

## Chapter III: Emissions Standards Feasibility

For the past 30 or more years, emission control development for gasoline vehicles and engines has concentrated most aggressively on exhaust aftertreatment devices. These devices currently provide as much or more than 95 percent of the emission control on a gasoline vehicle. In contrast, the emission control development work for diesels has concentrated on improvements to the engine itself to limit the emissions leaving the combustion chamber.

However, during the past 15 years, more development effort has been put into diesel exhaust aftertreatment devices, particularly in the area of PM control. Those developments, and recent developments in diesel NO<sub>x</sub> control devices, make the advent of viable diesel exhaust aftertreatment feasible. Through use of these devices, we believe emissions control similar to that attained by gasoline applications will be possible with diesel applications. However, without low sulfur diesel fuel, these technologies cannot be practically implemented on heavy-duty or light-duty diesel applications.

Several exhaust aftertreatment devices have been developed to control harmful diesel PM constituents -- the diesel oxidation catalyst (DOC), and the many forms of particulate filters, or traps. DOCs have been shown to be durable in-use, but they control only a relatively small fraction of the total PM and, consequently, do not address our PM concerns sufficiently. Uncatalyzed diesel particulate traps demonstrated high efficiencies many years ago, but the level of the PM standard was such that it could be met through less costly and more reliable "in-cylinder" control techniques. Catalyzed diesel particulate traps have the potential to provide major reductions in diesel PM emissions and provide the durability and dependability required for diesel applications. Therefore, as discussed in the feasibility portion of this section, at this time we believe the catalyzed PM trap will be the control technology of choice for future control of diesel PM emissions. However, we believe that catalyzed PM traps cannot be brought to market on diesel applications unless low sulfur diesel fuel is available.

Diesel NO<sub>x</sub> control is arguably a more difficult challenge than is diesel PM control. Again, several exhaust aftertreatment devices have been developed to control diesel NO<sub>x</sub>, but only a couple of these show potential for very high efficiencies without large energy penalties. Diesel selective catalytic reduction, or SCR, has been developed to the point of nearing market introduction in Europe where diesel fuel is transitioning to low sulfur already. SCR has significant NO<sub>x</sub> control potential, but it also has many roadblocks to marketability in this country. These roadblocks include infrastructure issues that we believe will prove exceedingly difficult and potentially costly to overcome. Because of that, we believe that the NO<sub>x</sub> adsorber is the best technology for delivering significant diesel NO<sub>x</sub> reductions while also providing market and operating characteristics

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necessary for the U.S. market.<sup>a</sup> However, the NO<sub>x</sub> adsorber, like the catalyzed PM trap, cannot be brought to market on diesel applications unless low sulfur diesel fuel is available.

Improvements have also been made to gasoline emission control technology during the past few years, even the past 12 months. Such improvements include those to catalyst designs in the form of improved washcoats and improved precious metal dispersion. Much effort has also been put into improved cold start strategies that allow for more rapid catalyst light-off. This can be done by retarding the spark timing to increase the temperature of the exhaust gases, and by using air-gap manifolds, exhaust pipes, and catalytic converter shells to decrease heat loss from the system.

These improvements to gasoline emission control have been made in response to the California LEV-II standards and the federal Tier 2 standards. Some of this development work was contributed by EPA in a very short timeframe and with very limited resources in support of the Tier 2 rule.<sup>1</sup> These improvements should transfer well to the heavy-duty gasoline segment of the fleet. With such migration of light-duty technology to heavy-duty vehicles and engines, we believe that considerable improvements to heavy-duty emissions can be realized, thus enabling much more stringent standards.

The following discussion provides more detail on the technologies we believe are most capable of enabling very stringent heavy-duty emission standards. The goal of this discussion is to highlight the emission reduction capability of these emission control technologies and to highlight their need for diesel sulfur levels like those being proposed. We start with diesel applications, the technology expected and its need for low sulfur diesel fuel, and finish with gasoline applications.

### **A. Feasibility of the Proposed Heavy-Duty Diesel Standards**

#### **1. Engine Out Improvements**

Diesel engines have made great progress in lowering engine out emissions from 6.0 g/bhp-hr NO<sub>x</sub> and 0.6 g/bhp-hr PM in 1990 to 4.0 g/bhp-hr NO<sub>x</sub> and 0.1 g/bhp-hr PM in 1998. These reductions came initially with improvements to combustion and fuel systems. Introduction of electronic fuel systems in the early 1990s allowed lower NO<sub>x</sub> and PM levels without sacrificing fuel economy. This, combined with increasing fuel injection pressures, have been the primary technologies that have allowed emission levels to be reduced to current levels.

Further engine out NO<sub>x</sub> reductions to the levels necessary to comply with the 2004 standard of 2.5 g/bhp-hr NO<sub>x</sub>+NMHC will come primarily from the addition of cooled exhaust gas recirculation (EGR). This method recirculates a portion of the exhaust back to the intake manifold where it is drawn into the combustion chamber. There may be more than one factor involved in the

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<sup>a</sup> The NO<sub>x</sub> adsorber was originally developed for stationary source emission control and was subsequently developed for use in the lean operating environment of gasoline direct injection engines.

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reduction of NO<sub>x</sub> by EGR, including the heat capacity increase from the CO<sub>2</sub> in the EGR and oxygen dilution from the lower O<sub>2</sub> found in EGR. Some may argue that the change in heat capacity is not significant, however. The O<sub>2</sub> dilution theory holds that lowering the O<sub>2</sub> concentration lowers O<sub>2</sub> partial pressure which in turn lowers its propensity to oxidize N<sub>2</sub> to NO and NO<sub>2</sub> (NO<sub>x</sub>) during the combustion process.

The earliest EGR systems were uncooled. A shortcoming of uncooled EGR systems is that they raise the intake manifold temperature. This temperature rise reduces the NO<sub>x</sub> benefit of EGR since the NO<sub>x</sub> formation rate is strongly tied to temperature.<sup>2</sup> The intake manifold temperature rise also reduces the density of the fresh air, thus reducing the mass of fresh air drawn into the combustion chamber and lowering the air-fuel ratio. Lower air-fuel ratios generally increase PM emissions because there is less available oxygen to fully combust the carbon. To overcome the lower air-fuel ratio, the turbocharger can be adjusted to increase the intake manifold pressure and regain the fresh air mass flow, but this requires more work from the turbocharger and can result in a fuel economy penalty.

To counter these effects, the EGR can be cooled. However, the degree of cooling is limited by condensation concerns since a significant portion of the exhaust gases is water vapor.<sup>3</sup> The water vapor is corrosive due to sulfuric acid that is dissolved in the water. The sulfuric acid is the result of the combustion of sulfur in the fuel which can result in SO<sub>3</sub>. SO<sub>3</sub> rapidly reacts with oxygen and water to form sulfuric acid (H<sub>2</sub>SO<sub>4</sub>). The level of EGR cooling is thus limited by the desire to prevent condensation of corrosive water and sulfuric acid mixture. Therefore, the intake manifold temperature in an EGR equipped engine, even a cooled EGR engine, is usually higher than that found in a non-EGR engine.

The EGR reduces the air-fuel ratio at a given engine load by two mechanisms: dilution of the fresh air charge; and, increased charge temperature. Both of these mechanisms were described in the previous paragraphs. These mechanisms will have to be countered by higher intake manifold pressures to maintain power density and air-fuel ratios sufficient to prevent excessive PM increases. The additional pressure will increase the charge density and maintain the desired air-fuel ratio. To accomplish this, turbomachinery will be pushed to higher pressure ratios to accommodate use of EGR to meet the 2004 emission standards.

More sophisticated electronic control systems will be necessary to control the EGR system and turbomachinery. EGR control algorithms will require additional engine condition information, possibly including mass air flow, oxygen, NO<sub>x</sub>, or EGR valve position sensors. These inputs will be necessary to control the EGR rate via an EGR valve or possibly a variable geometry turbocharger (VGT). These turbochargers will also require a sophisticated control algorithm to take advantage of their transient response, EGR pumping, and air flow control characteristics. In addition, the turbomachinery used with EGR will likely be pushed near the limits of its capability, and the engine's electronic control module (ECM -- the engine's control computer) will need to ensure the limits of the hardware are not exceeded. Consequently, the 2004 standards are expected to dramatically increase the capabilities of future ECMs compared to current non-EGR equipped

ECMs.

We believe that reductions in engine out emissions beyond the 2004 levels may be attainable with low sulfur fuel and more experience with cooled EGR systems. Low sulfur fuel would allow more EGR to be used at lower temperatures because of the reduced threat of sulfuric acid formation. In addition, recirculating the exhaust gases from downstream of a PM trap may allow different EGR pumping configurations to be feasible. Current EGR systems draw exhaust gases from the exhaust manifold upstream of the turbocharger and recirculate them through the EGR cooler and into the intake manifold downstream of the compressor and aftercooler. Such a system is called a high pressure loop EGR system because the gases are drawn from high pressure upstream of the turbocharger and recirculated to high pressure downstream of the aftercooler.

By contrast, a low pressure loop EGR system could draw some exhaust gases from the exhaust downstream of the turbocharger and any aftertreatment devices and recirculate those gases through the aftercooler and into the air intake system upstream of the compressor. The low pressure loop approach increases the efficiency of the EGR system because it eliminates the high pressure loop EGR system's dependency on the pressure variations that exist between the intake and exhaust manifolds. To date, low pressure loop EGR has not been considered viable for HD applications because of the potential durability concerns associated with recirculating exhaust gas containing particles and sulfuric acid through the turbocharger compressor and aftercooler. The particles and acid accumulate in the aftercooler (typically made of aluminum) plugging and corroding it. The turbocharger compressor is also subject to particulate buildup and corrosion. But, by adding a PM trap and low sulfur fuel, the particles and acid should be reduced significantly and these durability concerns should be minimized.

Low pressure loop EGR systems provide many advantages over high pressure loop EGR systems. For example, low pressure loop EGR allows more EGR to be pumped across a wider engine operating range than with some other EGR configurations. As already pointed out, the EGR does not have to be pumped against changing turbocharger pressure differentials found in high pressure loop EGR systems that pump exhaust from the exhaust manifold upstream of the turbocharger through an EGR cooler to the intake manifold. The pressure differential between the exhaust and intake manifolds can vary from very favorable at rated speed to very unfavorable near torque peak for promoting EGR. The unfavorable pressure differential requires work to be done to provide EGR near torque peak, for instance. This pumping work does not provide work at the crankshaft, thus causing a fuel economy penalty relative to a low pressure loop system that does not require this additional EGR pumping work. The low pressure loop system is not dependent on the pressure differential characteristics of the turbocharger. Given the removal of this characteristic, we believe low pressure loop systems may allow increased EGR rates, improved fuel economy, and further reductions of engine out emissions, though not enough to meet the emission standards.

These potential engine out emission reductions are expected to be modest and are not expected to be sufficient to meet the emission standards alone. However, they will allow greater flexibility in choosing the combination of technologies used to meet the emission standards. With

lower engine out emissions, it might be most cost effective to use smaller and less expensive aftertreatment devices, for instance. Also, the combination of engine out and aftertreatment could be chosen for the best fuel economy. The fuel economy trade-offs between lower engine out emissions and more effective aftertreatment might be such that a combination of the two methods provide fuel economy that is better than either method on its own. It is also expected that the ability to lower engine out emissions will be used to complement the emission reduction characteristics of the aftertreatment devices, improving the ability to meet the NTE requirement. As a result, additional engine out emission reductions are expected to add additional flexibility in combination with aftertreatment in achieving optimized costs, fuel economy, and emissions even though engine out emission reductions alone will not be sufficient to meet the emission standards.

### **2. Meeting the Proposed PM Standard**

Diesel PM consists of three primary constituents: unburned carbon particles, which make up the largest portion of the total PM; the soluble organic fraction (SOF), which consists of unburned hydrocarbons that have condensed into liquid droplets or have condensed onto unburned carbon particles; and sulfates, which result from oxidation of fuel-borne sulfur in the engine's exhaust.

Several exhaust aftertreatment devices have been developed to control diesel PM constituents -- the diesel oxidation catalyst (DOC), and the many forms of particulate filters, or traps. DOCs have been shown to be durable in use, but they effectively control only the SOF portion of the total PM which, especially on today's engines, constitutes only around 10 to 30 percent of the total PM. Therefore, the DOC alone does not address our PM concerns sufficiently.

At this time, only the PM trap is capable of providing the level of control sought by the proposed PM standards. In the past, the PM trap has demonstrated high trapping efficiency, but regeneration of the collected PM has been a serious challenge. The PM trap works by passing the exhaust through a ceramic or metallic filter to collect the PM. The collected PM, mostly carbon particles but also the SOF portion, must then be burned off the filter before the filter becomes plugged. This burning off of collected PM is referred to as "regeneration," and can occur either:

- on a periodic basis by using base metal catalysts or an active regeneration system such as an electrical heater, a fuel burner, or a microwave heater; or,
- on a continuous basis by using precious metal catalysts.

Uncatalyzed diesel particulate traps demonstrated high PM trapping efficiencies many years ago, but the level of the PM standard was such that it could be met through less costly "in-cylinder" control techniques. Also, the regeneration characteristics were not dependable. As a result, some systems employed electrical heaters or fuel burners to improve upon regeneration, but these complicated the system design and still did not provide the durability and dependability required for HD diesel applications.

### a. Catalyzed Diesel Particulate Traps

We believe the most desirable PM trap, and the type of trap that will prove to be the industry's technology of choice, is one capable of regenerating on an essentially continuous basis. We also believe that such traps are the most promising for enabling very low PM emissions because:

- they are highly efficient at trapping all forms of diesel PM;
- they employ precious metals to reduce the temperature at which regeneration occurs, thereby allowing for passive regeneration under normal operating conditions typical of a diesel engine;<sup>b</sup>
- they have lower average backpressure thereby reducing potential fuel economy impacts, because they regenerate continuously; and,
- they need no extra burners or heaters like would be required by an active regeneration system thereby reducing potential fuel economy impacts.

These catalyzed PM traps are able to provide in excess of 90 percent control of diesel PM. However the catalyzed PM trap cannot regenerate properly with current fuel sulfur levels as such sulfur levels inhibit the NO to NO<sub>2</sub> reaction to the point of stopping trap regeneration.<sup>4</sup> Also, because SO<sub>2</sub> is so readily oxidized to SO<sub>3</sub> across the precious metals, very low PM standards cannot be achieved with current sulfur levels because of the resultant increase in sulfate PM emissions. See the discussion later in this chapter for further information on PM traps and sulfur.

More than one aftertreatment manufacturer is developing these precious metal catalyzed, passively regenerating PM traps. In field trials, they have demonstrated highly efficient PM control and promising durability. A recent publication documents results from a sample of these field test engines after years of use in real world applications.<sup>5</sup> The sampled filters had on average four years of use covering more than 225,000 miles in applications ranging from city buses to garbage trucks to intercity trains. Yet when tested on the US Heavy-Duty Federal Test Procedure (HD FTP), they demonstrated PM reductions in excess of 90 percent.

