DEMONSTRATION OF ADVANCED EMISSION CONTROL TECHNOLOGIES ENABLING DIESEL-POWERED HEAVY-DUTY ENGINES TO ACHIEVE LOW EMISSION LEVELS

Final Report

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Figures and Tables

Executive Summary

The Manufacturers of Emission Controls Association (MECA) instituted a test program at Southwest Research Institute (SwRI) to evaluate the performance of a variety of commercially available exhaust emission control technologies on a current design heavy-duty diesel engine with standard Number 2 diesel (368 ppm), lower sulfur (54 ppm) diesel fuel, and, in a limited number of cases, zero ppm sulfur fuel. The technologies evaluated included:

- diesel oxidation catalysts (DOCs),
- diesel particulate filters (DPFs),
- selective catalytic reduction (SCR),
- fuel-borne catalysts (FBCs) in combination with filters and oxidation catalysts,
- combinations of the above technologies.

The program targets were established to demonstrate that a variety of exhaust emission control technologies could be used to substantially reduce emissions from a modern MY 1998 heavy-duty diesel engine. Specifically, the program was designed to: 1) demonstrate that PM emissions of 0.03 g/bhp-hr combined with NOx + HC emissions of 1.5 g/bhp-hr could be achieved on commercially available diesel fuel (368 ppm in this instance) and 2) demonstrate that PM emissions of 0.01 g/bhp-hr combined with NOx + HC of 1.5 g/bhp-hr could be achieved on lower sulfur fuel (54 ppm in this instance). The results of the test program clearly indicate that the above emission levels can indeed be met. Further testing demonstrated that even lower emissions could be achieved with zero sulfur diesel fuel.

A 1998 12.7 L Detroit Diesel Corporation (DDC), 400 horsepower, Series 60 engine was selected to represent a typical current design on-road heavy-duty diesel engine. Exhaust gas recirculation (EGR) was incorporated onto the engine for some of the testing.

Diesel Oxidation Catalysts

Several different DOCs were tested to determine the potential emission reductions that could be achieved with 368 ppm, 54 ppm, and, to a limited extent, zero ppm sulfur diesel fuels. A catalyst was also tested in combination with a FBC and in one instance, a catalysts was tested in combination with a FBC and exhaust gas recirculation (EGR) to determine the combined affect on PM and NOx + HC emissions.

The catalysts formulated for use with Number 2 diesel fuel reduced transient emissions of particulate by 23 to 29 percent and demonstrated the capability of reducing emissions below 0.05 g/bhp-hr when an optimized catalyst volume is used. Furthermore, hydrocarbons were reduced by 52 to 88 percent, and carbon monoxide by 13 to 68 percent. The toxic hydrocarbon emissions were also analyzed over the US FTP cycle. The DOCs had an average polyaromatic hydrocarbon reduction of 53 percent.

The oxidation catalyst tested in combination with a FBC with 368 ppm sulfur fuel resulted in PM emission levels of 0.042 g/bhp-hr on the MY 1998 engine. Also, carbon monoxide and hydrocarbon emissions were reduced by 53 and 39 percent, respectively. It is important to note that this result with the FBC was achieved using a catalyst with a volume significantly less than the engine displacement. Optimizing the catalyst volume would have resulted in even lower emissions.

Using 54 ppm sulfur fuel lowered the engine out particulate by 13 percent and allowed the use of more active DOCs. With the more active DOCs and the 54 ppm sulfur fuel, particulate emissions were further reduced by 27 to 32 percent to levels as low as 0.042 g/bhp-hr. Combining a DOC and a FBC catalyst using the 54 ppm sulfur fuel resulted in PM emissions of 0.036 g/bhp-hr. Again, both of these tests were run using a catalysts with volumes significantly less than engine displacement. The hydrocarbon and carbon monoxide emissions were reduced by 37 to 71 percent.

Combining EGR with the combination of a DOC and a FBC achieved NO_x + HC emissions of less than 2.5 g/bhp-hr while offsetting the otherwise increased particulate emissions by 33 percent. Carbon monoxide and hydrocarbons were reduced by 33 and 46 percent over the EGR baseline respectively.

At the conclusion of the test program, a DOC was tested on 54 ppm sulfur fuel and zero ppm sulfur fuel to quantify the benefits of using very low sulfur fuel. Transient particulate emissions of 0.045 g/bhp-hr were measured when tested with 54 ppm sulfur fuel. Using zero ppm sulfur fuel with the DOC resulted in particulate emissions of 0.038 g/bhp-hr representing a further reduction of 15 percent.

Diesel Particulate Filters

Three different filter technologies were tested to examine potential emission reductions with standard Number 2 and lower sulfur diesel fuel. Two filters were tested with regular diesel fuel (368 ppm S). One system had a catalytic coating applied directly to the filter element and the other incorporated a fuel-borne catalyst used in conjunction with an uncatalyzed filter element. These technologies reduced transient emissions of particulate by 70 percent or more, total hydrocarbons by as much as 94 percent, and carbon monoxide by up to 63 percent. On regular sulfur fuel, the DPF technologies tested reduced transient PM emissions to 0.022 g/bhp-hr and 0.016 g/bhp-hr. These systems were also tested in combination with exhaust gas recirculation (EGR) to determine the combined effect on PM and NO_x + HC emissions. Combining EGR with the systems, achieved NO_x + HC emissions of less than 2.5 g/bhp-hr while reducing PM emissions to significantly below 0.05 g/bhp-hr in both instances, and as low as 0.01 g/bhp-hr.

As noted above, using 54 ppm sulfur fuel lowered the engine out particulate by 13 percent to 0.063 g/bhp-hr. A low sulfur catalytic filter utilizing an upstream NOx conversion catalyst was tested. It was also tested in combination with EGR. Particulate emission reductions of 87 percent, hydrocarbon emission reductions of 95 percent, and carbon monoxide emission reductions of 93 percent were achieved. On the low sulfur fuel, the DPF technology designed for this type of fuel reduced PM emissions to 0.008 g/bhp-hr. Testing the system with EGR showed that NOx + HC emissions below 2.5 g/bhp-hr can be achieved while reducing PM emissions to substantially below 0.05 g/bhp-hr.

The capability of DPFs to reduce polyaromatic hydrocarbon emissions was evaluated for both the 368 ppm and 54 ppm sulfur fuels. Reductions in excess of 80 percent were found in both instances.

At the conclusion of the test program, a filter system originally tested on 368 ppm sulfur fuel was tested on zero sulfur fuel to quantify the benefits of the very low sulfur levels. PM emission levels of 0.005 g/bhp-hr were achieved. Substantial reductions of 62 and 52 percent respectively were measured for carbon monoxide and hydrocarbons emissions.

Selective Catalytic Reduction

SCR was tested on 368 ppm sulfur fuel alone and in combination with a DOC technology, as well as in combination with two different DPF technologies. SCR was also tested in combination with a DOC technology using 54 ppm sulfur fuel. Once fully optimized, the SCR system alone resulted in NOx + HC emissions of 1.22 g/bhp-hr accompanied PM emissions of 0.062 g/bhp-hr. Installing a DOC in combination with the system resulted in simarily low NOx + HC emissions and reduced PM emissions to 0.05 g/bhp-hr for certification purposes. Again, it is important to note that the catalysts had a volume of only 60 percent of the engine displacement. A more optimally sized catalyst would have reduced PM emissions even further. Replacing the DOC with two different DPF technologies resulted in NOx + HC emissions in the range of 1.10 to 1.17 g/bhp-hr and PM emissions of 0.002 to 0.01 g/bhp-hr.

Using 54 ppm sulfur fuel, the SCR was tested in combination with a DOC technology. This resulted in NOx + HC emissions of 1.30 g/bhp-hr along with PM emissions of 0.042 g/bhp-hr.

Off-Cycle Emission Testing

Throughout the test program, most of the testing was performed on the transient US Federal Test Procedure. In several instances, off-cycle emissions were also analyzed. The off-cycle emissions testing was conducted over a 13-mode steady state test cycle with some limited European OICA (European Steady Cycle (EST)) type testing. The results of all the off-cycle testing indicated that by properly matching the fuel, engine operation, and exhaust emission control technologies, off-cycle emissions can be substantially reduced from engine baseline levels.

Cost-Effectiveness

A cost-effectiveness analysis was performed based on the measured reductions found for the various technologies evaluated in the test program. Cost-effectiveness for the PM control technologies evaluated was in the $2,250 to $6,500/metric ton range and the cost-effectiveness for the control of NOx emissions with SCR was in the $250/metric ton range. The analysis did not include the benefits in the additional reductions of CO, HC, and toxic emissions.

