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sierra research
1801 J Street
Sacramento, CA 95811
Tel: (916) 444-6666
Fax: (916) 444-8373
Ann Arbor, MI
Tel: (734) 761-6666
Fax: (734) 761-6755

August 30, 2007

Memo to: Rick Martin, APCO
North Coast Unified Air Pollution Control District

From: Gary Rubenstein

Subject: PM Control Efficiency of Diesel Oxidation Catalysts

At your request, we have assembled and summarized the information available regarding the expected control efficiency of Diesel oxidation catalysts (DOCs) on both PM_{10} and $PM_{2.5}$ (collectively referred to as particulate matter, or PM). As you know, the engines proposed for use at the Humboldt Bay Repowering Project will be equipped with oxidation catalysts, but the emission limits presented in the Application for Authority to Construct do not take credit for any benefits these catalysts will provide with respect to PM emissions. Oxidation catalysts act on the liquid hydrocarbon portion of PM, oxidizing the hydrocarbons to CO_2 and water.

According to the attached summary from the Washington State University Extension Energy Program (Attachment 1), "[a]bout 30 percent of the total particulate matter (PM) mass of diesel exhaust is attributed to liquid hydrocarbons, or soluble organic fraction (SOF)...Under certain operating conditions, [Diesel oxidation catalysts] have achieved SOF removal efficiencies of 80 to 90 percent... As a result, the reduction in overall PM emissions from DOC use is often cited at 20 to 50 percent."

Attachment 1 cites a 1999 US EPA review of emissions data for heavy-duty two- and four-stroke engines using DOC technology, which found PM reductions ranging from 19 to 50 percent, with an average reduction of 33 percent. Attachment 1 also cites a CARB review, which found reductions ranging from 16 to 30 percent.

Attachment 2 is a slide presentation on DOC performance presented by Engelhard to CARB in 2001. This presentation indicates that DOCs typically reduce particulate matter by 25 to 50 percent, with an average in field performance of about 35%.

The Clean Air Fleets emission control technology summary in Attachment 3 indicates that precious metal oxidation catalysts are expected to reduce DPM emissions by up to 40%. This emission reduction is the same as that quoted by US EPA in its Diesel Retrofit Technology Verification Technical Summary (Attachment 4).

DCL International Inc. (Attachment 5) cites typical conversion efficiencies of 10 to 40% for its DOCs.

The summary of emission control technologies for off-road Diesel equipment prepared by the Manufacturers of Emissions Control Technology (MECA) (Attachment 6) indicates that retrofit oxidation catalysts have been verified to provide at least a 25 percent reduction in PM emissions.

The control efficiencies cited by the various references are summarized in the following table.

Reference	Cited DOC Control Efficiency
WSU Extension Energy Program (EPA)	19 to 50%
WSU Extension Energy Program (CARB)	16 to 30%
Engelhard	20 to 50%
Clean Air Fleets	up to 40%
US EPA Diesel Retrofit Technology Verification Technical Summary	up to 40%
DCL International	10 to 40%
MECA	at least 25%

These references indicate a range of efficiencies from 10 to 50%, with the majority of the results falling between 25 and 40%. Because many of these studies include retrofit rather than original equipment installations, we believe the lower end of the cited efficiencies is unrealistically low. Overall, a control efficiency of 30% represents the middle of the range of cited efficiencies and probably underestimates the true PM emissions reductions that will be achieved by the DOCs.

If you have any questions regarding the information we are providing, please do not hesitate to call.

attachments

Attachment 1

Washington State University Extension Energy Program

Diesel Oxidation Catalyst

A diesel oxidation catalyst (DOC) is a flow through device that consists of a canister containing a honeycomb-like structure or substrate. The substrate has a large surface area that is coated with an active catalyst layer. This layer contains a small, well dispersed amount of precious metals such as platinum or palladium. As the exhaust gases traverse the catalyst, carbon monoxide, gaseous hydrocarbons and liquid hydrocarbon particles (unburned fuel and oil) are oxidized, thereby reducing harmful emissions.

About 30 percent of the total particulate matter (PM) mass of diesel exhaust is attributed to liquid hydrocarbons, or soluble organic fraction (SOF). (See Ref. 1.) Under certain operating conditions, DOCs have achieved SOF removal efficiencies of 80 to 90 percent. (Refs. 1, 2) As a result, the reduction in overall PM emissions from DOC use is often cited at 20 to 50 percent. Actual emission reductions vary however, as a result of engine type, size, age, duty cycle, condition, maintenance procedures, baseline emissions, test procedure, product manufacturer and the fuel sulfur level.

Emissions

In their 1999 review of heavy-duty diesel retrofits, the U.S. Environmental Protection Agency summarized emissions data for 60 heavy-duty diesel two and four stroke engines utilizing DOC technology (Ref. 3). The following table presents these results, which ranged from 19 to 50 percent reduction in total PM, with an average PM reduction of 33 percent.

Table 1
Diesel Oxidation Catalyst Use in Heavy Duty Diesel

Study/report	PM Reductions
Urban Bus and Engelhard Data	38% avg.-two stroke; 27% avg.-four stroke
SAE 960134	32.8% avg. (2-two stroke; 5-four stroke)
SAE 970186	24% avg. (5-twostroke; 5-four stroke)
SAE 932982	44-60% (four stroke)
SAE 950155	32-41% (two stroke)
London Bus Report –MBK 961165	45% (6-four stoke)
Engelhard Report-980342	49% (avg for three catalysts)
APTA Report	19-44% (two stroke)

Source: Heavy-Duty Diesel Emission Reduction Project Retrofit/Rebuild Component, US EPA, EPA420-R-99-014, June 1999.

In developing the California Diesel Risk Reduction Program, the California Air Resources Board (CARB) also reviewed a number of products and technologies that were reported to reduce diesel particulate emissions.(Ref. 2) While much of this information was based on manufacturer provided data, it provides a reasonable summary of DOC technology at that time. The PM reductions identified are similar to those reported by EPA's 1999 study of diesel retrofit technologies. CARB reported achievable emission reductions resulting from DOC use ranging from 16 to 30 percent depending on product and test cycle. A summary of the CARB analysis is presented in Table 2.

Table 2
Diesel Oxidation Catalyst PM Emission Test Results

Test	Engine type	PM Control Efficiency
ISO 8178-D2	Ford-150 hp	8%
ISO 8178-D2	Ford-150 hp	21%
8-mode	1979 Deutz F6L-	16%

steady- state	912W	
Transient cycle-bulldozer	Cummins TD-25G 450 Hp	24%
FTP	1992 Cummins L-10 280 Hp	30%
FTP	1998 DDC Series 60 400Hp	5 separate DOCs- 23%, 25%, 5%, 29%, 27%.

