

Catalyzed Diesel Filters

Abstract: Most catalyzed diesel filters utilize monolithic wall-flow substrates coated with a catalyst. The catalyst lowers the soot combustion temperature, allowing the filter to self-regenerate during periods of high exhaust gas temperature. A number of diesel filter catalysts have been developed, including both noble and base metal formulations. Catalyzed ceramic filters exhibit very good PM filtration efficiencies, but are characterized by relatively high exhaust gas pressure drop.

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Introduction

In the catalyzed diesel particulate filter (CDPF), a catalyst is applied onto the filter media to promote chemical reactions between components of the gas phase and the soot (carbon) collected in the filter. The main purpose of the catalyst is to facilitate passive [regeneration](#) of the filter by enabling the oxidation of diesel particulate matter under exhaust temperatures experienced during regular operation of the engine/vehicle, typically in the 300-400°C range. In the absence of the catalyst, particulates can be oxidized at appreciable rates only at temperatures around 550-650°C, which can occur only at full load conditions in the diesel engine and in most cases are rarely seen during real-life operation.

The use of fully passive filter [systems](#) is practically limited to retrofit applications. In most OEM applications, catalyzed filters are used with mixed passive-active regeneration, where the filter regenerates passively at high engine loads. Under light load conditions, the exhaust gas temperature is actively increased—typically to about 500°C—to trigger periodic regeneration whenever the maximum soot load is reached in the filter. Increased temperatures are realized through such means as engine management or injection of fuel into the exhaust gas, followed by HC oxidation over a warm-up catalyst. In these filter systems, the role of the catalyst—in addition to lowering the soot ignition temperature—is to accelerate the soot oxidation rate to

minimize the fuel economy penalty. Shorter duration of the regeneration also minimizes the chances for unforeseen and unwanted interruptions (e.g., due to changed engine operating conditions where the engine management strategy to increase temperature can be no longer sustained). Finally, active oxidation catalysts may be able to minimize the high CO emissions that could otherwise occur during active regeneration, when large amounts of soot are burned during a short time period.

Application of a catalyst has been attempted with virtually all diesel filter media. Reported catalyst applications include [wall-flow](#) monoliths, wire mesh, ceramic foams, ceramic fibers, and other media. In the most common design, the CDPF utilizes a ceramic wall-flow monolith made of either cordierite or silicon carbide, packaged into a steel housing, as shown in Figure 1. The porous walls of the monolith are coated with the catalyst. As the diesel exhaust aerosol permeates through the walls, the soot particles are deposited within the wall pore network, as well as over the inlet channel surface. The catalyst, through a number of possible mechanisms discussed below, facilitates PM oxidation under the lean conditions in the diesel exhaust.

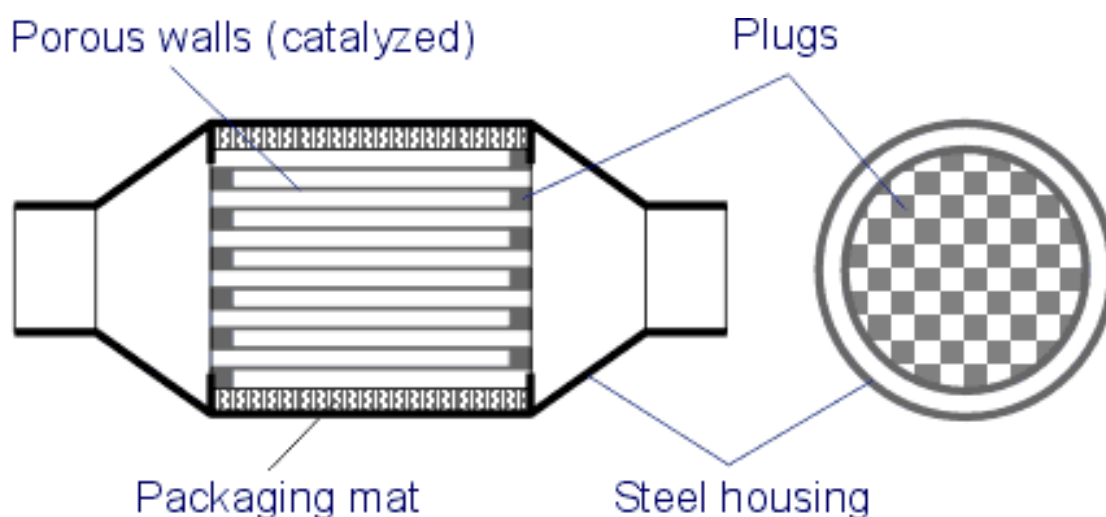


Figure 1. Catalyzed Diesel Particulate Filter

Catalyzed ceramic filters were developed in the early 1980s. Their first applications included diesel powered cars and, later, underground mining machinery. Catalyzed filters were commercially introduced on Mercedes cars sold in California in 1985. Mercedes models 300SD and 300D with turbocharged engines were equipped with 5.66" diameter \times 6" filters, Figure 2, fitted between the engine and the turbocharger [Abthoff 1985].



Figure 2. CDPF for Mercedes Benz 300D

(Courtesy of Per Stobbe)

The use of diesel filters on cars was later abandoned, due to such issues as insufficient durability, increased pressure drop, and filter clogging. As these issues are being gradually solved, catalyzed ceramic filters have been established as one of the most important diesel particulate filter technologies. Catalyzed ceramic filters are commercially available as both OEM and aftermarket (retrofit) product. The evolution of the CDPF market can be summarized as follows:

- Since the early 1990s, limited quantities of catalyzed filters have been used in underground mining (North America, Australia) and in stationary engine applications.
- Since mid-1990s CDPFs have been used for retrofitting of heavy-duty diesel vehicles, such as urban buses and municipal trucks, mostly in the USA and EU.
- After being re-introduced to the light-duty application in 2003, CDPFs are increasingly used in diesel passenger cars in Europe (in competition to [fuel additive](#) regenerated filters).
- Wide-scale application of CDPFs is anticipated in new US 2007 heavy-duty diesel engines.

Suppliers of catalyzed filters include Umicore (formerly OMG, dmc², Degussa), Engelhard, Delphi, as well as several smaller emission control manufacturers who specialize primarily in the off-road markets.

Catalytic Oxidation of Soot

Reaction Mechanisms

The mechanisms of catalytic oxidation of soot are complex, and not entirely understood. It is certain that a number of processes occur in parallel, which can be promoted by different types of catalysts. The mechanisms that play important role in the regeneration of catalyzed filters can be classified as follows:

- Catalytic oxidation by oxygen—Carbon particles are oxidized by oxygen adsorbed on catalytic sites. This mechanism is limited to particles that physically contact catalytic sites (i.e., particles deposited directly on the catalyzed media).
- Oxidation by nitrogen dioxide—NO₂, which can be generated by catalytic oxidation of NO, is more effective in oxidizing carbon than oxygen (compare the paper on [filter regeneration](#)). Furthermore, nitrogen oxides may be also enhancing the regeneration due to synergistic effects with DPF catalysts.
- Thermal oxidation by oxygen—Catalytic oxidation of hydrocarbons and other gas species, as well as the carbon particulates themselves, can create local zones of increased temperature due to the exothermal heat of reaction. The increased temperature may be sufficient (> 600°C) to support non-catalytic, thermal oxidation of soot deposits. This oxidation mode is believed to be important during periodic regeneration, when the soot bed “ignited” through some of the catalytic processes continues to burn on its own.

Catalytic combustion of carbon was first investigated in relation to coal gasification. It has been shown that the gasification rate of carbon is accelerated in the presence of almost any inorganic compound [Mims 1991]. Later studies focused on platinum group metal catalysts, as well as a number of transition and alkaline earth metal oxides.

Heterogeneous catalytic processes in the gas phase occur on contact of gas molecules with the solid catalyst, i.e., the reactions take place on the catalyst surface. The contact is of critical importance for soot oxidation, as indicated by several authors [Ciambelli 2000]. Relatively good contact can be provided by such methods as doping the fuel with the catalyst precursor (fuel additive), resulting in catalyst particles being incorporated into the soot. But under the conditions in the CDPF, it must be doubtful if solid particles, several orders of magnitude larger and heavier than gas molecules, have sufficient mobility to physically contact the catalyst. Only those particles that are deposited within the catalyzed pore network inside the walls or directly on the wall surface would have such a chance. Indeed, other mechanisms have been discovered that involve gas phase molecules acting as an *oxygen carrier* between the catalyst and carbon particles.

Nitrogen oxides are best suited to perform such a role in the diesel exhaust. It has been known

that NO_2 —which can be generated through catalytic oxidation of NO in the CDPF—is more active in oxidizing diesel soot than oxygen [Cooper 1989]. The NO_2 regeneration has been fully utilized in the [CRT filter](#), which includes an NO_2 generating catalyst positioned upstream of an uncatalyzed filter. Considering the availability of NO_2 for soot oxidation, the CRT design is superior to the CDPF. In the CDPF, nitrogen dioxide is available primarily to particles positioned very close to or downstream of catalyst sites, generally within the pore network. Oxidation of the soot layer in the inlet channels, upstream of the catalyst would have to rely on diffusional transfer of NO_2 counter currently to the gas flow—not a very effective reactor design. However, there may be advantages from using NO_2 *in situ nascendi*, generated and utilized in close proximity, within the same reaction zone. We should keep in mind that the role of NO_x in the regeneration of particulate filters is a relatively recent topic which still needs more research. Exchange of scientific information on this subject has been also restrained—perhaps more so than in other diesel emission control technologies—by patent law considerations.

Most models begin with the NO_2 generation by catalytic oxidation of NO :



The NO_2 reacts then with solid carbon to form CO and to recreate the NO molecule. In several models, this step involves formation of active oxygen— O^* in Equation (2) and Equation (3)—but more complex mechanisms were also proposed, involving carbon-oxygen intermediary complexes [Mul 1998][Jacquot 2004].