The experience gained in these field tests also helps to clarify the need for very low sulfur diesel fuel. In Sweden and some European city centers where below 10 ppm diesel fuel sulfur is readily available, more than 3,000 catalyzed diesel particulate filters have been introduced into

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<sup>b</sup> For PM trap regeneration without precious metals, temperatures in excess of 650°C must be obtained. At such high temperatures, carbon will burn provided sufficient oxygen is present. However, while the largest heavy-duty diesels may achieve temperatures of 650°C under some operating conditions, these conditions do not occur with sufficient frequency to ensure reliable regeneration. Furthermore, smaller diesel engines, particularly light-duty and light heavy-duty diesel engines, will rarely achieve such high temperatures. For example, exhaust temperatures on the HDE Federal Test Procedure cycle typically range from 100°C to 450°C. Precious metal catalyzed traps use platinum to oxidize NO in the exhaust to NO<sub>2</sub>, which is capable of oxidizing carbon at temperatures as low as 250°C to 300°C.

retrofit applications without a single failure. This success on 10 ppm sulfur fuel is all the more impressive as some of these units have been in operation for more than six years and have accumulated 600,000 km. The field experience in areas where sulfur is capped at 50 ppm has been less definitive. In regions without extended periods of cold ambient conditions (such as the United Kingdom) field tests on 50 ppm cap low sulfur fuel have been extremely positive, matching the success at 10 ppm. However, field tests in Finland where colder winter conditions are sometimes encountered (similar to many parts of the United States) have revealed a failure rate of 10 percent (14 failures in the test program). This 10 percent failure rate has been attributed to insufficient trap regeneration due to fuel sulfur in combination with low ambient temperatures.<sup>6</sup> As the ambient conditions in Sweden are expected to be no less harsh than Finland, we are left to conclude that the increased failure rates noted here are due to the higher fuel sulfur level in a 50 ppm cap fuel versus a 10 ppm cap fuel. From these results, we can also theorize that lighter applications (such as large pick-up trucks and other light heavy-duty applications), having lower exhaust temperatures than heavier applications, may experience similar results and would, therefore, need very low sulfur fuel. Further, we are unaware of any field failures in areas having fuel sulfur levels below 10 ppm. These results illustrate the effect of sulfur on the trap's ability to create sufficient NO<sub>2</sub> to carry out proper trap regeneration. Without the NO<sub>2</sub>, the trap continues to trap at high efficiency, but it is unable to oxidize, or regenerate, the trapped PM. The possible result is a plugged trap.

Much development effort is underway worldwide to bring PM aftertreatment to market. One of the drivers is the Euro IV PM standard set to become effective in 2005.<sup>c</sup> This standard sets a PM trap forcing emission target. In anticipation of the 2005 introduction date, field testing is already underway in several countries with catalyzed particulate filters. We believe the experience gained in Europe with these technologies will coincide well with our proposed emission standards. The timing of the new standards harmonizes the heavy-duty highway PM technologies with those expected to be used to meet the light-duty highway Tier 2 standards. With this level of development already under way, we are confident that the proposed PM standards would be met provided low sulfur fuel is made available.

The data currently available show that catalyzed particulate filters can provide significant reductions in PM. Precious metal catalyzed particulate filters, in conjunction with low sulfur fuel, have been shown to be more than 90 percent efficient over the FTP and across the NTE zone.<sup>7</sup> Figure III.A-1<sup>d, 8</sup> shows representative HD FTP catalyzed PM trap efficiencies with fuel sulfur levels near 15 ppm.<sup>9, 10, 11</sup> Since diesel particulate filter efficiency is roughly linear with fuel sulfur (as shown in the DECSE program results<sup>12</sup>), it can be seen from Figure III.A-1 that even at the 15 ppm sulfur cap, current PM traps are readily able to meet the 90 percent trapping efficiency we estimate

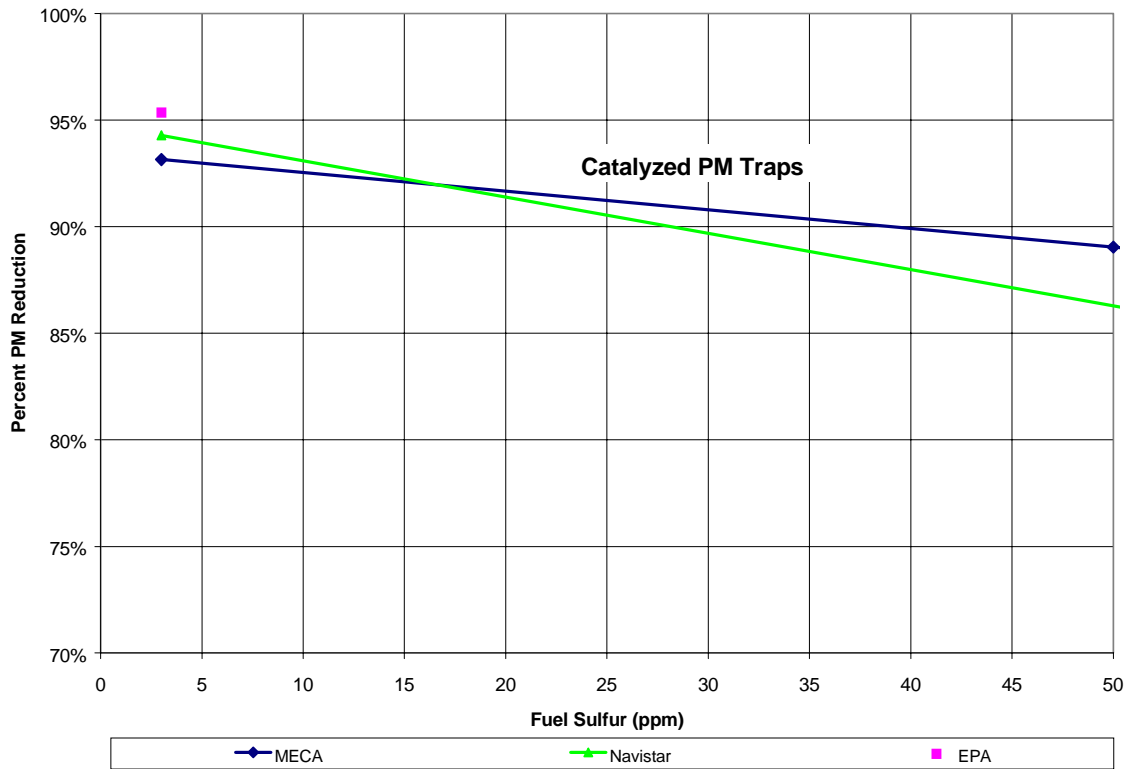
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<sup>c</sup> The Euro IV standards are 2.6 g/hp-hr NO<sub>x</sub> and 0.015 g/hp-hr PM over the European Stationary Cycle and European Transient Cycle.

<sup>d</sup> Figure III.A-1 was generated using a Navistar data point at 200 ppm sulfur and 61 percent PM reduction; this data point does not appear in the figure so that the data from 0 ppm sulfur to 50 ppm sulfur can be more easily viewed.

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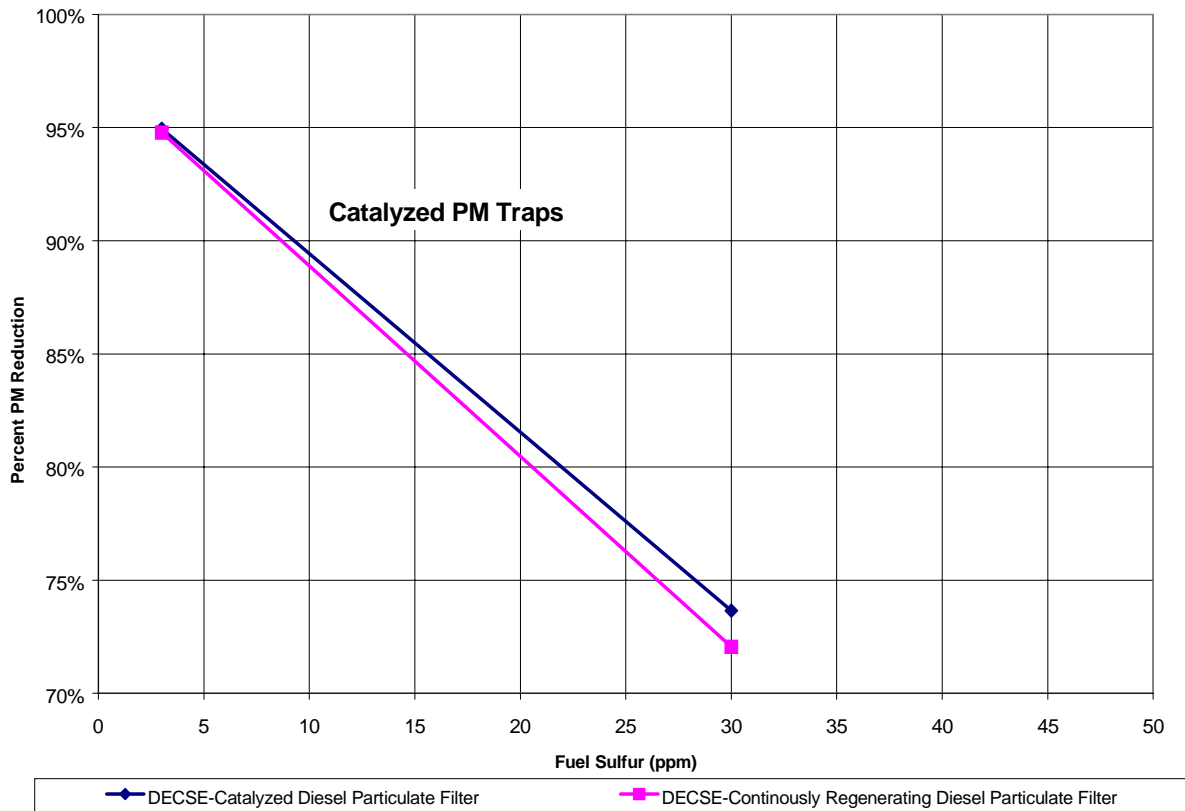
would be necessary to meet the proposed 0.01 g/bhp-hr PM standard over the HD FTP.



**Figure III.A-1. HD PM Trap Efficiency Over the Federal Test Procedure**

Since the traps are mechanical filters, their particulate trapping efficiency is not affected by engine operating conditions, so the 90 percent efficiency would apply to the NTE zone as well. However, engine operation will affect the filter regeneration and oxidation of  $\text{SO}_2$  to sulfate PM (i.e., “sulfate-make”). Sulfate-make will reduce the measured PM trapping efficiency at some NTE and supplemental steady-state modes, even at the 15 ppm fuel sulfur cap. Figure III.A-2<sup>13</sup> shows the trap efficiency as a function of fuel sulfur. From the graph, it can be seen that fuel sulfur level has a stronger effect on the trapping efficiency over the supplemental steady-state test than over the HD FTP. This increased sensitivity to fuel sulfur is caused by the higher temperatures that are found at some of the steady-state modes. High exhaust temperatures promote the oxidation of  $\text{SO}_2$  to  $\text{SO}_3$  (which then forms sulfate) across the precious metals found in catalyzed particulate filters. The sulfate is then measured as PM.





**Figure III.A-2. HD PM Trap Efficiency Over the Supplemental Steady-State Test**

Nonetheless, as shown in Table III.A-1, today’s filters are capable of meeting the supplemental steady-state standard with 15 ppm fuel and would easily meet the standard at the in-use sulfur level of 7 ppm expected with the proposed 15 ppm cap. Table III.A-1 shows data from the Diesel Emission Control Sulfur Effects (DECSE) test program, a program conducted by the US Department of Energy in cooperation with industry to provide insight into the relationship between advanced emission control technologies and diesel fuel sulfur levels. Interim report number four of this program gives the total particulate matter emissions from a heavy-duty diesel engine operated with a diesel particulate filter on several different fuel sulfur levels. Table III.A-1 shows a straight line fit through these data illustrating the expected total PM emissions from a heavy-duty diesel engine on the supplemental steady state test cycle. As shown, the PM emissions at a 15 ppm sulfur level would be 0.009 g/bhp-hr, ten percent below the proposed standard of 0.01 g/bhp-hr; therefore, the proposed standard would be feasible at 15 ppm sulfur.

**Table III.A-1. PM Emissions from a Heavy-Duty Diesel Engine at the Indicated Fuel Sulfur Levels**

<i>Fuel Sulfur Level</i>	<i>Supplemental Steady State</i>	
	<i>Tailpipe PM [g/bhp-hr]</i>	<i>Relative to Proposed Standard (%)</i>
3	0.003	-70
7*	0.006	-40
15*	0.009	-10
30	0.017	70
150	0.071	610

\* The PM emissions at these sulfur levels are based on a straightline fit to the DECSE program data;<sup>14</sup> PM emissions at other sulfur levels are actual DECSE data.

There may be a need to remove, clean, and reverse these traps at regular intervals to remove ash build-up resulting from engine oil. Small amounts of oil can enter the exhaust via the combustion chamber (past the pistons rings and valve seals), and via the crankcase ventilation system. This can lead to ash build-up, primarily as a result of the metallic oil additives used to provide pH control. This pH control is necessary, in part, to neutralize sulfuric acid produced as a byproduct of burning fuel containing sulfur. However, with reduced fuel sulfur, these oil additives could be reduced, thereby reducing the rate of ash build-up and lengthening any potential cleaning intervals. It may also be possible to use oil additives that are less prone to ash formation to reduce the need for periodic maintenance to at least those specified in CFR 86.004-25 (100,000 miles or 3,000 hours for light heavy-duty vehicles, and 150,000 miles or 4,500 hours for medium- and heavy-duty engines). Periodic maintenance would consist of reversing the trap and/or washing it out with compressed air or water. Consequently, we believe that catalyzed PM traps should be able to meet the required emission life with minimal maintenance.

**b. Control Ultra-Fine PM**

Diesel particulate traps reduce particulate matter (PM) by capturing and burning particles. Ninety percent of the PM mass resides in particle sizes that are less than 1000 nanometers (nm) in diameter, and half of these particles are less than 200 nm. Fortunately, PM traps have very high particle capture efficiencies. PM less than 200 nm is captured efficiently by diffusion onto surfaces within the trap walls. Larger particles are captured primarily by inertial impaction onto surfaces due to the tortuous path that exhaust gas must take to pass through the porous trap walls. Capture efficiency for elemental carbon (soot) and metallic ash is nearly 100 percent; therefore, significant PM can only form downstream of the trap. Volatile PM forms from sulfate or organic vapors via nucleation, condensation, and/or adsorption during initial dilution of raw exhaust into the atmosphere. Kleeman,<sup>15</sup> et. al., and Kittelson,<sup>16</sup> et. al., independently demonstrated that these

volatile particles reside in the ultra-fine PM range (i.e. <100 nm range).