Source: Diesel PM Control Technologies-Appendix IX, California Air Resources Board, October, 2000.

A number of other studies also document the effectiveness of DOCs in reducing PM emissions, with PM emission reductions of 23 percent or more. (Refs. 4,5) However, emission results will vary and retrofit device performance should be verified. To date, the EPA has verified PM reductions of 25 percent for three manufacturers of DOCs. Verification data is available at http://www.epa.gov/otaq/retrofit/retroverifiedlist.htm. California also provides a list of verified DOCs at http://www.arb.ca.gov/diesel/verifieddevices/verdev.htm.

Cost

The initial cost of DOCs will vary with engine size, application, and sales volume. CARB reported costs ranging from $2,100 for a 275 horsepower engine, to as much as $20,000 for a 1,400 hp engine.(REF. 2) A 1999 study of diesel particulate control devices for the underground mining industry indicated a cost of $8 to $12 per horsepower for DOCs, while the Manufacturers of Emissions Controls Association (MECA) recently reported DOC costs of $425 to $1,150 per device. (Ref. 5, 6) The Everett School District in Washington State is currently paying $2,500 per DOC for school bus retrofits. (Ref. 7) DOC costs for heavy duty construction equipment retrofits in Massachusetts are ranging from $1,500 to $3,000. (Ref. 8)

An oxidation catalyst retrofit system consists of either an in-line engine muffler replacement or an add-on control device. The size of the DOC will need to be matched to engine displacement and the exhaust system. Installation can take as little as 1½ hours to 3 or 4 hours depending on the application, with corresponding costs of $170 to $500. (Ref. 2,4) MECA reports that oxidation catalysts require very little maintenance, do not increase engine fuel use, shorten engine life or adversely affect vehicle drivability. The CARB reports annual maintenance costs of $64 to $712 per year for DOCs can be expected, based on the need to thermally clean the device from one to as many as four times per year. (Ref. 2) The Massachusetts Diesel Retrofit Program has retrofitted more than 120 diesel construction equipment engines with DOCs and has experienced no additional maintenance costs over the first three years of operation. (Ref. 8)

Other issues

Oxidation catalysts have a long history of performance. Retrofit of DOCs has been under way for more than 20 years in the off-road vehicle sector, most notably in the underground mining industry, with over 250,000 engine retrofits. An additional 20,000 DOCs have been installed on buses and highway trucks in the United States and Europe since 1995, with several thousand more installed in Asia and other parts of the world. DOCs can be specified for most new engine purchases and will become a standard feature for new engines by 2004 or earlier.

For the most part, DOC retrofit applications are less restrictive than diesel particulate filter technologies. This is due in part because a DOC operates as a flow through device with the catalytic reaction occurring on the surface of the device. As a result, DOCs are less impacted by exhaust loading than particulate filters, and can work well with older, higher emitting engines. (Ref. 9)

In general, DOCs also operate well within the normal exhaust temperatures of a diesel engine. (Ref. 9) However, elevated exhaust temperatures, such as those sustained near peak torque, may adversely affect DOC performance in the presence of high sulfur concentrations. (Ref. 10) At higher temperatures, catalysts can oxidize sulfur dioxide to form sulfate particulates (sulfuric acid). Therefore, higher sulfur fuels can increase total particulate matter emissions and may offset soluble organic fraction emissions reductions.

Although DOCs can be designed or tailored to operate under high sulfur concentrations, the use of lower sulfur fuels should improve the devices particulate reduction efficiency. (Refs. 2,5,9). As a result, some manufacturers recommend a maximum sulfur content of 500 parts per million or less to enhance DOC durability and performance. (Ref. 2) To minimize the effect of sulfate formation on DOC performance and maximize DOC reduction efficiency, CARB staff have suggested the use of ultra-low sulfur diesel fuels of 15 ppm. (Ref. 1)

Manufacturers claim that the useful life of the device will vary with the application and can range from 4,000 to 10,000 operating hours.(Ref. 2) Some manufacturers suggest the useful life of the device is consistent with the rebuild cycle of the associated engine, and should be changed accordingly. The Big Dig project in Massachusetts retrofit more than 120 construction vehicles. They are currently examining a select number of these devices after three years of operation, and expect to get an additional two to three years before replacement. (Ref. 8)

DOCs may suffer thermal degradation when exposed to temperatures above 650° C (1,200°F) for prolonged periods of time. Diesel engines have intrinsically cool exhaust gases and thermal catalyst deterioration is not likely to take place under normal operating conditions. (Ref. 9) Several chemical elements, such as phosphorous, lead and heavy metals, may also damage some catalysts. Some of these elements may be contained in engine lube oil. To avoid this possibility, low lube oil consumption and the use of low-phosphorous oils may be required for some catalysts. Although DOCs impose additional exhaust gas flow restrictions of 4 to 11 inches of water column this appears to be within the normal range of engine manufacturer specifications. (Ref. 2) As a result, DOCs do not appear to affect original engine warranties. (Ref. 2,8)

References

1. California Air Resource Board Staff Report, *Initial Statement of Reasons for Proposed Regulation for the Verification Procedure for In-Use Strategies for Controlling Emissions from Diesel Engines-Appendix B. Diesel Engine Emission Control Technologies,* March 29, 2002.
2. California Air Resource Board, *Diesel PM Control Technologies, Appendix IX*, October 2000.
3. U.S Environmental Protection Agency, *Heavy-Duty Diesel Emission Reduction Project Retrofit/Rebuild Component,* EPA420-R-99-014, June 1999.
4. *Construction Equipment Retrofit Project- Summary Report*, Northeast States for Coordinated Air Use Management.
5. *Diesel Emission Control Strategies Available to the Underground Mining Industry,* ESI international, February 24, 1999.
6. *Diesel Exhaust Retrofit Programs-Available Control Technologies and Retrofit Program Considerations*, Manufacturers of Emission Controls Association, Waterfront Diesel Emissions Conference, Long Beach, California, October, 25, 2001.
7. Personal communication, Brian Higginbotham, Durham School Services, September, 2002.
8. Personal communication, Coralie Cooper, Northeast States for Coordinated Air Use Management, September, 2002.
9. Personal communication, Marty Lassen, Johnson Mathey, September 2002.
10. U.S. Department of Energy, *Diesel Emission Control-Sulfur Effects Projects Summary,* June 2001.