Summary

The test program demonstrates that a current on-road heavy-duty diesel engine can meet a particulate standard of 0.05 g/bhp-hr by incorporating current catalyst technology. The testing also demonstrates that different, commercially available exhaust emission control technologies can be used to significantly reduce toxic hydrocarbon emissions and can be used to meet the very low emissions targets outlined above. The testing further shows that that the performance of exhaust emission control technologies efficiency can be greatly enhanced if low sulfur fuel is used. Finally, it was demonstrated that off-cycle emissions can be kept low by properly matching fuel sulfur level, engine operation, and exhaust emission control technologies.

1.0 Test Methods and Engine Specifications

1.1 Engine

The test engine for this demonstration program was a 1998 model DDC 6067TK60 EUI engine (DDC series 60) with the following specifications shown in Table 1.

Table 1

Item	Description
Emission Calibration	1998 Federal
Serial Number	06RO422316
Engine Displacement	12.7 liters/775 cubic inches
Aspiration	Waste-gate After-cooled Turbocharger
Injection	Electronic Unit Injection
Rated Horsepower	400 @ 1800 rpm
Rated Torque	1650 lb-ft @ 1200 rpm
Configuration	In line 6 Cylinder
Injection Timing	Electronically Controlled

1.2 Fuel

Emission grade Number 2 diesel fuel was obtained from Phillips Petroleum for this test program. The nominal sulfur content of this fuel was 368 ppm by weight. This fuel was blended with 0 ppm sulfur No. 2 diesel to obtain a 54 ppm sulfur by weight diesel fuel for use during the low sulfur fuel tests. The zero sulfur No. 2 diesel fuel was used for some limited testing.

1.3 Test Methods

Regulated emissions were measured over the heavy-duty engine transient US Federal Test Procedure (FTP) and a 13-mode test derived to investigate emissions outside of the FTP during steady state operation. Table 2 below outlines the 13-mode steady state test. Additional off-cycle testing was performed using the European Steady Cycle test procedure. Particulate was collected for 30 minutes at each steady state mode.

This test program measured hydrocarbon (HC), carbon monoxide (CO), oxides of nitrogen (NOx), and particulate matter (PM). Hydrocarbons were measured using continuous sampling techniques employing a heated flame ionization detector. Carbon monoxide was measured using non-dispersive infrared instruments. Oxides of nitrogen were measured continuously using a chemiluminescence detector. Total PM was determined by collective particulate matter on a set of 90 mm Pallflex filters that were weighed before and after the test cycle.

Table 2

Mode	Speed, rpm	Torque, %
1	600	0
2	840	50
3	840	100
4	1080	50
5	1080	100
6	1380	50
7	1380	100
8	1560	50
9	1560	75
10	1560	100
11	1800	50
12	1800	75
13	1800	100

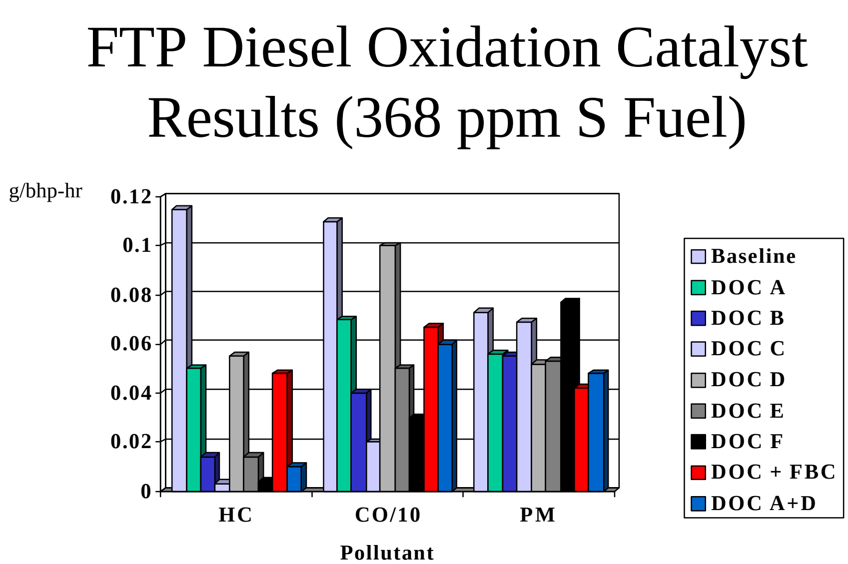
2.0 Test Results and Discussion

2.1 Diesel Oxidation Catalyst Control Performance Results

The baseline emissions for this Series 60 engine were relatively low with PM at 0.073 g/bhp-hr, HC at 0.116 g/bhp-hr and CO at 1.111 g/bhp-hr. Six different catalyst formulations were tested on this engine. The catalysts can be grouped into low (catalysts A and D), medium (catalysts B and E) and high (catalyst C and F) activity groups. The high activity catalysts were designed for use with low sulfur diesel fuel. All of the catalysts, as well as one catalyst in combination with a FBC, were tested on standard No. 2 diesel fuel over the US FTP. Figure 1 below shows the results. The data shows that gaseous emission reductions are directly related to the catalyst activity. The low activity catalysts reduced HC and CO by about 55 percent and 13 to 40 percent, respectively. The medium activity catalysts reduced HC by 88 percent and CO by 57 to 70 percent. The high activity catalysts reduced HC by 97 percent and CO by 77 to 80 percent. The catalyst combined with the FBC reduced HC by 53 percent and CO by 39 percent.

One of the goals of the demonstration program was to demonstrate that DOC technology can reduce engine PM below 0.05 g/bhp-hr. Catalysts D and E came very close to 0.05 at 0.052 and 0.053 respectively. While 0.052 and 0.053 would round to 0.05 for EPA certification purposes, the program's goal was to demonstrate control levels below 0.05 g/bhp-hr PM. The largest single catalyst support had a volume approximately 65 percent of the Series 60's 775 cubic inch displacement. For optimum performance, a catalyst at least equivalent to the engine displacement is desirable. This volume of catalyst would be used in commercial applications.

Figure 1



To demonstrate the effect of using a properly sized catalyst, Catalyst D and A were combined in series. This is not an optimum configuration because the two units are completely separate converters and this causes an increase in backpressure. This system was approximately 1.2 times the engine displacement and reduced the FTP PM emissions to 0.048 g/bhp-hr PM. These results can be duplicated without adversely impacting back pressure by using a single catalyst support with a volume of 1.2 times the test engine's displacement.

The combination of an oxidation catalyst with a FBC achieved the test program goal of 0.05 g/bhp-hr with PM emissions of 0.042 g/bhp-hr. Again, this result was achieved using an undersized catalyst.

2.1.1 Effects of Sulfur and DOC Activity on Particulate Matter Control

Particulate emission reductions are related to the activity of the catalyst, but in a different manner than gas phase emissions. The effect of catalyst activity on PM control can be better understood by examining the breakdown of the constituents of the particulate. The low and medium activity catalysts reduced particulates by 23 to 29 percent, but the high activity catalysts made marginal particulate reductions or actually increased the particulate emissions. This relationship is directly related to the sulfur content and the gas phase activity of a catalyst. The sulfur in the fuel is converted to gaseous sulfur dioxide (SO_2) during combustion, which can be converted to sulfate (SO_3) over an active gas phase catalyst. The SO_3 condenses with water on the particulate and is measured as particulate. The sulfate data collected in this program clearly shows the direct relationship between catalyst activity and sulfate formation. The high activity catalysts provide higher reductions of the volatile organic fraction (VOF) and insolubles, but they also make a significant amount of sulfate. The conversion of sulfur dioxide to sulfate offsets the reduction of other particulate components.

The catalyst evaluations using standard No. 2 diesel fuel clearly show that fuel sulfur plays a major role in specifying a catalyst and determining how a catalyst will function on an engine. Nevertheless, the data also confirms that with a properly sized and formulated catalyst, emission levels below the 0.05 g/bhp-hr PM standard are achievable with the use of No. 2 diesel fuel and that significant reductions in HC and CO can also be achieved.