Modern catalyzed PM traps have been shown to be very effective at reducing PM mass. In addition, they can significantly reduce the overall number of emitted particles when operated on low sulfur fuel. Hawker, et. al., found that a modern catalyzed PM trap reduced particle count by over 95 percent, including ultrafine particles (< 50 nm) at most of the tested conditions. The lowest observed efficiency in reducing particle number was 86 percent. No generation of particles by the PM trap was observed under any tested conditions.<sup>17</sup> Kittelson, et. al., confirmed that ultrafine particles can be reduced by a factor of ten by oxidizing volatile organics, and by an additional factor of ten by reducing sulfur in the fuel. Catalyzed PM traps efficiently oxidize nearly all of the volatile organic PM precursors, and elimination of as much fuel sulfur as possible will dramatically reduce the number of ultrafine PM emitted from diesel engines. Therefore, the combination of PM traps with low sulfur fuel is expected to result in a very large reduction in PM mass, and ultrafine particles will be almost completely eliminated.

### **3. Meeting the Proposed NOx Standard**

Historically, reduction of NOx emissions in the oxygen-rich environment typical of diesel exhaust has been difficult because known NOx reduction mechanisms tend to be highly selective for oxygen rather than NOx. Nevertheless, there are aftertreatment devices that reduce the NOx to form harmless oxygen and nitrogen. These devices are the lean NOx catalyst, the NOx adsorber, selective catalytic reduction (SCR), and non-thermal plasma.

#### **a. Lean NOx Catalysts**

Lean NOx catalysts have been under development for some time, and two methods have been developed for using a lean NOx catalyst depending on the level of NOx reduction desired. The “active” lean NOx catalyst injects a reductant that serves to reduce NOx to N<sub>2</sub> and O<sub>2</sub> (hydrocarbons work well as reductants; typically diesel fuel is used as the reductant). The reductant is introduced upstream of, or into, the catalyst. The presence of the reductant provides locally oxygen poor conditions which allows the NOx emissions to be reduced by the catalyst.

The lean NOx catalyst washcoat incorporates a zeolite that acts to adsorb hydrocarbons from the exhaust stream. Once adsorbed on the zeolite, the hydrocarbons will oxidize and create a locally oxygen poor region that is more conducive to reducing NOx. To promote hydrocarbon oxidation at lower temperatures, the washcoat can incorporate platinum or other precious metals. The platinum also helps to eliminate the emission of unburned hydrocarbons that can occur if too much reductant is injected, referred to as “hydrocarbon slip.” With platinum, the NOx conversion can take place at the lower exhaust temperatures that are typical of diesel engines. However, the presence of the precious metals can lead to production of sulfate PM, as already discussed for PM control technologies.

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Active lean NOx catalysts have been shown to provide up to 30 percent NOx reduction under limited steady-state conditions. However, this NOx control is achieved with a fuel economy penalty upwards of 7 percent<sup>18</sup> due to the need to inject fuel into the exhaust stream. NOx reductions over the HD transient FTP are only on the order of 12 percent due to excursions outside the optimum NOx reduction efficiency temperature range for these devices.<sup>19</sup> Consequently, the active lean NOx catalyst does not appear to be capable of enabling the significantly lower NOx emissions required by the NOx standard.

The “passive” lean NOx catalyst uses no reductant injection. Therefore, the passive lean NOx catalyst is even more limited in its ability to reduce NOx because the exhaust gases normally contain very few hydrocarbons. For that reason, today’s passive lean NOx catalyst is capable of best steady state NOx reductions of less than 10 percent, eliminating it from serious consideration for enabling the proposed NOx standards without major improvements.

### **b. NOx Adsorbers**

NOx adsorbers were first introduced in the power generation market less than five years ago. Since then, NOx adsorber systems in stationary source applications have enjoyed considerable success. In 1997, the South Coast Air Quality Management District of California determined that a NOx adsorber system provided the “Best Available Control Technology” NOx limit for gas turbine power systems.<sup>20</sup> Average NOx control for these power generation facilities is in excess of 92 percent.<sup>21</sup>

Recently, the NOx adsorber’s stationary source success has caused some to turn their attention to applying NOx adsorber technology to lean burn engines in mobile source applications. With only a few years of development effort, NOx adsorber catalysts have been developed and are now in production for lean-burn gasoline vehicles in Japan. The 2000 model year will see the first U.S. application of this technology with the introduction of the Honda Insight, which will be certified to the California LEV-I ULEV standard.

Although diesel vehicle manufacturers have not yet announced production plans for NOx adsorber-based systems, they are known to have development efforts underway to demonstrate its potential. In Europe, both Daimler-Chrysler and Volkswagen, driven by a need to meet stringent Euro IV emission standards in 2005,<sup>°</sup> have published results showing how they would apply the NOx adsorber technology to their diesel powered passenger cars. Volkswagen reports that it has already demonstrated NOx emissions of 0.137 g/km (0.22 g/mi) on a diesel powered Passat passenger car equipped with a NOx adsorber catalyst.<sup>22</sup>

Likewise, in the United States, heavy-duty engine manufacturers have begun investigating

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<sup>°</sup> The Euro IV standards are 0.25 g/km NOx and 0.025 g/km PM over the ECE Urban Driving Cycle (UDC) plus the Extra Urban Driving Cycle (EUDC)

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the use of NO<sub>x</sub> adsorber technologies as a more cost effective means to control NO<sub>x</sub> emissions when compared to more traditional in-cylinder approaches. Cummins Engine Company reported, at DOE's 1999 Diesel Engine Emissions Reduction workshop, that they had demonstrated an 80 percent reduction in NO<sub>x</sub> emissions over the Supplemental Steady State test and 58 percent over the heavy-duty FTP cycle using a NO<sub>x</sub> adsorber catalyst.

In spite of these promising developments, work in the United States on NO<sub>x</sub> adsorbers has been limited in comparison to the rest of the world for at least a couple of reasons: (1) prior emission standards have not necessitated the use of NO<sub>x</sub> aftertreatment on heavy-duty diesel engines; and, (2) there has not been a commitment in the U.S. to guarantee the availability of low sulfur diesel fuel needed by NO<sub>x</sub> adsorbers. This is in stark contrast to Europe where the Euro IV and Euro V emission standards, along with the commitment to low sulfur diesel fuel, have led to rapid advancements of NO<sub>x</sub> aftertreatment technology.

The diesel NO<sub>x</sub> adsorber is an adaptation from technology developed for gasoline direct injection (GDI) engines. These GDI engines typically operate very oxygen rich, or fuel lean, like a diesel, but can also run near stoichiometric like a normal gasoline engine. The NO<sub>x</sub> adsorber concept was developed to provide a NO<sub>x</sub> storage feature, a NO<sub>x</sub> adsorber, during periods of fuel lean operation when the three-way catalyst is an inefficient NO<sub>x</sub> reducer. This combination of adsorber plus three-way catalyst allows storage of NO<sub>x</sub> on the adsorber during oxygen rich operation, then NO<sub>x</sub> removal from the adsorber and NO<sub>x</sub> reduction over the three way catalyst during fuel rich operation (NO<sub>x</sub> regeneration).

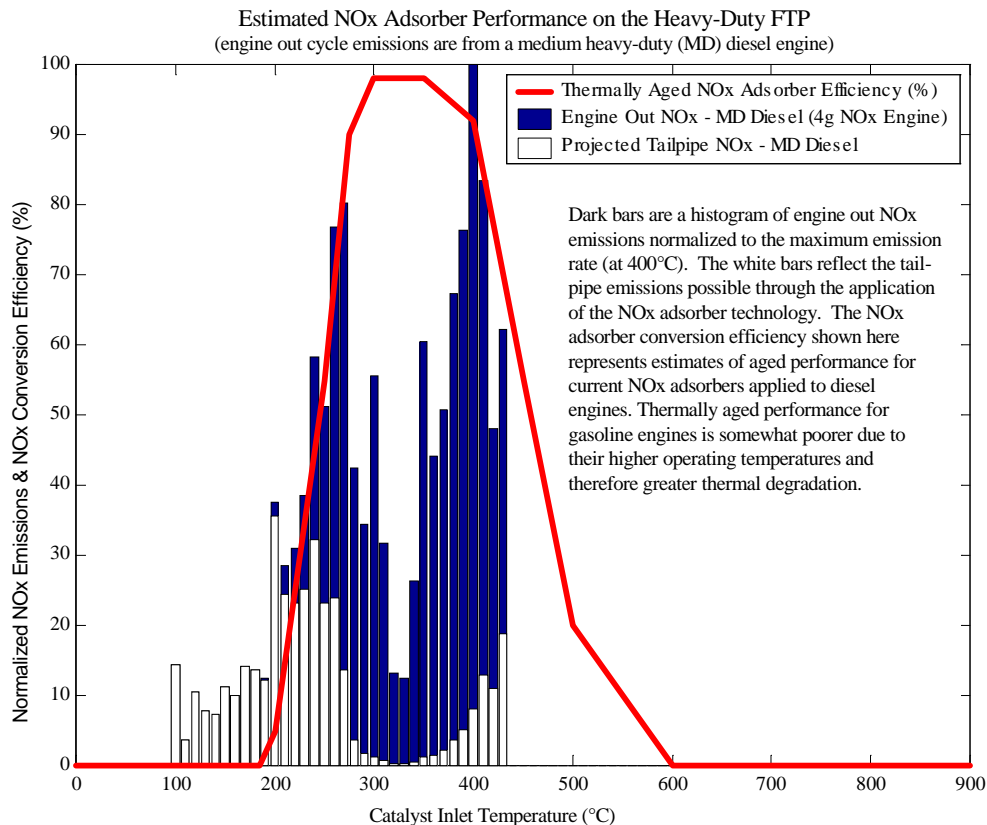
Like the gasoline three-way catalyst, the NO<sub>x</sub> adsorber device contains a washcoat consisting of platinum and rhodium to carry out the NO<sub>x</sub> reduction step. The NO<sub>x</sub> adsorbing component is typically an alkali or alkaline earth carbonate. The NO<sub>x</sub> is adsorbed as an alkali or alkaline earth nitrate that releases the NO<sub>x</sub> under fuel rich exhaust conditions. The precious metals in the three way catalyst reduce the NO<sub>x</sub> under these exhaust conditions to N<sub>2</sub> and O<sub>2</sub>.<sup>23, 24</sup>

The NO<sub>x</sub> adsorber concept works well in the gasoline direct injection engine because these engines can quite easily force fuel rich, high temperature operation necessary to regenerate. Such rich operation is difficult for diesel engines, which makes the application of NO<sub>x</sub> adsorber technology to diesel engines a challenge. Diesels normally run oxygen rich so that there is plenty of oxygen to mix quickly with the fuel when it is injected into the cylinder. Quick mixing of the fuel and oxygen allows more complete combustion of the fuel, reducing the release of partial combustion products (particulates, hydrocarbons, carbon monoxide, etc.) into the exhaust. The mixing process can also be sped up by increasing fuel injection pressure or by increasing air motion, for instance. Fuel economy is reduced under extremely fuel rich operation due to the incomplete combustion.

Current NO<sub>x</sub> adsorbers have a fairly broad temperature range of high reduction efficiency when fresh (>90 percent NO<sub>x</sub> reduction with exhaust temperatures from approximately 250°C to 450°C<sup>25</sup>). We project that relatively soon the thermally aged performance will match these current unaged performance levels, as shown in Figure III.A-3. Using this estimated adsorber performance,

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and NO<sub>x</sub> vs. exhaust temperature measured from a 1999 medium heavy-duty diesel (MHD) engine, the projected performance of this adsorber would be about 68 percent over the heavy-duty FTP. This is still far short of the estimated 90 plus percent cycle efficiency projected as needed to meet the proposed NO<sub>x</sub> standard, but this result compares well with heavy-duty FTP data that shows 58 percent NO<sub>x</sub> reduction with a 4-5 percent fuel economy penalty.<sup>26</sup> As can be seen in Figure III.A-3, extending the effective temperature range by about 50°C, particularly at low temperatures, will allow much higher composite FTP efficiencies.



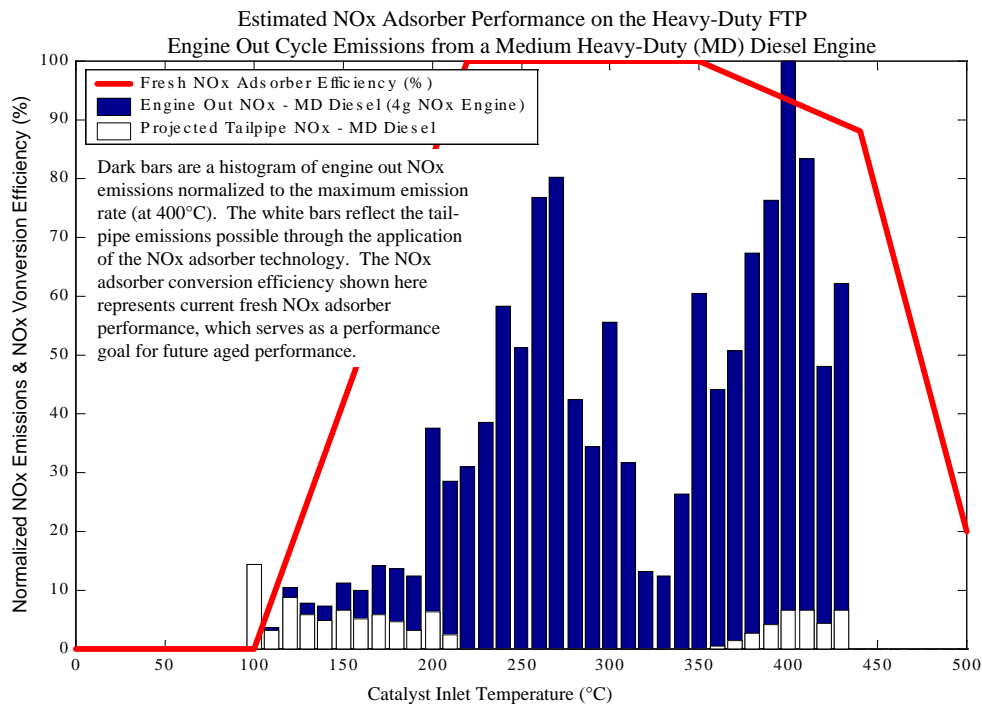
**Figure III.A-3. Near-Term Projected NO<sub>x</sub> Adsorber Performance**

We expect that the temperature window can be extended to higher temperatures based on current NO<sub>x</sub> adsorber experience with gasoline direct injection engines which have much higher exhaust temperatures than diesel engines. In addition, today's three-way catalysts are capable of nearly 100 percent NO<sub>x</sub> reduction efficiency under some conditions and we expect NO<sub>x</sub> adsorbers to be able to match this performance over a limited temperature range. Low temperature performance enhancement will require the development of improved catalyst formulations to improve the match between NO<sub>x</sub> adsorber performance and the low diesel exhaust temperatures.

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Given the progress made to date on NO<sub>x</sub> adsorber formulations, we are confident that significant improvements can be made to optimize them for diesel engines.