Attachment 2

Description of a Diesel Oxidation Catalyst

- ***DOC's are typically flow through designs***
- ***The design is composed of the following elements***
  - ***Catalyst wash coat - Base Metal Oxide and Precious Metal***
  - ***Substrate - ceramic or metallic***
  - ***Canning - separately as a converter or in the muffler***

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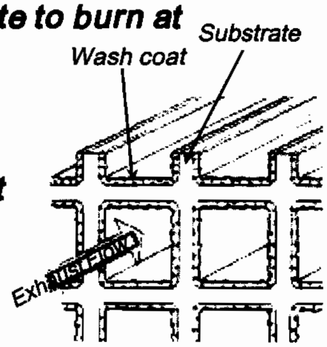
How the DOC Functions

- ***The catalyst interacts with the exhaust as it passes through the converter***
- ***The Catalyst causes the particulate to burn at normal exhaust temperatures.***
- ***The DOC burns the gaseous HC and CO emissions, and the lube oil, unburned fuel and carbon soot of the TPM***



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Typical DOC Performance

- *Total Particulate Matter Reduction of 25% to 50%*
- *Hydrocarbon reduction of more than 50%*
- *Carbon Monoxide reduction of more than 40%*

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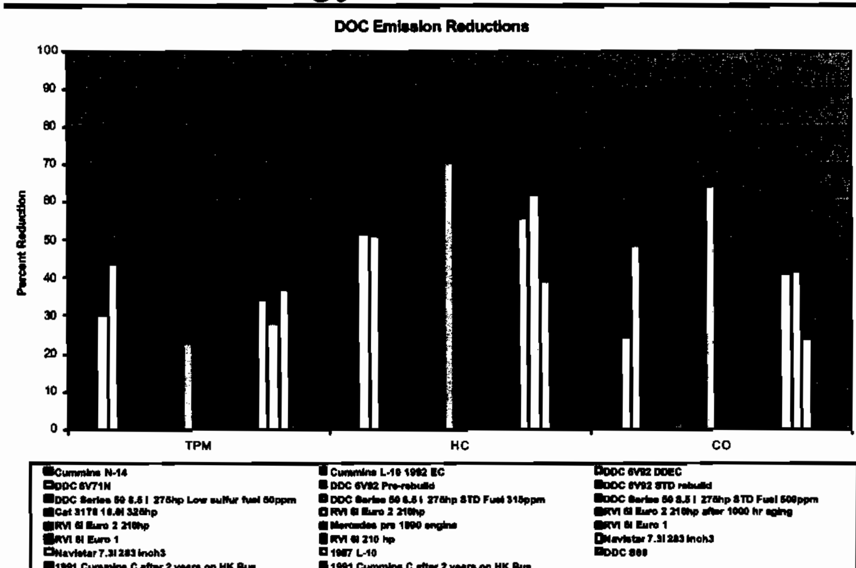
DOC Technology Diesel Emissions



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DOC Field Performance

			Percent Reduction				
Location	Vehicle	Engine	CO	NOx	HC	TPM	Smoke
Mexico City	Truck	Perkins	89.6	0	81.1	46	NA
Mexico City	Truck	Mercedes	72.1	0	74.8	28.8	NA
Hong Kong	Bus	Gardner	NA	NA	NA	38	35
USA	Truck	Cummins	38.7	0	18.5	23.5	NA
USA	Truck	Caterpillar	38.1	0	65.6	44	NA
USA	Bus	DDC	22.7	0	34.9	24.5	NA
USA	Bus	Cummins	48	0	54	32	NA
USA	Dozer	Caterpillar	NA	NA	NA	26	NA
France	Bus	RVI	22	0	27	52	NA
Average			47.31		50.84	34.98	

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Conclusions

- **If ARB wants some particulate reduction for all vehicles a 30% minimum is to high**
- **A properly sized DOC can obtain 25% TPM reduction on diesel engines**
- **The lower the sulfur in the fuel the greater the ability to of the DOC to reduce TPM emissions**
- **This technology is proven and available for all on and off road diesel engine applications**

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Attachment 3

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Emission Control Technology

There have been tremendous developments in the design and application of emission control technologies in the last decade to substantially reduce levels of particulate matter (PM), carbon monoxide (CO), nitrogen oxide (NOx), and hydrocarbon (HC) pollutants. The two most common technologies – diesel particulate filters (DPF) and oxidation catalysts (DOC) – effectively control the levels of pollutants in the exhaust on their own or when used together. For example, a diesel oxidation catalyst can lessen the formation of particulate matter prior to the exhaust passing through a particulate filter, thereby increasing the performance and longevity of the filter. Additional technologies are designed to control specific pollutants, such as NOx.

While some of these technologies are affected less by the sulfur content of diesel fuel, all perform better at reducing emissions when used with ultra-low sulfur diesel fuel (ULSD), which has a sulfur content of less than 15 ppm. For example, diesel oxidation catalysts and some DPFs can reduce CO, HC, and PM emissions with fuels that contain sulfur levels greater than 15 ppm while catalyst-based DPFs are more sensitive and are more effective with ULSD. (See the insert on "Alternative Fuels" for more information.)

Costs for individual technologies vary. This insert cites costs from an independent cost survey conducted in November 2000 by the Manufacturers of Emission Controls Association (MECA). Generally, the larger the engine being retrofitted, the more expensive the device. However, higher sales volumes will begin to lower the costs of these technologies. Given the recent market penetration, costs should begin to decrease. Prices cited in association with specific technologies and their pollution reduction potential are provided by the U.S. Environmental Protection Agency (EPA). The reader is encouraged to contact individual manufacturers for exact costs.

Diesel Particulate Filters (DPF)

	NOx	PM	HC	CO	Price
Base Metal Oxidizing PM Filter	--	80%	50%	50%	$6.5-10K
Highly Oxidizing Precious Metal PM Filter	0-5%	>90%	90%	90%	$6.5-10K

	NOx	PM	HC	CO	Price
Base Metal Oxidation Catalyst	--	10-30%	50%	50%	$1-2K
Precious Metal Oxidation Catalyst	--	>20-40%	90%	90%	$1-3K

Diesel particulate filters (DPFs) are one class of emission control technologies that lower PM emissions. By trapping the particulates as the exhaust gas passes through the filter, DPFs are able to achieve PM reductions of 80 – 90 percent. Numerous studies have documented the effectiveness of DPFs in both on- and off-road applications. The systems are relatively easy to maintain, but do require users to monitor their condition and occasionally remove the filter, blowing out the ash and replacing it.

Fuel sulfur content plays a key role in the performance of DPFs since it has a direct impact on the level of particulate matter in the exhaust. Numerous studies have found that DPFs, regardless of their manufacturer, achieve higher PM emission reductions with the use of ultra-low sulfur diesel fuel.