Finally, the CO can be catalytically oxidized to CO_2 :



In spite of the similarity of the overall chemical reactions, differences exist between NO_x chemistry in the CDPF and the CRT. Some interesting observations can be summarized as follows:

- In the CDPF, regeneration is enhanced by the presence of nitric oxide not only with Pt catalysts, but also with base metal catalysts [Mul 1998][Ciambelli 2000]. While it is believed that in both cases nitrogen dioxide is produced as an intermediary, the reaction mechanisms must be different as evidenced by the often substantial increase of tailpipe

NO_2 with Pt catalysts, which does not occur with base metals.

- Sulfated base metal catalysts mostly preserved their soot oxidation activity, provided NO and H_2O were present in the gas phase [Ciambelli 2000]. In contrast, regeneration in the CRT filter (Pt catalyst) is totally blocked by sulfur.
- The presence of NO and H_2O was also reported to affect the selectivity (CO_2/CO ratio) with a base metal catalyst [Ciambelli 2000].
- Soot oxidation rates may be enhanced by both NO_x and CO, but only with some catalysts (CuO) [Mul 1998].

Two types of catalysts play especially important role in CDPF regeneration: (1) platinum, and (2) metal oxides with oxygen storage capacity (OSC). OSC materials are oxides where the metal can cycle between two valence states, thus adsorbing and releasing oxygen. Ceria (CeO_2) is an OSC compound that has been widely used for a number of years in three-way catalysts for spark-ignited engines. Other OSC materials include oxides of iron, manganese, or copper (the avid reader will notice that the same materials—cerium and iron—have been used as the most effective fuel [additives](#) for filter regeneration).

It was shown that significant synergistic effects that enhance soot oxidation may exist between OSC catalysts and NO_2 . Figure 3 illustrates carbon oxidation rates measured in a laboratory reactor with and without an undisclosed OSC catalyst (presumably Ce or Ce/Fe), with and without NO_2 [Jacquot 2004]. Clearly, NO_2 highly enhanced the low temperature activity of the catalyst (compare the performance at 300°C).

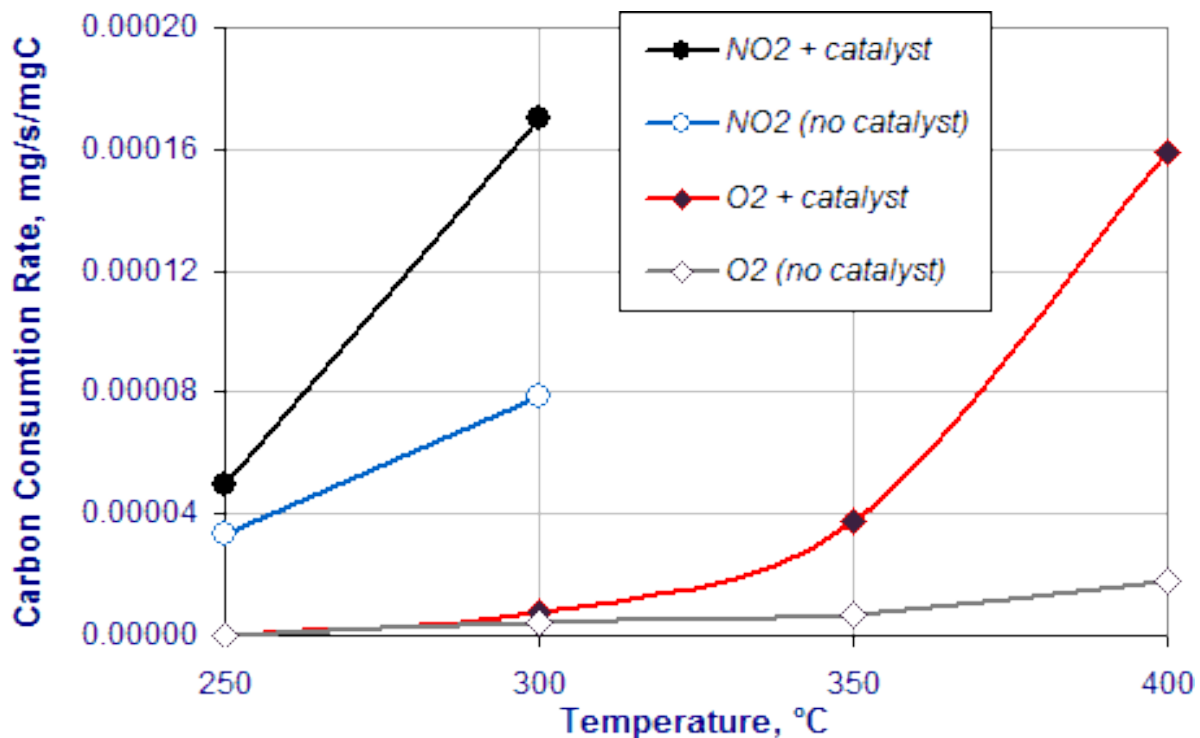


Figure 3. Impact of OSC Catalyst and NO₂ on Soot Oxidation Rate

*Laboratory reactor data; "O2" gas = 10% O₂ + 5% H₂O + He
balance; "NO2" gas = 1000 ppm NO₂ + 1% O₂ + 5% H₂O + He
balance.*

In Figure 3, experiments with catalysts were performed using soot obtained through the use of an OSC fuel additive, but the same trends were seen with soot physically mixed with the OSC catalyst. In a CDPF, the magnitude of the effect may be lower due to less contact between soot and the catalyst, but the general trend is believed to be relevant.

Another important group of CDPF catalysts are compounds with NO_x storage capacity, such as barium or magnesium (compare the paper on NO_x [adsorbers](#)). It is not clear what is the synergism, if any, between NO_x storage capacity and filter regeneration. Designers of the Toyota [DPNR](#) system—a particulate filter coated with NO_x adsorber for simultaneous NO_x and PM control—reported that active oxygen released during the adsorber regeneration under rich exhaust conditions enhanced soot oxidation [Nakatani 2002]. But only marginal soot oxidation rate improvement under rich/lean cycling with NO₂ was measured in other studies [Jacquot 2004]. It was also suggested that the role of Ba/Mg may be to release an NO₂ spike under lean conditions, which ignites the soot for the subsequent combustion with oxygen [Pfeifer 2004].

Catalyst Coating

Catalysts can be applied on wall-flow diesel filter substrates using one of two methods:

- impregnation with water-based solutions of catalyst precursors, or
- washcoating with suspensions (slurries) of insoluble oxides or salts.

The first method—using water solutions of catalyst precursors, noble and/or base metals, followed by drying and calcining—is indeed a very convenient way of applying a catalyst onto the ceramic monolith. A common method of coating is to apply a predetermined quantity of solution—based on a water absorption test of the substrate—by pouring it over the inlet face of the filter. The solution soaks throughout the substrate resulting in a uniform distribution of the catalyst throughout the porous filter walls. Hence, the filter has no preferred direction of flow for exhaust gases and can be reversed in the exhaust system (of course, one could use less solution than needed to soak through the part to apply more catalyst near one end of the filter, resulting in a non-symmetrical coating). The final catalyst, usually metal or metal oxide, is formed from the precursor at elevated temperatures (typically 500-600°C) during the calcining process.

Platinum group metals, including platinum and palladium, are compatible with *cordierite* and can be directly applied to ceramic monoliths without a transition metal oxide carrier or washcoat layer. Although various catalyst carriers, such as alumina, silica and zirconia, have been suggested [Domesle 1983], many diesel filter catalysts—especially those manufactured in the 1990s—did not include a high surface area catalyst carrier.

Catalytic coating using water-based techniques is also possible with SiC filter substrates. While some authors suggested applying some kind of intermediate oxide layer on SiC parts [Taoka 2001][NoTox 1997], it is possible to apply such layer with several oxides through impregnation from water-based precursors, thus, avoiding washcoat (i.e., suspension-based) technologies.

However, the coating process using water solutions also has several disadvantages. The choice of catalytic materials is limited, as many compounds, such as high surface area catalyst carriers, can only be applied from slurries. The resulting “carrier-less” diesel filter catalysts have very low physical surface area. In theory, such catalysts should be troubled by durability problems, including catalyst sintering or reactions between the catalytic components and the ceramic substrate (but the published data is insufficient to determine if such phenomena indeed happened in CDPFs). Washcoats also allow for more flexibility in designing the catalyst system—for instance, it is possible to apply different catalysts in the inlet and outlet channels of the monolith.

For these reasons, many diesel filter catalysts are applied from water suspensions of insoluble oxides or salts. Several vanadium-based formulations designed as early as in the 1980s were coated from suspensions [Hartwig 1985][Strutz 1989]. Washcoats are increasingly used in mass-produced filters, such as those introduced in Euro 4 diesel passenger cars.

Application of [coating](#) technologies from slurries (colloidal suspensions) to filter monoliths is somewhat more challenging than washcoating flow-through catalyst substrates. Whenever suspensions are used, the particle size distribution of the suspended material, as well as other process parameters, must be carefully controlled. Improperly applied washcoats can substantially increase the filter pressure drop due to clogging and/or narrowing of the pores in the substrate walls. Wall-flow monoliths introduced to the market in the 1990s typically had average pore diameters of about 10-15 μm . Washcoating of such substrates required powders of smaller particle sizes than those used for flow-through catalysts. Pore sizes and substrate porosity can also present a limitation on the maximum washcoat loading. Monoliths of larger [pores](#) and increased porosity have been developed to allow higher washcoat loadings and more complex catalyst systems [Ichikawa 2003].

Washcoating of wall-flow monoliths is usually performed by pouring a volume of slurry over the face of the substrate. To achieve uniform washcoat distribution and to minimize pore blocking, compressed air from an air knife or vacuum suction can be applied to the substrate. The amount of slurry per filter is preferably determined through a water uptake test (absorption test) for a given substrate. Using larger amount of slurry and blowing away the excess by compressed air may be problematic, as suspended washcoat particles could become filtered on the substrate walls. Due to this filtering effect on the porous walls, filter washcoats are not

symmetrical. More washcoat material is present in the channels the slurry was poured over. This can provide an advantage, as the catalyst to lower soot ignition temperature can be coated in the inlet channels—where it would be in contact with soot—while another catalyst to treat gases exiting the filter can be coated in the exit channels. The filter, however, becomes directional and cannot be reversed in the exhaust system.