This expanded temperature window of high NO<sub>x</sub> reduction efficiency would allow the 90 plus percent cycle efficiency necessary to meet the NO<sub>x</sub> standard. Given this, we project that the performance of future NO<sub>x</sub> adsorbers will look something like Figure III.A-4, with more than 90 percent NO<sub>x</sub> reduction efficiency from 200°C to 450°C when fresh<sup>27</sup> (NO<sub>x</sub> adsorber conversion efficiency used in this graph is based on SAE 962045 figure 3). This NO<sub>x</sub> adsorber would be capable of more than 90 percent NO<sub>x</sub> reduction over the HD FTP which would be necessary to meet the proposed 0.2 g/hp-hr NO<sub>x</sub> standard. The supplemental steady state modes also encompass exhaust temperatures from roughly 300°C to 500°C, which corresponds well to the performance of the NO<sub>x</sub> adsorber. This will allow the supplemental steady state standard to be met. The proposed NO<sub>x</sub> NTE has an even broader temperature range, extending to lower temperatures than the supplemental steady state test. The expected NO<sub>x</sub> adsorber performance will probably be adequate to cover the NTE temperature range, though we expect that engine out emissions can be adjusted in those regions where the NO<sub>x</sub> adsorber performance is not optimal. Through such optimization, we expect the combination of engine out and NO<sub>x</sub> adsorber performance to allow the NO<sub>x</sub> NTE to be satisfied.



**Figure III.A.-4. Future Projected NO<sub>x</sub> Adsorber Performance**

We expect that the expansion of the high efficiency temperature range can be accomplished

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by modifications to the adsorber chemistry, or conversely, by increasing the engine exhaust temperatures to match the performance of the adsorber. Given the relatively early stage of diesel NOx adsorber development, we expect there will be great progress in optimizing the adsorber chemistry to the specific needs of the diesel engine. We expect that progress will also be made to integrate the NOx adsorber and engine so that they complement each other. Raising the exhaust temperature to match the adsorber performance characteristics is an example. Retarding timing, reducing air-fuel ratio, and exhaust brakes can all be used to increase the exhaust temperature. Therefore, given the early development stage of these devices, the progress made so far, and the lead time available, we are optimistic that these devices can provide the performance necessary to meet the proposed 0.2 g/hp-hr NOx standard.

NOx adsorbers will have to perform a NOx regeneration to purge the stored NOx from the adsorber bed every few minutes, depending on the engine NOx production and the storage efficiency of the adsorber. The regeneration will lower the O<sub>2</sub> content of the exhaust and provide a reductant (fuel or partial combustion products) to release the stored NOx and reduce it across the catalyst. These regeneration events are expected to take a few seconds to complete, depending on the adsorber and the regeneration conditions.

Providing oxygen lean exhaust for NOx regeneration could be accomplished by a combination of reducing the oxygen concentration of the intake charge going into the engine and increasing the fuel content of the exhaust. Reducing the intake oxygen concentration can be accomplished by reducing the fresh air flow via an increased EGR rate or a reduced boost pressure supplied by the turbocharger. Fuel systems that allow a second, late injection of fuel into the cylinder (post injection) have been used experimentally to reduce the oxygen content of the exhaust while allowing the engine to run at more favorable oxygen concentrations and low PM levels.<sup>28</sup> Common rail fuel systems, for instance, can inject a small amount of fuel just before the exhaust valve opens. Fuel injected this late in the combustion process will partially oxidize before the exhaust valve opens and the reactions stop. The partial oxidation products of this fuel not only consume some of the O<sub>2</sub> in the exhaust, they form species that are conducive to NOx reduction, such as CO. Fuel can also be injected directly into the exhaust if post injection is not feasible; however, raw fuel's efficiency as a reductant is not as high as the partial oxidation products formed by post injections.

NOx regeneration algorithms also need to be developed that minimize fuel economy and emissions penalties. The NOx regeneration event will require very good control of the air and fuel rates to make the adsorber feasible. The air and fuel rates will have to be controlled carefully to ensure that there is no emission slippage through the NOx adsorber during the regeneration. The engine control computer, or electronic control module (ECM), will have to control the air handling system to minimize the fresh air flow into the engine, while simultaneously providing additional fuel in the form of a post injection. Starting in 2004, the ECM will already have a great deal of control over the air handling system as part of the EGR control, so minimizing the fresh air flow for NOx regeneration could be an extension of the existing EGR control algorithm. The post injection is similar in execution to pilot injections which are expected to be commonly used in 2004 for noise



control. Therefore, this part of the NO<sub>x</sub> regeneration event could also be an extension of an existing algorithm on engines possessing multiple injection capability. For those engines without multiple injection capability, hardware could be added to inject fuel directly into the exhaust stream.

Additional ECM capability will be necessary to monitor the NO<sub>x</sub> adsorber and determine when the NO<sub>x</sub> regeneration events are necessary. This could be done in a variety of ways, though they fall into two general categories: predictive and reactive. The predictive method would estimate or measure the NO<sub>x</sub> flow into the adsorber in conjunction with the predicted adsorber performance to determine when the adsorber is nearly at capacity. Then, upon entering optimal engine operating conditions, a NO<sub>x</sub> regeneration would be performed. This particular step is similar to an on-board diagnostic (OBD) algorithm waiting for proper conditions to perform a functionality check. During the NO<sub>x</sub> regeneration, sensors would determine how accurately the predictive algorithm performed, and adjust it accordingly. The reactive method is envisioned to monitor NO<sub>x</sub> downstream of the NO<sub>x</sub> adsorber and, if NO<sub>x</sub> slippage is detected, a regeneration event would be triggered. This method is dependent on good NO<sub>x</sub> sensor technology. This method would also depend on the ability to regenerate under any given engine operating condition, since the algorithm would be reacting to indications that the adsorber had reached its NO<sub>x</sub> storage capacity. In either case, we believe these algorithms are not far removed from those used today for other purposes. And, when used in combination with the sophisticated control systems that will be available, we expect that NO<sub>x</sub> regeneration events can be seamlessly integrated into engine operation such that the driver may not be aware that the events are taking place.

Another potential method of performing NO<sub>x</sub> regeneration would be to use two NO<sub>x</sub> adsorbers. One adsorber would have most of the exhaust flowing through it while the second, with a reduced exhaust flow, would be regenerating. When regeneration is complete and the other adsorber is nearly full, most of the exhaust would be switched to the freshly regenerated adsorber while the now full adsorber is regenerated. There are at least two advantages to this method. The first is that, since the exhaust flow is reduced during the regeneration event, less oxygen is present and thus less fuel is required to achieve fuel rich conditions in the adsorber. The second advantage is that the regeneration time can be longer than would be desirable with a full flow system. A longer regeneration improves the efficiency of the fuel as a reductant. The disadvantage to such a dual NO<sub>x</sub> adsorber system is that it requires two adsorbers, probably two fuel injectors, and an exhaust flow diverter. There are probably many variations on this multiple adsorber approach, including a single housing which would contain several adsorber “cartridges.” A mechanism would allow the cartridges to be shut off individually from the exhaust flow, allowing them to be regenerated individually. The controller could then regenerate them as necessary. It is not clear to us at this time which method will be more desirable.

The biggest challenge to applying the NO<sub>x</sub> adsorber to the diesel engine is that the NO<sub>x</sub> adsorber is adversely impacted by sulfur. The NO<sub>x</sub> adsorber actually stores NO<sub>2</sub>, not all forms of NO<sub>x</sub>. Therefore, the platinum in the washcoat serves to oxidize NO to NO<sub>2</sub> which is then stored in the adsorber bed. As discussed for catalyzed PM traps, which also rely on the conversion of NO to NO<sub>2</sub>, fuel sulfur inhibits the necessary NO to NO<sub>2</sub> reaction because the SO<sub>2</sub> to SO<sub>3</sub> reaction will take

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precedence over the NO reaction. While the NO oxidation will still occur, it occurs at a far lower rate than it would otherwise occur when there is no sulfur in the fuel. The result is that the unreacted NO will flow through the device and be exhausted into the atmosphere. Furthermore, the NOx storage bed is also a very effective SO<sub>3</sub> storage bed. The SO<sub>3</sub> is harder to remove from the NOx storage bed than is NO<sub>2</sub>. Because of this, the SO<sub>3</sub> will slowly build up on the adsorber bed until no storage sites remain for storage of NO<sub>2</sub>. This means the sulfur effect actually carries a double impact -- inhibition of the necessary NO to NO<sub>2</sub> reaction, and blockage or poisoning of the necessary NO<sub>2</sub> storage.

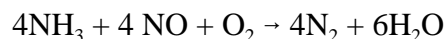
Critical to the ability of this device to meet the proposed useful life standard, along with low sulfur fuel, is the ability to desulfurize or otherwise prevent sulfur contamination of the adsorber. Current adsorber formulations require temperatures above those normally found in diesel exhaust for extended periods of time to desulfurize the adsorber bed. During the adsorber desulfurization process, the exhaust temperature will have to be elevated to around 650°C while simultaneously making the exhaust fuel-rich. These long, rich air-fuel desulfurization events will impact fuel economy. As a result, the shorter the desulfurization events and the less frequently they occur the better the fuel economy will be. We believe that this issue can be addressed by minimizing fuel sulfur concentration, through further development of NOx adsorber formulations, through the addition of SOx traps, or through widened engine operating temperatures. Since NOx adsorber technology is relatively new, we anticipate that the adsorber chemistry will evolve to allow both more rapid removal of SOx, and SOx removal at lower temperatures.

One possibility for desulfurization would be to modify the engine operation such that the sustained high temperatures required to desulfurize can be attained. There are several ways to increase the temperature of the exhaust, including retarded injection timing and lowering the air/fuel ratio. Since gasoline engines frequently operate in this temperature range, we believe the engine and turbomachinery could be designed to withstand these periodic, short-term high temperature excursions.

Given the lead time available and current progress, we believe NOx adsorbers can be developed to meet the proposed full useful life NOx standards. Just as gasoline aftertreatment technology has continued to be optimized, NOx adsorbers are expected to undergo rapid improvement and should be capable of more efficient NOx reductions in the future. But, given foreseeable development, 0.2 g/hp-hr NOx is the most stringent standard we believe is supportable by NOx adsorbers in the 2007 time frame.

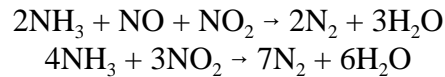
### c. Selective Catalytic Reduction (SCR)

Diesel Selective Catalytic Reduction (SCR) is an adaptation of stationary technology that has been in use for some time. Ammonia (NH<sub>3</sub>) is injected into the exhaust upstream of a vanadium/titanium (V<sub>2</sub>O<sub>5</sub>/TiO<sub>2</sub>) catalyst to reduce NOx. The following reactions occur:



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The ammonia is typically stored onboard the vehicle as a urea solution ((NH<sub>2</sub>)<sub>2</sub>CO) since ammonia is hazardous in its raw form. The urea solution is then injected upstream of the catalyst which breaks down the urea into ammonia and carbon dioxide. The ammonia must be injected in proportion to the NO<sub>x</sub> produced by the engine. If too much ammonia is injected for the amount of NO<sub>x</sub>, the excess ammonia can pass through the SCR unreacted (ammonia slip). In a mobile transient application, controlling the urea injection to prevent ammonia slippage is key. A diesel oxidation catalyst (DOC) containing platinum can be used downstream of the SCR system to control ammonia slippage by oxidizing any slipped ammonia to N<sub>2</sub> and H<sub>2</sub>O. A DOC can also be used upstream of the SCR system to improve NO<sub>x</sub> reduction performance by converting NO to NO<sub>2</sub>. The NO<sub>2</sub> is more readily reduced than NO at low temperatures. Optimum NO<sub>x</sub> reduction occurs when the NO<sub>x</sub> has a significant NO<sub>2</sub> fraction (note that diesel engine out NO<sub>x</sub> typically has only a small fraction of NO<sub>2</sub>). Systems that use a DOC to improve cold temperature performance are called “compact SCR” systems due to their relatively small size when compared to conventional SCR systems.

Selective Catalytic Reduction is at a more advanced state of development vis-à-vis the NO<sub>x</sub> adsorber. The urea SCR has been developed for stationary applications and is currently being refined for the transient operation found in mobile applications. The reduction efficiency window for this device is similar to the NO<sub>x</sub> adsorber, with greater than 80 percent efficiency at exhaust temperatures as low as 250 C.<sup>29</sup> Testing has shown HD FTP cycle NO<sub>x</sub> reductions of 77 percent.<sup>30</sup> Such efficiencies would allow NO<sub>x</sub> levels of 0.5 g/hp-hr to be possible with today’s technology starting with a 2.0 g/hp-hr cooled EGR engine. Lower levels would be possible with engine out emission reductions. Over the NTE zone the SCR has been shown to have 65-99 percent efficiency.<sup>31</sup> The high efficiency over a broad temperature range should also allow the supplemental steady-state requirement to be met. We believe the NO<sub>x</sub> efficiency of SCR can be further improved to meet NO<sub>x</sub> levels as low as 0.2 g/hp-hr NO<sub>x</sub> with additional development effort. Since SCR was developed for stationary applications where the life expectancy is typically much longer than mobile applications, we believe the devices will be able to meet the full useful life requirements.

Implementation of SCR poses unique difficulties due to the need to create a new supply chain for the urea. A SCR system consumes urea at a rate of 3-6 percent of the amount of fuel burned. Therefore, a line haul truck with a 300 gallon fuel tank would need 9 to 18 gallons of urea for every fill-up. Likewise, a large SUV with a 50 gallon fuel tank would need 1.5 to 3 gallons of urea for every fill-up. If the urea were distributed in liquid form, this would mean an additional on-board tank for urea that would probably have to be replenished at each refueling. Further, without an adequate urea supply onboard, whether by accident or by user intent, the SCR system would become useless, converting none of the NO<sub>x</sub>. Since the urea is expected to cost in the range of 60-80 cents per gallon, there would be some incentive for the user not to refill the urea tank. Since driving performance of the engine is not normally affected by the absence of urea, manufacturers would have to provide incentive for the users to continue refilling the urea tank so that the in-use

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benefit of the SCR system would be fully realized. What form such a refilling incentive would take is not known. Therefore, a standardized ammonia distribution format (liquid, solid, etc.), delivery infrastructure, and anti-tampering measures are all issues that would need to be addressed to make this technology viable.

While SCR systems are capable of operation on current sulfur level fuels, their efficiency is reduced at low temperatures and they run the risk of ammonia slip. Consequently, to achieve the proposed standards, the SCRs would likely need platinum-containing oxidation catalysts upstream and downstream. The presence of any platinum in the system, whether for conversion of ammonia slip or for conversion of NO to NO<sub>2</sub>, would lead to the production of sulfate PM and loss of NOx reduction efficiency. Therefore, like every aftertreatment technology discussed so far, the elimination of fuel sulfur is imperative for this technology to be effective.