Two DPF products – Engelhard's DPX Catalyzed DPF and the Johnson Matthey Continuously Regenerating Technology (CRT) Particulate Filter – reduce PM, CO, and HC by 60 percent as verified – but are capable of reducing emissions by 80 – 90 percent. Both technologies are verified by EPA's National Voluntary Diesel Retrofit Program – which tests and validates technologies for fleet managers and operators – for their performance. These products are verified with ULSD. Today's technology could be utilized in many off-road applications but requires active regeneration technology being developed for on-road use to make it applicable to all off-road applications. DPF retrofit programs for trucks and buses are underway in California and New York City, where the city plans to retrofit its 3,500 buses with DPFs by the end of 2003.

Diesel Oxidation Catalysts (DOC)

Diesel oxidation catalysts (DOCs) are a section of the exhaust system coated with metals that trigger chemical reactions which breakdown pollutants (CO, HC, PM) into harmless gases, when engine exhaust passes through it. Since 1995, more than 500,000 trucks and buses have been retrofitted with DOC systems.

On- and off-road applications of DOCs are virtually maintenance free, requiring only periodic inspections. DOCs also work to improve the effectiveness and performance of DPFs, by attracting excess soot from the exhaust before it passes through the filter. The cost of diesel oxidation catalyst devices range from several hundred to several thousand dollars per device depending on engine size, sales volume, and whether the installation is a muffler replacement or an in-line installation. MECA's 2000 survey reported that average diesel oxidation catalyst costs ranged from $465 to $1,750 per vehicle. The majority of devices are designed to replace the muffler and installations typically take less than two hours.

Like DPFs, DOCs are also affected by sulfur. The sulfur content of diesel fuel is critical to applying catalyst technology, as the reaction caused by the catalysts rely on the sulfur content and the temperature of the exhaust gases.

NOx Reduction Technologies

The first verified system to reduce NOx and PM is a NOx reduction catalyst. This system combines a NOx catalyst with a particulate filter or oxidation catalyst to provide additional PM reductions. The Longview system from Cleaire (and offered by Fleetguard Emission Solutions) is verified to reduce NOx by 25 percent and PM by 85 percent.

In addition to the exhaust gas recirculation (EGR) technology to lessen NOx during the combustion process (see the insert on "Advances in Diesel Engine Technology" for more information), post-combustion emission controls for NOx include selective catalytic reduction (SCR) and NOx adsorber technologies.

SCR devices have been used for years to control NOx from stationary sources and are now being applied to mobile sources to cut the pollutant by over 70 percent. Unlike DOCs, the SCR system requires the addition of a reductant (typically urea or ammonia) to convert NOx pollutants to nitrogen and oxygen. Based on the oxidizing metals used in the SCR, additional pollutant reductions can be achieved. (See the insert on "Off-Road Heavy-Duty Diesel Vehicles" for more information.)

NOx adsorber catalyst technology is also undergoing extensive research and development in anticipation of the 2007 on-road, heavy-duty diesel engine regulations. Researchers have demonstrated the ability of NOx adsorbers to control up to 90 percent or more of NOx emissions over a broad temperature range.

NOx adsorbers act to store NOx emissions during lean engine operation and release the stored

NOx by periodically creating a rich exhaust environment by either engine operation or the injection of a reductant in the exhaust stream. While EPA estimates that the technology can cut NOx (as well as HC and CO) by more than 90 percent, it is still largely in the research and development phase for on-road applications.

Crankcase Emission Control

In the majority of turbo-charged diesel engines, the crankcase breather is vented to the atmosphere often using a downward directed draft tube, therefore allowing a substantial amount of PM to be released into the atmosphere. One solution to this emissions problem is the use of a multi-stage filter designed to collect and return the emitted lube oil to the engine's sump or a CCV system (available from Fleetguard). These systems allow filtered gases to return to the intake system, balancing the differential pressures involved and allowing the systems to eliminate crankcase emissions. EPA has verified one manufacturer's crankcase filtration system. In addition to the Donaldson closed crankcase filtration system's ability to lower crankcase emissions, it also reduces PM emissions by 25 – 32 percent and CO by 14 – 18 percent, according to EPA.

Additional Technology Potential

The California Air Resources Board recently verified the use of a diesel engine retrofit technology that simultaneously achieves reductions of at least 85 percent in PM and 25 percent in NOx emissions. The system produced by Cleaire Advanced Emission Controls is actually a combination of a lean NOx catalyst and a diesel particulate filter. The system has been verified for use on specific on-road diesel engines operating on ultra-low sulfur diesel fuel. In addition to DOC technology used to treat exhaust gases, EPA estimates that catalysts included in diesel fuel for commercial use will cut NOx up to 10 percent, PM up to 33 percent, and HC and CO up to 50 percent during the combustion process.

The Lubrizol Corporation has developed a water-in-diesel fuel emulsion product that produces a low-emission, emulsified diesel fuel. PuriNOx reduces NOx emissions up to 30 percent and PM up to 65 percent when compared to conventional No. 2 diesel fuel. Average emission reductions, considering data from numerous tests, indicate a NOx reduction of approximately 20 percent and a PM reduction of approximately 54 percent. The application areas for fuel powered by PuriNOx are centrally-fueled fleets, such as pick-up and delivery vehicles, urban and school buses, waste management fleets, and agricultural, mining, and construction equipment.

Sources

DieselNet – http://www.dieselnet.com/
Manufacturers of Emission Controls Association – http://www.meca.org/
U.S. Environmental Protection Agency, Voluntary Diesel Retrofit Program – www.epa.gov/otaq/retrofit

Attachment 4

Diesel Retrofit Technology Verification

Technical Summary

The following table lists information collected by EPA staff showing the potential capabilities of a variety of both currently available and future emissions reduction technologies. This list may not be used to provide formal emission reduction claims for SIP purposes, compliance programs, or consent decree projects. This list is intended to provide guidance in selecting appropriate technology for air quality program needs and to provide a general estimate of the emissions reduction capabilities of the various technologies. Actual emissions reductions, cost, fuel economy penalty will be a function of the individual applications and situations. EPA has created a verification program that will officially evaluate the emission performance of technology as individual manufacturers submit their products to the verification program. EPA will list the official performance data and associated information on our Diesel Retrofit Program's Verified Technology List.

