist to reduce emissions from in-use diesel engines, care must be given to properly structuring a retrofit control program to insure that these benefits are truly realized. The successful operation of a diesel emission retrofit control program depends on a number of elements. The program should define: 1) which vehicles are suitable for retrofit; 2) which technologies are suitable for retrofitting and the achievable emissions reductions — in the case where it is not known, what data would be required for the verification of the technologies suitability and the achievable reductions; 3) the training and education needs of the vehicle operators and public; and 4) the degree to which incentives or regulations are required to encourage or regulate the use of retrofit control technologies.

Furthermore, when retrofitting emission control technologies to existing vehicles, several factors should be considered regarding both the vehicle to be retrofitted and the quality of the fuel to be used. These considerations may impact the ultimate selection of the appropriate technology. The targeted emission reduction will also play an important role. For optimum results, the existing engine should be rebuilt to manufacturer's specifications before the catalyst, filter system, or other system is retrofitted on the engine. These considerations include:

— fuel quality,
— vehicle maintenance, and
— the vehicle and engine application.

*Conclusions*

Although diesel emissions from mobile sources have raised health and welfare concerns, a number of promising control strategies exist or are being developed that can greatly reduce emissions from diesel-powered motor vehicles. Retrofitting of diesel oxidation catalysts, diesel particulate filters, selective catalytic reduction, engine component and management devices, and air enhancement technologies both onroad and nonroad vehicles has been successfully accomplished and offers an opportunity to greatly reduce a significant source of particulate emissions and other pollutants as well. In conclusion:

- Oxidation catalyst technology can substantially reduce particulate, HC, smoke, and odor from diesel engines, and improvements in oxidation catalyst technology continue to evolve to further enhance the application of this technology to diesel engines.

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

- Filter technology can reduce harmful particulate emissions by up to 90 percent or more, as well as substantially reduce smoke.

- Air enhancement technologies can be used to reduce emissions of PM, CO, and smoke. They can also be used to enhance the performance of other retrofit controls such as oxidation catalysts.

- Both oxidation catalysts and filters can be used in conjunction with engine management techniques, e.g., injection timing retard or EGR, to reduce diesel particulate and $NO_x$ emissions.

- Several oxidation catalysts systems have been approved under U.S. EPA's urban bus rebuild/retrofit program along with three 0.1 g/bhp-hr systems. Another 0.1 g/bhp-hr system has been submitted for certification approval.

- For oxidation catalyst retrofit applications, fuel sulfur levels below 0.05% wt are desirable, but not required. Lower fuel sulfur levels increases the PM reductions provided and makes vehicle integration simpler. However, levels of 0.25% wt and higher have been effectively controlled by catalyst retrofit systems employing new catalyst formulations.

- Both filter and SCR technologies have been used to control diesel emissions at fuel sulfur levels in the 0.5% wt range.

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

- Properly maintained vehicles will insure that retrofit control technology performs at its designed performance level and that the technology will perform problem-free.

# Emission Control Retrofit of Diesel-Fueled Vehicles

## 1.0 INTRODUCTION

Complaints about diesel smoke from trucks and buses have plagued city officials for years, and over the past decade air quality officials have expressed a growing concern over the health effects of diesel emissions. A study by Small and Kazimi of the University of California Irvine published in 1995 analyzed the economic benefits of reducing diesel NOx and PM emissions based on health benefits alone. The study focused on the diesel fleet in Los Angeles in 1992. The authors concluded that a 50% reduction in these emissions would result in a health benefit of $13,500 for PM emissions and $9,200 for NOx emissions over the life of each vehicles. Increasing the reduction to 90% for both pollutants increases the benefit to $24,300 and $16,600, respectively. It is important to note that these economic benefits are based solely on the health benefits of decreasing the emissions. Visibility and building soiling were not included.

Despite the continued complaints, increased health concerns, and the costs associated with the health effects of diesel emissions, the diesel engine remains a popular form of power for trucks and buses. Indeed, most buses and heavy-duty trucks are powered by diesel engines and for good reasons: they are reliable, fuel efficient, easy to repair, and inexpensive to operate. Perhaps most impressive is the durability of the diesel engine. It is not uncommon for diesel engines to have a life of 1,000,000 miles in heavy-duty trucks or to power city buses for up to 15-20 years.

A number of countries worldwide have established emission limits for new diesel engines. However, because of the durability of the diesel engine, even in these countries older, uncontrolled diesel vehicles make up a significant portion of the heavy-duty vehicle fleet. Consequently, a growing interest in cleaning up these older, uncontrolled vehicles has occurred, especially in urban centers where diesel emissions contribute significantly to particulate, toxic HC, and NOx pollution. For example in midtown Manhattan in New York City, diesel vehicles are responsible for over 50% of the PM10 inventories.

**Diesel particulates** are small (less than 2.5 microns) and complex substances. Particulate consists of an uncombusted carbon core, adsorbed hydrocarbons from engine oil and fuel, adsorbed sulfates, water, and inorganic materials such as those produced by internal engine abrasion.