If washcoat technologies are used, there are three possible methods of applying noble metal catalysts (each producing somewhat different catalyst):

1. platinum (or other noble metal) can be impregnated after the washcoat is calcined, followed by a second calcination
2. platinum catalyst precursor can be added to the slurry
3. platinum can be fixed on the washcoat powder (e.g., on alumina) and calcined before the slurry is prepared

Catalyst Systems

Various catalyst systems used for diesel filters utilize noble metals, base metals, as well as mixtures of noble and base metals. Platinum is the most active and the most commonly used noble metal (palladium, rhodium or ruthenium catalysts and their mixtures are possible but uncommon). The list of common non platinum-group metals that have or had been used in diesel filters includes vanadium, cerium, magnesium, calcium, strontium, barium, manganese, iron, copper, and silver.

CDPF catalysts can be divided into two categories: (1) platinum-based, and (2) base metal catalysts. As will be discussed later, these two catalyst groups exhibit certain differences in their emission performance:

- Base metals tend to be less active in promoting filter regeneration (thus requiring higher regeneration temperatures) and have low activity for the oxidation of CO and HC. On the positive side, they form little or no sulfate particulates and/or nitrogen dioxide emissions.
- Platinum (usually combined with promoters) is typically more active in supporting filter regeneration and for oxidizing CO and HC. The latter function is important in applications where gaseous emission reductions are also required. The disadvantages of Pt include production of sulfate particulates (which limits its applicability with high sulfur fuels) and increased levels of tailpipe NO₂.

Base Metals. Vanadium used to be one of the most popular base metal catalysts used in diesel particulate filters. The CDPF commercialized in Mercedes cars in California in the mid-1980s (see Figure 2) was coated with vanadium pentoxide (V₂O₅) catalyst by Degussa. This catalyst promoted filter regeneration at temperatures of 380-400°C. One of the potential problems with vanadium based catalysts is the volatility of V₂O₅ at increased temperatures, as may be

encountered during filter regeneration. The evaporation of V_2O_5 may lead to gradual catalyst losses and shorten the filter lifespan, not to mention vanadium emission issues. Catalysts were developed that utilized vanadium compounds other than V_2O_5 , for example silver [Domesle 1984] or copper vanadates. Another problem encountered during the development of early catalysts for Mercedes cars was loss of mechanical strength of the cordierite substrate caused—according to one theory—by reactions between vanadium and cordierite at elevated temperatures.

An example copper vanadate base metal catalyst was developed by Heraeus [Strutz 1989]. The catalyst was prepared by doping and calcining copper vanadate $Cu_3V_2O_8$ with potassium carbonate in the molar ratio Cu:V:K 3:2:0.13. Diesel filters were then coated with the catalyst from a water suspension. The catalyst loading was between 10 and 80 g per 1 m² of the filtration surface area. Soot ignition temperature measured by the differential thermal analysis (DTA) amounted to 365°C with this catalyst and to 500°C without catalyst. The use of copper was later practically abandoned due to the findings that Cu catalysts can generate secondary emissions of dioxins and furanes in diesel exhaust [Heeb 1998].

Another base metal catalyst that deserves mentioning is iron, still used in limited markets, e.g., in some CDPFs in underground mining where concerns exist about NO₂ emissions. There is also ongoing research in base metal catalysts. For instance, Ford revealed a base metal catalyst utilizing ceria stabilized with silver and cobalt [Chigapov 2003]. The reported regeneration activity of the catalyst matched that of a Pt catalyst at a 100 g/ft³ loading. With the increased availability of low sulfur fuels, however, platinum has gradually become the catalyst of choice in most commercial filters.

Noble Metals. Although a number of noble metals are named as filter catalysts in the patent literature—including platinum, palladium, rhodium, and others—most commercial noble metal-based filters utilize platinum, typically with such promoters as alkaline earths. Ceria has been introduced as a promoter in more recent catalyst formulations.

Typical platinum loadings in filters used for relatively hot-running off-road engines through the 1990s were between 35 and 50 g/ft³. When the use of catalyzed filters was extended to engines of much lower exhaust gas temperatures—urban buses, school buses, or municipal trucks—higher platinum loadings were often needed (in spite of the cleaner engine technology and low sulfur fuels) to support low temperature regeneration. Passive filters used in low temperature applications have typically platinum loadings of 50-75 g/ft³, but higher figures are possible. One of the objectives of the filter catalyst research is to develop more active catalysts which could maintain satisfactory regeneration activity using less noble metal.

An example platinum catalyst developed by Engelhard is composed of 5-150 g/ft³ Pt/Rh at 5:1 ratio and 30-1500 g/ft³ of MgO (barium can be also used in place of magnesium) [Dettling 1992]. The catalyst is impregnated onto cordierite monoliths from water based solutions. A filter coated with the catalyst requires exhaust temperatures of 375-400°C to regenerate. The

function of rhodium in the above formulation is to suppress the catalytic oxidation of SO₂ and, thus, the sulfate make in the catalyst. The final effect depends on the Pt/Rh ratio. Table 2 lists SO₂ oxidation data generated in a laboratory flow-through reactor. However, even though effective in controlling sulfates, the addition of Rh to Pt catalysts results in a significant increase in the filter regeneration temperature [Cooper 1989].

Table 2
Catalytic Oxidation of SO₂

Pt:Rh Ratio (wt.)*	SO ₂ Conversion, %
100% Pt	41
10 Pt : 1 Rh	33
5 Pt : 1 Rh	13
3 Pt : 1 Rh	6
1 Pt : 1 Rh	7
* Catalyst loading 1.77 g/dm ³ (50 g/ft ³), catalyst volume 0.9 dm ³ , gas flow 1.7 Nm ³ /h, 300 ppm SO ₂ , temperature 400°C	

Platinum can be also used together with vanadium. An example formulation revealed by Süd-Chemie utilizes a Pt-Mg-V catalyst on a tungsten-doped titania washcoat [Huang 2004].

Example loadings are 25 g/ft³ for Pt and 10-35 g/dm³ for the washcoat, the latter figure notably low in comparison to washcoats in flow-through catalysts. The TiO₂ washcoat was chosen in preference to alumina in order to, among other reasons, avoid reactions between Mg and Al₂O₃ and the resulting loss of surface area. Pt-V catalysts can be expected to have reduced sulfate make, as vanadium is a known sulfate suppressant in diesel oxidation catalysts.

Theoretically, the sulfate make in active noble metal filter catalysts can be controlled using a number of [methods](#) that were developed for selective diesel oxidation catalysts, e.g., by low Pt loadings, the use of vanadium, or other sulfate-suppressing additives. However, as it was the case in the Pt/Rh catalyst example in Table 2, one always has to accept a penalty in the catalytic activity when designing a more selective catalyst. In particulate filters, such penalty manifests itself as a deterioration in the filter regeneration performance. In other words, sulfate-suppressed CDPFs require higher exhaust temperatures for regeneration. Since in most CDPF applications no regeneration penalty can be accepted, the preferred method of sulfate control in catalyzed filters is through the use of ultra low sulfur fuel. As we will show later (Figure 7), the regeneration of catalyzed filters is also enhanced in the absence of sulfur.

Sulfur-free fuels (≤10 ppm S) are used for type approval testing of Euro 4 cars. An example catalyst coatings for this application, intended for use with active regeneration support by

engine management, was developed by Umicore [Schafer-Sindlinger 2004]. The coating includes two catalyst layers: (1) a soot ignition temperature reducing catalyst, washcoated in the inlet channels of the filter, and (2) a CO/HC oxidation catalyst washcoated in the outlet channels. The first catalyst includes an OSC component, such as a cerium-zirconium mixed oxide, in combination with other oxides (MnO_2 , CaO) and platinum. The CO/HC catalyst—which has a light-off temperature of less than 150°C —utilizes Pt on a high surface area support (alumina, silica, zeolite,...).

Another catalyst for the same application combined platinum with NO_x adsorbing materials (Ba/Mg) and OSC oxides (Ce/Mn) [Pfeifer 2004]. At a weight ratio of $\text{CeO}_2:\text{MnO}_2:\text{BaCO}_3:\text{MgO} = 2:2:1:1$, the material was found to be effective in releasing NO_2 at temperatures above $300\text{--}400^\circ\text{C}$ under lean conditions, which triggered subsequent regeneration by oxygen. Example loadings were 90 g/ft^3 for Pt and 150 g/dm^3 for the mixed oxides.

Emission Performance

PM Filtration Efficiency

As with any type of diesel filter, the filtration efficiency for solid fractions of diesel particulates, including inorganic carbon and metal ashes, is determined by the properties of the filter substrate. Most catalyzed particulate filters use wall-flow monoliths of proven, high efficiency in capturing of solid particulates. The filtration efficiency increases with increasing soot load in the filter. Somewhat lower efficiencies are seen when soot is collected within the pore network in the walls during the initial filtration period. After a layer of soot stabilizes in the monolith channels, the efficiency for solid particulates increase to typically between 95% and nearly 100%.

The large differences in reported total filtration efficiency of catalyzed filters, which usually varies between some 60 and 95%, are explained by the filter activity towards non-solid fractions of diesel particulates—sulfate particulates and the organic fraction of PM, known as SOF. Most of these compounds are passing through the filter as vapors, especially at higher exhaust temperatures (compare the paper on [particulate filters](#)). Being a part of the gas phase, these compounds cannot be trapped and retained in the filter the way solid particulates are. Rather, their transformation in the CDPF depends entirely on chemical reactions that may occur upon contact with the filter catalyst.

At high exhaust temperatures, CDPFs may generate [sulfates](#) by catalytic oxidation of the exhaust SO_2 to SO_3 , the precursor of sulfuric acid. At high temperatures, the gaseous SO_3 can penetrate the porous walls and freely leave the filter. Later, it combines with water and forms sulfate particulates when cooled down in the PM sampling system. The “sulfate make” may be a big problem with catalyzed filters. When fuels of higher sulfur content are used, catalyzed

filters may even increase the total particulate matter output, i.e., exhibit an overall negative filtration efficiency. This will happen when the quantity of generated sulfates is higher than the amount of particulates trapped in the filter.