Related Information

- All EPA Verified Technologies
- Nonroad Engine Technologies

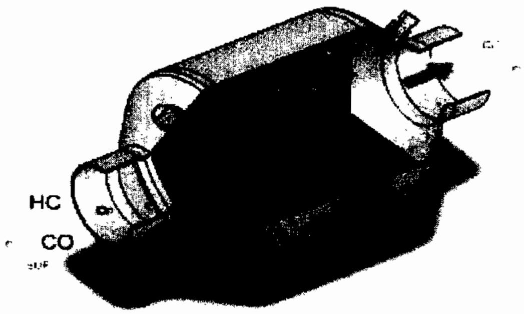
Summary of Potential Retrofit Technologies

Technology	Emission Reduction				Price ($)	Sulfur Tolerance (ppm)	Fuel Penalty (%)	Performance Penalty	Availability/Maturity	Issues/Comments
	NOx	PM	HC	CO						
Base Metal Oxidation Catalyst	--	10-30	50	50	1-2K	<500	0-2	--	commercial; proven	designed to minimize oxidation of sulfur
Precious Metal Oxidation Catalyst	--	20-40	90	90	1-3K	<15	0-2	--	commercial; demo	designed for maximum reductions
Base Metal Oxidizing PM Filter	--	80	50	50	6.5-10K	<500	2-4	--	commercial; demo	reliable regeneration without supplemental addition of heat limits application based on duty-cycle, ambient condition considerations
Highly Oxidizing Precious Metal PM Filter	0-5	>90	90	90	6.5-10K	<15	1-3	--	commercial; demo	with care can be applied to all applications
Active Lean NOx Catalyst (requires supplemental fuel injection)	20	--	--	--	6.5-10K	<250	4-7	--	commercial; demo	possible N_2O generation; 10k hr durability data exists
4-Way Catalyst (ActiveLean NOxCat + PM Filter)	20	80	70	70	8-10K	<500	4-7	--	commercial; demo	currently undergoing durability testing
NOx Adsorber	>90	10-30	90	90	--	<15	--	--	2007; R&D	requires engine integration, means for supplemental fuel injection
Diesel Emulsion	5-30	20-50	--	--	0.01/gal	above 500	none	requires engine re-calibration to maintain power, PM benefit due to engine de-rate calibration changes may mean no PM	commercial; demo	undergoing health effects testing, injection system durability issues, cold start PM/HC/CO emissions can increase, additives used to prevent emulsion freezing can make aldehydes/

								benefit		formaldehyde
Selective Catalytic Reduction	60	0-30	50	50	10-20k Urea 0.80/gal	<500	urea consumption ~4% of fuel use	--	commercial; demo; proven for stationary	infrastructure; requires engine integration: NOx sensor or engine NOx-map; ammonia slip possible vanadium emissions
Compact Selective Catalytic Reduction	90	10-30	90	90	10-20k Urea 0.80/gal	<50	urea consumption ~6% of fuel use	--	--	uses precious metal oxidation catalysts to improve NOx control and to limit Ammonia slip; issues same as above
Fuel Borne Catalyst	<10	<33	<50	<50	.05-.06/gal.	<350	(8)	--	commercial; demo	not much known; undergoing health effects testing, potential for fine metallic emissions, some providers now only sell product when operated with a PM filter
FBC w/lightly catalyzed oxidation catalyst	<10	30-60	<50	<50	1-1.5K .05-.06/gal.	<350	(4-6)	--	commercial; demo	potential for fine metallic emissions, some providers now only sell product when operated with PM filter
FBC w/lightly catalyzed PM filter	<10	85	80	80	3.5-4.5K .05-.06/gal.	<50	2-(2)	--	commercial; demo	designed to meet CARB target of 0.01g/bhp-hr. exhaust temperature needed for regeneration limits applications based on duty cycle, ambient condition considerations .
Cooled-EGR	50	see issues	--	--	--	<500	0-5	--	commercial demo from engine manufacturers; R&D as a retrofit	requires major engine integration: fuel and air management system upgrades needed to counteract increased PM from EGR; condensation concerns; packaging constraints

Attachment 5

Diesel Oxidation Catalyst



The diesel oxidation catalyst (DOC) is effective for the control of carbon monoxide (CO), hydrocarbons (HC), odor causing compounds, and the soluble organic fraction (SOF) of particulate matter (PM_{10}).

Typical Conversion Efficiencies

NOx	CO	HC	Aldehydes (odor causing)	PM_{10}*
Nil	70-95%	70-90%	70-90%	10-40%

** Less than 50 ppm sulphur in diesel fuel is required for PM_{10} conversion*

Reactions

Carbon Monoxide	$CO + ½ O_2 \rightarrow CO_2$	(1)
Gas Phase Hydrocarbons	$C_mH_n + (m + n/4) O_2 \rightarrow m CO_2 + n/2 H_2O$	(2)
Liquid Phase Hydrocarbons (SOF)	$C_mH_n + (m + n/4) O_2 \rightarrow m CO_2 + n/2 H_2O$	(3)
Aldehydes, Ketones, etc.	$C_mH_nO + (m + n/4 - 0.5) O_2 \rightarrow m CO_2 + n/2 H_2O$	(4)

Off-Road Diesel Equipment

Emission Control Technologies for Off-Road Diesel Equipment

Catalytic Converters

- *Diesel Oxidation Catalysts*: In most applications, a diesel oxidation catalyst consists of a stainless steel canister that contains a honeycomb structure called a substrate or catalyst support. There are no moving parts, just large amounts of interior surface area. The interior surfaces are coated with catalytic metals such as platinum or palladium. It is called an oxidation catalyst because the device converts exhaust gas pollutants into harmless gases by means of chemical oxidation. In the case of diesel exhaust, the catalyst oxidizes CO, HCs, and the liquid hydrocarbons adsorbed on carbon particles. In the field of mobile source emission control, liquid hydrocarbons adsorbed on the carbon particles in engine exhaust are referred to as the soluble organic fraction (SOF) -- the soluble part of the particulate matter in the exhaust. Diesel oxidation catalysts are efficient at converting the soluble organic fraction of diesel particulate matter into carbon dioxide and water.

  Oxidation catalyst retrofits have proven effective at reducing particulate and smoke emissions on older vehicles. Under the U.S. EPA's urban bus rebuild/retrofit program, five manufacturers certified diesel oxidation catalysts as providing at least a 25 percent reduction in PM emissions for in-use urban buses. Certification data also indicates that oxidation catalysts achieve substantial reductions in CO and HC emissions. Currently, under the ARB and EPA retrofit technology verification processes, several technology manufacturers have verified diesel oxidation catalysts as providing at least a 25 percent reduction in PM emissions.

Figure. DOC

- *SCR Systems*: A Selective Catalytic Reduction (SCR) system uses a metallic or ceramic wash-coated catalyzed substrate, or a homogeneously extruded catalyst and a chemical reductant to convert nitrogen oxides to molecular nitrogen and oxygen in oxygen-rich exhaust streams like those encountered with diesel engines. In mobile source applications, an aqueous urea solution is usually the preferred reductant. Upon thermal decomposition in the exhaust, urea decomposes to ammonia which serves as the reductant. In some cases ammonia has been used as the reductant in mobile source retrofit applications. As exhaust and reductant pass over the SCR catalyst, chemical reactions occur that reduce NOx emissions to nitrogen and water. SCR catalysts can be combined with a particulate filter for combined reductions of both PM and NOx.