Diesel particulates, because of their chemical composition and extremely small size, have raised a host of health and welfare issues. Health experts have expressed concern that they contribute to or aggravate chronic lung diseases such as asthma, bronchitis, and emphysema, and there is growing evidence about the potential cancer risk from exposure to diesel particulate. These particles also contain adsorbed toxic hydrocarbons, impair visibility, soil buildings, and contribute to structural damage through corrosion. In addition, diesel exhaust gives off a pungent odor.

A comprehensive assessment of the available health information was carried out by the International Agency For Research on Cancer (IARC) in June 1988. The IARC Working Group 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 addition to the study cited above, a 1993 EPA report, entitled *Motor Vehicle-Related Air Toxics Study*, listed diesel particulate as one of the most serious hazardous pollutants emitted from mobile sources. In August 1998, California's Air Resources Board declared PM emissions from diesel-fueled engines to be a toxic air contaminant. Recent health studies in Europe suggest that the carbon core of diesel particulate emissions also poses a serious health concern.

Currently, considerable efforts are being focused on the health effects of diesel particulate emissions as a function of particle size, number, and size distribution, as well as the investigation of appropriate measurement techniques and methods.

**$NO_x$ emissions** from diesel engines pose a number of health and environmental concerns. Once in the atmosphere, $NO_x$ reacts with volatile organic compounds (VOC) in the presence of sunlight to form ozone. Ozone is corrosive and contributes to many pulmonary function 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. Ozone also can destroy vegetation, reduce crop yield, and damage exposed materials by contributing to cracking, fading, and weathering. $NO_x$ emissions themselves can damage respiratory systems and lower resistance to respiratory infection. As with ozone, children and the elderly are particularly susceptible to $NO_x$ emissions.

## 2.0 AVAILABLE RETROFIT CONTROLS

Several types of retrofit emission controls are available.

First, a *flow-through oxidation catalysts* installed on a vehicle can reduce the soluble organic fraction of the particulate by as much as 90 percent and total particulate by as much as 25 to over 50 percent depending on the composition of the particulate being emitted. Smoke emissions from older vehicles can be reduced by over 50 percent and a catalyst can virtually eliminate the obnoxious odor of diesel exhaust. Furthermore, reductions of 60 percent to 90 percent of CO and HC (including those HC considered to be toxic) emissions can be achieved.

*Diesel particulate filter systems* have also been retrofitted to existing vehicles. In some markets like forklift trucks, simplified higher energy external heat addition systems have been found to be useful and are sold commercially in Europe. Research and development has also resulted in second-generation regeneration systems of less complexity. These systems rely on fuel-born catalysts like cerium, copper, iron, and platinum; catalysts placed in front of the filter; or catalysts coated directly on the filter to initiate the regeneration process. These systems have also been retrofitted on both a commercial and demonstration basis in different areas of the world.

Diesel particulate filters can achieve up to, and in some cases greater than, a 90 percent reduction in particulate. The filter is extremely effective in controlling the carbon fraction of the particulate, which recently has attracted the attention of health experts in Europe as posing a possible serious health threat.

*Selective catalytic reduction (SCR)* using urea as a reducing agent has also 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.

*Air enhancement technologies*, such as *electronic superchargers*, are very effective in reducing the insoluble organic fraction of particulate matter, exhibiting total PM reduction of 20 – 40% and visible smoke reductions of 25 – 90%. Concurrently, they can reduce CO by 30 – 60%.

Catalytic exhaust control and particulate filter technologies have been shown to decrease the levels of polyaromatic hydrocarbons, nitro-polyaromatic hydrocarbons, and mutagenic activity.

In some applications, catalyst and filter technologies can be combined to provide even greater control and can be used in combination 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 $NO_x$.

## 2.1 DIESEL OXIDATION CATALYSTS

The diesel oxidation catalyst has become a leading retrofit control strategy in both the onroad and nonroad sectors throughout the world, reducing not only PM emissions but also emissions of CO and HC. Using oxidation catalysts on diesel-powered vehicles is not a new concept. Oxidation converters have been installed on off-highway vehicles around the world for over 20 years and have been installed on urban buses and highway trucks in Europe and the U.S. for over two years with well over 10,000 units having been installed.

### 2.1.1 Operating Characteristics and Control Capabilities

The concept behind an oxidation catalyst is that it causes chemical reactions without being changed or consumed. An oxidation catalytic converter consists of a stainless steel canister that typically contains a honeycomb-like structure called a substrate or catalyst support. There are no moving parts, just acres of interior surfaces on the substrate coated with catalytic precious metals such as platinum or palladium. It is called an oxidizing catalyst because it transforms pollutants into harmless gases by means of oxidation. In the case of diesel exhaust, the catalyst oxidizes carbon monoxide (CO), gaseous hydrocarbons (HCs), and the liquid hydrocarbons adsorbed on the carbon particles. The liquid hydrocarbons are referred to as the soluble organic fraction (SOF) and make up part of the total particulate matter.

