# In Use Diesel Vehicle Control Options

## 1. Re-Engining

Substantial emissions benefits can be obtained by repowering older vehicles (equipped with high emitting diesel engines) with the latest low emissions diesel technology. Heavy-duty engines are typically overhauled and rebuilt several times over the life of the vehicle, at a cost of $4000 to $8000 or more, depending on the size and the circumstances. Instead of rebuilding the existing engine, in many cases it would be possible to replace it with a new diesel engine meeting current standards.

The United States (US) and the European Union (EU) are introducing successively tighter emission standards for diesel trucks and buses. The potential of emission control devices to reduce pollutant emissions depends on a number of factors, including the type of technology used, whether or not low sulfur diesel is used, and whether adequate inspection and maintenance is carried out.

Compliance with the Euro I standards generally required modest changes in engine design to minimize particulate emissions, as well as improvements to the fuel injection system. Compliance with the Euro 2 standards is somewhat more difficult, generally requiring the use of turbochargers and aftercoolers as well as high-pressure fuel injection - sometimes with computer electronic control of the fuel injection timing. However, the turbocharger and aftercooler should also help to reduce fuel consumption by about 10%. Meeting the U.S. 1998 and/or Euro 3 standards will require further improvements in fuel injection and electronic engine control systems. The incremental cost compared to the Euro 2 standard can be US $1,000 to $1500. These numbers do not reflect the cost of producing diesel fuel with lower sulfur content, which would be a prerequisite for gaining the full emissions reduction benefits of using Euro 3 engines. In Europe, Euro 4 engines will be introduced in 2005 and Euro 5 in 2008; these engines and associated pollution control technologies will require very low sulfur fuel – in some cases as low as 10 PPM maximum.

An approximate estimate of the incremental costs of complying with different engine standards is provided in the table below. It should be noted that the typical experience has been that over time these costs tend to come down as manufacturers become more proficient in designing their engines and as economies of scale take effect.

| Emissions Standards | Estimated Approximate Costs – US$ |
|---|---|
| Euro 1 | 500$ |
| Euro 2 | 2500$ |
| Euro 3 | 3500$ |
| Euro 4 | 4000$ |

|  |  |
|---|---|
| Euro 5 | 7000$ |

Further costs that have to be taken into account include those for inspection and maintenance, fuel economy penalty (or gain) and low sulfur fuel. The actual emerging costs will be a function of the individual applications and situations. The US EPA estimated the additional cost for low sulfur fuel (15 PPM maximum compared to 500 PPM maximum) at 4 - 5 cents per gallon.

## 2. Retrofit

The term retrofit is defined here as the adjustment of emissions to a level below that of a vehicle's original levels. Although traditionally this concept has been related to the installation of after treatment emissions control systems in vehicles already in use, as is the case with oxidation catalytic converters and particulate filters, it is currently being used in a wider sense. The definition now covers any actions not foreseen in the original vehicle or engine design that are meant to reduce pollutant emissions. We can thus characterize "retrofit" actions within the following range:

- after treatment of exhaust-pipe emissions
- crankcase emissions filtering
- limiting engine operation at idle speed when the vehicle is stopped for long periods of time
- replacing engine and injection pump components with ones that reduce emissions
- replacing the vehicle or engine with a new one, an adapted one, or one that runs on bi-fuels or alternative fuels, with lower emissions
- using cleaner fuels

Retrofit measures are usually adopted as part of programs designed to substantially reduce diesel vehicles' contributions to air pollution, and they target fleets that, due to the nature of their design or usage, represent a significant portion of pollutant emissions. Urban bus fleets, public services agency trucks, and garbage trucks are, among others, frequently included in retrofit programs. One feature of these programs is the existence of governmental incentives to finance the adoption of the measures needed. Another is the definition of specific emissions limits and/or minimum performance requirements for the various alternatives to be adopted, with a mandatory official certificate of conformity. These programs, be they voluntary or mandatory, normally require authorities to take legal and administrative measures to ensure their viability.