  Open loop SCR systems can reduce NOx emissions by 75 to 90 percent. Closed loop systems on stationary engines can achieve NOx reductions of greater than 95 percent. SCR systems are also effective in reducing HC emissions up to 80 percent and PM emissions 20 to 30 percent. Like all catalyst-based emission control technologies, SCR performance is enhanced by the use of low sulfur fuel.

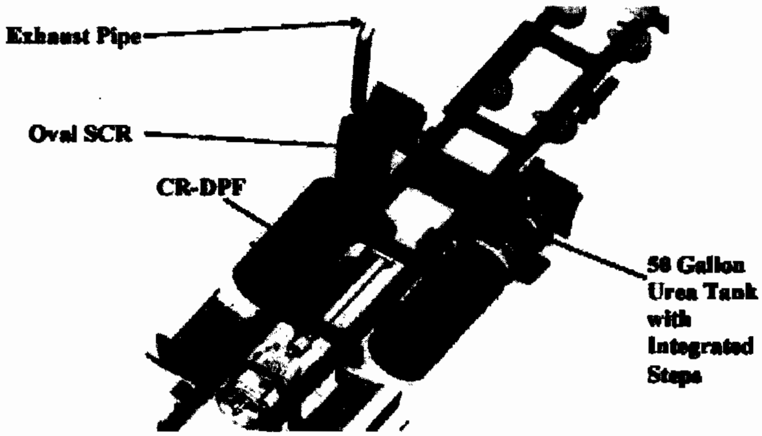


Figure. SCR system

- *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 H2) 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 (LNC) systems inject a small amount of diesel fuel or other reductant into the exhaust upstream of the catalyst. The fuel or other hydrocarbon reductant serves as a reducing agent for the catalytic conversion of NOx to N2. Other systems operate passively without any added reductant at reduced NOx conversion rates. A lean NOx catalyst often includes a porous material made of zeolite (a micro-porous material with a highly ordered channel structure), along with either a precious metal or base metal catalyst. The zeolites provide microscopic sites that are fuel/hydrocarbon rich where reduction reactions can take place. Without the added fuel and catalyst, reduction reactions that convert NOx to N2 would not take place because of excess oxygen present in the exhaust. Currently, peak NOx conversion efficiencies typically are around 10 to 30 percent (at reasonable levels of diesel fuel reductant consumption).

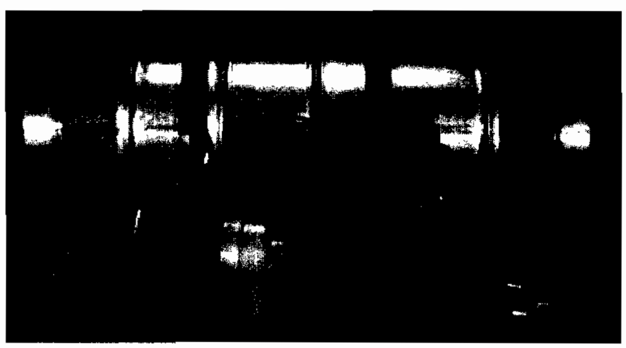


Figure. LNC

- *Lean NOx Traps*: Another type of catalyst being developed for diesel engines are known as lean NOx traps (LNT) because they function by trapping the NOx in the form of a metal nitrate during lean operation of the engine. The most common compound used to capture NOx is Barium Hydroxide or Barium Carbonate. Under lean air to fuel operation, NOx reacts to form NO2 over a platinum catalyst followed by reaction with the Barium compound to form BaNO3. Following a certain amount of lean operation, the trapping function will become saturated and must be regenerated. This is commonly done by operating the engine in a fuel rich mode for a brief period of time to facilitate the conversion of the barium compound back to a hydrated or carbonated form and giving up NOx in the form of N2 or NH3. LNT catalyst can be combined with a zeolite based SCR catalyst to trap ammonia and further reduce NOx via a selective catalytic reduction reaction to nitrogen.

Particulate Filters

Diesel particulate filters remove particulate matter found in diesel exhaust by filtering exhaust from the engine. Diesel particulate filters or (DPF) can come in a variety of types depending on the level of filtration required. The simplest form of particulate removal can be achieved using a DOC as discussed as part of the diesel catalyst section. Diesel particulate filters can be either partial, flow through devices or wall flow designs which achieve the highest filtration efficiency.

- *Partial or Flow Through Filters*: The first level of filtration can be achieved using a partial or flow through particulate filter. In this type of device, the filter element can be made up of a variety of materials and designs such as, sintered metal, metal mesh or wire, or a reticulated metal or ceramic foam structure. In this type of device the exhaust gasses and PM follow a tortuous path through a relatively open network. The partial filtration occurs as particles impinge on the rough surface of the mesh or wire network of the filter element. Partial filters can be catalyzed or uncatalyzed and are less prone to plugging than the more commonly used wall flow filters discussed below.

Figure. FTF

- *High Efficiency Wall Flow Filters*: In order to meet the stringent particulate emissions that are required for diesel light duty vehicles starting with the 2007 model year, the highest efficiency particulate filter is required. These are commonly made from ceramic materials such as cordierite, aluminum titanate, mullite or silicon carbide. The basis for the design of wall flow filters is a honeycomb structure with alternate channels plugged at opposite ends. As the gasses passes into the open end of a channel, the plug at the opposite end forces the gasses through the porous wall of the honeycomb channel and out through the neighboring channel. The ultrafine porous structure of the channel walls results in greater than 85% percent collection efficiencies of these filters. Wall flow filters capture particulate matter by interception and impaction of the solid particles across the porous wall. The exhaust gas is allowed to pass through in order to maintain low pressure drop.

  Since a filter can fill up over time by developing a layer of retained particles on the inside surface of the porous wall, engineers that design engines and filter systems must provide a means of burning off or removing accumulated particulate matter and thus regenerating the filter. A convenient means of disposing of accumulated particulate matter is to burn or oxidize it on the filter when exhaust temperatures are adequate. By burning off trapped material, the filter is cleaned or "regenerated" to its original state. The frequency of regeneration is determined by the amount of soot build-up resulting in an increase in back pressure. To facilitate decomposition of the soot, a catalyst is used either in the form of a coating on the filter or a catalyst added to the fuel. Filters that regenerate in this so-called "passive" fashion cannot be used in all situations. The experience with catalyzed filters indicates that there is a virtually complete reduction in odor and in the soluble organic fraction of the particulate. Despite the high efficiency of the catalyst, a layer of ash may build up on the filter requiring replacement or servicing. The ash is made up of inorganic oxides from the fuel or lubricants used in the engine and will not decompose during the regular soot regeneration process.