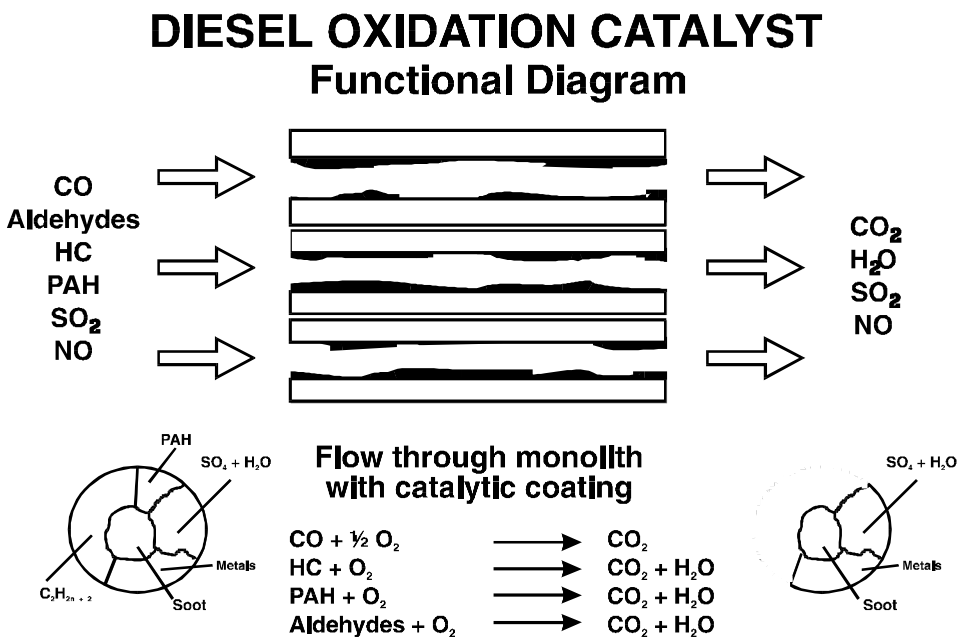
The operating principle of a diesel oxidation catalyst is shown in Figure 1.

The level of total particulate reduction is influenced in part by the percentage of SOF in the particulate. For example, a Society of Automotive Engineers (SAE) Technical Paper (SAE No. 900600) reported that oxidation catalysts could reduce the SOF of the particulate by 90 percent under certain operating conditions, and could reduce total particulate emissions by 40 to 50 percent. 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 are also effective in reducing particulate and smoke emissions on older vehicles. Under the U.S. EPA's urban bus rebuild/retrofit program, five manufacturers have certified diesel oxidation catalysts as providing at least a 25 percent reduction in PM emissions for in-use urban buses. The certification data also indicates substantial reductions in CO and HC emissions. An SAE paper (940235) reported that 120 buses in Argentina retrofitted with oxidation catalysts averaged over a 50 percent reduction in smoke opacity levels during a field demonstration.

Combining an oxidation catalyst with engine management techniques can be used to reduce $NO_x$ emissions from diesel engines. This is achieved by adjusting the engine for low $NO_x$ emissions which is typically accompanied by increased CO, HC, and particulate emissions. An oxidation catalyst can be added to offset these increases, thereby lowering the exhaust levels for all of the pollutants. Often, the increases in CO, HC, and particulate can be reduced to levels

**Figure 1**




lower than otherwise could be achieved. In fact, a system which uses an oxidation catalyst combined with proprietary ceramic engine coatings and injection timing retard to provide over a 40 percent $NO_x$ reduction while maintaining low particulate emissions has been approved under EPA's urban bus rebuild/retrofit program. This same system has also been approved as reducing PM emissions to below 0.1 g/bhp-hr. Also, a system employing catalysts and a propriety cam shaft has also been approved as providing PM emissions below 0.1 g/bhp-hr. A third system using an electronic super charger and an oxidation catalyst has been also been approved as providing PM emissions less than 0.1 g/bhp-hr.

Oxidation catalysts have also been installed on over 1.5 million new heavy-duty highway trucks since 1994 in the U.S. These systems have operated trouble free for hundreds of thousands of miles.

### 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 dependant 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. The low sulfur fuel (0.05% wt) which was introduced in 1993 throughout the U.S. has facilitated the application of catalyst technology to diesel-powered vehicles. Furthermore, the very low fuel sulfur content (<0.005% wt) available in several European countries has further enhanced catalyst performance.

Needless to say, catalysts have also been effectively retrofitted to vehicles which run on fuel containing sulfur levels above 0.05% wt. Typical nonroad retrofit applications reduce PM, HC, and CO emissions when fuel containing 0.25% wt sulfur is used. In some instances, CO and HC emissions have been effectively controlled with sulfur levels as high as 0.5% wt. However, the performance of an oxidation catalyst in the presence of elevated fuel sulfur level is hard to predict since it will vary with catalyst formulation, engine type, and duty cycle.

### 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 $NO_x$ emissions. Retrofitting oxidation catalysts on existing diesel engines is relatively straight-forward. 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 and recently, nearly 20,000 oxidation catalysts have been retrofitted to urban buses and trucks in Europe and the U.S. The earliest installations have accumulated well over 150,000 km and have proven to be virtually maintenance free.

Oxidation catalysts have also been retrofitted in other areas of the world for particulate control. In Mexico, over 3,000 units have been retrofitted to buses and trucks. In the Province of Mendoza, Argentina, 120 buses equipped with Mercedes Benz OM352 engines were retrofitted with catalysts. Over the six-month demonstration period, the buses in Argentina averaged a smoke opacity reduction of over 50 percent. Over 2,000 delivery trucks in Mexico have also been retrofitted with catalysts. Taiwan recently completed the initial phase of retrofit demonstration program which included the successful evaluation of catalyst technology retrofitted to diesel vehicles. Hong Kong has recently embarked on a retrofit program for urban buses where the criteria used is a 25 percent smoke reduction.