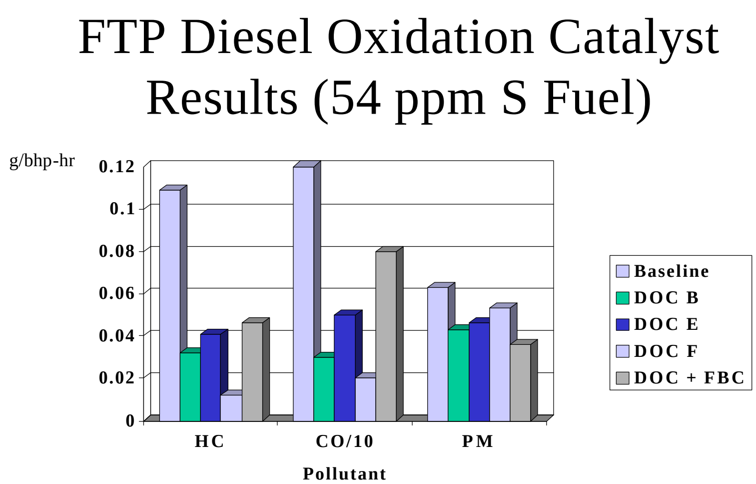
2.1.2 Impact of Catalyst Formulation on Particulate Control Using Low Sulfur Fuel

To examine the effect of catalyst formulation on PM control using low sulfur fuel, several of the more active catalysts and a catalyst combined with a FBC were tested with 54 ppm sulfur low sulfur fuel. Also, a catalyst was tested on zero sulfur fuel. Figure 4 below contains the FTP test results.

Reducing the sulfur in the fuel to 54 ppm, reduces the baseline PM to 0.063 and allows the higher activity catalysts and the combination of a catalyst and FBC to reduce the PM well below the 0.05 g/bhp-hr PM target to 0.036 g/bhp-hr. These results were achieved even with catalysts that have a volume less than the engine displacement.

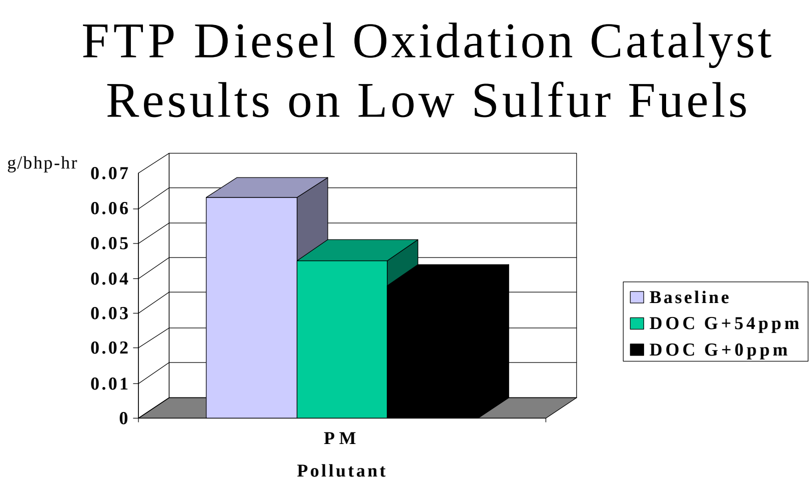
Nonetheless, even with 54 ppm sulfur fuel, the greater the gas phase reductions (high activity) of the catalyst, the greater the potential for sulfation to occur as seen in the case of catalyst F. The highly active Catalyst F only reduced PM emissions by approximately 16 percent due to the offsetting effect of sulfation.

Figure 2



Catalyst G was tested to determine the benefit of using zero sulfur fuel over fuel containing 54 ppm sulfur. The results are shown in Figure 3.

Figure 3



The zero sulfur fuel enabled the catalyst to reduce PM emissions from 0.045 g/bhp-hr when tested with 54 ppm sulfur fuel to 0.038 g/bhp-hr when tested with it.

2.1.3 Control of Toxic Compounds

As the data discussed above demonstrates, oxidation catalysts with and without FBCs are very effective in reducing hydrocarbon emissions from a diesel engine. The toxic properties of diesel exhaust are under continued evaluation and California's Air Resources Board recently listed diesel PM emissions as a toxic air contaminant. Table 3 below shows the polyaromatic hydrocarbon reductions for Catalysts B and D over the FTP using standard No. 2 diesel fuel. Some of the compounds analyzed are known carcinogens.

The data shows that diesel oxidation catalysts are extremely effective at reducing polyaromatic hydrocarbons and other toxic hydrocarbon emissions as reflected by the dramatic reductions found for total hydrocarbon emissions.

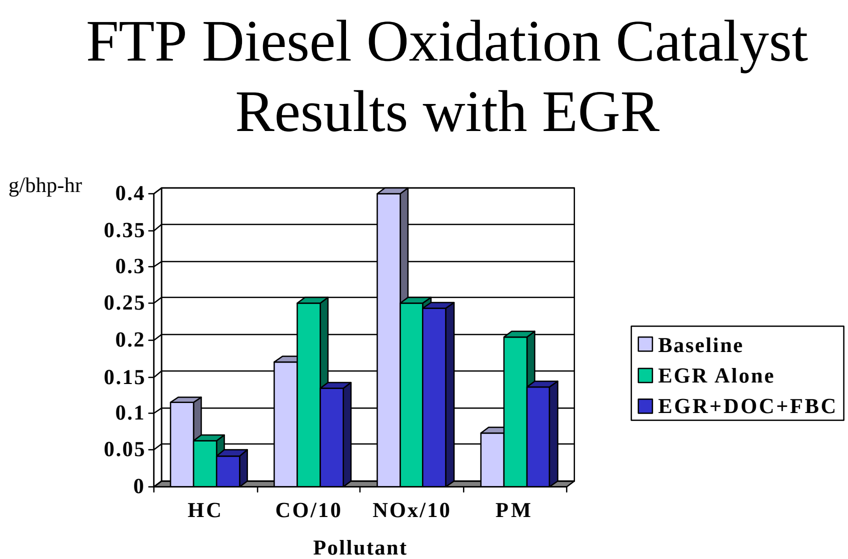
Table 3

Compound	Baseline	Cat B	Cat D	% Red Cat B	% Red Cat D
Napthalene	295	159	182	46.1%	38.3%
2-Methylnapthalene	635	278	277	56.2%	56.4%
Acenapthalene	40	13	13.6	67.5%	66.0%
Acenapthene	46	25	24.4	45.7%	47.0%
Fluorene	72	29	28.9	59.7%	59.9%
Phenanthrene	169	54	56	68.0%	66.9%
Anthracene	10	2.6	2.8	74.0%	72.0%
Fluoranthene	7.7	2.6	4.9	66.2%	36.4%
Pyrene	14	5	6.4	64.3%	54.3%
Benzo(a)anthracene	0.22	0.05	0.18	77.3%	18.2%
Chrysene	0.51	0.16	0.33	68.6%	35.3%
Benzo(b)fluoranthene	0.26	0.09	0.12	65.4%	53.8%
Benzo(k)fluoranthene	0.15	0.05	0.08	66.7%	46.7%
Benzo(e)pyrene	0.26	0.08	0.14	69.2%	46.2%
Perylene	0.01	0	0	100.0%	100.0%
Indeno(123-cd)pyrene	0.13	0.04	0.07	69.2%	46.2%
Dibenz(ah)anthracene	0.01	0	0	100.0%	100.0%
Benzo(ghi)perylene	0.32	0.1	0.22	68.8%	31.3%
Total	**1290.57**	**568.77**	**597.14**	**55.9%**	**53.7%**
Average Reduction				**68.5%**	**54.1%**

2.1.4 The Use of EGR in Combination with Catalyst Technology

To investigate the use of EGR in combination with catalyst technology, a cooled EGR system was fabricated and installed on the engine. The system was tested in conjunction with a catalyst combined with a FBC on Number 2 diesel fuel (368 ppm). Although the EGR system resulted in NOx + HC emissions below 2.5 g/bhp-hr, PM and CO emissions were significantly increased. Using the catalyst in combination with a FBC significantly offset these increased emissions and further reduced HC emissions as shown in Figure 4. Although directionally encouraging, further optimization of the system is needed. Further adjusting the EGR rate to account for increases in exhaust back pressure due to the installation of the oxidation catalyst could have been used to decrease PM emissions to a greater degree. Also, using zero sulfur fuel would have allowed for the use of a highly active catalyst which could have offset the increased emissions even further.

Figure 4



2.1.5 Off-Cycle Emissions

An oxidation catalyst was evaluated on the off-cycle test cycle outlined above. For the test, 368 ppm sulfur fuel was used. CO and HC emissions either remained unchanged or were reduced on all 13 modes of the test cycle. The results for the particulate emissions are shown in Figure 5 on the next page. As can be seen in the figure, off-cycle PM emissions were decrease in all engine operating modes except mode 3 where there was a slight increase.

2.2 Diesel Particulate Filter Control Performance

As noted above, the baseline emissions for this Series 60 engine were: PM at 0.073 g/bhp-hr, HC at 0.116 g/bhp-hr and CO at 1.111 g/bhp-hr. Three different filter technologies were evaluated as a part of the test program: a diesel particulate filter with a catayst coated directly on the filter element (DPF-A), a low sulfur catalytic particulate filter utilizing a NOx conversion catalyst (DPF-B), and a particulate filter used in combination with a fuel-borne catalyst (FBC) (DPF-C). The first technology was tested on Number 2 diesel fuel (368 ppm) with and without EGR engaged, the second technology was tested on 54 ppm sulfur fuel with and without EGR engaged, and the latter technology was tested on Number 2 diesel fuel (368 ppm) with and without EGR engaged. The results of the testing without EGR engaged are shown in Figure 6.