  In some applications or operating cycles, the exhaust never achieves a high enough temperature to completely oxidize the soot even in the presence of a catalyst. In these instances, an "active" regeneration system must be employed. Active regeneration utilizes a fuel burner or a resistively heated electric element to heat the filter and oxidize the soot. Active regeneration can be employed either in-place on the vehicle or externally. During external regeneration, the filter is removed from the vehicle and heated in a controlled chamber.

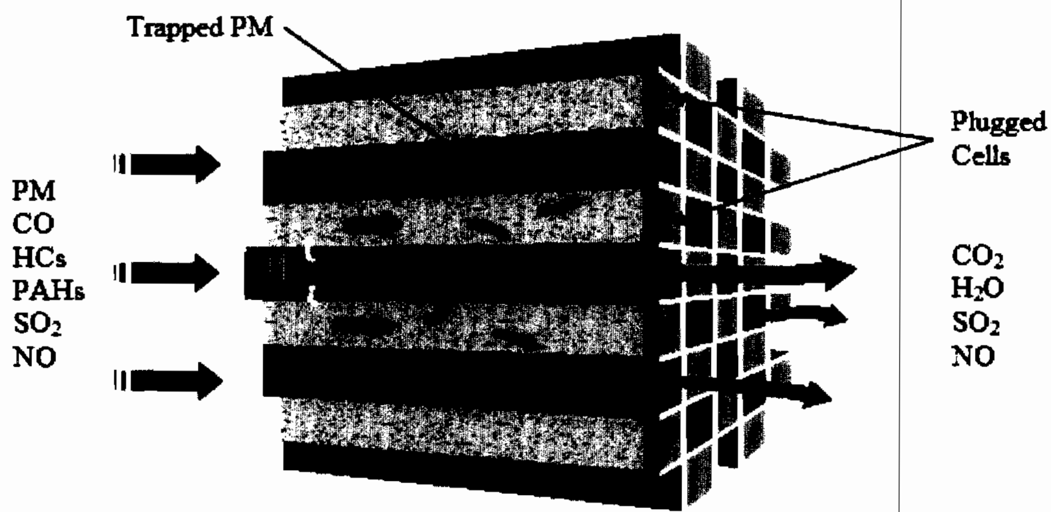


Figure. DPF

Sensor Technologies

- *Temperature Sensor.* Temperature sensors are used for two purposes: The first is as a warning system, typically on obsolete oxidation-only catalytic converters. The function of the sensor is to warn of temperature excursions above the safe operating temperature of the catalytic converter. However, modern catalytic converters are not as susceptible to temperature damage. Many modern three-way Platinum-based converters are able to handle temperatures of 900 degrees C sustained, while many modern three-way Palladium-based converters are able to handle temperatures of 925 degrees C sustained. Temperature sensors are also used to monitor the temperature rise over the catalytic converter core.
- *Oxygen Sensor.* Oxygen sensors are part of the closed loop fuel feedback control system, associated with modern three-way catalyst emission control systems on gasoline engines. The closed loop fuel feedback control system is responsible for controlling the air/fuel ratio of the catalytic converter feed gas. During the closed loop operation, the electronic control module (ECM) keeps the air/fuel ratio adjusted to around the ideal 14.7 to 1 ratio. Signal from the oxygen sensor is used to determine the exact concentration of oxygen in the exhaust stream. From this signal, the ECM determines whether the mixture is richer or leaner than the ideal 14.7 to 1 air/fuel ratio. If the air/fuel ratio deviates from its preprogrammed swings, catalyst efficiency decreases dramatically, especially for NOx reduction. The oxygen sensor informs the ECM of needed adjustments to injector duration based on exhaust conditions. After adjustments are made, the oxygen sensor monitors the correction accuracy and informs the ECM of additional adjustments. The oxygen sensor is also an integral part of the onboard diagnostic (OBD) system which monitors the proper functioning of the emission control system of the vehicle. If the sensor detects oxygen content of the exhaust that is outside the specified range of the engine calibration, it will trigger the engine light to come on in the instrument cluster.
- *NOx Sensor.* NOx sensors represent state of the art technology that can be applied to gasoline lean burn engines as part of a broader engine control or diagnostic system used to insure proper operation of the NOx emission control system. These sensors can be incorporated independent of the NOx emission control technology used on the vehicle and their function is primarily to monitor the NOx conversion efficiency of the catalyst. The sensors can work as part of a feedback loop to the control unit on the emissions system to make real time adjustments and optimize NOx conversion. The principle of operation of one type of NOx sensor is based on proven solid electrolyte technology developed for oxygen sensors. The dual chamber zirconia sensing element and electro-chemical pumps work in conjunction with precious metal catalyst electrodes to control the oxygen concentration within the sensor and convert the NOx to NO and nitrogen. The sensor sends output signals in volts that are directly proportional to ppm NOx concentration. The sensors can be incorporated upstream and downstream of the catalyst, for example, to provide a feedback control loop to the ECU of the emissions system. The ECU can than make adjustments to optimize NOx conversion performance. The ECU can than make adjustments to optimize NOx conversion performance. In the case of SCR technology, feedback can also be provided to the urea dosing system whereas in the case of lean NOx trap technology a feedback loop could signal the regeneration of the trap.

Thermal Management Strategies

The majority of emissions from today's gasoline and diesel engines occur during cold start before the catalyst can achieve optimum operating temperatures. Exhaust system manufacturers have been working together with catalyst companies to develop ways to heat up the catalyst as quickly as possible. The greatest impact came from the introduction of close coupled catalysts (CCC) to supplement the existing underfloor systems in the mid-1990. This positioned a smaller catalytic converter close to the exhaust manifold to allow rapid oxidation of CO and hydrocarbons. The exothermic heat generated in the CCC by these reactions facilitates the rapid heat up of the down stream, larger, underfloor, TWC. In later developments, the CCC was sometimes formulated to be a fully functional TWC with the underfloor unit serving as a clean-up catalyst to convert the final 10-20% of the pollutants.

The beneficial impact on reducing cold start emissions via thermal management has led to numerous improvements to the exhaust system components up stream of the converter in order to retain as much heat as possible in the exhaust gases. Manufacturers have developed ways to insulate the exhaust manifold and exhaust pipe. Attaching the CCC to a double walled, stainless steel exhaust pipe containing an air gap within the tube walls is probably the most common thermal management strategy used today. To meet the tightest SULEV and PZEV regulations required attention to the temperature distribution at the face of the CCC. This led to new inlet cone designs and modification to the shape of the space in front of the close coupled substrate.

Engine/Fuel Management

Achieving near-zero exhaust emission targets requires a systems approach. Engine manufacturers are focusing on ways to control engine operation to reduce engine out emissions as low as possible and reduce the burden on the catalysts.