On the nonroad side, oxidation catalysts have been retrofitted to diesel vehicles for well over 20 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 retrofitted as well. 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. More recently, Boston's Central Artery/Tunnel Project, the largest highway construction in U.S. history announced plans to retrofit a variety of heavy construction equipment with oxidation catalysts. Also, several large airports in the northeastern U.S. announced plans to retrofit oxidation catalysts on a variety of air ground equipment.

### 2.1.4 Costs

Diesel oxidation catalysts sold into the U.S. as part of the EPA's urban bus rebuild/retrofit program have a life cycle cost of less than $2,300 which includes not only the cost of catalyst unit itself, but also the cost to install the unit on the vehicle and any required maintenance. Projected costs range from $230 to $750 depending on engine size and sales volume. These systems are designed to replace the original muffler on the bus and, as such, not only provide emissions reductions but further provide the appropriate level of noise attenuation and also allow for easy installation — typically, less than 2 hours. The systems installed on highway trucks are slightly higher in cost to account for the larger sizes needed for higher rated engines.

For the systems which use additional technologies to reach the very low 0.1 g/bhp-hr PM emission level which have been certified or for certification under the U.S. EPA's urban bus rebuild/retrofit program, additional costs will be incurred for the purchase and application of ceramic engine coatings, turbochargers, and/or modified cam shafts. Using catalyst technology in combination with modified engine calibrations, e.g., injection timing retard, to reduce NOx emissions will not necessarily add to the cost of the system, but may require additional labor during installation and calibration.

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. Costs of the technology vary accordingly but can range from under $200 for a small in-line unit to $300 to $600 for relatively small muffler replacements units to several thousand dollars for the large units used on the large nonroad vehicles.

## 2.2 DIESEL PARTICULATE FILTERS

### 2.2.1 Operating Characteristics and Performance

The diesel particulate filter system consists of a filter positioned in the exhaust stream designed to collect a significant fraction of the particulate emissions while allowing the exhaust gases to pass through the system. Since the volume of particulate matter generated by a diesel engine is sufficient to fill up and plug a reasonably sized filter over time, some means of disposing of this trapped particulate must be provided. The most promising means of disposal is to burn or oxidize the particulate in the filter, thus regenerating, or cleansing, the filter. However, in nonroad applications there has also been use of a disposal filter system. The disposal filter is sized to collect enough particulate for a working shift or two of operation while remaining within the engine manufacturers backpressure specification and then it is removed and properly disposed.

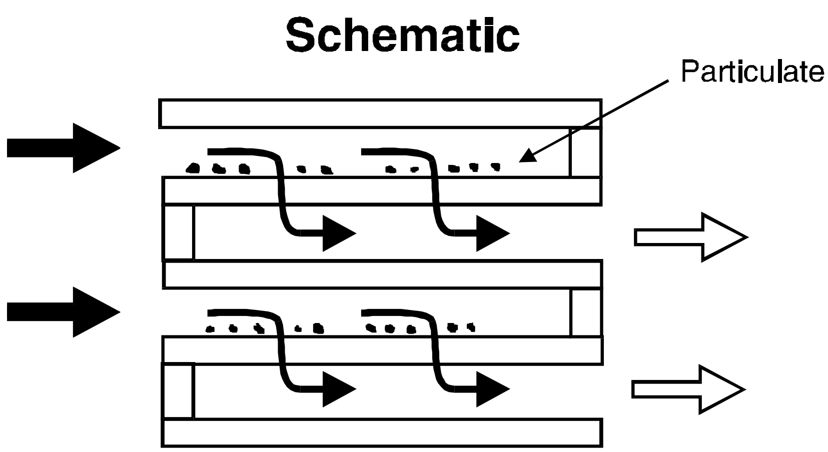
A complete filter system consists of the filter and the means to facilitate the regeneration if not of the disposable type.

Filter Material   A number of filter materials have been tested, including ceramic monoliths and 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 percent to over 90 percent. Currently, the ceramic monoliths, fiber wound cartridges, and paper filters have been used commercially.

All of the technologies function in a similar manner; that is, forcing particulate-laden exhaust gases through a porous media and trapping the particulate matter on the intake side. Excellent filter efficiency has rarely been a problem with the various filter materials listed above, but work has continued with the materials, for example, to: (1) optimize high filter efficiency with accompanying low back pressure, (2) improve the radial flow of oxidation through the filter during regeneration, and (3) improve the mechanical strength of the filter designs. Figure 2 shows an example of the filtration mechanism.