Platinum has the strongest tendency to form sulfates among all diesel filter catalysts. Sulfates are typically formed over platinum catalysts at relatively high exhaust temperatures of about 350-450°C. Active catalysts can convert as much as 50% and more of the exhaust SO₂ to sulfates. High Pt loading catalysts can effectively control total PM emissions only in conjunction with ultra low sulfur fuels. Fuels of 300-500 ppm S, commonly referred to as “low sulfur fuels”, can still cause considerable sulfate emission problems.

The PM conversion efficiency in a noble metal catalyzed filter at different levels of sulfur in the fuel is shown in Figure 4 [DECSE 2000a]. Particulate emissions were measured over three engine test procedures, as indicated in the graph, all of which were characterized by high temperatures which favored the sulfate make. PM reduction efficiencies between 93-95% were measured with 3 ppm S fuel. When 30 ppm S fuel was used, the efficiency dropped to 72-80%. The CDPF efficiency decreased to zero at about 150 ppm sulfur content (with some differences between the test cycles). At that point, the amount of sulfate generated in the CDPF became approximately equal to the amount of solid particulates captured in the filter. The efficiency of the CDPF with the US ultra low sulfur fuel of 15 ppm S interpolated over the ESC test would be 88%.

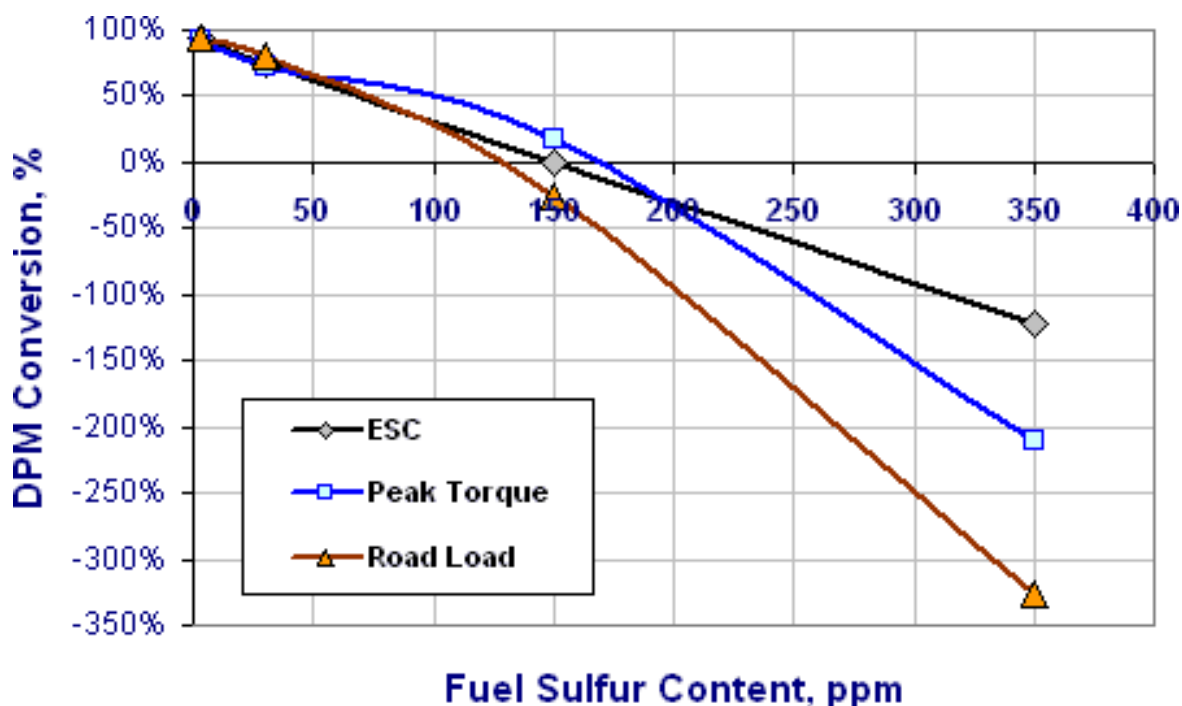


Figure 4. Conversion of PM in Pt-Based CDPF at Different Fuel Sulfur Levels

CDPF: 10.5" dia. × 12", 100 cpsi, 17 mil wall; Engine: CAT 3126, 6 cyl., 7.2 liter, 205 kW (275 hp) @2200 rpm

It should be emphasized that the sulfate considerations depend on the regulatory definition of diesel particulate matter. It is common in occupational health regulations to exclude sulfates from the definition of diesel particulates and measure PM as either total carbon (i.e., inorganic carbon + SOF) or elemental carbon (example: German occupational health regulations [BMA 2001]). If sulfates are neglected, catalyzed filters will show excellent filtration efficiencies, even with high levels of sulfur in the fuel. Care must be taken, however, that active catalysts do not cause air quality problems with other pollutants, such as SO_3 or NO_2 .

The organic fraction (SOF) is also largely vaporized in the filter during high temperature operation and cannot be physically trapped. The SOF performance of the CDPF will depend on the activity and the temperature of the catalyst. An active catalyst, such as Pt, will oxidize the SOF vapors. However, if a low activity catalyst is used, such as some base metal catalysts, or the temperature is too low, the SOF vapors may pass through the filter. As a result, the CDPF may show decreased PM filtration efficiency.

CDPF are also very effective in reducing particle (and nanoparticle) number emissions, provided the nanoparticles are solid. If liquid nanoparticles, such as composed of sulfuric acid or hydrocarbons, are created through condensation downstream of the filter, they obviously cannot be controlled by the filter. This issue, which applies to all filter types, was discussed in the paper on [particulate filters](#). The formation of sulfate nanoparticles after the CDPF increases with the fuel sulfur content and with temperature. In a study with fuel of 371 ppm S, a CDPF was found to decrease particle numbers by about 80% at a lower temperature mode, and increase particulate numbers by some 140% (due to an estimated over 300% increase in sulfates) at a higher temperature mode [Suresh 2001]. Formation of increased HC nanoparticle numbers is possible at low temperatures, below the catalyst light-off for HC/SOF.

Gaseous Emissions Performance

Catalyzed particulate filters also facilitate a numbers of oxidation reactions in the gas phase, which are similar to those occurring in the diesel [oxidation catalyst](#). Gaseous emission performance of a CDPF varies depending on the type and activity of catalyst. In general, platinum based catalysts, especially those with high Pt loadings, will be very active in the oxidation of hydrocarbons and carbon monoxide. On the other hand, some base metal catalysts used in diesel filters are quite inactive in respect to the gas phase components. They do not cause significant changes in the concentrations of CO and HC.

Platinum based CDPFs typically achieve about 80-90% conversion of CO. The example data in Figure 5 [DECSE 2000a] showing 95% CO conversion was generated on the [ESC](#) test cycle, characterized by high average load factors and high exhaust temperatures which favor catalytic reactions. The carbon monoxide performance also depends on the regeneration cycle. If a filter with high loading of particulates rapidly regenerates, oxygen may become depleted in the reaction zone leading to partial combustion of soot. Under such conditions secondary CO emissions can be generated in the filter. We are not familiar with any literature data showing how these temporary conditions may affect the overall CO emission reduction over the vehicle

duty cycle.

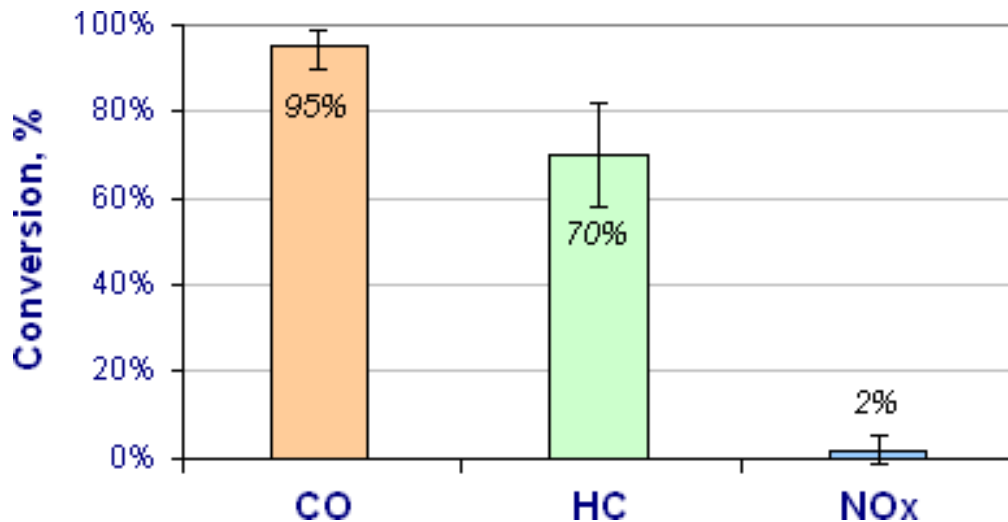


Figure 5. Conversion of Gases in Pt-Based CDPF

ESC (OICA) test cycle; CDPF and engine as in Figure 4; Data shown represents averages from several measurements with fuel sulfur changing from 3 ... 350 ppm

Pt CDPFs typically show a 60-70% conversion of hydrocarbons due to catalytic oxidation, as shown in Figure 5 [DECSE 2000a] and confirmed by other studies [Suresh 2001].

A slight reduction of NO_x emission, which is typically measured in CDPFs (between 4.9% and -1.5% in Figure 5), is likely caused by internal exhaust gas recirculation due to increased pressure levels in the exhaust manifold, rather than by catalytic reactions. However, just like other oxidation catalysts, CDPFs also change the proportion between NO_x constituents (NO₂/NO) by increasing the NO₂ emissions through the oxidation of NO. Although there is no change in the total NO_x emission, that phenomenon is perceived as a disadvantage, due to the high toxicity of nitrogen dioxide (occupational health!) and possible effects on ozone formation. Example data from chassis dynamometer tests of CDPF-equipped school buses is shown in Figure 6 [LeTavec 2002]. The particulate filter increased NO₂ levels from below 5% to about 30% of the total NO_x. This increase is generally comparable to that measured in the [CRT filter](#), which produced NO₂ levels ranging from 26 to 34% when tested using the same test cycle and fuels (but different vehicles) [LeTavec 2002]. Especially significant increase in NO₂ is caused by filters with Pt catalysts at high loadings, while several base metal formulations are relatively inactive. The results in Figure 6 were obtained using platinum-containing CDPFs of undisclosed Pt loadings.