Approaches aimed at reducing cold start emissions involve retarding the ignition timing so as to allow some hydrocarbons to pass through in the exhaust and light off the catalyst sooner. Variable valve timing (VVT) is being used to introduce some fraction of exhaust gas into the combustion process and reduce HC and NOx emissions. On clean diesel engines, Exhaust Gas Recirculation (EGR) is used to dilute intake air with some fraction of exhaust gas to lower the combustion temperatures resulting in lower engine out NOx emissions.

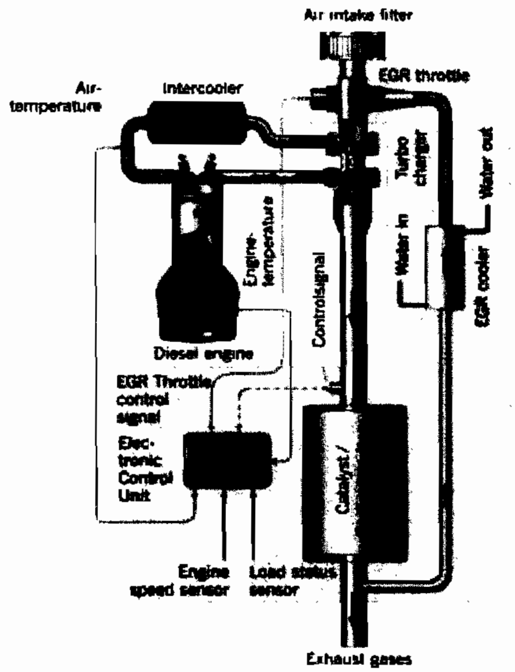


Figure. Low-pressure EGR + DPF

Direct injection of fuel into the cylinders rather than port injection has allowed better control of the air fuel ratio during combustion and resulted in better fuel utilization. Improved turbulence and mixing in the intake port of some low emission engines have resulted in a 24% fuel savings. Clean diesel engines have benefited significantly from common rail fuel injection which allows for electronically controlled injection at very high pressures. Through the use of pilot and retarded injection strategies or in combination with injection rate shaping clean diesels have achieved significant reduction in NOx over conventional diesel injection such as pipe-line or unit injection. Common rail and electronic injection control is very effective in carefully controlling post injection of fuel making it suitable for use with emission control devices such as particulate filters, NOx adsorbers and lean NOx catalysts requiring brief periods of fuel rich exhaust to facilitate regeneration of the catalyst or filter.

Evaporative Emission Controls

Evaporative emissions are generally classified into two broad categories: HC emissions associated with the release of vapors due to elevated ambient temperatures (diurnal losses) and HC emissions associated with the release of vapors during normal vehicle operation ("running losses"). Modern light-duty gasoline vehicles have implemented a variety of approaches and technologies to reduce evaporative emissions from these sources. In the early 1970s, carbon canisters were installed on vehicles to control gasoline vapor losses from fuel tanks. The canister systems include purge systems to release HCs absorbed on the carbon-based absorbent back into the combustion chamber once the engine is running. In addition to carbon canisters, other measures are being implemented on light-duty gasoline vehicles as tighter evaporative emission controls have been introduced as part of the EPA Tier 2 and ARB LEV II programs. New multi-layer polymer materials have been developed that have extremely low vapor permeation rates for use in gas tanks and, fuel line connectors and seals to reduce evaporative emissions. HC adsorber elements have been developed for use in air induction systems to reduce diurnal losses associated with fuel delivery components such as fuel injectors. These adsorber elements can be based on monolithic carbon honeycombs or metal substrates coated with zeolitic materials that have a high affinity for HC vapors.

Enhanced Combustion Technologies

Understanding and controlling the combustion process is the first step in reducing engine out emissions and reducing the burden on the emission control systems within the exhaust. Engine design is an important part of controlling and facilitating the combustion process.

In diesel engines, controlling combustion is the key approach to reducing engine out particulate emissions by optimizing the mixing between the fuel and air. Some common ways to increase mixing is through combustion chamber modifications to facilitate turbulent flow as well as fuel injector design to modify the spray pattern. Variable geometry turbocharging (VGT), which delivers variable quantities of pressurized air based on driving conditions, has been effective in reducing PM emissions by maintaining lean combustion in the engine. Reducing compression ratios have been shown effective in reducing combustion temperatures and in turn NOx emissions.

Some common approaches to enhance air turbulence and improve fuel distribution within the cylinders include improvements to the design of fuel injectors, combustion chambers and injection ports. Some engine manufacturers have been able to achieve improvements to the combustion during cold start by making modifications to the design of intake air control valves resulting in a 40-50% reduction in HC emissions and injection ports among others.

Crankcase Emission Control Technologies

Today, in most turbocharged aftercooled diesel engines, the crankcase breather is vented to the atmosphere often using a downward directed draft tube. While a rudimentary filter is often installed on the crankcase breather, substantial amount of particulate matter is released to the atmosphere. Emissions through the breather may exceed 0.7 g/bhp-hr during idle conditions on recent model year engines. For MY 1994 to 2006 heavy-duty diesel engines, crankcase PM emissions reductions provided by crankcase emission control technologies range from 0.01 g/bhp-hr to 0.04 g/bhp-hr or up to 25 percent of the tailpipe emission standards.

One solution to this emissions problem is the use of a multi-stage filter designed to collect, coalesce, and return the emitted lube oil to the engine's sump. Filtered gases are returned to the intake system, balancing the differential pressures involved. Typical systems consist of a filter housing, a pressure regulator, a pressure relief valve and an oil check valve. These systems greatly reduce crankcase emissions. Crankcase emission controls are available as a retrofit technology for existing diesel engines or as an original equipment component of a new diesel engine.

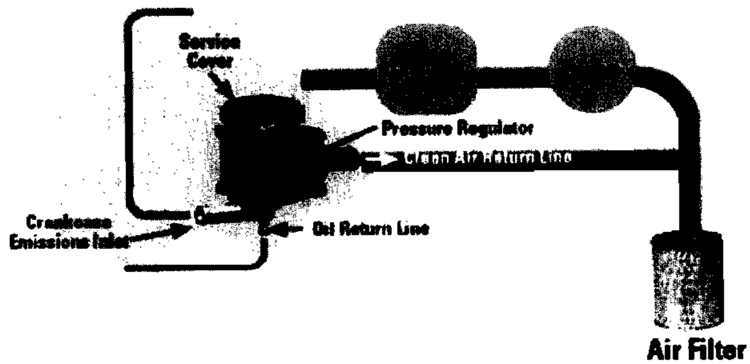


Figure. Crankcase emission control system