### **d. Non-Thermal Plasma Assisted Catalysts**

Another approach to NOx reduction is the non-thermal plasma assisted catalyst. This system works by applying a high voltage across two metal plates in the exhaust stream to form ions that serve as oxidizers. Essentially, the plasma would displace a conventional platinum based oxidation catalyst in function. Once oxidized to NO<sub>2</sub>, NOx can be more readily reduced over a precious metal catalyst or used as an oxidizer, as in catalyzed particulate traps. A potential drawback of this technology is the high voltage and power requirement. Generation of this power is expected to entail a 2-3 percent fuel economy penalty.<sup>32</sup> We expect that, if and when the non-thermal plasma approach to NOx control becomes viable, it will also require the use of low sulfur diesel fuel (in the range of that being proposed) due to its reliance on a precious metal catalyst to reduce the NO<sub>2</sub>.<sup>33</sup>

### **e. Summary**

Based on the discussion above, we believe that NOx aftertreatment technology, in combination with low sulfur diesel fuel, is capable of meeting the very stringent NOx standards. The certainty that this rule provides in ensuring the availability of very low sulfur diesel fuel in the future and the emission standards which necessitate advanced NOx controls will spur rapid development of these technologies. The NOx adsorber technology has shown incredible advancement in the last five years, moving from stationary source applications to lean-burn gasoline, and now to diesel engines. Given this rapid progress, the assured availability of very low sulfur diesel fuel, and the lead time provided, we are confident that applying NOx adsorbers to diesel engines will enable manufacturers to comply with the proposed standards. Compact SCR has been slower in developing than NOx adsorbers but could be applied to mobile source applications if the difficult urea infrastructure issues can be addressed.

## **4. Meeting the Proposed NMHC Standard**

Meeting the proposed NMHC standard should not present any special challenges to diesel

manufacturers. Since all of the devices discussed above -- catalyzed particulate filters, NO<sub>x</sub> adsorbers, and SCR -- contain platinum and other precious metals to oxidize NO to NO<sub>2</sub>, they are also very efficient oxidizers of hydrocarbons. Reductions of greater than 95 percent have been shown over transient FTP and supplemental steady-state modes.<sup>34</sup> Given that typical engine out HC is expected to be in the 0.2 g/bhp-hr range for engines meeting the 2004 standards, this level of HC reduction will easily allow the 0.14 g/bhp-hr NMHC standard to be met over the transient FTP, the supplemental steady-state test, and the NTE zone.

### 5. Meeting the Crankcase Emissions Requirements

The most common way to eliminate crankcase emissions has been to vent the blow-by gases into the engine air intake system, so that the gases can be re-combusted. This approach is directly analogous to the Positive Crankcase Ventilation (PCV) systems used by gasoline engines for more than 20 years. Until today's proposal, we have required that crankcase emissions be controlled only on naturally aspirated diesel engines. We have made an exception for turbocharged heavy-duty diesel engines because of concerns in the past about fouling that could occur by routing the diesel particulates (including engine oil) into the turbocharger and aftercooler. However, this is an environmentally significant exception since most heavy-duty diesel trucks use turbocharged engines, and a single engine can emit over 100 pounds of NO<sub>x</sub>, NMHC, and PM from the crankcase over the lifetime of the engine.

We anticipate that the heavy-duty diesel engine manufacturers will be able to control crankcase emissions through the use of closed crankcase filtration systems or by routing unfiltered blow-by gases directly into the exhaust system upstream of the emission control equipment. The closed crankcase filtration systems work by separating oil and particulate matter from the blow-by gases through single or dual stage filtration approaches. These systems are required for new heavy-duty diesel vehicles in Europe starting this year. Oil separation efficiencies in excess of 90 percent have been demonstrated with production ready prototypes of two stage filtration systems.<sup>35</sup> By eliminating 90 percent of the oil that would normally be vented to the atmosphere, the system works to reduce oil consumption and to eliminate concerns over fouling of the intake system (primarily the intercooler) when the gases are routed through the turbocharger.

An alternative approach could be to route the blow-by gases into the exhaust system upstream of the catalyzed diesel particulate filter which would be expected to effectively trap and oxidize the engine oil and diesel PM. This approach may require the use of low sulfur engine oil to ensure that oil carried in the blow-by gases does not compromise the performance of the sulfur sensitive emission control equipment. Depending upon the need or availability of low sulfur engine oil this alternative approach could prove to be less expensive when compared to filtration systems described here. In either case crankcase emissions can be eliminated for turbocharged diesel engines just as they have been for naturally aspirated diesel engines and all forms of gasoline engines.

### 6. The Complete System

We expect that the technologies described above will be integrated into a complete emission control system. The engine out emissions will be traded off against the aftertreatment package in such a way that the result is the most beneficial from a cost, fuel economy and emissions standpoint. The engine out characteristics will also have to be tailored to the needs of the aftertreatment devices used. The NO<sub>x</sub> adsorber, for instance, will require periods of oxygen depleted exhaust flow in order to regenerate. This may be most efficiently done by reducing the air-fuel ratio that the engine is operating under during the regeneration to reduce the oxygen content of the exhaust. Further, it is envisioned that the PM device will be integrated into the exhaust system upstream of the NO<sub>x</sub> reduction device. This placement will allow the PM trap to take advantage of the engine out NO<sub>x</sub> as an oxidant for the particulate, while removing the particulate so that the NO<sub>x</sub> aftertreatment device will not have to deal with large PM deposits which may cause a deterioration in performance. Of course, there is also the possibility of integrating the PM and NO<sub>x</sub> aftertreatment devices into a single unit to replace a muffler and save space. Particulate free exhaust may also allow for new options in EGR system design to optimize its efficiency, such as low pressure loop EGR which takes exhaust gases from downstream of the turbine and recirculates them upstream of the compressor (see section A.1 of this chapter for an explanation of low pressure loop EGR).

We also expect that the aftertreatment emission reduction efficiency will vary with temperature and space velocity<sup>f</sup> across the NTE zone. Consequently, to maintain the NTE emission cap, the engine out emissions will have to be calibrated with aftertreatment performance characteristics in mind. This would be accomplished by lowering engine out emissions where the aftertreatment was less efficient. Conversely, where the aftertreatment is very efficient at reducing emissions, the engine out emissions could be tuned for higher emissions and better fuel economy. These trade-offs between engine out emissions and aftertreatment performance characteristics are similar to those of gasoline engines with three-way catalysts in today's light-duty vehicles. Managing and optimizing these trade-offs will be crucial to effective implementation of aftertreatment devices on diesel applications.

### 7. The Need for Low-Sulfur Diesel Fuel

To enable the technologies capable of achieving the proposed heavy-duty vehicle emission standards, we believe it is appropriate to establish a diesel fuel sulfur standard of 15 ppm. This section will build upon the brief sulfur sensitivity points made earlier in this section by providing a more in-depth discussion of sulfur's effect on the most promising diesel aftertreatment technologies. This in-depth discussion will serve to clarify the need for a fuel sulfur level of 15 ppm.

In order to evaluate the effect of sulfur on diesel exhaust control technologies we identified three key factors which we used to categorize the impact of sulfur in fuel on emission control

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<sup>f</sup> The term, "space velocity," is a measure of the volume of exhaust gas that flows through a device.

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function. These factors were efficiency, reliability, and fuel economy. Taken together these three factors lead us to believe that diesel fuel sulfur levels of 15 ppm will be required in order to make feasible the proposed heavy-duty vehicle emission standards. Brief summaries of our analyses for each of these factors are provided below.

The efficiency of emission control technologies to reduce harmful pollutants is directly affected by sulfur in diesel fuel. Initial and long term conversion efficiencies for NO<sub>x</sub>, HC, CO and diesel PM emissions are significantly reduced by catalyst poisoning and catalyst inhibition due to sulfur. NO<sub>x</sub> conversion efficiencies with the NO<sub>x</sub> adsorber technology in particular are dramatically reduced in a very short time due to sulfur poisoning of the NO<sub>x</sub> storage bed. In addition, total PM control efficiency is adversely impacted by the formation of sulfate PM. As explained in detail in the following sections, all of the advanced NO<sub>x</sub> and PM technologies described here have the potential to make significant amounts of sulfate PM under operating conditions typical of heavy-duty vehicles. The formation of sulfate PM is likely to be in excess of the total PM standard for diesel fuel sulfur levels above 15 ppm. Based on the strong negative impact of sulfur on emission control efficiencies for all of the technologies evaluated, we believe that 15 ppm represents an appropriate diesel fuel sulfur level.

Reliability refers to the expectation that emission control technologies must continue to function as required under all operating conditions for the life of the vehicle. As discussed in the following sections, sulfur in diesel fuel can prevent proper operation of both NO<sub>x</sub> and PM control technologies. This can lead to permanent loss in emission control effectiveness and even catastrophic failure of the systems. Sulfur in diesel fuel impacts reliability by decreasing catalyst efficiency (poisoning of the catalyst), increasing diesel particulate filter loading, and by negatively impacting system regeneration functions. Among the most serious reliability concerns with sulfur levels greater than 15 ppm are those associated with failure to properly regenerate. In the case of the NO<sub>x</sub> adsorber, failure to regenerate will lead to rapid loss of NO<sub>x</sub> emission control as a result of sulfur poisoning of the NO<sub>x</sub> adsorber bed. In the case of the diesel particulate filter, sulfur in the fuel reduces the reliability of the regeneration function. If regeneration does not occur, catastrophic failure of the filter could occur. It is only by the availability of very low sulfur diesel fuels that these technologies become feasible. The analysis given in the following section indicates that diesel fuel sulfur levels of 15 ppm are needed in order to ensure robust operation of the technologies we believe would be needed to meet the proposed standards under the variety of operating conditions anticipated to be experienced in the field.

Fuel economy impacts due to sulfur in diesel fuel are associated with both NO<sub>x</sub> and PM control technologies. The NO<sub>x</sub> adsorber sulfur regeneration cycle (desulfurization cycle) can consume significant amounts of fuel unless fuel sulfur levels are very low. The larger the amount of sulfur in diesel fuel, the greater this impact on fuel economy. As sulfur levels increase above 15 ppm, the fuel economy impact quickly transitions above one percent and doubles with each doubling of fuel sulfur level. Likewise, PM trap regeneration is inhibited by sulfur in diesel fuel. This leads to increased PM loading in the diesel particulate filter and increased work to pump exhaust across this restriction. With very low sulfur diesel fuel, diesel particulate filter regeneration

can be optimized to give a lower (on average) exhaust backpressure and thus better fuel economy. Thus for both NO<sub>x</sub> and PM technologies the lower the fuel sulfur level the better.

### a. Diesel Particulate Filters and the Need for Low-Sulfur Fuel

As discussed earlier in this section, un-catalyzed diesel particulate filters require exhaust temperatures in excess of 650°C in order for the collected PM to be oxidized by the oxygen available in diesel exhaust. That temperature threshold for oxidation of PM by exhaust oxygen can be decreased to 450°C through the use of base metal catalytic technologies. Unfortunately, for a broad range of operating conditions diesel exhaust is significantly cooler than 400°C. If oxidation of the trapped PM could be assured to occur at exhaust temperatures lower than 300°C, then diesel particulate filters would be expected to be robust for most applications and operating regimes. The only means that we are aware of to ensure oxidation of PM (regeneration of the trap) at such low exhaust temperatures is by using oxidants which are more readily reduced than oxygen. One such oxidant is NO<sub>2</sub>.

NO<sub>2</sub> can be produced in diesel exhaust through the oxidation of the nitrogen monoxide (NO), created in the engine combustion process, across a catalyst. The resulting NO<sub>2</sub>-rich exhaust is highly oxidizing in nature and can oxidize trapped diesel PM at temperatures as cool as 250°C.<sup>36</sup> Some platinum group metals are known to be good catalysts to promote the oxidation of NO to NO<sub>2</sub>. Therefore in order to ensure passive regeneration of the diesel particulate filters, significant amounts of platinum group metals (primarily platinum) are being used in the wash-coat formulations of advanced diesel particulate filters. The use of platinum to promote the oxidation of NO to NO<sub>2</sub> introduces several system vulnerabilities affecting both the durability and the effectiveness of the catalyzed diesel particulate filter when sulfur is present in diesel exhaust. The two primary mechanisms by which sulfur in diesel fuel limits the robustness and effectiveness of diesel particulate filters are inhibition of trap regeneration (as a result of inhibition of the oxidation of NO to NO<sub>2</sub>) and a dramatic loss in total PM control effectiveness due to the formation of sulfate PM. Unfortunately these two mechanisms tradeoff against one another in the design of diesel particulate filters. Changes to improve the reliability of regeneration by increasing catalyst loadings lead to increased sulfate emissions and thus loss of PM control effectiveness. Conversely, changes to improve PM control by reducing the use of platinum group metals and, therefore, limiting sulfate make leads to less reliable regeneration. In our view, the only means of achieving good PM emission control and reliable operation is to reduce sulfur in diesel fuel to 15 ppm, as shown in the following subsections.

#### i. *Inhibition of PM Trap Regeneration Due to Sulfur*

The passively regenerating diesel particulate filter technologies rely on the generation of a very strong oxidant, NO<sub>2</sub>, to ensure that the carbon captured by the PM trap's filtering media is oxidized under normal operating conditions. NO<sub>2</sub> is produced through the oxidation of NO in the exhaust across a platinum catalyst. This oxidation is inhibited by the presence of SO<sub>2</sub> in the exhaust stream because the preferential reaction across the platinum is oxidation of SO<sub>2</sub> to SO<sub>3</sub>, rather than



oxidation of NO to NO<sub>2</sub>.<sup>37</sup> This inhibition limits the total amount of NO<sub>2</sub> available for oxidation of the trapped diesel PM, thereby raising the minimum exhaust temperature required to ensure trap regeneration. The balance point temperature is the temperature at which PM accumulation matches the PM oxidation rate in a catalyzed PM trap. In other words, the lowest temperature at which the filter would never plug due to PM buildup. Figure III.A-5 shows that going from three ppm sulfur fuel to 30 ppm sulfur fuel significantly increases the balance point of these filters<sup>8</sup> through inhibition of the NO<sub>2</sub> conversion process.<sup>38</sup> This seemingly small change in balance point temperature (approximately 10 percent) is significant because temperatures in the range shown here are representative of likely exhaust temperatures for many diesel vehicles under normal driving cycles. Were typical exhaust temperatures in excess of 400°C for most engine operating conditions, this change would be less important. Without sufficient NO<sub>2</sub>, the amount of PM trapped in the diesel particulate filter will continue to increase and can lead to excessive exhaust back pressure, low engine power, and even catastrophic failure of the diesel particulate filter itself.