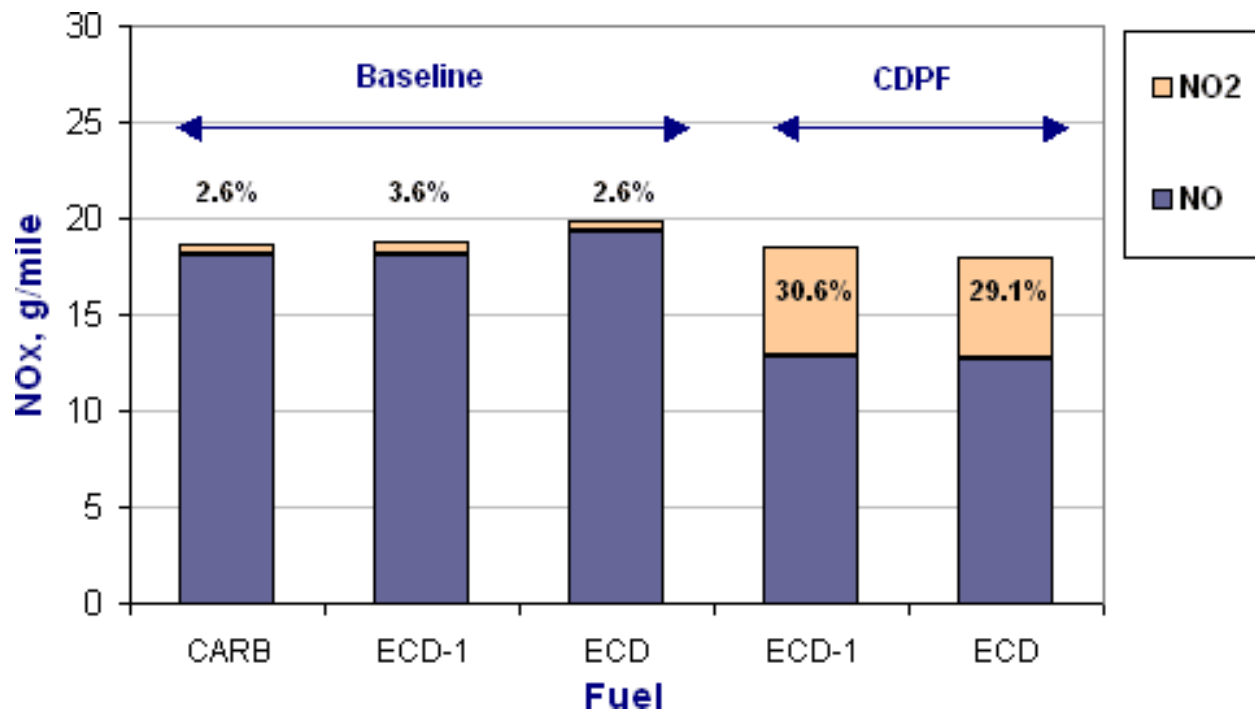


Figure 6. Impact of CDPF on NO₂ Emissions

CSHVR dynamometer driving cycle, average results from 2 school buses, CARB and ARCO (BP) EC diesel fuels

Experiments with fuel sulfur levels changing from 3 to 350 ppm concluded that fuel sulfur does not significantly affect the CO, HC, and total NO_x performance of a platinum based CDPF [DECSE 2000a].

Catalytic conversion of hydrocarbons also results in conversions of particulate SOF and other hydrocarbon derivatives, such as aldehydes or particle- and vapor-phase PAH. The conversion of aldehydes is typically higher than that of HCs and may exceed 90%. Conversions of PAHs after a CDPF were measured anywhere from less than 40% to as much as 97%, depending on the PAH type, association (particle or vapor phase) and test mode [Suresh 2001]. The filter used in the study had a Pt loading of only 5 g/ft³; CDPFs of higher Pt loadings would likely produce higher PAH conversions. Many PAHs were measured at levels below the minimum detectable limit of the measuring equipment, making it difficult to precisely quantify the effect of the CDPF. The same study found an increase of 1-nitropyrene after the CDPF at one engine mode. This nitro-PAH species could have been produced in catalytic reactions in the particulate filter, but could be also an artifact generated by reactions taking place in the PM sampling filter.

The impact of the CDPF on the mutagenic activity results, as determined by the [Ames](#) test, was inconclusive [Suresh 2001]. However, the samples in general showed very little mutagenic activity.

Practical Embodiments

Filter Design

A schematic of a catalyzed ceramic diesel filter was shown in Figure 1 [fig]. The main component of the filter is a catalyzed ceramic wall-flow [monolith](#) made of cordierite or SiC. Cordierite is used mostly in filters for heavy-duty engines, while silicon carbide mostly in light-duty applications. The ceramic monolith is packaged into steel housing using typical wall-flow monolith [packaging](#) techniques. To minimize the total exhaust system back pressure, soot filters are often installed without mufflers. Wall flow monoliths have their own noise attenuation properties and are in most cases a sufficient replacement for the muffler. To minimize installation costs, filter housing may be designed as a direct-fit replacement of the vehicle muffler. Such CDPF-muffler design is common in retrofit urban bus applications.

Since the filter regeneration critically depends on high temperatures, thermal management measures must be carefully considered. The filter unit should be installed as close to the engine exhaust manifold as possible. In OEM applications, where the filter system can be fully integrated with the engine, the pre-turbo position of the particulate filter would provide exposure to the highest possible exhaust temperatures. In practice, however, a pre-turbo CDPF due to its high thermal mass would have a negative impact on the turbocharger response. Therefore, in most engines the preferred CDPF position is immediately after the turbocharger (close-coupled position in passenger cars). To further prevent heat losses—especially if space constraints prevent installation close to the turbocharger—thermal insulation of the inlet exhaust piping and of the filter are often provided in retrofit installations. Both insulation and air-gap exhaust piping can be used in filters designed for new engines. Typically, insulation can prevent about 10°C or more temperature decrease per 1 m of exhaust pipe length due to heat losses.

CDPF sizing varies greatly, depending on the engine technology, duty cycle, fuel quality, and other factors. The most important parameter affecting the filter sizing is the engine-out PM emission, which influences both the regeneration process itself, and the soot holding capacity requirement of the filter. Old, high PM-emission engines typically require much larger filter sizes than cleaner engines. Approximate filter sizing rules depending on engine technology, mostly based on various retrofit applications, are listed in Table 1. The numbers listed under high PM engine category roughly correspond to filter sizing used for older, mechanical engines in underground mine applications. The sizing rules given for low PM emission engines describe the smallest filter volumes as used in certain US 1994 compliant or cleaner highway engines.

Table 1
Typical CDPF Sizing Ranges in Heavy-Duty Engines*

Parameter	Engine PM Emission	
	Low (≤ 0.05 g/ bhp-hr)	High (≥ 0.30 g/ bhp-hr)

Space velocity, 1/h	80,000	25,000
Filter volume/engine displacement ratio	1.5	4
Filter volume/engine rated power, cm ³ /hp	40	150
* Based on 100/17 wall-flow monolith geometry. Smaller filter sizes may be sufficient if monoliths of higher specific filtration surface area are used.		

Passive Filters

Catalyzed filters in their passive form rely on the exhaust gas temperature for thermal [regeneration](#). Through the use of the catalyst, the temperatures required for soot oxidation (normally 550-650°C) are lowered to levels that are seen in real life operation of the engine (300-400°C). As it is the case with catalytic processes, exhaust gas temperature is the most important factor influencing the filter regeneration. The rate of soot oxidation increases with the filter temperature. If the temperature is too low, soot accumulates in the filter causing excessive flow restriction, high exhaust gas pressure losses and, eventually, clogging of the unit. Units overloaded with soot are also prone to uncontrolled regenerations, leading to a mechanical failure of the filter substrate (melting, cracking) due to excessive temperature or temperature stress.

In practical applications, the minimum exhaust gas temperature required to sustain adequate self-regeneration of the CDPF is typically described as the filter inlet temperature that must be reached over a certain minimum percentage of the engine operating time. Using an arbitrary example, one could require that, for a given CDPF application, a temperature of 350°C be reached or exceeded over at least 30% of the duty cycle. Commercial CDPFs offered for a number of nonroad applications over the 1990s typically required exhaust temperatures of 380-420°C over some 25% of the time. Lower exhaust temperatures are sufficient for filters used on newer, cleaner engines, especially in conjunction with ultra low sulfur fuel. One of commercial retrofit systems, the DPX filter by Engelhard, requires an average exhaust gas temperature of at least 225°C for use with a maximum 15 ppm S fuel on post-1994 highway engines in California [Kenny 2001]. Requirements specified in the terms of *average* temperatures are difficult to compare with the previously given figures (and also less suitable for describing the required filter temperatures), but the filters were shown to regenerate at lower exhaust temperatures. In a test on hybrid diesel-electric urban buses in New York City, it was possible to operate DPX filters at exhaust temperatures that hardly exceeded 300°C [Bunting 2001]. The hybrid bus application is characterized by especially low engine-out PM emission due to the absence of rapid engine accelerations and other transients in the hybrid powertrain.

The impact of sulfur on CDPF regeneration is illustrated in Figure 7 [DECSE 2000a]. Balance temperatures for the Engelhard DPX filter were measured in a laboratory as a function of the fuel sulfur content using a nonroad engine of relatively high PM emissions. The balance

temperature was determined using the DECSE 5-mode [balance point](#) test.