Figure 5

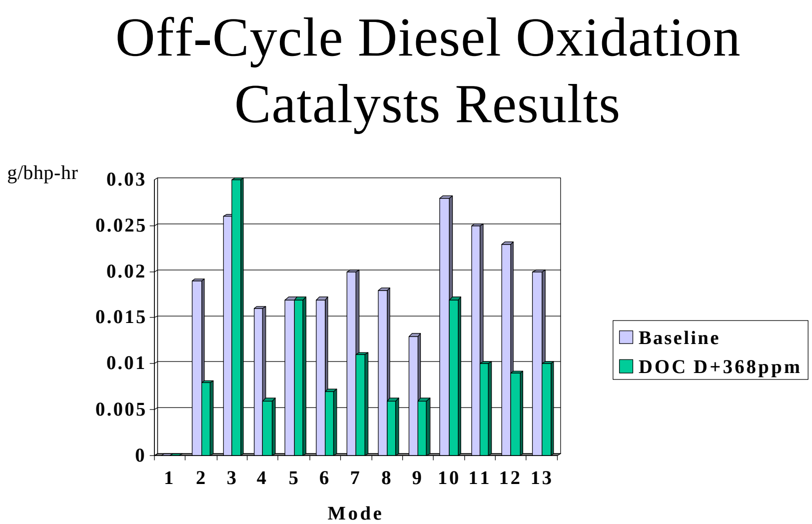
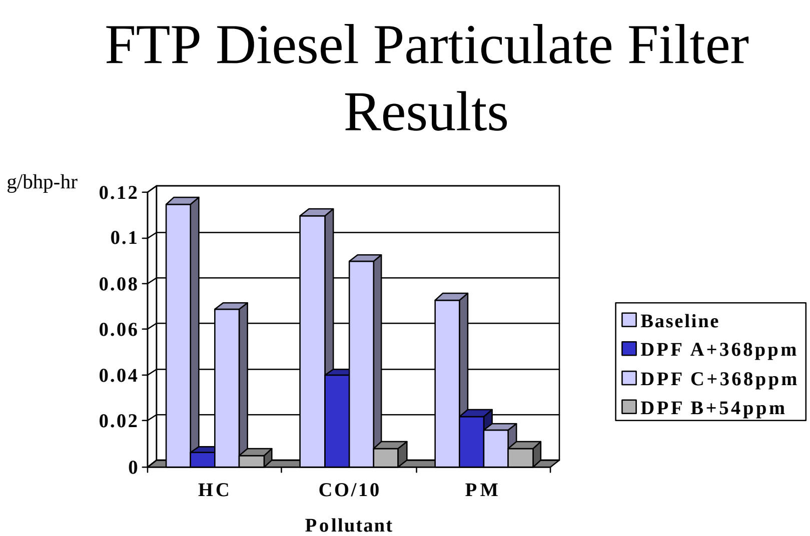


Figure 6



The data shows that filter performance over the US FTP resulted in substantial reductions of all three pollutants for both fuels. DPF-A used with 368 ppm sulfur fuel reduced PM, HC, and CO emissions by 70, 94, and 63 percent respectively. Although DPF-C did not reduce HC and CO emissions as dramatically as did DPF-A when used with 368 ppm sulfur fuel, PM emissions were reduced to 0.016 g/bhp-hr. One of the goals of the program was to demonstrate that PM emission levels below 0.03 g/bhp-hr could be achieved with regular sulfur fuel. Both of these tests demonstrate that this is indeed feasible with DPF technology. PM emissions below 0.022 g/bhp-hr were in fact achieved as shown in Figure 6 on the previous page.

2.2.1 Impact of Filter Technology on Emissions Using Low Sulfur Fuel

Figure 6 also highlights the benefits of using lower sulfur fuel. As indicated, a filter designed specifically for low sulfur fuel (DPF-B) was evaluated with the 54 ppm sulfur low sulfur fuel. As shown, the filter technology further increased the reductions in HC, CO, and PM emissions as compared to the reductions found with filters designed for higher sulfur fuels. HC reductions were in excess of 95 percent. CO reductions were over 93 percent, and PM reductions were 87 percent resulting in a PM emission level of 0.008 g/bhp-hr. This demonstrated that the program target of PM emissions of less than 0.01 g/bhp-hr could be achieved with lower sulfur fuel.

The higher reductions found with DPF-B resulted from the fact that the technology incorporates a highly active catalyst. Not only are higher reductions possible due the minimization of sulfation, but the high activity catalysts reduce the temperature required for filters to regenerate. This makes the technology suitable for a broader range of vehicle applications.

As another part of the test program, the first filter (DPF-A) tested on fuel containing 368 ppm sulfur which achieved a PM emission level of 0.022 g/bhp-hr (within the program targets of 0.03 g/bhp-hr) was also tested on fuel containing 54 ppm sulfur. The lower sulfur fuel allowed PM emissions to be brought to a level below the program target of 0.01 g/bhp-hr. This same filter, when tested on zero sulfur fuel, achieved a PM emission level of 0.005 g/bhp-hr. These improved PM reductions were a direct result of reduced sulfation. The benefits of using low sulfur fuel on PM emissions are shown in Figure 7.

Another benefit of using low sulfur fuel in conjunction with catalyst DPF technology is that it allows the manufacturer to use highly active catalysts. The use of a highly active catalyst lowers the temperature require to regenerate filter technology, thereby increasing the number of applications with which it is suitable for use.

2.2.2 Control of Toxic Compounds

As the data discussed above demonstrates, DPF technology can be very effective in reducing hydrocarbon emissions from a diesel engine. As noted above, the toxic properties of diesel exhaust are under continued evaluation and California's Air

Resources Board recently listed diesel PM emissions as a toxic air contaminant. Table 4 below shows the polyaromatic

Figure 7

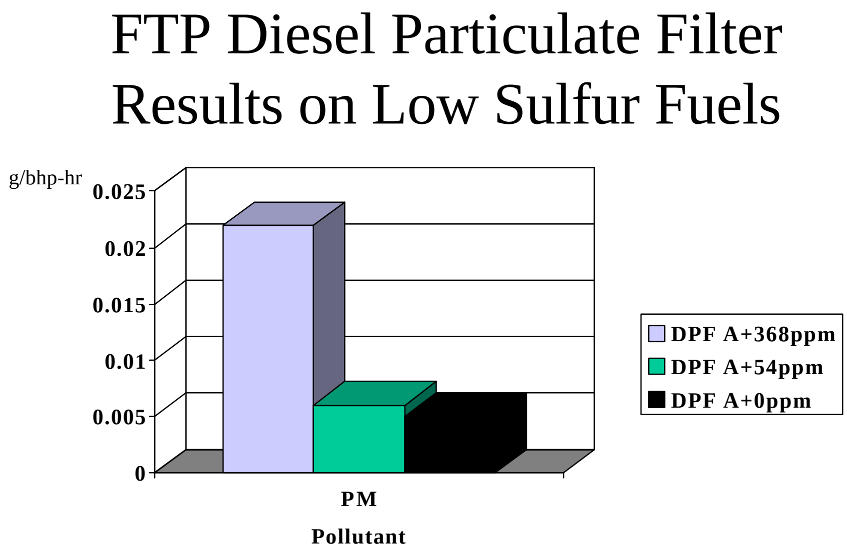


Table 4

Compound	Baseline	DPF-A	DPF-B	% Red DPF-A	% Red DPF-B
Napthalene	295	50	0	83.0%	100.0%
2-Methylnapthalene	635	108	68	83.0%	89.3%
Acenapthalene	40	0.8	1	98.0%	97.5%
Acenapthene	46	6.7	11	85.4%	76.1%
Fluorene	72	29	12	59.7%	83.3%
Phenanthrene	169	33	26	80.5%	84.6%
Anthracene	10	1	1	90.0%	90.0%
Fluoranthene	7.7	0	2	100.0%	74.0%
Pyrene	14	0	2	100.0%	85.7%
Benzo(a)anthracene	0.22	0	0.01	100.0%	95.4%
Chrysene	0.51	0	0	100.0%	100.0%
Benzo(b)fluoranthene	0.26	0	0	100.0%	100.0%
Benzo(k)fluoranthene	0.15	0	0	100.0%	100.0%
Benzo(e)pyrene	0.26	0	0	100.0%	100.0%
Perylene	0.01	0	0	100.0%	100.0%
Indeno(123-cd)pyrene	0.13	0	0	100.0%	100.0%
Dibenz(ah)anthracene	0.01	0	0	100.0%	100.0%
Benzo(ghi)perylene	0.32	0	0	100.0%	100.0%
Average Reduction				**89**	**84%**