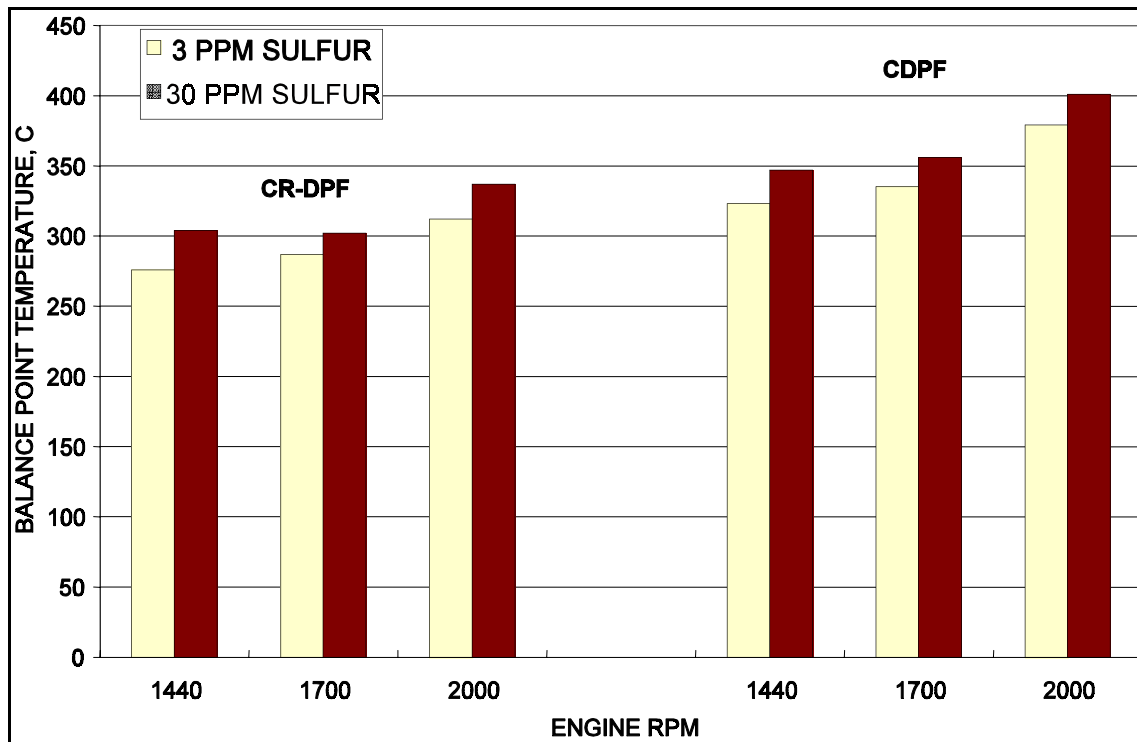


Figure III.A-5. Effect of Fuel Sulfur on Regeneration Temperature

Full field test evaluations and retrofit applications of these catalytic trap technologies are

<sup>8</sup> CR\_DPF in the figure refers to a continuously regenerating diesel particulate filter, CDPF refers to a catalyzed diesel particulate filter.

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occurring in parts of Europe where low-sulfur diesel fuel is already available.<sup>h</sup> The experience gained in these field tests helps to clarify the need for very low sulfur diesel fuel. In Sweden and some European city centers where below 10 ppm diesel fuel sulfur is readily available, more than 3,000 catalyzed diesel particulate filters have been introduced into retrofit applications without a single failure. With the large number of vehicles participating in these test programs and the extended time periods of operation (some vehicles have been operating with traps for more than 4 years and in excess of 300,000 miles<sup>39</sup>) this is a strong indication of the robustness of this technology on 10 ppm low sulfur diesel fuel. The field experience in areas where sulfur is capped at 50 ppm has been less definitive. In regions without extended periods of cold ambient conditions (such as the United Kingdom) field tests on 50 ppm cap low sulfur fuel have also been positive matching the success at 10 ppm. However, field tests in Finland where colder winter conditions are sometimes encountered (similar to many parts of the United States) have revealed a failure rate of 10 percent. This 10 percent failure rate has been attributed to insufficient trap regeneration due to fuel sulfur in combination with low ambient temperatures.<sup>40</sup> As the ambient conditions in Sweden are expected to be no less harsh than Finland, we are left to conclude that the increased failure rates noted here are due to the higher fuel sulfur level in a 50 ppm cap fuel versus a 10 ppm cap fuel. The failure of some fraction of the traps to regenerate on 50 ppm cap fuel is believed to be primarily due to inhibition of the NO to NO<sub>2</sub> conversion as described here. At fuel sulfur levels less than 10 ppm, we are unaware of any issues with regeneration of advanced diesel particulate filters.

The failure mechanisms experienced by diesel particulate filters due to low NO<sub>2</sub> availability vary significantly in severity and long term consequences. In the most fundamental sense, the failure is defined as an inability to oxidize the stored particulate at a rate fast enough to prevent net particulate accumulation over time. The excessive accumulation of PM over time blocks the passages through the filtering media, making it more restrictive to exhaust flow. In order to continue to force the exhaust through the now more restrictive filter the exhaust pressure upstream of the filter must increase. This increase in exhaust pressure is commonly referred to as increasing “exhaust backpressure” on the engine.

The increased exhaust backpressure represents increased work being done by the engine to force the exhaust gas through the increasingly restrictive particulate filter. Unless the filter is frequently cleansed of the trapped PM, this increased work can lead to reductions in engine performance and increases in fuel consumption. This loss in performance may be noted by the vehicle operator in terms of poor acceleration and generally poor driveability of the vehicle. This progressive deterioration of engine performance as more and more PM is accumulated in the filter media is often referred to as “trap plugging.” Whether trap plugging occurs, and the speed at which it occurs, will be a function of many variables in addition to the fuel sulfur level; these variables include the vehicle application, its duty cycle, and ambient conditions. However, if the fuel sulfur level is sufficient to prevent trap regeneration in any real world conditions experienced, trap

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<sup>h</sup> Through tax incentives 50 ppm cap sulfur fuel is widely available in the United Kingdom while 10 ppm sulfur fuel is available in Sweden and in certain European city centers.

plugging can occur with perhaps just one fill up<sup>i</sup>. This is not to imply that any time a vehicle is refueled once with high sulfur fuel trap plugging will occur, rather it is important to know that the use of fuel with sulfur levels higher than 15 ppm significantly increases the chances of catalyzed particulate filter failure.

Catastrophic failure of the filter can occur when excessive amounts of PM are trapped in the filter due to a lack of NO<sub>2</sub> for oxidation. This failure occurs when excessive amounts of trapped PM begin to oxidize at high temperatures (combustion-like temperatures of >1000°C) leading to a “run-away” combustion of the PM. This can cause temperatures in the filter media to increase in excess of that which can be tolerated by the particulate filter itself. For the cordierite material commonly used as the trapping media for diesel particulate filters, the high thermal stresses caused by the high temperatures can cause the material to crack or melt. This can allow significant amounts of the diesel particulate to pass through the filter without being captured during the remainder of the vehicle’s life. That is, the trap is destroyed and PM emission control is lost.

As shown above, sulfur in diesel fuel inhibits NO oxidation leading to increased exhaust backpressure, reduced fuel economy, and compromised reliability. We, therefore, believe that in order to ensure reliable and economical operation over a wide range of expected operating conditions a diesel fuel sulfur level of 15 ppm will be needed. With these very low sulfur levels we believe, as demonstrated by experience in Europe, that catalyzed diesel particulate filters will prove to be both durable and effective at controlling diesel particulate emissions to the very low levels required by this proposed standard.

### *ii. Loss of PM Control Effectiveness*

In addition to inhibiting the oxidation of NO to NO<sub>2</sub>, the sulfur dioxide (SO<sub>2</sub>) in the exhaust stream is itself oxidized to sulfur trioxide (SO<sub>3</sub>) at very high conversion efficiencies, by the precious metals in the catalyzed particulate filters. The SO<sub>3</sub> serves as a precursor to the formation of hydrated sulfuric acid (H<sub>2</sub>SO<sub>4</sub>+H<sub>2</sub>O), or sulfate PM, as the exhaust leaves the vehicle tailpipe. Virtually all of the SO<sub>3</sub> is converted to sulfate under dilute exhaust conditions in the atmosphere as well in the dilution tunnel used in heavy-duty engine testing. The sulfate formed in the dilution tunnel is then collected and measured as part of the total PM. Since virtually all sulfur present in diesel fuel is converted to SO<sub>2</sub>, the precursor to SO<sub>3</sub>, as part of the combustion process, the total sulfate PM is directly proportional to the amount of sulfur present in diesel fuel. Therefore, even though diesel particulate filters are very effective at trapping the carbon and the SOF portions of the total PM, the overall PM reduction efficiency of catalyzed diesel particulate filters drops off rapidly

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<sup>i</sup> Assuming a 10 liter engine, that a trap is plugged when it accumulates 7 g/l of trap volume, the trap is two times the volume of the engine, the engine emits 0.1 g/hp-hr PM, the trap does not regenerate, and a HD engine produces 3.013 hp-hr/mi (from MOBILE6). Then PM is emitted at a rate of 0.1 g/hp-hr times 3.013 hp-hr/mi, or 0.3 g/mi. Given that the trap can contain 7g/l times 10 l times 2, or 140 g of PM, then the trap will plug in 140 g PM divided by 0.3 g/mi, or 462 miles. HD trucks typically have a cruising range of more than 500 miles, so it is conceivable that the trap could plug in as little as one tank of fuel.

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with increasing sulfur levels due to the production of sulfate PM (i.e., “sulfate make,” see Figures III.A-1 and III.A-2).

SO<sub>2</sub> oxidation is promoted across a catalyst in a manner very similar to the oxidation of NO, except it is converted at higher rates (Figure III.A-6<sup>j</sup>), with peak conversion rates in excess of 50 percent (Table III.A-2).<sup>41</sup> The SO<sub>2</sub> oxidation rate for a platinum based oxidation catalyst typical of the type which might be used in conjunction with, or as a washcoat on, a catalyzed diesel particulate filter can vary significantly with exhaust temperature. At the low temperatures typical of some urban driving and the heavy-duty federal test procedure (HD-FTP), the oxidation rate is relatively low, perhaps no higher than ten percent. However at the higher temperatures that might be more typical of non-urban highway driving conditions and the supplemental steady state test (also called the EURO III or 13 mode test), the oxidation rate may increase to 50 percent or more. These high levels of sulfate make across the catalyst are in contrast to the very low SO<sub>2</sub> oxidation rate typical of diesel engines (less than 2 percent). This variation in expected diesel exhaust temperatures means that there will be a corresponding range of sulfate production expected across a catalyzed diesel particulate filter.

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<sup>j</sup> In Figure III.A-6, the legend shows values of 42,000 hr<sup>-1</sup> and 373,000 hr<sup>-1</sup>. These values refer to “space velocity,” which is a measure of the volume of exhaust gas that flows through a device; these can be taken to mean “low flow rate” at 42,000 hr<sup>-1</sup> and “high flow rate” at 373,000 hr<sup>-1</sup>.

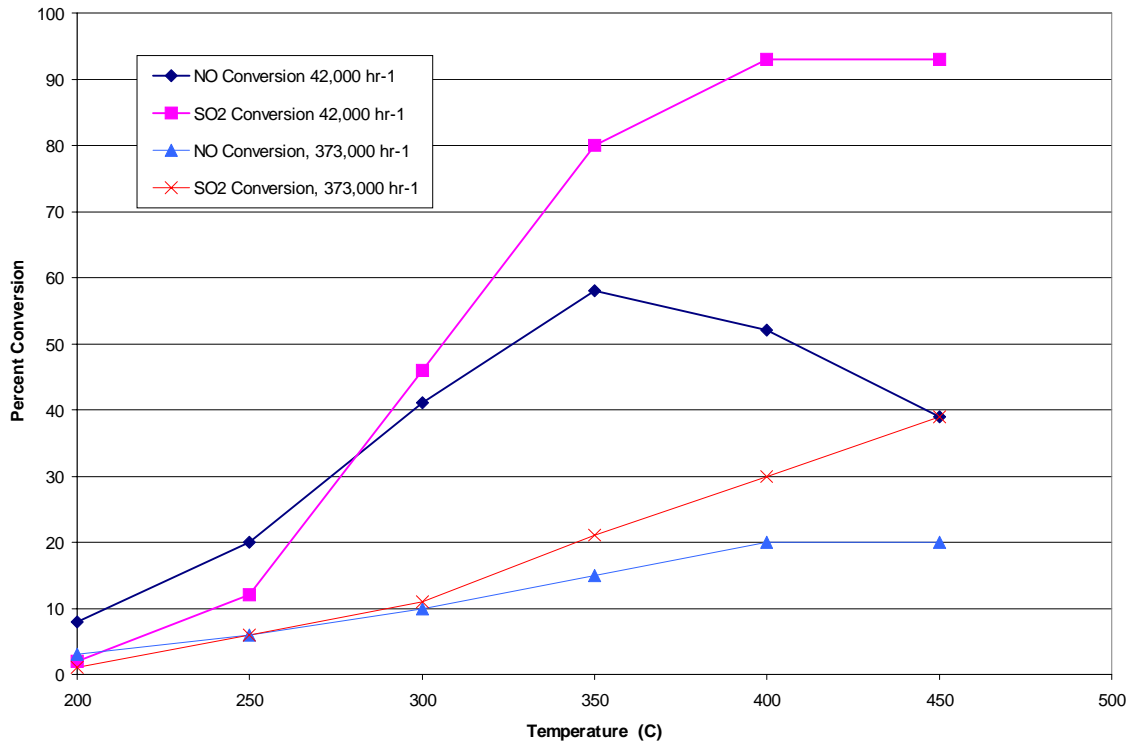


Figure III.A-6. NO and SO<sub>2</sub> Conversion Rates Over Platinum

Table III.A-2. SO<sub>2</sub> Oxidation Rates for a Platinum Oxidation Catalyst at the Indicated Catalyst Inlet Temperatures

<i>Catalyst Temperature</i>	<i>SO<sub>2</sub> Oxidation* Rate</i>	<i>Operation Represented</i>
200°C	1-3%	Idle, very low load
250°C	4-11%	HD-FTP some Urban Driving
300°C	10-45%	EURO III some Rural Driving
350°C	20-80%	EURO III some Rural Driving
400°C	30-90%	EURO III some Rural Driving
450°C	40-90%	Peak Torque and Rated Conditions

\*range in oxidation rates accounts for variations in exhaust flow through the catalyzed filter, at very high flow rates SO<sub>2</sub> oxidation is minimized and at low flow rates SO<sub>2</sub> oxidation is maximized

The US Department of Energy in cooperation with industry conducted a study entitled Diesel Emission Control Sulfur Effects (DECSE) to provide insight into the relationship between advanced emission control technologies and diesel fuel sulfur levels. Interim report number four of this program gives the total particulate matter emissions from a heavy-duty diesel engine operated with a diesel particulate filter on several different fuel sulfur levels. A straight line fit through this data is presented in Table III.A-3 below showing the expected total direct PM emissions from a heavy-duty diesel engine on the supplemental steady state test cycle.<sup>k</sup>

**Table III.A-3. Estimated PM Emissions from a Heavy-Duty Diesel Engine at the Indicated Average Fuel Sulfur Levels**

<i>Fuel Sulfur [ppm]</i>	<i>Supplemental Steady State*</i>	
	<i>Tailpipe PM [g/bhp-hr]</i>	<i>Relative to 3 ppm Sulfur Test Point</i>
3	0.003	--
7*	0.006	100 %
15*	0.009	200 %
30	0.017	470 %
150	0.071	2300 %

\* The PM emissions at these sulfur levels are estimated based on a straight-line fit to the DECSE program data; PM emissions at other sulfur levels are actual DECSE data.<sup>42</sup>

Table III.A-3 makes it clear that there are significant PM emission reductions possible with the application of catalyzed diesel particulate filters and low-sulfur diesel fuel. At the observed sulfate PM conversion rates, the DECSE program results show that the proposed total PM standard is feasible for diesel particulate filter equipped engines operated on fuel with a sulfur level at or below 15 ppm. The results also show that diesel particulate filter control effectiveness is rapidly degraded at higher diesel fuel sulfur levels due to the high sulfate PM make observed with this technology. It is clear that PM reduction efficiencies are limited by sulfur in diesel fuel and that, in order to realize the PM emissions benefits sought in this rule, diesel fuel sulfur levels must be very low. As discussed in Section IV, we believe that 15 ppm sulfur for highway diesel fuel is the appropriate level given consideration to all factors.