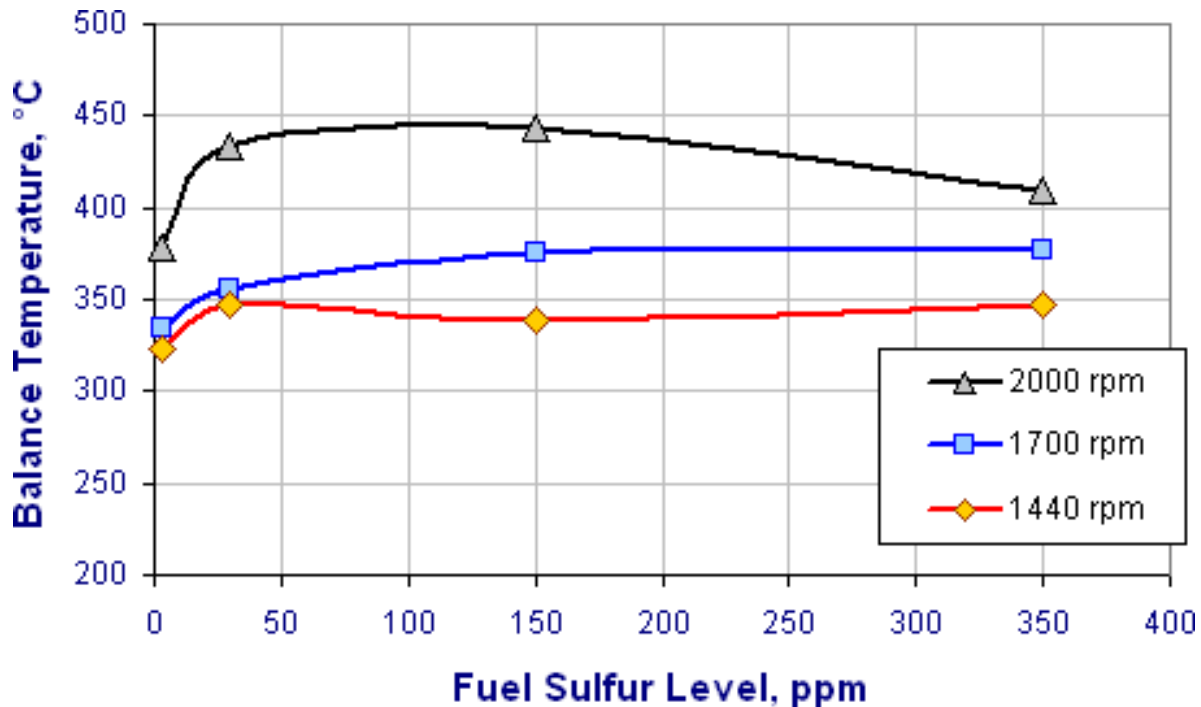


Figure 7. CDPF Balance Temperature at Different Fuel Sulfur Levels

See note in Figure 4 for CDPF and engine information

Laboratory determined balance temperatures, even though not necessarily a good approximation of the temperature requirements in the field, are very valuable in studying the relative changes of the balance point in response to changing system variables. Figure 7 illustrates such changes in response to changing fuel sulfur content and engine speed (exhaust gas flow). There are more variables influencing the CDPF requirements in regards to the minimum operation temperatures, the most important factors being:

- Engine-out PM emission—CDPFs can regenerate at lower temperatures on cleaner engines (compare the discussion of diesel filter [regeneration](#)).
- Sulfur content in the fuel—decreasing the sulfur level from 30 to 3 ppm provided about 30°C improvement in the balance temperature (Figure 7). However, the balance temperature remained relatively constant when sulfur levels were further increased beyond 30 ppm.
- Exhaust gas space velocity—increasing the engine speed and, as a consequence, the exhaust gas flow was found to increase the balance temperature (Figure 7). This finding would suggest that larger filters can regenerate at lower temperatures. However, increasing the filter size beyond a certain point is likely to deteriorate the regeneration due to the “extinguishing” effect of the filter heat capacity on transient temperature spikes.

In a suitable, high temperature application the regeneration of catalytic soot filters is practically continuous and loading and regeneration phases are not well pronounced. Rather, the unit is operating close to balance conditions and the amount of PM oxidized in the filter is approximately equal to the amount entering the filter. This kind of application is illustrated in Figure 8 [Bickel 1993]. Exhaust gas pressure drop and temperature in the catalytic filter were recorded during more than 40 hours of operation on an underground mining vehicle. The engine, CAT 3306 PCTA rated 175 kW at 2200 rpm, was equipped with a ceramic monolith filter 15" diameter \times 15", catalyzed with a base metal catalyst. Temperatures during periods with high engine load were constantly above 450°C. The corresponding pressure drop was fluctuating around 5 kPa (20" H₂O) with no apparent tendency to increase or decrease.

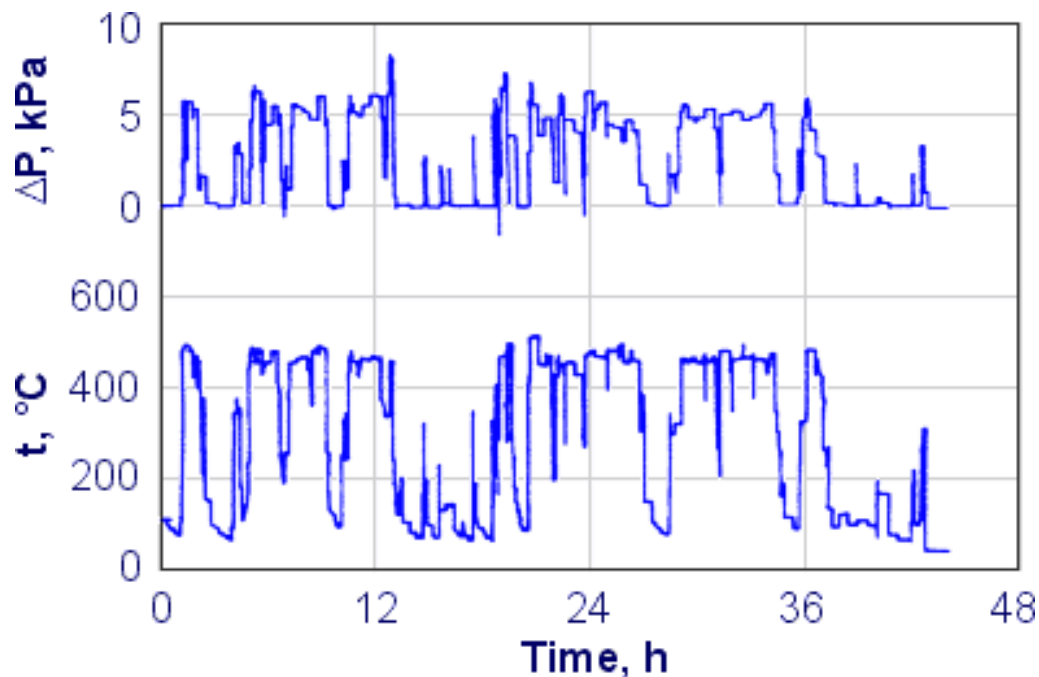


Figure 8. Pressure Drop and Temperature in a CDPF—High Temperature Application

Applications with lower exhaust temperatures may experience a different regeneration and pressure drop pattern. Soot may accumulate during low temperature periods and then rapidly regenerate when the temperature increases, resulting in periodic regenerations. This type of CDPF operation is illustrated in Figure 9, which shows maximum engine backpressure data collected from six CDPF-equipped hybrid diesel electric urban buses during the New York City study [Bunting 2001]. The fluctuation of CDPF pressure drop are a clear indication that regeneration occurred periodically in all filter units.

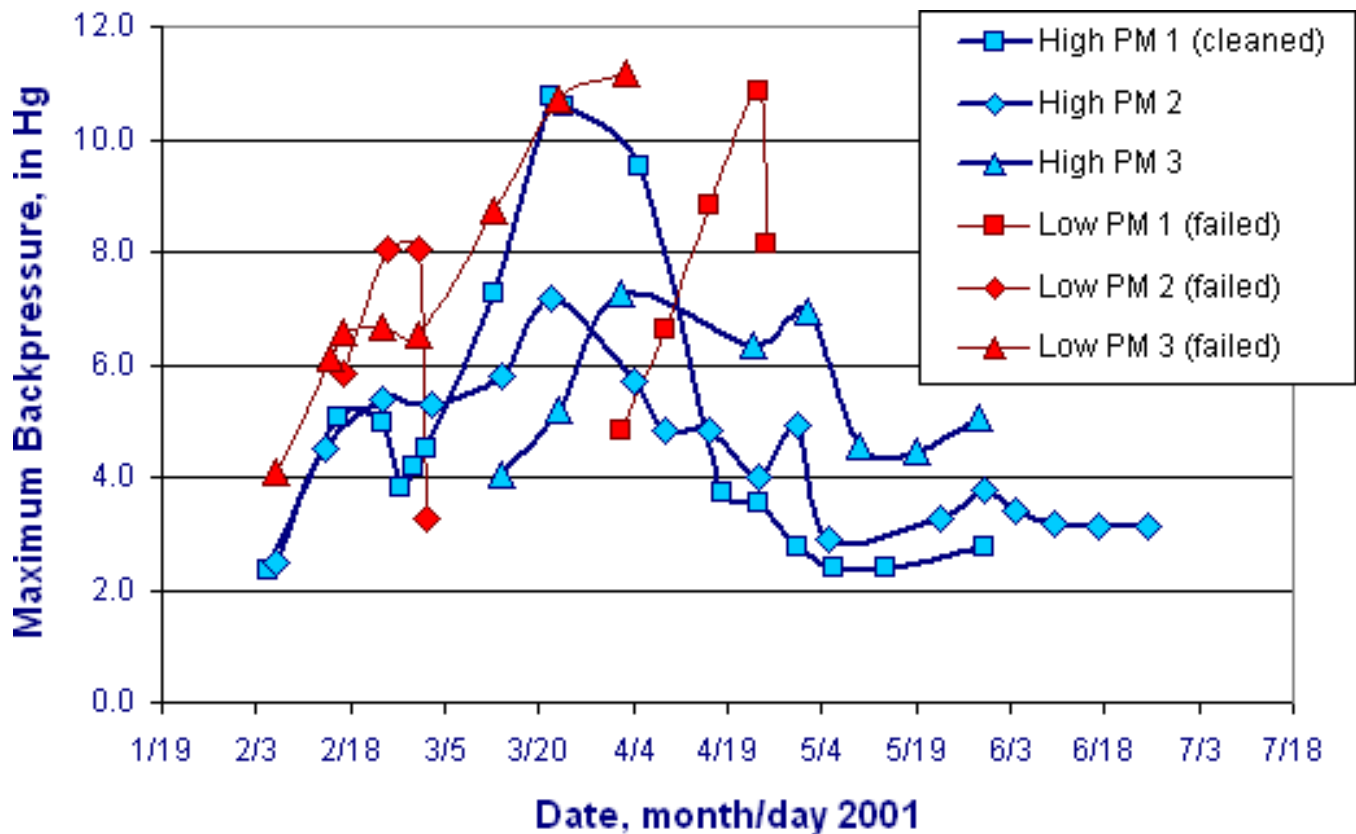


Figure 9. Pressure Drop in a CDPF—Low Temperature Application

Such periodic regeneration pattern carries a danger of an uncontrolled regeneration, which occurs when excess soot becomes ignited during momentary high load operation. If engine speed drops to idle after the soot ignites, the exhaust flow becomes too low to carry away the heat released in the reaction. As a result, internal filter temperatures and/or temperature gradients become high enough to damage the filter substrate. Among the six filters shown in Figure 9, three failed due to uncontrolled regeneration. All of the failed units were filters of low platinum loading, as indicated in the graph. However, even one of the high Pt loading units, which all survived the 6-month field test, had to be removed from the vehicle for cleaning to lower its excessive pressure drop.