Vehicles in Mexico City have participated in programs of this nature. In the 90's, approximately 27,000 buses and trucks, and 1300 mini-vans, were converted to use LPG. In another instance, nearly 4100 city buses were outfitted with new engines. In the U.S., the EPA has a permanent program, voluntary in nature, directed toward cities and regions interested in reducing the emissions of vehicles in circulation. In one of these programs, the State of Washington has allotted $5 million per year to finance environmental upgrading of school buses. This has been done by using new motors, after treatment systems for exhaust-pipe emissions, and diesel fuel with 30 ppm sulfur content.

Many after treatment emissions control systems require virtual elimination of fuel sulfur. Whereas systems less sensitive to sulfur contamination require a maximum sulfur content level of 500 ppm in diesel fuel, more advanced systems require fuels with a sulfur level of less than 15 ppm. Diesel oxidation catalysts, for example, can operate on 500 ppm sulfur fuel and can reduce particulate emissions in the range of 20-50% and emissions of carbon monoxide and hydrocarbons by more than 90%, however their performance is enhanced when operated on fuel containing less than 15 ppm sulfur.

One of the known difficulties with diesel vehicles – reducing nitrogen oxide emissions – has been overcome by new retrofit technologies. Such is the case with a system that combines a catalytic converter for nitrogen oxides and a particulate filter. Test results derived by the California Air Resources Board in May, 2003, indicate that the system can reduce nitrogen oxides emissions by nearly 25%, and those of particulates by more than 85%.

In general, using retrofit methods represents greater savings than purchasing new vehicles with low emissions rates. A summary of diesel control technologies is contained as Appendix A.

## 3. Shifting To Alternative Fuels With Tight Emissions Standards

Switching to alternative fuels such as CNG or alcohols can significantly reduce emissions from new vehicles. Similarly, replacing existing engines with new engines that operate on alternative fuels can also substantially reduce emissions, especially if these engines have been certified to certain emissions performance levels such as Euro V or EEV levels. Existing engines can also be improved in some cases by switching to the use of cleaner and in some cases alternative fuels. Some of the available options will be discussed below.

It is always important to consider different approaches such as pool with low sulfur diesel, blend with biodiesel etc. to assess non-refinery possibilities, addressed at least to implementation in local fleets of urban buses, public services, deliveries of goods and taxis.

### A. Shifting To Natural Gas

The environmental advantages CNG engines have over diesel are lower emissions of particulate matter, nitrogen oxides, sulfur oxides and toxic substances. Notwithstanding, one aspect that merits closer consideration is the CNG hydrocarbon emission signature, primarily methane. Although methane has low photo-chemical reactivity (hence is not considered an ozone forming pollutant) and low toxicity, it is one of the primary greenhouse gases. An additional point that needs to be addressed is propensity of CNG engines to emit ultrafine particles (particles ranging from 10 – 500 ηm in diameter). California has demonstrated that ultrafine PM from CNG vehicles can be dramatically reduced through the use of an oxidation catalyst. Requiring CNG vehicles to meet Euro IV or even better Euro V standards should help to assure the use of this technology.

## B. Shifting To Alcohol Fuels

Among the most viable possibilities offered by the use of alcohol as a substitute for diesel, these options stand out:

### *i. Alcohol-Diesel Mixtures*

These are of great interest, since they require almost no vehicle modifications. They can be prepared with the help of special additives and/or mechanical mixing processes to dissolve the alcohol in the diesel fuel. Depending on the characteristics of the diesel fuel to be used in preparing the mixture, it is wise to use a series of additives including ignition enhancers to compensate for the lower cetane number caused by the presence of the alcohol, lubricant additives to assure the mixture's lubricity and corrosion inhibitors and dispersers. Companies that specialize in producing fuel additives have been developing new generations of products that can be used in ever lower concentrations while showing better performance. No official specifications have yet been defined for alcohol-diesel mixtures, nor have specific analytic methods been developed for their analysis, although standardizing entities such as the ASTM (American Society of Testing and Materials) recently began work in this field given the interest in a number of countries. Mixtures with alcohol levels in the range of 3% to 15% have been evaluated in Brazil with results indicating that alcohol levels of 7% by volume show a good compromise between performance, fuel use, and pollutant emissions. Smoke opacity tests under free acceleration, done on 10 trucks that had already clocked more than 340,000 km (212,500 mi) each since 1998, using said mixture, showed reductions greater than 40% in opacity. On the other hand, these vehicles were found to have an average increase of 2.3% in fuel consumption and a slight loss in power and torque. Emissions tests carried out in the U.S. following the transitory cycle of a 12.7 liter (1270 cc) diesel motor, using a 10% mixture of alcohol and 2% package of additives resulted in a 27% reduction in particulate emissions, 4% for nitrogen oxides, and 20% for carbon monoxide. Negligible variations in hydrocarbons emissions were observed.