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<sup>k</sup> Note that direct emissions are those pollutants emitted directly from the engine or from the tailpipe depending on the context in which the term is used, and indirect emissions are those pollutants formed in the atmosphere through the combination of direct emissions and atmospheric constituents.

### *iii. Increased Maintenance Cost for Diesel Particulate Filters Due to Sulfur*

In addition to the direct performance and durability concerns caused by sulfur in diesel fuel, it is also known that sulfur can lead to increased maintenance costs, shortened maintenance intervals, and poorer fuel economy for particulate filters. Diesel particulate filters are highly effective at capturing the inorganic ash produced from metallic additives in engine oil. This ash is accumulated in the filter and is not removed through oxidation, unlike the trapped carbonaceous PM. Periodically the ash must be removed by mechanical cleaning of the filter with compressed air or water. This maintenance step is anticipated to occur on intervals of well over one hundred thousand miles. However, sulfur in diesel fuel increases this ash accumulation rate through the formation of metallic sulfates in the filter, which increases both the size and mass of the trapped ash. By increasing the ash accumulation rate the sulfur shortens the time interval between the required maintenance of the filter and negatively impacts fuel economy.

### **b. Diesel NO<sub>x</sub> Catalysts and the Need for Low-Sulfur Fuel**

All of the NO<sub>x</sub> aftertreatment technologies discussed previously in Section III are expected to utilize platinum to oxidize NO to NO<sub>2</sub> to improve the NO<sub>x</sub> reduction efficiency of the catalysts at low temperatures or as in the case of the NO<sub>x</sub> adsorber, as an essential part of the process of NO<sub>x</sub> storage. This reliance on NO<sub>2</sub> as an integral part of the reduction process means that the NO<sub>x</sub> aftertreatment technologies, like the PM aftertreatment technologies, will have problems with sulfur in diesel fuel. In addition NO<sub>x</sub> adsorbers have the added constraint that the adsorption function itself is blocked by the presence of sulfur. These limitations due to sulfur in the fuel affect both overall performance of the technologies and, in fact, the very feasibility of the NO<sub>x</sub> adsorber technology.

### *i. Sulfate Particulate Production for NO<sub>x</sub> Control Technologies*

Two advanced NO<sub>x</sub> control technologies that are likely to be able to meet the NO<sub>x</sub> emission standard are NO<sub>x</sub> adsorber catalyst systems and compact SCR systems. The NO<sub>x</sub> adsorber technology relies on an oxidation function to convert NO to NO<sub>2</sub> over the catalyst bed. For the NO<sub>x</sub> adsorber this is a fundamental step prior to the storage of NO<sub>2</sub> in the catalyst bed as a nitrate. Without this oxidation function the catalyst will only trap that small portion of NO<sub>x</sub> emissions from a diesel engine which is NO<sub>2</sub>. This would reduce the NO<sub>x</sub> adsorber effectiveness for NO<sub>x</sub> reduction from in excess of 90 percent to something well below 20 percent. The NO<sub>x</sub> adsorber relies on platinum to provide this oxidation function due to the need for high NO oxidation rates under the relatively cool exhaust temperatures typical of diesel engines.

The compact SCR technology, like the NO<sub>x</sub> adsorber technology, uses an oxidation catalyst to promote the oxidation of NO to NO<sub>2</sub> at the low temperatures typical of much of diesel engine operation. By converting a portion of the NO<sub>x</sub> emissions to NO<sub>2</sub> upstream of the ammonia SCR reduction catalyst, the overall NO<sub>x</sub> reductions are improved significantly at low temperatures. As discussed previously in Section III, platinum group metals, primarily platinum, are known to be

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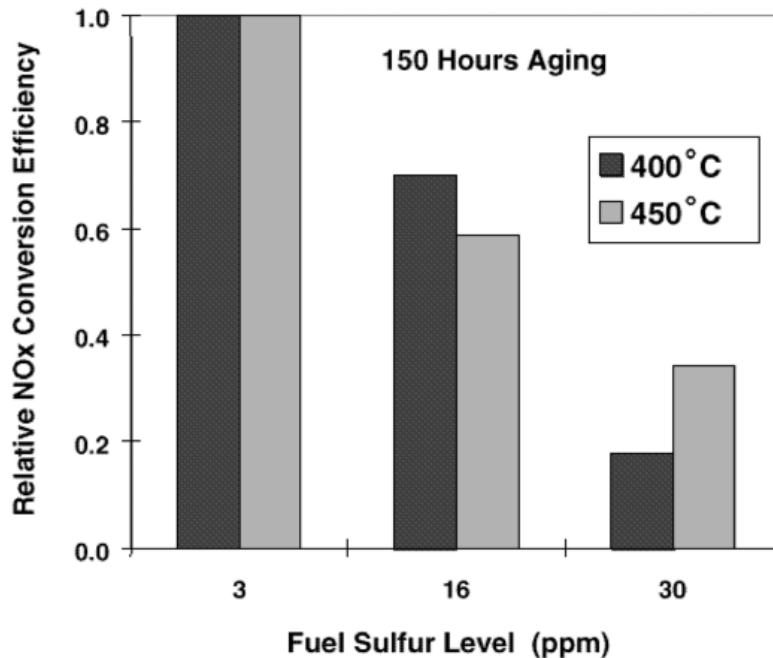
good catalysts to promote NO oxidation, even at low temperatures. Therefore, future compact SCR systems are expected to rely on a platinum oxidation catalyst in order to provide the required NOx emission control.

The NOx adsorber technology may be able to limit its impact on sulfate PM emissions by releasing stored sulfur as SO<sub>2</sub> under rich operating conditions. The compact SCR technology, on the other hand, has no means to limit sulfate emissions other than through lower catalytic function or lowering sulfur in diesel fuel. The degree to which the NOx control aftertreatment technologies increase the production of sulfate PM through oxidation of SO<sub>2</sub> to SO<sub>3</sub> varies somewhat from technology to technology, but it is expected to be similar in magnitude and environmental impact to that for the PM control technologies discussed previously. Thus, diesel fuel sulfur levels must be very low in order to apply these advanced NOx control technologies (see discussion in Section III.A.1). Without this low sulfur fuel, the advanced NOx control technologies are expected to create PM emissions in excess of the PM standard regardless of the engine out PM levels.

### *ii. Sulfur Poisoning (Sulfate Storage) on NOx Adsorbers*

The NOx adsorber technology relies on the ability of the catalyst to store NOx as a nitrate on the surface of the catalyst, or adsorber (storage) bed, during lean operation. Because of the similarities in chemical properties of SOx and NOx, the SO<sub>2</sub> present in the exhaust is also stored by the catalyst surface as a sulfate. The sulfate compound that is formed is significantly more stable than the nitrate compound and is typically not released and reduced during the NOx release and reduction step. Since the NOx adsorber is essentially 100 percent effective at capturing SO<sub>2</sub> in the adsorber bed, the poisoning of the catalyst occurs rapidly. As a result, sulfate compounds quickly occupy all of the NOx storage sites on the catalyst thereby rendering the catalyst ineffective for NOx reduction (poisoning the catalyst). Figure III.A-7 clearly illustrates this effect at 3, 16, and 30 ppm fuel sulfur levels.<sup>43</sup>





**Figure III.A-7. Diesel Fuel Sulfur Effect on NO<sub>x</sub> Adsorber Performance after 150 hours**

The stored sulfur compounds can be removed by exposing the catalyst to hot (>650°C) and rich (air-fuel ratio below the stoichiometric ratio of 14.5 to 1) conditions for a brief period.<sup>44</sup> Under these conditions, the stored sulfate is released and reduced in the catalyst.<sup>45,46</sup> Because the exhaust must be taken to a hot and rich condition, there is a fuel consumption impact associated with the desulfation cycle. We have developed a spreadsheet model that estimates the frequency of desulfation cycles from published data and then estimates the fuel economy impact from this event.<sup>47</sup> Table III.A-4 shows the estimated fuel economy impact for desulfation of a NO<sub>x</sub> adsorber at different fuel sulfur levels assuming a desired 90 percent NO<sub>x</sub> conversion efficiency. The estimates in the table are based on assumed average fuel sulfur levels associated with different sulfur level caps.

**Table III.A-4. Estimated Fuel Economy Impact from Desulfation of a 90 Percent Efficient NOx Adsorber**

<i>Fuel Sulfur Cap [ppm]</i>	<i>Average Fuel Sulfur [ppm]</i>	<i>Fuel Economy Penalty [%]</i>
500	350	27
50	30	2
25	15	1
15	7	< 1
5	2	<<< 1

The table shows that the fuel economy penalty associated with sulfur in diesel fuel is noticeable even at average sulfur levels as low as 15 ppm and increases rapidly with higher sulfur levels. It also shows that the 15 ppm sulfur cap would be expected to result in a fuel economy impact of less than 1 percent absent other changes in engine design.

As a consequence of requiring desulfation to occur before the NOx adsorber catalyst degrades to a level below 90 percent, the fuel economy impacts at higher sulfur levels described here are substantial. Therefore it would be logical to consider the possibility of allowing further degradations in NOx performance (below 90 percent) before desulfation in order to reduce this fuel economy impact. Recent results from industry contradict that position, however, indicating that when deep poisoning of the catalyst occurs due to higher fuel sulfur levels (or presumably extend periods of poisoning without desulfation) the ability of the catalyst to recover from the sulfur poisoning is compromised<sup>48</sup>. This data from a gasoline direct injection application indicates that desulfation events sequenced on a fixed interval with only minimal poisoning allowed for full recovery of NOx performance (eight ppm sulfur fuel, regenerated on a fixed driving cycle with 32,000 km of vehicle operation). These good results are contrasted with performance on 30 ppm sulfur fuel in which NOx adsorber desulfation occurred on the same fixed interval (thus allowing greater levels of poisoning before desulfation). For this case NOx control performance was never fully recovered at each desulfation step and, therefore, continued to gradually decrease over time from an initial efficiency of 95 percent to 80 percent over the same 32,000 km of vehicle operation.

Future improvements in the NOx adsorber technology are expected and needed if the technology is to provide the environmental benefits we have projected today. Some of these improvements are likely to include improvements in the means and ease to remove stored sulfur from the catalyst bed. However because the stored sulfate species are inherently more stable than the stored nitrate compounds (from stored NOx emissions), we expect that a separate release and reduction cycle (desulfurization cycle) will always be needed in order to remove the stored sulfur. Therefore, we believe providing fuel with a sulfur level of 15 ppm sulfur would avoid a large and

expensive fuel economy impact.

### *iii. Sulfur Impacts on Catalytic Efficiency*

In general, the technologies discussed previously rely on some form of catalytic function in order to promote favorable chemical reactions needed in order to accomplish the desired NO<sub>x</sub> emission reductions. In each case, platinum and/or other precious group metal catalysts are anticipated to be used to accomplish these functions. From our experience with gasoline three-way catalysts, and from the extensive body of work in the literature, we know that these catalytic functions are inhibited by sulfur. Sulfur deposits on the precious metal sites in the catalyst and causes a decrease in the catalytic function of the device. This causes an increase in the light-off temperature for the catalyst along with a significant reduction in the oxidation and reduction efficiencies of all of the devices.<sup>49</sup> As discussed at length in the Tier 2 rulemaking, sulfur reductions in the fuel are a very effective way to reduce catalyst poisoning of this type in order to maintain high catalyst efficiency and to ensure reliable operation.

### **c. Contribution of Sulfur from Engine Lubricating Oils**

Current engine lubricating oils have sulfur contents which can range from 2,500 ppm to as high as 8,000 ppm by weight. Since engine oil is consumed by heavy-duty diesel engines in normal operation, it is important that we account for the contribution of oil derived sulfur in our analysis of the need for low sulfur diesel fuel. One way to give a straightforward comparison of this effect is to express the sulfur consumed by the engine as an equivalent fuel sulfur level. This approach requires that we assume specific fuel and oil consumption rates for the engine. Using this approach, estimates ranging from two to seven ppm diesel fuel sulfur equivalence have been made for the sulfur contribution from engine oil.<sup>50,1</sup> If values at the upper end of this range accurately reflect the contribution of sulfur from engine oil to the exhaust this would be a concern as it would represent 50 percent of the total sulfur in the exhaust under a 15 ppm diesel fuel sulfur cap (with an average sulfur level assumed to be approximately seven ppm). However, we believe that this simplified analysis, while valuable in demonstrating the need to investigate this issue further, overstates the likely sulfur contribution from engine oil by a significant amount. Current heavy-duty diesel engines operate with open crankcase ventilation systems which “consume” oil by carrying oil from the engine crankcase into the environment. This consumed oil is correctly included in the total oil consumption estimates, but should not be included in estimates of oil entering the exhaust system for this analysis, since as currently applied this oil is not introduced into the exhaust.

As an alternate approach to estimate the amount of oil and thus oil born sulfur present in the exhaust, projected emission rates for 2004 technology engines can be made. The 2004 HD emission

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<sup>1</sup> This estimate assumes that a heavy-duty diesel engine consumes 1 quart of engine oil in 2,000 miles of operation, consumes fuel at a rate of 1 gallon per 6 miles of operation and that engine oil sulfur levels range from 2,000 to 8,000 ppm.

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standards set a 0.1 g/bhp-hr PM emission rate for all classes of heavy-duty diesel vehicles. If we assume that virtually all oil consumed by the engine is emitted as diesel PM and that this soluble organic fraction (SOF) makes up 30 percent of diesel PM we can estimate how much oil is consumed. Using this approach we have estimated that the equivalent fuel sulfur level from engine oil is approximately 1 ppm.<sup>m</sup>

As a further attempt to better understand the amount of sulfur contributed from engine oil in the exhaust we have looked at the results from the DECSE test program. The DECSE program reports sulfate emissions from a heavy-duty diesel engine equipped with highly catalyzed diesel particulate filters and operated on diesel fuel at several fuel sulfur levels. A commonly used motor oil with sulfur content of approximately 3,500 ppm was chosen for this testing. Since the PM emission control technologies used in this testing are very sensitive to sulfur (converting sulfur to sulfate PM emissions at a rate of approximately 40 percent) they should reveal sensitivities to sulfur from lube oil. By taking the sulfate emission results reported by DECSE at fuel sulfur levels of 3 and 30 ppm sulfur we can estimate the amount of sulfate emissions (and thus sulfur contribution) from the engine oil. The intercept (the predicted sulfate emissions at 0 ppm sulfur fuel) of a straight-line fit through the two test points should reveal the amount of sulfate produced from oil derived sulfur. Figure III.A-8 below shows the results of this analysis. The intercept value shown in the figure is slightly below zero indicating that in spite of the high sulfur conversion rate typical of these emission control devices the amount of lube oil derived sulfate emissions is unmeasurable. Although some amounts of sulfur from lubricating oils will almost certainly present in the exhaust, this analysis seems to indicate that it will not be a significant fraction of the total sulfur even for fuel sulfur levels as low as 15 ppm.