**Figure 2**

**DIESEL PARTICULATE FILTER**




*Particulate-laden diesel exhaust enters the filter, but because the cell of the filter is capped at the opposite end, the exhaust cannot exit out the cell. Instead the exhaust gases pass through the porous walls of the cell. The particulate is trapped on the cell wall. The exhaust gases exit the filter through the adjacent cell.*

Regeneration   The exhaust temperature of diesels is not always sufficient to initiate regeneration in the filter. A number of techniques are available to bring about regeneration of filters. It is not uncommon for some of these various techniques to be used in combination. Some of these methods include:

- Using a catalyst coated on the filter element. The application of a base or precious metal coating applied to the surface of the filter reduces the ignition temperature necessary for oxidation of the particulate;

- Using a NOx conversion catalyst upstream of the filter to facilitate oxidation of NO to $NO_2$ which adsorbs on the collected particulate substantially reducing the temperature required to regenerate the filter;

- Using fuel-born catalysts to reduce the temperature required for ignition of the accumulated material;

- Throttling the air intake to one or more of the cylinders, thereby increasing the exhaust temperature;

- Using fuel burners, electrical heaters, or combustion of atomized fuel by catalyst to heat the incoming exhaust gas to a temperature sufficient to ignite the particulate;

- Using periodically compressed air flowing in the opposite direction of the particulate from the filter into a collection bag which is periodically discarded or burned; and

- Throttling the exhaust gas downstream of the filter. This method consists of a butterfly valve with a small orifice in it. The valve restricts the exhaust gas flow, adding back pressure to the engine, thereby causing the temperature of the exhaust gas to rise and initiating combustion.

Diesel particulate filter system are being optimized for the particular application to insure that any adverse effects of the system on engine or vehicle performance are minimized or completely eliminated.

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. The low sulfur fuel (0.05% wt) currently available in the U.S. has greatly facilitated these efforts, although many other filter systems have operated successfully when used with higher fuel sulfur levels. Many of the systems used in the nonroad sector operate with fuel containing 0.25% wt sulfur and possibly as high as 0.5% wt sulfur fuel.

Diesel particulate filter systems, which replace mufflers in retrofit applications, have achieved sound attenuation equal to a standard muffler.

A very slight fuel economy penalty has been experienced with diesel particulate filter technology which is attributable to the back pressure of the system. Some forms of regeneration involve the use of diesel fuel burners, and to the extent those methods are used, there will be an additional consumption of fuel. It is expected that the systems can be optimized to minimize, or in some cases possibly eliminate, any noticeable fuel economy penalty. For example, in a demonstration program in Athens, no noticeable fuel penalty was recorded when the filter was regenerated with a cerium fuel-born catalyst (SAE 920363).

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. Various filter systems have been designed so that driveability should not be affected, or at least effects can be minimized, most notably by limiting back pressure.

### 2.2.2 Operating Experience

Diesel particulate filter retrofit demonstration programs began in the 1980s and culminated in the early 1990's with the installation of almost 2,000 first generation systems in New York City on urban buses. The complexity of these first generation systems made reliability an issue which prompted manufacturers to develop the less complex more reliable systems mentioned above.

Development and commercialization of a number of second-generation filter systems capable of an 80 percent to greater than 90 percent PM emission reduction is now underway. In Europe, diesel vehicles retrofitted with filters are being offered commercially. Sweden's Clean Cities program has resulted in the commercial introduction of diesel particulate filters on urban buses. Over 3,000 buses have been equipped with a passive filter system with some of the buses having accumulate in excess of 250,000 miles. Sweden's very low (<0.005% wt) fuel sulfur levels enables this technology to perform as designed. Buses and trucks are also being retrofitted with filters in Great Britain where low sulfur (<0.005% wt) fuel is available. Filters are also being retrofitted on heavy-duty vehicles in Finland, Denmark, Germany, and France.

Retrofit demonstration programs are currently being carried out in South Korea and Taiwan. In Taiwan, over hundreds of buses have been equipped with ten different retrofit technologies including both catalysts and filter systems. In Korea, over 200 filter systems were evaluated on truck and buses. The systems were evaluated for 50,000 km on the city buses and 20,000 km on the trucks initially with 0.15% wt sulfur in the diesel fuel. The fuel sulfur level subsequently changed to 0.10% wt.

Diesel particulate filters have been commercially retrofitted to nonroad equipment since 1986 and currently, over 2,500 systems have been retrofitted and are in operation worldwide with some of the systems having operated for over 15,000 hours or over 5 years and are still in use. The types of equipment include, mining equipment, material handling equipment such as forklift trucks, street sweepers and utility vehicles. Catalyzed filter systems, systems using fuel borne catalysts to facilitate regeneration and systems which are regenerated using factory shore power are in use in the nonroad sector.

Germany and Austria have established mandatory filter retrofit requirements for underground mining equipment. Switzerland is expected to impose a similar requirement later this year.

### 2.2.3 Costs

The cost of filter systems varies depending on the application, but is typically in the $30 to $50 per hp range. The costs would be expected to decline as production volumes increase. Costs in the range of $600 to approximately $2,000 per vehicle are anticipated depending on the given technology and application.

## 2.3 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 mobile sources including trucks, marine vessels, and locomotives. Applying SCR to diesel-powered vehicles provides simultaneous reductions of NOx, PM, and HC emissions.