### *ii. Alcohol With An Ignition Enhancer*

The use of alcohol with an ignition enhancer in diesel engines has had a commercial application in Sweden. In 1989, the Transit Authority of Greater Stockholm took an interest in the subject, seeking to reduce the pollution from diesel buses and to promote the use of renewable fuels. Between 1990 and 1993, field tests were done on the first 32 buses powered by a mixture of 95% alcohol, 5% ignition enhancing additive with a polyethylene glycol base, and 2 ppm of a corrosion inhibitor. However, to make the alcohol workable in the diesel, the following modifications were made:

- Increasing the compression ratio of the engine (from 18:1 to 24:1)

- Increasing the capacity of the fuel injection system
- Regulating the ignition advance
- Increasing the fuel tank capacity
- Using compatible materials in the fuel filters and other components coming into contact with the fuel
- Optimizing the turbocharger to reduce HC and CO.

In 1998, a second generation of alcohol-additive motors was introduced into the Swedish market, equipped with oxidizing catalytic converters to reduce emissions of organic compounds. Later, a new catalyst design allowed them to meet the EURO IV limits. In comparison with diesel, the use of alcohol with additives[1] resulted in reducing CO by 92%, particulates by 93%, HC by 87%, nitrogen oxides by 52%, and nearly all the sulfur oxides. A disadvantage of this technology is the increase in fuel cost, due to the presence of the additive and the volumetric increase in fuel consumption by nearly 65% in relation to ordinary diesel fuel. The modifications made on the motor and auxiliary systems also added a small cost to the final price of the vehicle. In addition, there is a need for more frequent maintenance of the fuel injection system. There are currently more than 400 buses running on this fuel in Sweden.

### *iii. Alcohol In Vehicles With Otto Cycle Motors*

Given the high octane characteristics of ethyl alcohol, the most obvious way to use it is in spark ignition (Otto cycle) engines, similar to what occurs with CNG. The use of high compression ratios – greater than 14:1 – in "poor combustion" engines equipped with advanced fuel injection systems, with efficient air supercharging systems and high-powered, "intelligent," electronic ignition systems, can induce the types of performance needed for commercial vehicles (mainly medium-size vans, microbuses, and urban delivery trucks). Vehicles with hybrid propulsion systems could also use these systems. Benefits would include lower cost engines than diesels, and substantial environmental gains, such as reducing emissions of particulates, nitrogen oxides, non-regulated toxic substances and sulfur compounds, as well as a reduction in noise levels.

### *iv. Biodiesel*

Biodiesel is an additional alternative for reducing diesel engine emissions. Its low sulfur content and its renewable nature give it a high environmental value, and it can be mixed with ordinary diesel in any proportion, thus allowing for a gradual implementation strategy as the country's ability to produce it increases.

Recent studies by the University of São Paulo and other research centers in Brazil have made it possible to develop a manufacturing process for biodiesel using ethyl alcohol

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[1] The additive used to enhance the conditions for spontaneous combustion needed in diesel motors is a derivative of polyethylene glycol, considered to be safe by Swedish authorities, from both environmental and operational perspectives.

instead of methyl alcohol in the trans-sterification of vegetable oils. This technological innovation will enable the production of a totally renewable biodiesel.

Estimated data indicate that to produce 1000 liters of biodiesel, about 100 liters of alcohol is necessary. Ethyl esters evidence physio-chemical properties similar to those of methyl esters, indicating the possibility of comparable results in their use. Thus, in the case of mixtures with diesel fuel containing up to 20% biodiesel (B20), there is no expectation of a need to adapt engine parts and components, or of the need for recalibration. However, for higher proportions in mixtures or for the use of pure biodiesel, it will be necessary to adjust the compatibility of materials coming into contact with the fuel, due to its solvent effect, and to recalibrate the engine for optimal performance. If we assume, based on international experience, that the B20 mixture will be the preferred formulation, in the short term, and that the results of using ethyl esters are in fact similar to those of using methyl esters, one can infer that neither engine performance nor fuel consumption should vary significantly in relation to using ordinary diesel.