Exhaust gas temperatures were very low during the NYC hybrid study. In the winter months (February - March), the exhaust temperatures on most buses exceeded 300°C over only about 10% of the engine running time. During the following warmer months, the 10% temperature oscillated around 325°C . Filter regeneration was observed only once in several bus runs during cold weather conditions.

CDPFs were operated under more favorable, warmer conditions (in regards to both the engine duty cycle and the climate) during the ARCO/BP EC-Diesel Technology Validation Program conducted in California, where passive filters were installed on highway trucks operated with ultra low sulfur diesel. One of the DPX-equipped trucks accumulated over 370,000 miles over a 3.5 year period [Kimura 2004]. The engine produced exhaust gas temperatures above 240°C for over 70% of the duty cycle. The filter sustained passive regeneration, as indicated by the

engine backpressure levels which remained below 2" Hg (6.8 kPa = 27" H₂O) over 70% of the time.

High pressure drop is one of the inherent features of all passive filters, including catalyzed diesel filters. The maximum pressure drop on properly regenerating units in high temperature applications in most cases exceeds 5 kPa (20" H₂O = 1.5" Hg). Low temperature applications can experience much higher exhaust gas pressure losses. Maximum engine backpressure levels exceeding 6" Hg (20 kPa = 80" H₂O) and more are not uncommon in Figure 9. Pressure loss levels of similar magnitude are reported in a number of other field test reports. The filter pressure drop is causing a certain fuel economy penalty associated with this technology, in many cases estimated between 2 and 4%. A fuel economy penalty up to 2% was associated with particulate filters by the DECSE program [DECSE 2000a], which carried out its measurements on a test bench, with filters properly regenerating on relatively hot test cycles. An average fuel economy penalty measured for the CDPF device on the ESC (OICA) cycle amounted to 0.5%.

Mixed Passive-Active Regeneration

In OEM applications, catalyzed filters are often used in systems with active regeneration support. Active regeneration is triggered whenever exhaust temperatures are too low to sustain passive regeneration and the filter accumulates its maximum allowed soot load. This type of filter system is featured in several models of Euro 4 passenger cars in Europe.

In this case, the CDPF becomes just one component of a larger system, which serves more functions than PM control alone. In Euro 4 cars, for instance, CO and HC emissions must be also controlled. The emission control system is integrated with the engine (as engine management strategies are often used to support filter regeneration) and its impact on fuel economy and performance must be optimized. Ideally, one would use a single catalyzed filter in the close-coupled position to control PM, CO, and HC at all operating conditions, including cold start. In practice, a number of different filter configurations have been used, often with an oxidation catalyst (warm-up/NO₂) upstream of the filter. Examples include a close-coupled oxycat-DPF unit or a close-coupled oxycat and an underfloor DPF (with or without an upstream oxycat).

Figure 10 shows a particulate filter introduced in October 2003 for Mercedes E- and C-Class passenger cars with 4-cylinder diesel engines. The filter unit—installed in the close-coupled position—is housing an oxidation catalyst (2.5 liter, >120 g/ft³ Pt) and an SiC-DPF (2.5 liter, 30-40 g/ft³ Pt) [Seguelong 2004].

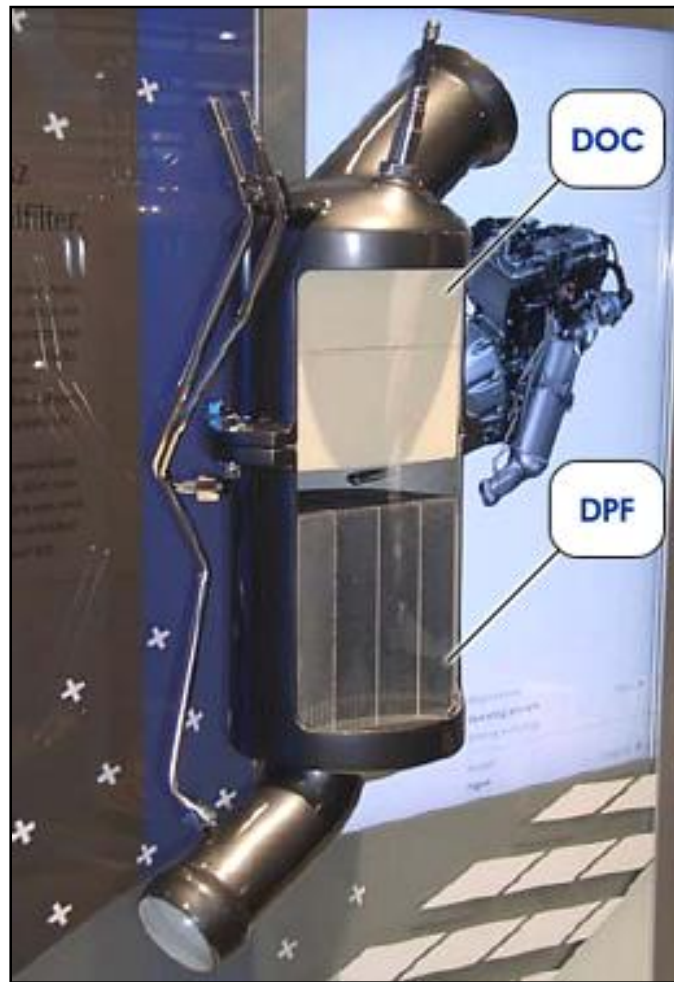


Figure 10. Diesel Particulate Filter for Mercedes-Benz E-Class

There are no clear rules as to Pt loadings in systems with active regeneration—the metal loading is a system design variable. Filters with higher Pt loads rely to a higher degree on passive regeneration, those with lower loadings require more active regeneration. High loadings are possible (which can also promote cold start CO control), as the sulfur-free (10 ppm S) fuel used for Euro 4 type approval testing eliminates sulfate make problems. On the other hand, the filter systems have to be designed to operate and regenerate using the regular Euro 4 fuel (50 ppm S), as well as to tolerate high sulfur fuels in case the vehicle travels to countries where ultra low sulfur diesel is not available.

Filters of similar passive-active regeneration strategy have been also developed for heavy-duty engines. A schematic of particulate filter system commercialized by Hino under the trade name DPR (Diesel Particulate Reduction) is shown in Figure 11. The system has been introduced to a number of engine models. On the 13 liter Hino E13C engine, the DPR system utilizes a 6 liter oxidation catalyst and a 17 liter wall-flow filter [Minamikawa 2005]. Both the DOC and the DPF are coated with a Pt-based catalyst of undisclosed loading. A high porosity cordierite substrate for the DPR was developed by Hitachi Metals (260 cpsi, 12 mil wall, 63% porosity, 21.5 μm avg. pore size). NO_x emissions were controlled by a combination of external and internal EGR.

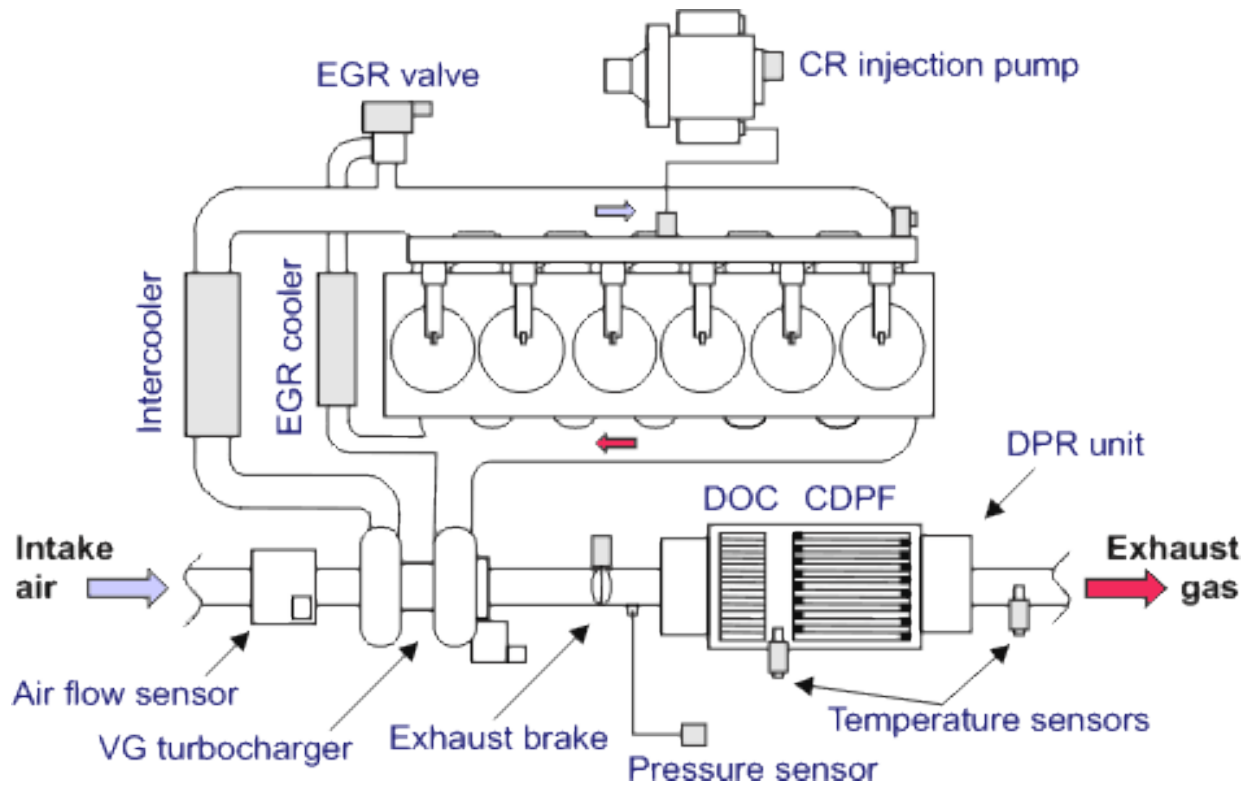


Figure 11. Hino DPR Filter System Schematic

MY 2003 Hino E13C engine (DI, 6 cyl., 12.913 liter, 390-520 hp)

The catalyzed filter can sustain continuous, passive regeneration at engine loads approximately above 40% of the maximum load. At low engine load, active regeneration is triggered by increasing filter temperature to about 600°C through a combination of engine management strategy and a warm-up catalyst.