### 2.3.1 Operating Characteristics and Control Capabilities

Like an oxidation catalyst, SCR causes chemical reactions without being changed or consumed. However, unlike oxidation catalysts, a reductant is added to the exhaust stream in order to convert NOx to nitrogen and oxygen in an oxidizing environment. The reductant can be ammonia but in mobile source applications, urea is normally preferred. The reductant is added at a rate calculated from an algorithm which estimates the amount of NOx present in the exhaust stream as a function of the engine operating conditions, e.g., vehicle speed and load. As the exhaust gases along with the reductant pass over a catalyst applied to either a ceramic or metallic substrate, 75 to 90% of NOx emissions, 50 to 90% of HC emissions, and 30 to 50% of PM emissions are reduced. SCR also reduces the characteristic odor produced by a diesel engine and the diesel smoke.

The catalyst composition of SCR and its mode of operation are such that the formation of sulfate particulate matter because of elevated fuel sulfur levels is not very significant. Even at temperatures in excess of 500 $^{o}$C, only 5% of the sulfur in the fuel would be converted to sulphate which still allows for significant net PM emission reductions. Many of the systems in operation today are on sources which are powered by diesel fuel containing 0.3% sulfur by wt.

### 2.3.2 Operating Experience

SCR is currently being used on both onroad and nonroad vehicles. Applications include trucks, marine vessels, and locomotives with over 40 units installed. Highway trucks were first tested with SCR systems in 1994 and currently 12 trucks are being demonstrated in Europe with several vehicles having accumulated over 200,000 miles. The trucks range from 40 hp to 400 hp and the systems have been operating effectively throughout the demonstration.

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 that it will equip its fleet of vessels with SCR technology to reduce NOx emissions by 90 percent.

#### 2.3.3 Costs

SCR costs vary depending on the size of the diesel engines. The cost of a SCR system for a truck or bus, because this is a new application for the technology, is difficult to estimate at this time. However, manufacturers are targeting a cost in the range of $2,500.

### 2.4 AIR ENHANCEMENT TECHNOLOGIES

Electronic supercharger systems monitor the demand for power and instantly supply additional air to the engine during transient increases in engine load. As a result, more oxygen is available for optimized combustion, reduced emissions (PM, CO, smoke) and enhanced engine performance.

#### 2.4.1 Operating Characteristics and Performance

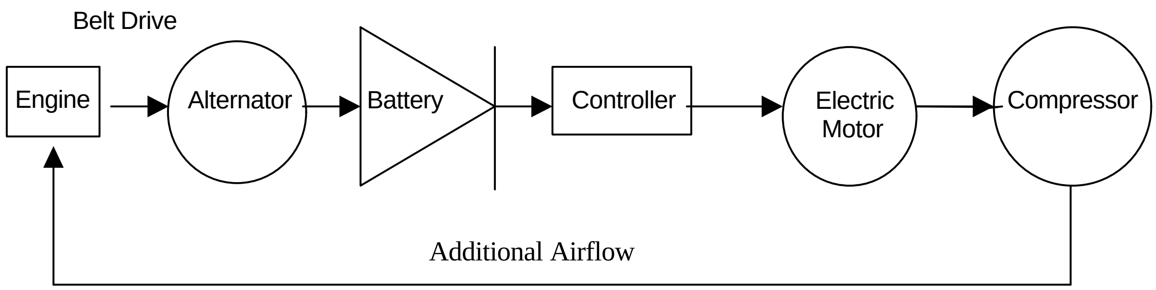
During acceleration and stop-and-go traffic, heavy-duty diesel engines often have too much fuel and not enough air, resulting in a fuel rich mixture. The fuel rich mixture promotes unburned pollutant emissions in the form of hydrocarbons, carbon monoxide, particulate matter and smoke. These pollutants are in fact wasted fuel, which, due to oxygen starvation, have not had a chance to contribute their thermal energy fully to the combustion process. Wasted fuel also results in reduced efficiency and performance gaps.

In turbocharged engines, this performance gap is termed “turbolag.” Turbolag occurs during initial acceleration when the flow of exhaust gases is insufficient to power the turbocharger, leading to a lag in the amount of air flow to the engine. As a result, engine power is compromised because several seconds may elapse before the turbocharger accelerates to operating speed. Also, a disproportionate amount of emissions occur during the turbolag period.

To address the above issues, an electronic supercharger system can be utilized to provide instantaneous boost, promote optimum combustion and prevent the over-enrichment of the engine during transients. As a result, emissions of PM, CO and visible smoke are significantly reduced, engine oil becomes cleaner, low-end torque is enhanced and (in turbocharged vehicles) turbolag is eliminated.

An electronic supercharger consists of an electric motor, a centrifugal compressor, an electronic controller and sensors for vehicle interface. In essence, the electronic supercharger uses an electric motor to replace the exhaust turbine side of a turbocharger.

The electric motor is connected to an electronic controller that interfaces with the vehicle’s battery and remote sensors (accelerator pedal sensor, pressure switches, etc.). As the “brain” of the electronic supercharger, the controller receives input for increased airflow via sensors and provides modulated power to the electric motor. The electric motor spins the compressor to more than 40,000 rpm in a quarter of a second, which is significantly faster start-up compared to typical turbochargers, resulting in instantaneous increased airflow to the engine. A simplified system block diagram of this is shown in the Figure below.