In addition to being able to substitute for, and make renewable, a portion of diesel consumption, emissions reductions with the B20 mixture present another plus to be considered. According to surveys done by the National Renewable Energy Laboratory, in the U.S., the use of the B20 mixture (with methyl ester) produces the following results, in comparison with the use of ordinary diesel (averages obtained in 14 engines typical of the American market, tested over the transitory cycle):

Carbon monoxide: -12.6%
Hydrocarbons: -11%
Particulate matter: -18%
Nitrogen oxides: +1.2%
Non-regulated toxic substances: -12% to -20%
Mutagenic potential: -20%
Carbon dioxide: -15.7%, in the lifecycle (with the substitution of ethanol for methanol, a greater reduction of this emission is to be hoped for).

A great advantage of biodiesel is that the product is biodegradable under normal ambient conditions, thus facilitating the recovery of soils and water affected by accidental spills. Since it has extremely low sulfur content, it also contributes to reductions in the emission of sulfur compounds into the atmosphere during its combustion. One note of care to be taken with biodiesel is monitoring the quality of the product stocked, since its compounds are easily oxidized. It may eventually be necessary to use antioxidant and biocide additives to maintain product quality.

### *v. Emulsifying Water In Diesel Fuel*

The use of water emulsions in diesel fuel has been introduced as an alternative for reducing emissions, mainly of particulates and nitrogen oxides. Only recently has the technology for making such emulsions advanced significantly enough to make its production economically viable. These are mixtures of 10-20% purified water with diesel fuel that, according to the manufacturers, remains in a stable state for up to a year in storage. The lack of direct contact between vehicle components and the water allows the vehicle to be used under its original specifications. This type of emulsion is recommended for captive fleets, being already in commercial use in France and the U.S. Available reports suggest that these emulsions provide an average reduction of 20% for nitrogen oxides and 54% for particulate matter when tested over a transitory cycle. However, there is a noticeable loss of engine power, on the order of 20% of maximum power and torque, which can limit the use of this alternative to merely those applications where the load on the engine is not intense. Fuel consumption can also increase considerably, possibly as much as 15%. The negative effects observed can be minimized by recalibrating the engine, which in some situations may be worthwhile, as in the case of garbage trucks and other urban service vehicles.

## 4. Conclusions

With regards to in use vehicles, several steps would be beneficial in reducing emissions and should be adopted:

- An inspection and maintenance program carefully designed, centralized, loaded mode test based for all diesel vehicles should be phased in over several years.

- An incentive program should be developed which would encourage older high polluting vehicles to choose one of three alternatives;
    - Retrofit (where low sulfur fuel is available) using systems which have been verified to meet specified emissions criteria,
    - Replacing uncontrolled engines with ones which meet at least Euro 3 emissions standards, or
    - Replacing the diesel engine with one designed to operate on an alternative fuel but which is certified to meet at least Euro 4 emissions standards.

- Develop an incentive program to encourage the use of clean fuels such as biofuels or emulsions.

## 5. Appendix A: Diesel Emissions Control Technologies

### A. Engine Modifications

Diesel engine emissions are currently controlled primarily through improvements to the basic engine, rather than through the use of aftertreatment devices (other than diesel oxidation catalysts). Control techniques are usually limited by a $NO_x$ and PM tradeoff, where strategies to reduce one pollutant may result in an increase to the other. Nitric oxide formation is directly related to combustion chamber temperature. Increased combustion temperatures result in higher $NO_x$ emissions. Nitric oxide reductions result from decreasing peak combustion temperatures and reducing the duration of high temperatures in the combustion chamber. Particulate matter, on the other hand, results from incomplete combustion of diesel fuel. Particulate matter emissions are reduced by an improvement in fuel combustion that results in higher combustion temperatures and increased $NO_x$. Currently, diesel emissions are reduced by turbocharging, aftercooling, optimizing combustion chamber design, retarding injection timing, and high-pressure fuel injection.