Two common rail injections can be performed during the expansion stroke to increase the combustion temperature and to enrich exhaust gases in hydrocarbons, which are then oxidized in the catalyst to further increase filter temperature. The late *post-injection* takes place immediately before the exhaust valves open (BDC). When the filter temperature is low, an early post injection (called the *after-injection*) is added just after the TDC. Both of the late injection events are controlled using the filter temperature feedback. Filter temperature and the relative quantity of post- and after-injection during regeneration at low speed driving condition are illustrated in Figure 12.

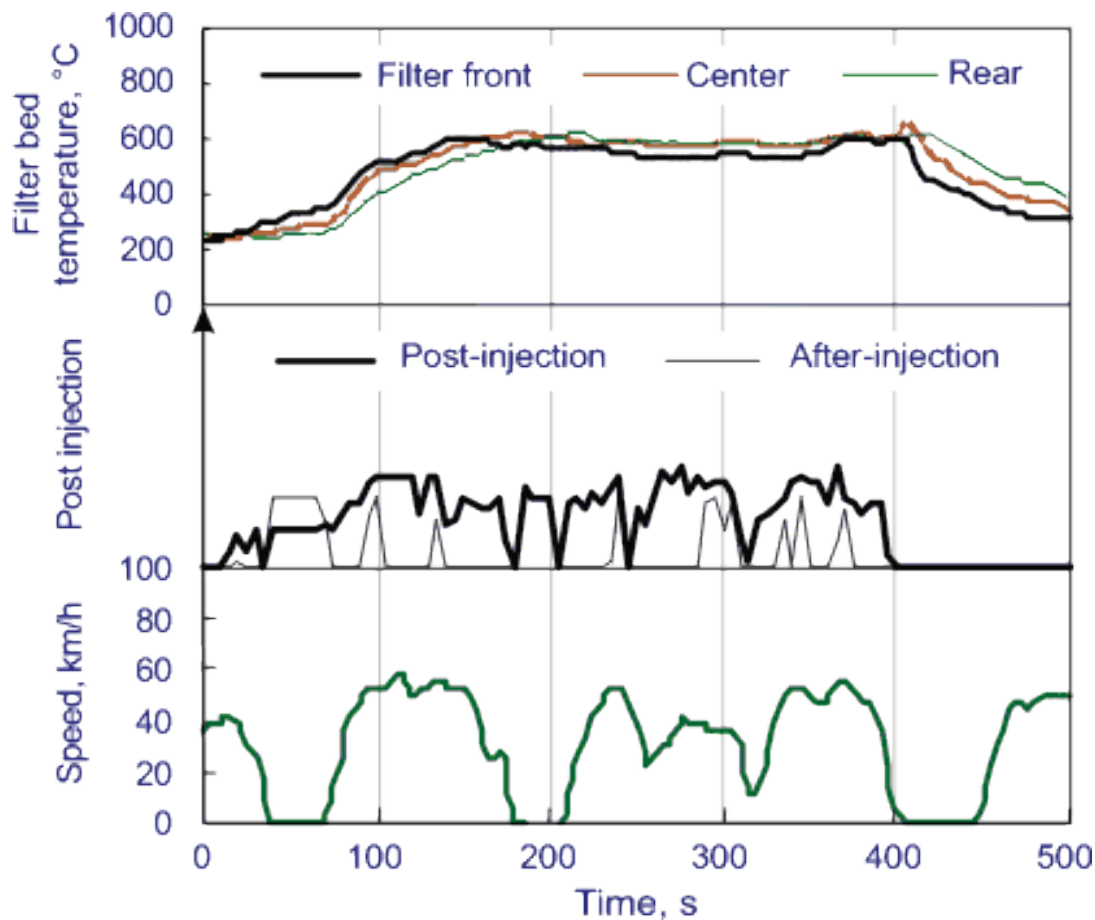


Figure 12. Active Regeneration Under City Driving Conditions

Average speed 25 km/h

A series of engine dynamometer durability tests were conducted (50 ppm S fuel and low ash oil), which showed no increased filter pressure drop, and no catalyst deterioration. Ash accumulation tests (800 hours with normal ash oil) showed a 10% pressure drop increase with passive regeneration, and no pressure drop increase with active regeneration. A filter analysis revealed that most of the ash was collected in the channel ends with active regeneration, as opposed to a more uniform ash distribution with more pore plugging along the channel walls in the passive regeneration test. In case filters accumulate ash during field operation, they can be cleaned by washing with water. The fuel economy penalty from operating the DPR system was less than 1%.

Durability Issues

Long term durability is the most important issue with catalyzed particulate filters, especially in the fully passive configuration. Since filter regeneration depends on the duty cycle, it is very difficult, if not impossible, to ensure failure free operation under all possible operating conditions and duty cycles. Even on hot engines, a single period of extended idling can lead to overloading of the filter with soot, followed by an uncontrolled regeneration and catastrophic

failure.

Proper engine maintenance is also of critical importance in assuring long filter life. In particular, filter catalysts are typically sensitive to poisoning by lubricating oil and its additives. CDPF equipped engines must be well maintained to avoid excessive oil consumption. Engine failures resulting in oil leaks to the exhaust system may result in immediate deactivation of the filter catalyst.

In retrofit applications, long filter lifespan can be ensured through:

1. careful verification (recording) of the exhaust temperature during real operation of the vehicle prior to retrofitting,
2. providing high level of engine maintenance (oil consumption!) after the retrofit, and
3. monitoring the exhaust backpressure on the retrofitted vehicle for early detection of problems.

Filter pressure drop monitors, which can be connected to dashboard-installed warning lights and/or the engine control module, are available with most commercial CDPF systems. The use of such monitors with CDPFs is actually required in some retrofit programs [Kenny 2001].

Excessively high pressure drop is an indication that the filter accumulated too much soot and may be facing an uncontrolled regeneration or plugging. In this case, the unit must be taken off the vehicle and cleaned. In retrofit highway truck applications, the filters are removed for cleaning when their pressure drop exceeds some 20 kPa (6" Hg = 80" H₂O). In the California EC-Diesel program, the alarm was triggered when engine backpressure remained over 6" Hg for 10% of operation in a continuous one hour period [Kimura 2004].

Low pressure drop levels, on the other hand, may be an indication that the filter has already lost its mechanical integrity and is leaking unfiltered exhaust gas. It must be realized that proper implementation of such CDPF monitoring program may result in substantial increase in the amount and cost of the engine and vehicle maintenance, especially if periodic filter cleaning is needed due to insufficient regeneration.

Filter Lifespan. Experience from underground mining indicates that the life time of a CDPF installed on a suitable, high temperature application varies between 5,000 and 10,000 engine hours. However, the average filter life is shorter due to premature filter failures in unsuitable applications (cold engine duty cycle, engine maintenance problems, etc.). According to the US Bureau of Mines estimates from the early 1990s, the average CDPF durability in underground mines was about 2,500 hours. For comparison, emission durability of 8,000 hours or 10 years is required by the US EPA for nonroad diesel engines above 50 hp.

Filters in OEM applications have to meet the regulatory emission durability requirements. The first CDPF-equipped engine that was emission certified in the USA—MY2001 Navistar 530 for school bus application—was a medium-heavy-duty engine of a 185,000 miles required emission durability. In the certification process, the manufacturer demonstrated this durability through accelerated 1000 hour engine dynamometer aging of the CDPF. Particulate filter

manufacturers who verified CDPF systems for the California diesel retrofit program (started in 2000) had to demonstrate emission durability of 150,000 miles and provide product warranty for 100,000 miles. At this time there is insufficient data to estimate the average CDPF life and failure rates in real field operation.

Ash Accumulation. Another source of increased maintenance in CDPF-equipped engines—pertinent to both retrofit and OEM applications—is related to ash emissions. Just like other types of filter systems, CDPFs retain most of metal oxide ash emissions which are generated (primarily) from lube oil additives. Since ashes are incombustible, their accumulation causes steady increase of the filter pressure drop. This problem may be alleviated by periodic cleaning of the filter using water, compressed air, steam, or other means (cleaning operations should conform to the manufacturers' recommendations to avoid any detrimental effect to the catalyst).

Experience from retrofit installations in the UK in the late 1990s indicates that de-ashing of CDPFs may be needed as often as every 30,000 km [Lemon 2001]. On the other hand, the EC-Diesel program in California found that maintenance/de-ashing intervals in CDPF retrofits were as long as 240,000 km (150,000 miles), exceeding the CDPF manufacturer recommendation of 60,000 miles [LeTavec 2002]. These differences are likely caused by different engine technologies and duty cycles, as well as different lubricating oil quality. In the California program, CDPFs were operated on highway trucks which were likely characterized by more favorable duty cycles with engines remaining warm for prolonged periods of time, resulting in less lube oil consumption. Filter cleaning intervals can be certainly maximized through the use of low ash lube oils.

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