**Airflow Enhancement System Block Diagram**
**Using Electronic Supercharger**

Depending on the configuration, an electronic supercharger can have a compound effect on turbocharged engines by providing additional air through the turbine of the engine turbocharger, causing the turbocharger to accelerate more rapidly.

Since an electronic supercharger operates only when needed, for short periods and at an overall low duty cycle, it is not taxing on a healthy vehicle electrical system.

### 2.4.2 Operating Experience

Electronic supercharger systems have been tested in independent laboratories, including the Southwest Research Institute and the Clean Air Vehicle Technology Center at its California Truck Testing Service (CaTTS) facility. Additional testing has been conducted at the University of Marseille, France as part of a French governmental evaluation program. Under the EPA's urban bus retrofit/rebuild program, a kit with an electronic supercharger and oxidation catalyst has been installed on over 250 buses in various transit agencies across the United States. Stand-alone electronic superchargers have been installed and are successfully operating on refuse trucks, transit buses, line haulers and water tankers in the U.S., Canada, Mexico, England, Germany, France, Russia, Brazil and New Zealand.

### 2.4.3 Costs

The costs of electronic superchargers vary depending on the system air flow requirements. Since the electronic supercharger is a relatively new technology, current prices for medium and heavy-duty applications range from around $3000 to $4000. However, once mass production commences, manufacturers are targeting a cost of $1500 to $2000.

## 3.0 OPERATING A DIESEL EMISSION RETROFIT CONTROL PROGRAM

The successful operation of a diesel emission retrofit control program depends on a number of elements. The program should define: 1) which vehicles are suitable for retrofit; 2) which technologies are suitable for retrofitting and the achievable emissions reductions — in the case where it is not known, what data would be required for the verification of the technologies suitability and the achievable reductions; 3) the training and education needs of the vehicle operators and public; and 4) the degree to which incentives or regulations are required to encourage or regulate the use of retrofit control technologies.

Two highly successful retrofit programs are currently operating in the world— the U.S. EPA's Urban Bus Retrofit/Rebuild Program and Sweden's Clean Cities Program.

The U.S. program affects all major urban areas in the United States and requires that at the time of engine rebuild, certified retrofit emission control technology or certified engine rebuild kits that provide a 25% reduction in PM emissions be installed on the urban bus providing a cost cap is met. If a technology has been certified to meet a 0.1 g/bhp-hr PM emission limit for an engine, then the transit authority must install this retrofit technology at the time of rebuild — again, provided that a cost cap is met. The transit operators also have the ability to use a fleet average emission limit where a combination of using certified retrofit technologies and certified engine rebuild kits, repowering with new cleaner engines, or retiring old buses can be used.

The Swedish program affects the three largest cities in that country -- Stockholm, Goteborg, and Malmo. Beginning in July 1996, in order for a heavy-duty diesel vehicle to be operated in the downtown areas it was required to meet EURO 2 emissions standards. However, older vehicles were exempted from the restriction if they were equipped with an approved retrofit emissions control device. Both oxidation catalysts and diesel particular filters have been retrofitted under this program.

The U.S. EPA recently announced the creation of a voluntary retrofit program for heavy-duty vehicles not covered by the federal Urban Bus Retrofit Program. 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. The EPA program sets up a protocol for calculating credits, the structure of a third-party verification system for approving retrofit technologies and an-use testing requirements to ensure that the emission reduction credits claimed are achieved in the field. Information regarding the EPA voluntary retrofit program can be found at http://www.epa.gov/oms/transp/vmweb/vmhvydty.htm.

## 3.1 VEHICLE SELECTION

Although in theory retrofit control technologies can be applied to any vehicle, it may be easier to administer and control a program by targeting vehicle fleets. Some examples of captured fleets include urban bus fleets, privately owned delivery fleets, publicly and privately owned construction equipment, publicly owned diesel- powered vehicles, and construction equipment at a given construction site. The advantages 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 OPTIONS

A variety of retrofit control technologies are available for use in a retrofit control program and these are discussed in detail in Section 4.0. 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 provide reductions in NOx emissions as well.

Different technologies can also result in different levels of control. Some technologies can offer very high reductions in some applications whereas more modest reductions may be offered by other technologies with broader application.

Costs of the different technologies should also be considered.

The applicability of the different retrofit control technologies should also be considered. Some technologies can be universally applied, such as oxidation catalysts, while others may be application specific, such as a diesel particulate filter system which requires a certain exhaust gas temperature to regenerate. In the instances where the technology is application specific, it should be insured that the application is suitable.

It is also important to insure 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. One possibility would be to accept the certifications of technologies already certified under EPA's urban bus program or Sweden's Clean Cities Program. In the case where the technology has not been certified under one of these programs, the same type of data should be required.

### 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 will not only enhance the success of the program, but will also insure acceptance of the concept.

Both vehicle operators and maintenance personnel should be trained on how a particular retrofit control device operates and any specialized maintenance that may be required. Any specialized lubricating oil requirements should also be outline, as well as any other item which is not associated with the normal operation of the vehicle.

### 3.4 INCENTIVES AND REGULATIONS

Incentives can also be used to encourage the use of retrofit control technologies. Such incentives could 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.

Also, it has been suggested that retrofitted vehicles could be required for any publicly funded construction project in urban areas.