Turbochargers reduce both $NO_x$ and PM emissions by ~33% compared with naturally aspirated engines. The turbocharger boosts the pressure (and temperature) of the air entering the engine. This allows more fuel to be added to increase power output, while inhibiting PM formation. Power to drive the turbocharger is extracted from the engine’s exhaust stream. The turbocharger also increases engine power and fuel efficiency. Aftercooling with turbocharging yields even larger $NO_x$ and PM reductions by decreasing the temperature of the charged air after it has been heated by the turbocharger during compression. Aftercooling improves cylinder filling because higher-density cool air sinks faster than hotter air. Engine coolant circulating through a heat exchanger is sometimes used for aftercooling. However, aftercooling using an air-to-air heat exchanger is more effective because it attains lower temperatures. Both approaches are most effective when vehicle motion provides fresh air to cool the radiator or aftercooler.

Modifications to the shape of the combustion chamber, location of the injection swirl, crevice volumes, and increased compression ratios also optimize fuel efficiency and multipollutant reductions. Improved understanding of diesel combustion and in-cylinder gas and particle formation is obtained via optical diagnostic techniques and computational models. Changes to combustion technology are continually being made to improve in-cylinder flow management, such as the geometrical design of the intake port and valve and increased swirl.

#### *i. Injection Timing Retard and High Pressure Fuel Injection*

Injection timing retard reduces the peak flame temperature, resulting in $NO_x$ reductions. However, timing retard typically lowers fuel efficiency, resulting in lower mileage and higher PM emissions. High-pressure fuel injection can regain some of the efficiency loss by improving the atomization of the fuel spray and air utilization, resulting in more complete combustion. Some fuel combustion efficiency has been traded for lower emissions to attain standards.

### *ii. Injection Rate Shaping*

Injection rate shaping tailors the fuel injection event to reduce peak flame temperatures without increasing fuel consumption. Injection rate shaping is possible because of electronic control and re-engineering of the fuel injectors. A pilot amount of fuel can be injected before the main injection event, or the main injection can be split into two or more events. Injection rate shaping has been shown to simultaneously reduce $NO_x$ by 20% and PM by 50% under certain operating conditions. Fuel injection methods that achieved effective rate shaping include the common rail injector; the mechanically actuated, electronically controlled unit injector and the hydraulically actuated, electronically controlled unit injector.

### *iii. Cooled EGR*

EGR routes a portion of the exhaust gas into the engine air intake. It reduces $NO_x$ formation in the combustion chamber by diluting the air with inert exhaust gas that reduces peak flame temperatures when fuel is ignited. Laboratory studies have shown that EGR can reduce $NO_x$ by 40–50% at rated power with no appreciable increase of PM emissions. Larger $NO_x$ reductions are found at other loads, with modest increases in PM emissions. Precise control of the EGR rate is needed to minimize PM augmentation. Recirculated exhaust must be cooled for effective $NO_x$ reductions, but this cooling causes higher PM emissions. Considering that cooling the inlet air, through the use of an aftercooler, improves efficiency and reduces emissions, large amounts of uncooled recirculated exhaust gas would heat the inlet charge air, partially offsetting its impact on $NO_x$ emission reductions. However, with proper EGR design, these undesirable effects can be minimized. Cooled EGR has been demonstrated to meet the US 2.4 g/bhp-hr HC + $NO_x$ standards with a 2% improvement in fuel economy; $NO_x$ emissions were reduced by 50%.