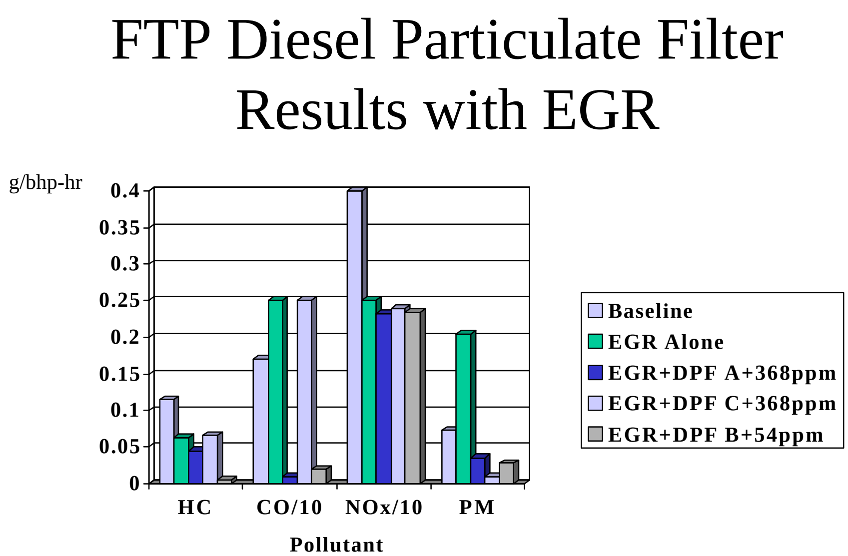
hydrocarbon reductions for DPF-A and DPF-B over the hot FTP using standard No. 2 diesel fuel and 54 ppm S fuel, respectively. Some of the compounds analyzed are known carcinogens.

The data shows that diesel particulate filters can be extremely effective at reducing polyaromatic hydrocarbons and other toxic hydrocarbon emissions as reflected by the dramatic reductions found for total hydrocarbon emissions discussed previously.

2.2.3 The Use of EGR in Combination with Filter Technology

To investigate the use of EGR in combination with filter technology, a cooled EGR system was fabricated and installed on the engine. The system was optimized and then tested in conjunction with DPF-A and DPF-C with 368 ppm sulfur fuel and DPF-B with 54 ppm sulfur fuel. The results are shown in Figure 8.

Figure 8

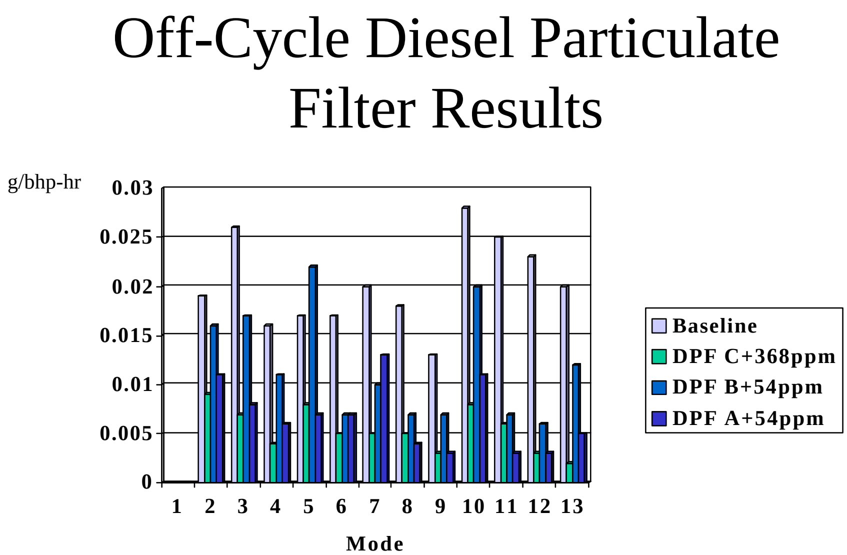


The results of the testing indicate that the combination of DPF technology and EGR achieves simultaneous NOx + HC emissions of less than 2.5 g/bhp-hr and PM emissions of less than 0.05 ghp-hr on both fuel containing 368 ppm and 54 ppm sulfur.

2.2.4 Off-Cycle Emissions

Diesel particulate filter technologies were also tested for their performance on off-cycle emissions on both 368 ppm and 54 ppm sulfur fuels. CO and HC emissions were either substantially unchanged or reduced on the off-cycle modes for all the filters tested. The off-cycle PM emissions are shown in Figure 9. As can been seen, for all the testing performed off-cycle PM emissions were reduced except in Mode 5 when testing with DPF B and 54 ppm sulfur fuel where a slight increase was measured. Nonetheless, the data indicates that diesel particulate filters can be used to substantially reduce off-cycle PM emissions.

Figure 9



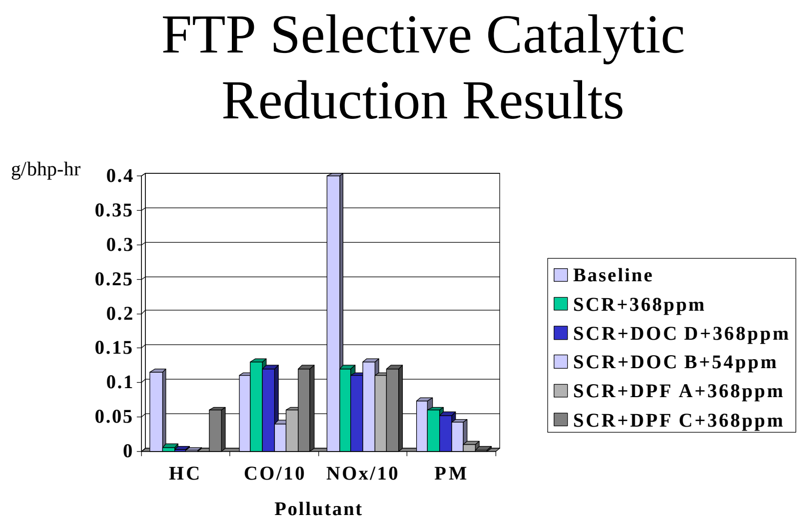
2.3 Selective Catalytic Reduction Control Performance (SCR)

As a part of the test program, SCR was tested. It was also tested in combination with diesel oxidation catalysts and different particulate filter systems. All tests were run using a 46 percent urea solution and two fuel sulfur levels (368 ppm and 54 ppm) were investigated. The results of the tests are shown in Figure 10.

As can be seen, the SCR system reduced NOx + HC emissions to levels below 1.5 g/bhp-hr in all cases. Incorporating a catalyst into the systems when testing with 368 ppm sulfur fuel reduced HC, CO and PM emissions. PM emissions of 0.052 g/bhp-hr were achieved. Using 54 ppm sulfur fuel and a more active catalyst further reduced PM emissions to 0.042 g/bhp-hr.

Using particulate filter technologies in combination with SCR dramatically reduced PM emissions to 0.01 g/bhp-hr while reducing NOx + HC emissions to 1.1 g/bhp-hr using 368 ppm sulfur fuel well below the program targets of 0.03 g/bhp-hr PM emissions and 1.5 g/bhp-hr NOx + HC emissions for the high sulfur fuel. In fact, the combinations met the program targets set for the lower sulfur fuel.

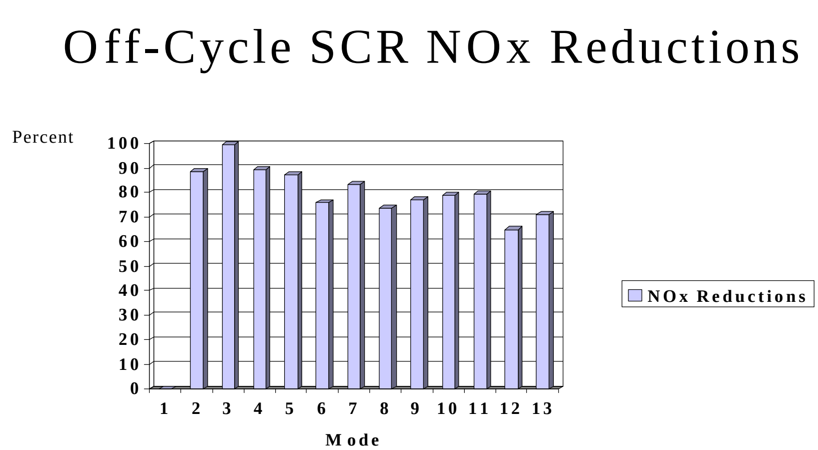
Figure 10



2.3.1 Off-Cycle Emissions

Off-cycle emission testing was also performed with the SCR system installed. Again, a 46 percent urea solution was used. Figure 11 outlines the percent reduction in NOx emissions at the off-cycle engine operation points. As indicated the SCR system reduced NOx emissions from 65 percent to in excess of 99 percent.