## 4.0 TECHNICAL ISSUES TO BE CONSIDERED WHEN RETROFITTING CONTROLS

When retrofitting emission control technologies to existing vehicles, several factors should be considered regarding both the vehicle to be retrofitted and the quality of the fuel to be used. These considerations may impact the ultimate selection of the appropriate technology. The targeted emission reduction will also play an important role. For optimum results, the existing engine should be rebuilt to manufacturer's specifications before the catalyst or filter system is retrofitted on the engine. These considerations include:

— fuel quality,
— vehicle maintenance, and
— the vehicle and engine application.

## 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 insuring the use of low sulfur fuel or placing the catalyst in the exhaust stream where the temperature of the gases can be used to minimize sulfation but still allow for emissions reductions. This may require some knowledge of the vehicle's duty cycle but has been successfully accomplished in the past.

In general, diesel fuel with low sulfur (0.05% wt or less) is recommended, but not necessarily required. Vehicles fueled by fuel containing higher sulfur levels have been successfully retrofitted with control technology. Nonetheless, lower sulfur levels broaden the range of available retrofit control technologies which can be used and in many instances, allows for maximum emissions reductions. Some retrofit control technologies, e.g., the filter system which employs a catalyst to convert NO to $NO_2$ for regeneration, requires very low sulfur fuel of less than 0.005% wt. These low sulfur containing fuels enhance the performance of this type of technology.

Although sulfur levels of 0.05% wt or less are recommended and allow for the effective utilization of retrofit emission control technologies, even lower levels (<0.005 % wt) allow for the use of a broader range of technologies and also allow for significantly improved emission reductions for those technologies that can be used with higher fuel sulfur levels. In any case, diesel engines powered with fuel sulfur levels in the range of 0.25% wt have been and will continue to be effectively controlled by retrofit control technology. If proper consideration is given to catalyst formulation, the duty cycle of the engine and the engine type, and catalyst placement in the exhaust stream, CO and HC emissions can be effectively controlled on engines powered by fuel containing levels of sulfur as high as 0.5% wt. Filter and SCR technologies have also shown that PM emissions can be controlled effectively at these elevated sulfur levels. SCR is also effective in controlling NOx along with CO and HC emissions at elevated sulfur levels.

## 4.2 IMPORTANCE OF VEHICLE MAINTENANCE

Exhaust emission controls are not a substitute for a well maintained and operated diesel engine. Engines equipped with retrofit control technology should receive routine maintenance. With particularly dirty engines, periodic removal or cleaning of a catalyst, in the case of diesel oxidation catalysts and SCR systems, should be considered and for those engines equipped with filter technology, back pressure should be monitored and if excessively high, the filter should be cleaned. However, in the case of catalysts and SCR, employing larger cells, e.g., 50 to 200 cells per square inch (cpsi), can considerably minimize the risk of plugging and fouling. Prime candidates for the use of retrofit emission control technologies are fleet-operated vehicles when preventative maintenance programs are often in place.

## 4.3 MATCHING RETROFIT TO ENGINE APPLICATION

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

- engine size and backpressure specification,
- engine duty-cycle and resultant exhaust gas temperatures,
- fuel sulfur level,
- desired emission reductions, and
- vehicle integration.

All 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 some retrofit control technologies as discussed above.

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 units, and others.

## 5.0 CONCLUSIONS

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

- Retrofit application of diesel oxidation catalysts, diesel particulate filters, and selective catalytic reduction for both onroad and nonroad vehicles have been successfully accomplished and offers an opportunity to greatly reduce a significant source of particulate emissions and other pollutants as well.

- Oxidation catalyst technology can substantially reduce particulate, HC (including toxic emissions), smoke, and odor from diesel engines, and improvements in oxidation catalyst technology continue to evolve to further enhance the application of this technology to diesel engines.

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

- Diesel particulate filter technology can reduce harmful particulate emissions by up to 90 percent or more, as well as substantially reduce HC (including toxic emissions), CO, and smoke.

- Air enhancement technologies can be used to reduce emissions of PM, CO, and smoke. They can also be used to enhance the performance of other retrofit controls such as oxidation catalysts.

- Both oxidation catalysts and particulate filters can be used in conjunction with engine management techniques, e.g., injection timing retard or EGR, to simultaneously reduce diesel particulate and $NO_x$ emissions.

- Several oxidation catalysts systems have been approved under U.S. EPA's urban bus rebuild/retrofit program along with three 0.1 g/bhp-hr systems. Another 0.1 g/bhp-hr system has been submitted for certification approval.

- For oxidation catalyst retrofit applications, fuel sulfur levels below 0.05% wt are desirable, but not required. Lower fuel sulfur levels increases the PM reductions provided and makes vehicle integration simpler. However, levels of 0.25% wt and higher have been effectively controlled by catalyst retrofit systems employing new catalyst formulations.

- Both filter and SCR technologies have been used to control diesel emissions at fuel sulfur levels in the 0.5% wt range.When selecting a retrofit control technology, it is important to insure that the technology is compatible with the duty cycle of the vehicle and the desired emissions reductions.

- Properly maintained vehicles will insure that retrofit control technology performs at its designed performance level and that the technology will perform problem-free.