### *iv. Homogeneous Charge Compression Ignition*

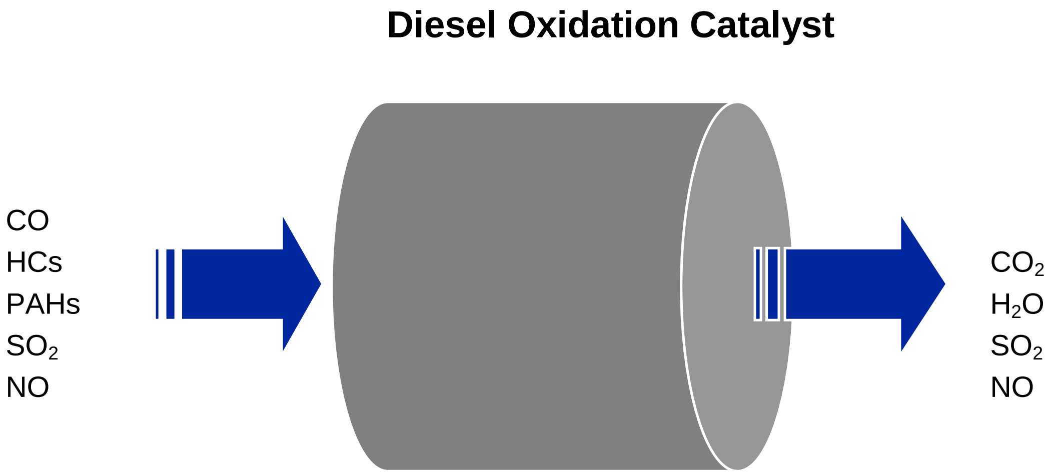
Conventional diesel engines inject fuel late in the compression stroke into hot, compressed air, resulting in auto ignition. The rate of combustion is controlled by the rate at which fuel can mix with air because chemical reaction rates are much faster than mixing rates. $NO_x$ formation is high on the lean side of the flame, and PM formation is high on the rich side of the flame. In homogeneous charge compression ignition (HCCI) systems, fuel and air are premixed prior to introduction into the combustion chamber. Ignition occurs spontaneously throughout the mixture as a result of compression. This process produces ignition at a large number of sites throughout the combustion chamber, eliminating locally lean and rich zones that cause high $NO_x$ and PM. EGR helps regulate the conditions under which controlled combustion occurs. Under low and medium loads, $NO_x$ reductions of 90–98% have been achieved. The thermal efficiency of HCCI is comparable to that of conventional diesel combustion at partial loads. However, reduced efficiencies were observed for certain diesel engines, such as those using partial fumigation and direct injection. Challenges associated with HCCI include the control of combustion initiation and rate, effective fuel and air mixture preparation, and the achievement of stable HCCI under high loads and full power output.

## B. Post Combustion Technologies

### *i. Oxidation Catalysts*

In the 1990s, oxidation catalysts were added to some truck engines and many urban bus engines to reduce PM emissions. Flow-through oxidation catalysts effectively oxidize gaseous HC and soluble organic fraction of PM. A recent test program showed that oxidation catalysts reduced transient FTP PM emissions by 23–29% and HC emissions by 52–88%, using a typical grade #2 diesel fuel (368 ppm sulfur). Testing with a low sulfur diesel fuel (54 ppm sulfur) resulted in an additional 13% reduction in PM.

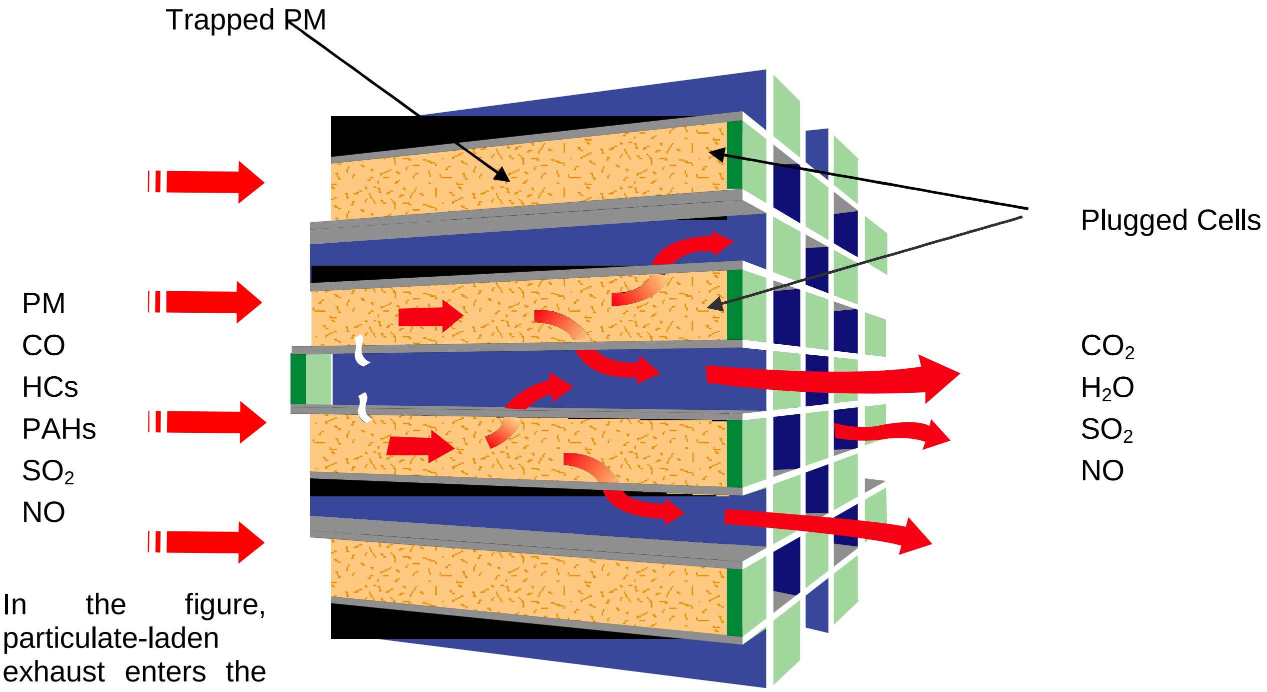
A conceptual diagram of a diesel oxidation catalyst is shown below.