Figure 11



3.0 Analysis of Operational and Other Criteria

The program was not only concerned with demonstrating the technical aspects of various emission control systems, but was also concerned with their commercial and operational viability. Background discussions with industry representatives, emission control manufacturers, and regulating agencies helped developed a set of criteria dealing with the several key commercial issues. A list of these criteria is as follows:

- Cost
- Cost-effectiveness
- Maintenance
- Fuel economy
- Ease of integration
- Noise and safety
- System optimization
- Durability
- Tampering resistance

Some technologies tested are more commercially mature than others, and as a consequence more information is available for these technologies. Nevertheless, an effort was made to provide an analysis on all technologies using the best information available.

3.1 Cost

3.1.1 Diesel Oxidation Catalysts

Diesel oxidation catalysts (DOC) have been used on off-road diesel engines since the 1960s and have been used on trucks and buses in the U.S. where over 1.5 million oxidation catalysts have been equipped on vehicles since the early 1990s. In general, engines with displacement greater than 9.0 L met particulate standards without needing DOCs. Medium heavy-duty engines with displacements below 9.0 L needed DOCs to help them meet the 0.10 g/bhp-hr particulate matter standard for heavy-duty diesels. One of the most popular substrate designs is a cylindrical ceramic cordierite, having a 9.0-in diameter and length of 6.0 to 7.0 inches. These substrates were catalyzed to suit a specific engine line. Diesel engine manufacturers who have used these DOCs have become quite comfortable with them because the technology is passive, requiring little attention and because it has proven durable.

One of the most important factors in product pricing is the production volume. Since medium diesels have enjoyed a dramatic increase in sales in the early 1990s, prices of DOCs have benefited from that volume increase and reached an average of $1.00 to $2.00 per rated engine horsepower.

3.1.2 Diesel Oxidation Catalysts Combined With Fuel-Borne Catalysts

Since this technology includes DOCs as part of the system, the same cost and background information above should also apply. In addition, there is an operational cost to account for the fuel-borne catalyst and its ancillary equipment. Whether the fuel-borne catalyst is added at the refinery level, point of delivery (island-dosing), or onboard the vehicle will play a major role in the final cost to the consumer. The most independent and straight forward course of action at the moment appears to be the onboard fuel-borne catalyst dispensing system. Some regulators would like assurances that the fuel-borne catalyst supply carried onboard will not run out during the service of the vehicle. Carrying a lifetime supply of the fuel-borne catalyst onboard the vehicle has been at least informally discussed as a means to address regulatory desires.

Most observers believe that the onboard dispensing system would cost between $50 and $150. Several figures for the per-gallon cost increase have been discussed in several publications, generally it is believed that using fuel-borne catalysts will add between 3 and 5 cents/gallon to the price of diesel fuel. However, the testing in this program indicated that the FBC may indeed improve fuel economy. This would serve to help offset the additional cost of the FBC.

3.1.3 Diesel Particulate Filters

DPF technology has improved considerably in recent years and the prospect of tighter particulate emission regulations have renewed interest in this technology. Makers of these filters as well as catalyst companies believe a market for the technology is about to emerge and they are making projections for limited production in Europe and in the U.S. Korea and Japan have been working with field demonstrations and technology improvements as well.

Once again, a very important factor in costing these systems is the production volume. So far, the most popular DPF design is the wall-flow ceramic cordierite, but silicon carbide and metallic filters are also emerging. The units tested in this program were cylindrical in shape, about 10 inches in diameter and 12 inches in length. This size would be typical for engines with displacements ranging from approximately 7-13 L. Three types of filters were evaluated in this test program:

- a filter with a catalyst coated directly on the filter element,
- a low sulfur catalytic filter utilizing a NOx conversion catalyst,
- a fuel-borne catalyst filter.

The projected cost of these systems, assuming production volume in area of 200,000 industry wide units per year, ranges from an estimated $625 to $2,250 depending on the regeneration system employed.

In addition to the cost of the DPF when using a fuel-borne catalyst for regeneration, an onboard fuel-borne catalyst dispensing system will have to be fitted and integrated into the control system of the vehicle, and there will be a 3 to 5 cent/gallon price increase to account for the fuel-borne catalyst material.

3.1.4 Selective Catalytic Reduction

Hardware cost of a urea SCR system depends on parameters such as NOx reduction performance, design lifetime, engine performance and emission characteristics, the particular vehicle integration design, and largely the production volume. Further, a cost evaluation should account for system components that may already exist in a current vehicle and can perform additional required functions for the SCR system, without adding hardware cost. Sharing signals and control functions with the engine control module and potentially using the SCR package for sound attenuation purposes are examples of cost savings that would reduce the net SCR installation cost. For a typical heavy-duty, 13.0 L displacement diesel engine, the SCR system cost is estimated to be approximately $2,000, assuming production volume.

3.1.5 Exhaust Gas Recirculation and Injection Timing Control

Extensive work in this technology resulted in EGR systems developed for NOx emissions of 2.0 to 2.4 g/bhp-hr. Several EGR valve designs ranging from the very sophisticated to the very simple have been experimented with. Production style designs are relatively simple, and are controlled via the engine electronic control module.

For the EGR system hardware and control equipment, manufacturers of heavy-duty engines are estimating $500 to $700 per engine. As an alternative to EGR, injection timing control can be used to maintain particulate matter at or near the same concentration. Since most on-highway engines are electronically controlled, changes in injection timing control would be made through software modification rather than through modifying the hardware. The cost required for this change is rather minimal.

3.2 Cost-Effectiveness

3.2.1 Diesel Oxidation Catalysts

Diesel oxidation catalyst effectiveness is based largely on their ability to reduce particulate emission. As seen in the demonstration program, DOCs reduce about 50 percent of the soluble organic fraction, or about 30 percent of total particulate emission

Using mode 8 (50 percent torque at 1560 rpm) to represent highway driving, the 400 hp diesel engine equipped with a $600 diesel oxidation catalyst would achieve total particulate emission reductions of 0.012 g/bhp-hr. Particulate emissions would be reduced in one hour of this type of engine operation by 2.4 grams, or 38.4 grams in 16 hours of operation in one day. If this vehicle is operated 300 days in the year, the total particulate matter reduced is about 11.52 kg/yr. Further assuming that the useful life of the DOC is 8 years, then the cost of reducing about 92 kg of particulate would be about $6,500/metric ton. Using FTP results and a load factor of 30 percent for urban driving, PM reductions of 3 g/hr would be achieved or 14.4 kg/yr. This results in a cost effectiveness of about $5,200/metric ton.

3.2.2 Diesel Oxidation Catalyst Combined With Fuel-Borne Catalyst

Use of fuel-borne catalysts tends to further improve the performance of DOCs, by another 10 to 15 percent on average, and requires an onboard dosing system. In the demonstration program, this technology yielded 0.031 g/bhp-hr total particulate reduction in the EPA FTP test. Taking these points into consideration and using the figure arrived at above, the net cost of reducing one metric ton of particulate for urban driving would be approximately $4,200 without accounting for the operating cost of the fuel-borne catalyst which could be offset in whole or in part by any fuel economy improvement resulting from the use of the FBC.

3.2.3 Diesel Particulate Filters

Using the assumptions above results from the demonstration program, the average particulate reduction for these technologies was about 80 percent, or 0.058 g/bhp-hr of particulate matter over the EPA FTP. Assuming a $1,500 average cost for a DPF, then the cost-effectiveness of this technology is about $2,250/metric ton of particulate matter reduced for urban driving. This does not take into account the consumption of FBC for systems that rely on its use.

3.2.4 Selective Catalytic Reduction with Urea Solution

Estimates are based on the following assumptions:

- Urea cost is $0.75/gal.
- Urea consumption is 4 percent of fuel consumption.
- Fuel mileage is 6.5 miles/gal.
- Useful life 500,000 miles or 120,000 miles/year.
- Average steady-state NO_x is 7 g/bhp-hr.
- Average NO_x conversion efficiency is 70 percent.
- Average speed is 40 miles/hr.

The cost-effectiveness of the SCR system would therefore be about $253/metric ton of NO_x reduced.