### *ii.* *Diesel Particulate Filters (DPF)*

A diagram of a typical diesel particulate filter system is shown below.

Diesel Particulate Filter



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

Regeneration As particles accumulate on the filter, they must be eliminate, else the exhaust stream will be clogged. This process of elimination is termed, "regeneration." Regeneration involves the oxidation of those captured particles. A powdery ash residue, the result of lubrication oil combustion is generally left behind. Hence these devices require a certain amount of maintenance, which involves a period cleaning to remove this ash (one time per year depending on vehicle usage). 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;

- 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. This technique is easy to use in electronically controlled fuel injection systems.

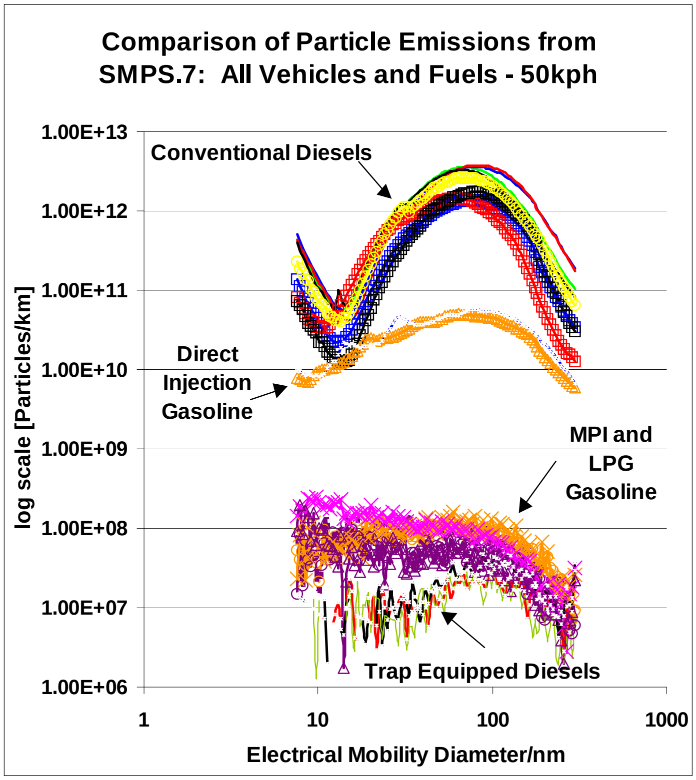
- On-board fuel burners or electrical heaters. Fuel burners or electrical heaters upstream of the filter can provide sufficient exhaust temperatures to ignite accumulated particles and regenerate the filter.

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

The experience with catalyzed filters indicates that there is a virtually complete reduction in odor and in the soluble organic fraction of the particulate, but some catalysts may increase sulfate emissions. Companies utilizing these catalysts to provide regeneration for their filters have modified catalyst formulations to reduce sulfate emissions. Low sulfur fuel (0.0015% wt – 15 ppm) is becoming available in the U.S. and has greatly facilitated these efforts. In Europe, diesel fuel with less than 10 ppm sulfur is increasingly available and will become widely available in every country by 2005.

The catalyzed DPF and the continuously regenerating DPF have been demonstrated to substantially reduce particle emissions. In one program in USA, using 54 ppm sulfur fuel, the DPF reduced PM by 87% to a level of 0.008 g/bhp-hr. Another program showed that heavy-duty trucks retrofitted with DPFs and fueled with ARCO's emission control-diesel fuel (EC-D, 7 ppm sulfur) emitted 91–99% less PM, compared with trucks fueled with California diesel fuel (121 ppm sulfur) and with no exhaust aftertreatment devices. These trucks have been operating reliably for more than 5 months, with an accumulation of ~50,000 mi per truck. As illustrated below, a continuously regenerating DPF reduced PM number counts by 1–2 orders of magnitude, as well as substantially reducing mass emissions. In European field tests, DPFs have demonstrated highly efficient PM control and promising durability, when operated with ultra-low sulfur fuel.

### *iii. Lean NOx Catalysts*



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

Some lean NOx catalyst systems inject a small amount of diesel fuel or other reductant into the exhaust. 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. Only a limited number of vehicles have been equipped with lean NOx catalyst systems in the U.S.

Two types of lean NOx catalyst systems 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.

### *iv. NOx Adsorbers*

$NO_x$ adsorbers operate by storing $NO_x$ under typical diesel engine operations ("lean" conditions). Before the $NO_x$ adsorbent becomes fully saturated, engine operating conditions and fueling rates are adjusted to produce a fuel-rich exhaust that reduces the stored $NO_x$ to nitrogen. $NO_x$ adsorbers have been demonstrated to reduce $NO_x$ emissions by more than 90% with ultra-low sulfur fuel for transient and steady-state conditions, but with reduced fuel economy. $NO_x$ adsorbers' strong affinity for sulfur can deactivate the active catalyst sites and make the adsorbers less efficient over time. Improved $NO_x$ adsorber desulfurization systems, active catalyst layers that are more sulfur-resistant and other methods are under development to maintain the $NO_x$ adsorber's high efficiency for the useful life of the engine. One type of $NO_x$ adsorber includes an $SO_2$ sorbate catalyst upstream of the $NO_x$ adsorber to protect the $NO_x$ catalyst from sulfur poisoning. Testing showed $NO_x$ reductions >95% using Grade No. 2 diesel fuel (sulfur <500 ppm).

### *v. Selective Catalytic Reduction (SCR)*

An SCR system uses a metallic catalyst and a chemical reagent, often ammonia or an aqueous urea solution, to convert nitrogen oxides to molecular nitrogen and oxygen in the exhaust stream. In mobile source applications of SCR, urea is usually the preferred reductant. The reductant is injected into the exhaust stream at a rate based on the amount of NOx present in the exhaust stream. As exhaust gases and the reductant pass over the SCR catalyst, chemical reactions occur that reduce NOx emissions 75 to 90 percent, HC emissions up to 80 percent, and PM emissions 20 to 30 percent. SCR also reduces the characteristic odor produced by a diesel engine and diesel smoke. Like all catalyst-based emission control technologies, SCR performance is enhanced by the use of low sulfur fuel.

The critical step in SCR systems is the estimation of NOx in the exhaust gases and hence the amount of reductant necessary to react with the NOx. Two main challenges exist with SCR technology. The first is the control of the rate of reagent injection to maximize $NO_x$ reductions without "ammonia slip" through the catalyst. Stoichiometric amounts of reagent are necessary to eliminate virtually all available NOx, however if more reagent is injected than available NOx, the excess reagent will be emitted in the form of ammonia. Current SCR systems use an algorithm to estimate NOx concentrations in the exhaust stream. This algorithm relates NOx emissions to engine parameters such as engine revolutions per minute (rpm) and load. Efforts are underway to develop a NOx sensor that would provide instant exhaust gas NOx concentrations used to meter reagent injection. The second challenge is ensuring that users properly replenished reagent levels throughout the vehicle life to ensure emission reductions. Additional concerns relate to the maintenance of the system in the case of a failure. If a failure occurs, a feedback mechanism is necessary to alert the vehicle user to perform the necessary maintenance.