3.2.5 Exhaust Gas Recirculation and Injection Timing Control

Assuming that a 400 hp diesel engine is equipped with a $600 EGR system, and that the total NO_x emission reduction is 1.50 g/bhp-hr, then in one hour of full power operation, 600 grams of NO_x will be eliminated, or 9.6 kg in 16 hours of operation in one day. If this vehicle is operated 300 days in the year, the total NO_x reduced will be about 2,900 kg. Further assuming that the useful life of the system is 5 years, then the cost of reducing about 14,500 kg of NO_x will amount to about $40/metric ton. Of course, this estimate may seem rather optimistic, and should be moderated by including the cost of reducing the EGR-caused particulate emission increase, fuel economy degradation cost, and durability degradation/more frequent oil change costs.

3.2.6 General Discussion on Cost-Effectiveness

The above analyses indicate that the technologies evaluated as a part of the test program do indeed offer cost-effective reductions in both NOx and PM emissions. It also demonstrates that the technologies can be used in combination for the simultaneous reduction of both pollutants. It should also be noted that the above analysis does not include the benefits of the substantial reductions in CO, HC, and toxic pollutants that can be achieved.

3.3 Maintenance

3.3.1 Diesel Oxidation Catalysts

Diesel engine manufacturers have collected data for several years and millions of road miles using this technology. Experience gathered from the application of DOCs in diesel engine-powered vehicles indicates that these devices are mostly passive and require very little maintenance. A key to their durability and compatibility with diesel applications is their proper canning and installation. Care must be exercised to avoid any water seepage into the DOC in some vertical installations. A number of design configurations have been developed to address this issue. Many applications have a combined DOC and muffler in one package with obvious savings.

3.3.2 Diesel Oxidation Catalyst Combined With Fuel-Borne Catalyst

The fuel-borne dispensing system maintenance should be considered when maintaining this system. Care must be exercised to ensure metering the right amount of fuel-borne catalyst material into the fuel supply system. Onboard dosing systems have been developed and are undergoing field tests to acquire experience with their performance, and any required maintenance should evolve during these field trials. Early indications are that these systems do not have major technical or cost issues.

3.3.3 Diesel Particulate Filters

It is anticipated that the systems evaluated in this test program are virtually maintenance free as is the case with diesel oxidation catalysts. For systems which employ a FBC to facilitate regeneration, the discussion above (Section 3.3.2) should be considered. Periodic inspections at major maintenance intervals may be advised to ensure trouble-free operation of these systems, even though they may be mostly passive (do not require the addition of outside sources of supplemental heat). Lube oil as well as fuel-borne catalyst (where used) ash as well as trace metals will accumulate in the filter after long service accumulation hours. Filter cleaning may be required if exhaust back pressure increases above a predetermined level. In practice, this usually occurs at 100,000 miles and takes about two hours.

3.3.4 Selective Catalytic Reduction With Urea Solution

Maintenance experience has been acquired from actual field tests and demonstration projects. System inspection and maintenance intervals are currently set at 30,000 miles for a quick routine check. Serial production SCR systems will have inspection and maintenance schedules concurrent with those of the engine. Maintenance will be performed by licensed truck maintenance facilities. Training at the OEM level and operating and maintenance manuals will be provided as required by training personnel.

3.3.5 Exhaust Gas Recirculation and Injection Timing Control

The fully developed EGR system is expected to be rugged enough for the diesel engine application. Each of its components has been tested in lab environments, and some companies have test fleets equipped with fully operational EGR systems to gather field data. As with a comparable automotive system, the EGR system is likely to perform in a trouble-free fashion with very little maintenance required. The usual care for wiring harnesses and system connectors will have to be taken. Feedback signals may be required to ensure proper EGR valve operation and EGR cooler performance.

3.4 Fuel Economy

3.4.1 Diesel Oxidation Catalysts

Diesel oxidation catalysts do not adversely affect fuel economy or engine performance. They have little or no impact on exhaust back pressure when properly sized for a specific application. Careful selection of space velocity not only ensures proper catalyst performance, but also avoids unnecessary restriction of the exhaust system.

3.4.2 Diesel Oxidation Combined With Fuel-Borne Catalyst

The discussion above (Section 3.4.1) applies. However, there has been an indication in the test program that the use of a FBC may have some benefits regarding fuel economy.

3.4.3 Diesel Particulate Filters

Installation of DPFs in exhaust systems leads to increased back pressures when engines operate at or near full load conditions. A small penalty of about 1 to 2 percent in fuel consumption is usually experienced at these conditions. However, if engines are operated mostly at part load conditions, fuel consumption rates are found to be nearly the same as without DPFs.

In addition to the load sensitivity, DPF installations have also shown the tendency toward minor fuel economy degradation as engine speeds increase. However, the systems evaluated in this test program are designed to lower the temperature required for carbon oxidation and therefore, maintain free flow through the filter. This process helps maintain reasonable back pressures and keeps fuel economy degradation to a minimum. Again, the use of a FBC may have some benefits with regard to fuel economy.

3.4.4 Selective Catalytic Reduction With Urea Solution

Because of the large NOx reductions afforded by SCR, it is possible that low NOx emissions can be achieved with an actual fuel economy benefit. Compared to internal engine NOx abatement strategies like EGR and timing retard, SCR offers a fuel economy benefit in the range of 3 to 10 percent as a result of being able to optimize engine timing for fuel economy and relying on the SCR system to reduce NOx emissions.

3.4.5 Exhaust Gas Recirculation and Injection Timing Control

Fuel economy figures from several experiments using this technology give a variety of fuel consumption increases. Depending on the specific implementation of the EGR system and its control strategy, as well as injection timing control strategy, fuel economy penalties may range from 3 to 6 percent.

3.5 Ease of Vehicle Integration

Vehicle integration of the technologies evaluated in this program can be accomplished with relative ease.

Diesel oxidation catalysts and particulate filters are easily integrated into the exhaust system. In fact, most installations have benefited from either completely eliminating the exhaust muffler, replacing it with the catalytic converter, or have combined both the catalyst and a reduced muffler in a new package referred to as a catalytic muffler.

For systems which require the use of a FBC, on-board injection technology has been developed and demonstrated. These systems are readily incorporated onto vehicles.

SCR systems can be integrated into the exhaust of existing trucks. The muffler may be replaced, or can be simplified due to additional inherent noise reduction provided by the SCR system. Onboard aqueous urea storage tanks are sized to provide range equivalent to that of the diesel fuel tanks. The volume of the urea tank is generally about 5 percent of the fuel tank capacity. The urea tank is small compared to the fuel tank and can be installed in a relatively small space. The electronic SCR system control can be provided in a designated control panel communicated via standard industry protocol with the engine control, or integrated with the engine ECM.

Exhaust gas recirculation systems are not new to the automotive application. They are only new to heavy-duty diesel engines. While EGR systems designed for the heavy-duty application are unique and face a different set of operating conditions and environmental considerations, it is believed that existing field experience from light-duty diesel applications can ease the transition to the heavy-duty market segment. As far as injection timing control is concerned, the integration will mainly be in the control code, consisting of software modifications and not involving any hardware.

3.6 Noise and Safety

Diesel oxidation catalysts and particulate filters installed in exhaust systems help reduce noise. They either supplement or replace exhaust mufflers in many cases. No safety problems associated with this technology are anticipated.

There is no effect from fuel-borne catalysts on noise. As far as safety is concerned, there is no special risk involved in storing fuel-borne catalyst onboard the vehicle. Suppliers of such catalysts point to carrying fuel onboard the vehicle and the risk it represents. Relative to fuel, fuel-borne catalysts are reported to be much less of a risk to vehicle occupants, catalyst handlers, and the environment.

SCR systems provide noise reduction, and may replace or supplement current mufflers. The aqueous urea solution is a non-hazardous, odorless, and non-flammable liquid. Urea is widely used in agriculture as a nutritional supplement for animals. It is also used in cosmetics and pharmaceuticals. Urea is safe to handle and there is no risk involved in making it available in refueling stations or truck stops. The catalyst material has proven to be reliable in numerous applications around the world, including coal-, oil-, and gas-fired power plants, boilers and incinerators as well as stationary and mobile diesel engine applications.

No impact on noise characteristics from EGR technology is contemplated beyond what is already known about the influence of injection timing on noise. Extra care should be given to the EGR control strategy to avoid excessive moisture condensation and potential corrosion of the EGR cooler material. Corrosion of the EGR cooler could eventually admit coolant into the engine (combustion chamber area) and cause serious damage to its internal components.

3.7 System Optimization

In order for heavy-duty diesel engines to meet very low emission levels, a systems approach including engine technology, exhaust emission control technology, and fuels will be needed. The evaluations performed in this test program demonstrated various approaches to achieving very low PM and NOx + HC emissions while simultaneously reducing toxics and CO.

Catalyst formulations and loading as well as precious metal selection and loading can be adjusted to allow system optimization when different fuel sulfur levels are made available. Exhaust temperature profile, exhaust flow, converter volume, and particulate composition are also important variables in optimizing DOCs for a specific application. For filter technologies which employ a catalyst, lower sulfur levels in the fuel allow the manufacturer to use higher activity catalyst which increase their control performance and allow for low temperature regeneration. Experience with these technologies has already shown that these technologies are readily optimized to a variety of applications.

Using fuel-borne catalysts gives an added opportunity for optimization by adjusting catalyst mix (if more than one metal is involved) and overall concentration.

As demonstrated in this test program, optimized combinations of technologies can be used to obtain very low emissions of all pollutants, for example:

- SCR in combination with oxidation catalysts and filters,
- EGR in combination with filters.

SCR, which has only recently found use in mobile source applications, will be developed as an integral part of the powertrain and in a manner analogous to 3-way catalysts for gasoline engines. This concept will provide an integrated, optimized technology rather than a retrofit exhaust control device. Moreover, if this design concept is adopted, then tradeoffs between fuel economy and emission controls will be less taxing to engineers and to the end user. The consumers can have good performance and extremely low emissions simultaneously. There is more opportunity to optimize catalyst volume and back pressure characteristics with the goal of achieving compact and efficient SCRs. There may be room for further improvement in catalyst efficiency, even if current performance is adequate for target emission standards. Consideration is given for including more sensors in the future, even though current control strategy is based on feed-forward or anticipatory logic. Additional emission sensors may be added to include fail-safe logic. It is also anticipated that a slight improvement in conversion efficiency may be achieved if ultra-low sulfur fuel (<<30 ppm by weight) can be made available.

3.8 Durability

Field experience with DOCs indicated that they have durability that meets heavy-duty diesel engine manufacturers' requirements. This is equally valid when used in conjunction with a fuel-borne catalyst. Field trials and emerging commercial experience in Europe with particulate filter technology do not disclose any major durability concerns.

EGR technology is not different from other automotive systems developed with heavy OEM participation. It is believed that once developed it will meet the durability requirements of heavy-duty diesel engine manufacturers.

SCR systems have been tested extensively in vehicles under real world operating conditions. Several trucks have accumulated over 200,000 miles with SCR systems fully functioning. The total mileage accumulated on the fleet of trucks equipped with SCR systems is more than 5,000,000 kilometers. No serious failure has been reported thus far. Catalyst deterioration is following the path predicted by its manufacturer.

3.9 Tampering

3.9.1 Diesel Oxidation Catalyst

If the DOC is a stand-alone device, it could be removed by the operator. If the DOC is part of a muffler package, it may be more tamper-resistant. Telltale electronic interlocking devices could be used to prevent any potential tampering.

3.9.2 Diesel Oxidation Catalyst Combined With Fuel-Borne Catalyst

Sensors would have to be developed and installed to sense the fuel-borne catalyst level and ensure that its dispensing system is functioning correctly. The same sensors could be involved in an anti-tampering scheme to prevent violating the system. More work is needed to develop an onboard diagnostic system to monitor system function.

3.9.3 Diesel Particulate Filters

The same concepts discussed for oxidation catalysts apply to diesel particulate filters including the concepts discussed for the use of a FBC for systems which incorporate their use.

3.9.4 Selective Catalytic Reduction With Urea Solution

SCR systems can be provided with the same tamper-resistant systems as other engine controls and/or emission control equipment. The SCR electronic controls are either integrated in the engine ECM, or provided separately. They will perform normal OBD functions or communicate with a central OBD system. The hardware and software of the SCR system prevent reprogramming. Sensors monitor the use and injection of the reducing agent. A tank sensor is designed to monitor urea solution level as well as distinguish between urea aqueous solution and water. Low cost urea solution should discourage using other chemicals instead. The urea supply and injection system is equipped with sensors to detect system malfunction. A NOx sensor could be added to assist as part of the tampering prevention scheme. All these measures can be used to ensure proper maintenance, inspection, and function of the system. Such measures could be supplemented with indicator lights, OBD records, engine control adjustments to reduce power output, or retarded timing for lower NOx emissions (will cause with high fuel consumption and should force servicing the system). It is also worth noting that the SCR system allows the engine to operate at excellent fuel economy, therefore eliminating the temptation to tamper with the system in the first place.

3.9.5 Exhaust Gas Recirculation and Injection Timing Control

Diesel engine manufacturers have developed excellent anti-tampering systems for electronic engine management. EGR systems and injection timing control are considered an integral component of the engine, and as such will receive the same kind of anti-tampering measures engine OEMs have already produced and tested then in real commercial applications.

4.0 Conclusions

- The test program demonstrated that advanced exhaust emission control technology can be used to meet the program targets of a 0.03 g/bhp-hr PM emission level combined with a 1.5 NOx + HC emission level for standard No. 2 diesel fuel (368 ppm) and a 0.01 g/bhp-hr PM emission level combined with a 1.5 NOx + HC emission level for lower sulfur No. 2 diesel fuel (54 ppm)

- Commercially available diesel oxidation catalysts significantly reduced hydrocarbon, carbon monoxide, and particulate emissions from a diesel engine over the heavy-duty engine FTP and off cycle test points. Optimized catalyst systems can achieve emission reductions in excess of 35 percent for PM, 70 percent for HC and CO.

- Diesel oxidation catalysts enable a current heavy-duty engine using standard No. 2 diesel fuel (368 ppm) to meet a particulate emission level of 0.05 g/bhp-hr.

- Diesel oxidation catalysts enable a current heavy-duty engine using 54 ppm sulfur No. 2 diesel fuel (368 ppm) to meet a particulate emission level of 0.046 g/bhp-hr.

- Diesel oxidation catalysts reduce toxic compounds in diesel exhaust, such as polyaromatic hydrocarbons, by an average of approximately 55 percent using standard Number 2 diesel fuel (368 ppm S).

- Reducing the sulfur content in the fuel from 54 ppm to zero improved the performance of a diesel oxidation catalyst reducing the PM emissions from 0.045 g/bhp-hr to 0.038 g/bhp-hr.

- Diesel oxidation catalysts used in conjunction with a fuel-borne catalyst achieved PM emission levels of 0.036 g/bhp-hr on 368 ppm sulfur fuel.

- Diesel oxidation catalysts can be used in conjunction with fuel-borne catalysts to offset increased PM emissions resulting from the use of EGR.

- Fuel sulfur restricts catalyst technology due to the conversion of sulfur dioxide to sulfate at high exhaust temperatures. Gas phase and VOF emission reductions are directly related to the catalyst activity. Highly active gas phase catalysts will make a significant amount of sulfate over the FTP. While catalyst formulations can be designed to provide significant HC, CO and PM control, utilizing low sulfur fuel increases the opportunity to use formulation which can achieve even greater HC, CO and PM control.

- Commercially available diesel particulate filters can be used to significantly reduce hydrocarbon, carbon monoxide, and particulate emissions from diesel engines over the heavy-duty engines FTP and off cycle test points. Optimized filter systems can achieve emission reductions in excess of 70 percent for PM, 80 percent for HC and 60 percent for CO regardless of fuel sulfur levels. Using low sulfur fuel increases the reductions to in excess of 87 percent, 95 percent, and 93 percent for PM, HC, and CO, respectively.

- Diesel particulate filters enable a current heavy-duty engine using standard road diesel to meet a particulate emission level of less than 0.03 g/bhp-hr using regular sulfur fuel (368 ppm) and less than 0.01 g/bhp-hr using low sulfur fuel (54 ppm).

- Diesel particulate filters reduce toxic compounds in diesel exhaust, such as polyaromatic hydrocarbons, by in excess of 80 percent whether tested on 368 ppm or 54 ppm sulfur fuel.

- PM emission levels of 0.005 g/bhp-hr were achieved using a diesel particulate filter with zero sulfur fuel.

- Diesel particulate filters used in combination with EGR can achieve NOx + HC emissions of less than 2.5 g/bhp-hr while maintaining very low PM emissions (as low as 0.01 g/bhp-hr) on regular sulfur fuel.

- SCR can be used to meet NOx + HC emission levels below 1.5 g/bhp-hr, as well as to substantially reducing off-cycle emissions from 65 to in excess of 99 percent.

- SCR in combination with diesel oxidation catalysts can be used to obtain PM emissions of 0.05 g/bhp-hr combined with NOx + HC emissions of less than 1.5 g/bhp-hr. Particulate filter technology can be used with SCR to further reduce the PM emissions to levels below 0.01 g/bhp-hr.

- A cost-effectiveness evaluation found that advanced exhaust emission control technologies afford PM emission reductions in the range of $3000/metric ton and NOx emission reductions in the range of $250/metric ton.

- The various technologies and combinations of technologies tested as a part of this test program afford cost-effective emissions reductions and pose no concerns regarding commercial and operational viability.