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<sup>m</sup> This estimate is made assuming that the engine oil has a sulfur content of 5,000 ppm, that 30 percent of PM emissions are from engine oil, and that the engine brake specific fuel consumption rate is 0.300 lbm/bhp-hr. A higher fuel consumption rate decreases the relative amount of sulfur from engine oil in this estimate.

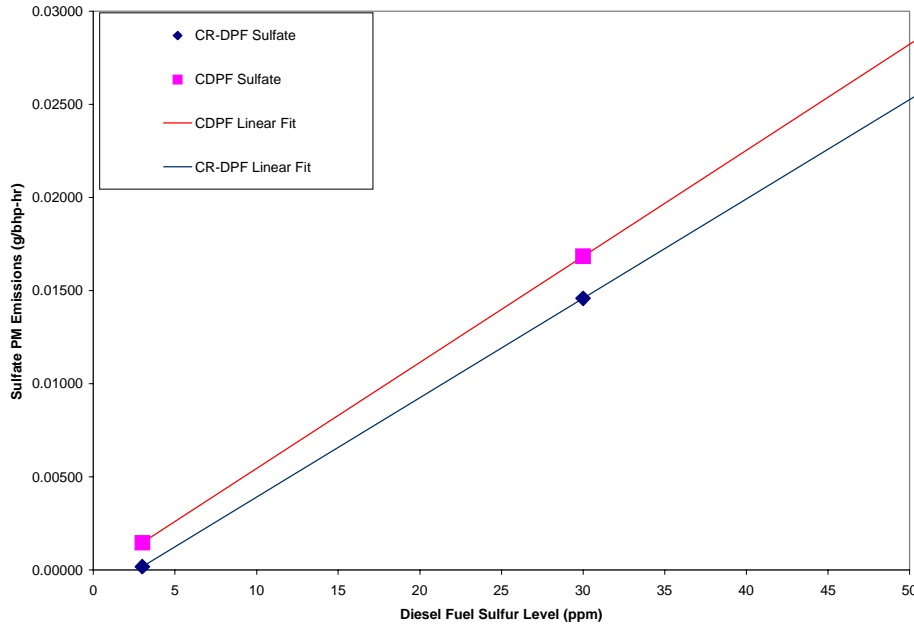


Figure III.A-8 Sulfate PM Emissions versus Diesel Fuel Sulfur Level with 3,500 ppm Sulfur Engine Oil<sup>51</sup>

## B. Feasibility of Stringent Standards for Heavy-Duty Gasoline Vehicles & Engines

Gasoline emission control technology has evolved rapidly in recent years. Emission standards applicable to 1990 model year vehicles required roughly 90 percent reductions in exhaust HC and CO emissions and a 75 percent reduction in NOx emissions compared to uncontrolled emissions. Today, some heavy-duty vehicles' emissions are well below those necessary to meet the current federal heavy-duty gasoline standards, the proposed 2004 heavy-duty gasoline standards, and the California Low Emission Vehicle (LEV) standards for medium-duty vehicles. The continuing emissions reductions have been brought about by ongoing improvements in engine air-fuel management hardware and software plus improvements in exhaust system and catalyst designs.

These improvements to gasoline emission control have been made in response to the California LEV-II standards and the new federal Tier 2 standards. Some of this development work was contributed by EPA in a very short timeframe and with very limited resources in support of our Tier 2 rulemaking effort.<sup>52</sup> These improvements should transfer well to the heavy-duty gasoline segment of the fleet. With such migration of light-duty technology to heavy-duty vehicles and engines, we believe that considerable improvements to heavy-duty emissions can be realized, thus enabling much more stringent standards.

We believe that the types of changes being seen on current vehicles have not yet reached

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their technological limits and continuing improvement will allow them to meet the proposed 2007 heavy-duty gasoline standards. There is no need to invent new technologies, although there will be a need to apply existing technology more effectively and more broadly. The focus of the effort will be in the application and optimization of these existing technologies.

The most significant improvements facilitating the low emission levels being realized on some vehicles today have been to traditional catalysts, which now warm up very rapidly and are substantially more durable than past catalysts, and to fuel metering, which is more precise and accurate than previous systems. Improvements have also been made to base engine designs, which have resulted in lower engine-out emissions. Reduction of combustion chamber crevice volumes and oil consumption are examples of improvements to base engine designs. Perhaps most important of all, emission control calibrations continue to become more refined and sophisticated.

In our Tier 2 rule for light-duty vehicles and trucks, we have required that gasoline sulfur levels be reduced to a 30 ppm average, with an 80 ppm maximum. This sulfur level reduction is the primary enabler for the Tier 2 standards. Similarly, we believe that the gasoline sulfur reduction, along with refinements in existing gasoline emission control technology, will be sufficient to allow heavy-duty gasoline vehicles and engines to meet the emission standards sought by today's proposal.

Table III.B-1 below lists specific types of emission controls that we project may be used on heavy-duty gasoline vehicles to meet the proposed 2007 heavy-duty standards. It is important to point out that all of these technologies would not necessarily be needed to meet the proposed 2007 heavy-duty standards. The choices and combinations of technologies will depend on several factors, such as current engine-out emission levels, effectiveness of existing emission control systems, and individual manufacturer preferences. In some cases, such as the need for increases in catalyst volume and precious metal loading, we believe that most, if not all, vehicles will use the specified emission control technique. The following section discusses in detail some of the technologies that may be used.

**Table III.B-1. Emission Control Hardware and Technologies That May be Used to Meet the 2007 Heavy-Duty Gasoline Standards**

Fast Light-Off Exhaust Gas Oxygen Sensor	Secondary Air Injection Exhaust
Retarded Spark Timing at Start-Up	Heat Optimized Exhaust Pipe
More Precise Fuel Control	Leak-Free Exhaust System
32-bit Microprocessor	Close-Coupled Catalyst
Manifold with Low Thermal Capacity	Improved Catalyst Washcoats
Air-Assisted Fuel Injection	Increased Catalyst Volume and Precious Metal Loading
Engine Modifications	Full Electronic Exhaust Gas Recirculation

**1. Technology Description**

The following descriptions provide an overview of the latest technologies capable of reducing exhaust emissions. The technology descriptions are divided into five categories:

- base engine improvements;
- improved fuel control;
- improved fuel atomization;
- improved exhaust and exhaust aftertreatment systems; and
- improved engine calibrations.

**a. Base Engine Improvements**

There are several design techniques that can be used for reducing engine-out emissions, especially for HC and NO<sub>x</sub>. The main causes of excessive engine-out emissions are unburned HCs and high combustion temperatures for NO<sub>x</sub>. Methods for reducing engine-out HC emissions include the reduction of crevice volumes in the combustion chamber, reducing the combustion of lubricating oil in the combustion chamber and developing leak-free exhaust systems. Leak-free exhaust systems are considered to be base engine improvements because any modifications or changes made to the exhaust manifold can directly affect the design of the base engine. Base engine control strategies for reducing NO<sub>x</sub> include the use of “fast burn” combustion chamber designs,

multiple valves with variable-valve timing, and exhaust gas recirculation.

*i. Combustion Chamber Design*

Unburned fuel can be trapped momentarily in crevice volumes (i.e., the space between the piston and cylinder wall) before being subsequently released. Since trapped and re-released fuel can increase engine-out HC, the reduction of crevice volumes is beneficial to emission performance. One way to reduce crevice volumes is to design pistons with reduced top “land heights.”<sup>n</sup> The reduction of crevice volume is especially desirable for vehicles with larger displacement engines, since they typically produce greater levels of engine-out HC than smaller displacement engines.

Another cause of excess engine-out HC emissions is the combustion of lubricating oil that leaks into the combustion chamber, since heavier hydrocarbons in oil do not oxidize as readily as those in gasoline. Oil in the combustion chamber can also trap gaseous HC from the fuel and release it as an unburned HC. In addition, some components in lubricating oil can poison the catalyst and reduce its effectiveness. To reduce oil consumption, vehicle manufacturers are expected to tighten tolerances and improve the surface finishes of cylinders and pistons, improve piston ring design and material, and improve exhaust valve stem seals to prevent excessive leakage of lubricating oil into the combustion chamber.

As discussed above, engine-out NO<sub>x</sub> emissions result from high combustion temperatures. Therefore, the main control strategies for reducing engine-out NO<sub>x</sub> are designed to lower combustion temperature. The most promising techniques for reducing combustion temperatures, and thus engine-out NO<sub>x</sub> emissions, are the combination of increasing the rate of combustion, reducing spark advance, and adding a diluent to the air-fuel mixture, typically via exhaust gas recirculation (EGR). The rate of combustion can be increased by using “fast burn” combustion chamber designs. A fast burn combustion rate provides improved thermal efficiency and a greater tolerance for dilution from EGR resulting in better fuel economy and lower NO<sub>x</sub> emissions. There are numerous ways to design a fast burn combustion chamber. However, the most common approach is to induce turbulence into the combustion chamber which increases the surface area of the flame front and thereby increases the rate of combustion. Many engine designs induce turbulence into the combustion chamber by increasing the velocity of the incoming air-fuel mixture and having it enter the chamber in a swirling motion (known as “swirl”). Further improvements can be realized by positioning the spark plug in the center of the combustion chamber. Locating the spark plug in the center of the combustion chamber promotes more thorough combustion and allows the ignition timing to be retarded, decreasing the dwell time of hot gases in the combustion chamber thereby reducing NO<sub>x</sub> formation.

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<sup>n</sup> “Land height” is the distance between the top of the piston and the first piston ring.



### *ii. Improved EGR Design*

One of the most effective means of reducing engine-out NO<sub>x</sub> emissions is exhaust gas recirculation. By recirculating exhaust gases into the combustion chamber, the overall air-fuel mixture is diluted, lowering peak combustion temperatures and reducing NO<sub>x</sub>. As discussed above, the use of high swirl, high turbulence combustion chambers can allow the amount of EGR to be increased from current levels of 15 to 17 percent to levels possibly as high as 20 to 25 percent,<sup>o</sup> resulting in a 15 to 20 percent reduction in engine-out NO<sub>x</sub> emissions.

Many EGR systems in today's vehicles utilize a control valve that requires vacuum from the intake manifold to regulate EGR flow. Under part-throttle operation where EGR is needed, engine vacuum is sufficient to open the valve. However, during throttle applications near or at wide-open throttle, engine vacuum is too low to open the EGR valve. While EGR operation only during part-throttle driving conditions has been sufficient to control NO<sub>x</sub> emissions for most vehicles in the past, more stringent NO<sub>x</sub> standards may require more precise EGR control to improve upon NO<sub>x</sub> emission control. Some manufacturers use a mechanical back-pressure system that measure EGR flow (via delta pressure across an orifice) rather than inferring flow from the EGR pintle position. This system uses electronic control of the vacuum actuation and has very precise control. Many manufacturers are now using electronic EGR in place of mechanical back-pressure designs. By using electronic solenoids to open and close the EGR valve, the flow of EGR can, in some cases, be more precisely controlled.

While most manufacturers agree that electronic EGR gives more precise control of EGR flow rate, not all manufacturers are using it. Numerous heavy-duty gasoline applications certified for the 1998 model year still use mechanical EGR systems, and in some cases, no EGR at all. Nonetheless, the use of EGR remains a very important tool in reducing engine-out NO<sub>x</sub> emissions, whether mechanical or electronic.

### *iii. Multiple Valves and Variable-Valve Timing*

Conventional engines have two valves per cylinder, one for intake of the air-fuel mixture and the other for exhaust of the combustion products. The duration and lift (distance the valve head is pushed away from its seat) of valve openings is constant regardless of engine speed. As engine speed increases, the aerodynamic resistance to pumping air in and out of the cylinder for intake and exhaust also increases. By doubling the number of intake and exhaust valves, pumping losses are reduced, improving the volumetric efficiency and useful power output.

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<sup>o</sup> Some manufacturers have stated that EGR impacts the ability to control net air-fuel ratios tightly due to dynamic changes in exhaust back pressure and temperature, and that the advantages of increasing EGR flow rates are lost partly in losses in air-fuel ratio control even with electronic control of EGR. Higher EGR flow rates can be tolerated by modern engines with more advanced combustion chambers, but EGR cooling may be necessary to achieve higher EGR flow rates within acceptable detonation limits without significant loss of air-fuel control.

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In addition to gains in breathing, the multiple-valve (typically 4-valve) design allows the spark plug to be positioned closer to the center of the combustion chamber (as discussed above) which decreases the distance the flame must travel inside the chamber. In addition, the two streams of incoming gas can be used to achieve greater mixing of air and fuel, further increasing combustion efficiency thereby lowering engine-out HC emissions.

Even greater improvements to combustion efficiency can be realized by using valve timing and lift control to take advantage of the 4-valve configuration. Conventional engines utilize fixed-valve timing and lift across all engine speeds. Typically the valve timing is set at a level that is a compromise between low speed torque and high engine speed horsepower. At light engine loads it would be desirable to close the intake valve earlier to reduce pumping losses. Variable valve timing can enhance both low speed torque and high speed horsepower with no necessary compromise between the two. Variable valve timing can allow for increased swirl and intake charge velocity, especially during low load operating conditions where sufficient swirl and turbulence tend to be lacking. By providing a strong swirl formation in the combustion chamber, the air-fuel mixture can mix sufficiently, resulting in a faster, more complete combustion, even under lean air-fuel conditions, thereby reducing emissions. Variable valve technology by itself may have somewhat limited effect on reducing emissions. Several vehicle manufacturers estimated emission reductions of 3 percent-10 percent for both NMHC and NO<sub>x</sub>, but reductions could be increased when variable valve timing is combined with optimized spark plug location and additional EGR.

Multi-valve engines already exist in numerous federal and California certified vehicles and are projected by ARB to become even more common. ARB also projects that, in order to meet LEV-II LEV and ULEV standards, more vehicles will have to make improvements to the induction system, including the use of variable valve timing.

#### *iv. Leak-Free Exhaust System*

Leaks in the exhaust system can result in increased emissions, but not necessarily from emissions escaping from the exhaust leak to the atmosphere. With an exhaust system leak, ambient air is typically sucked into the exhaust system by the pressure difference created by the flowing exhaust gases inside the exhaust pipe. The air that is sucked into the exhaust system is unmeasured and, therefore, unaccounted for in the fuel system's closed-loop feedback control. The excess air in the exhaust causes the computer to increase fuel to the engine, resulting in erratic and/or overly rich fuel control. This results in increased emission levels and potentially poor driveability. In addition, an air leak can cause an oxidation environment to exist in a three-way catalyst at low speeds that would hamper reduction of NO<sub>x</sub> and lead to increased NO<sub>x</sub> emissions.

Some vehicles currently use leak-free exhaust systems today. These systems consist of an improved exhaust manifold/exhaust pipe interface plus a corrosion-free flexible coupling inserted between the exhaust manifold flange and the catalyst to reduce stress and the tendency for leakage to occur at the joint. In addition, improvements to the welding process for catalytic converter canning could ensure less air leakage into the converter and further reduce emissions.

### **b. Improvements in Air-Fuel Ratio Control**

Modern three-way catalysts require the air-fuel ratio (A/F) to be as close to stoichiometry (the amount of air and fuel just sufficient for nearly complete combustion) as possible. This is because three-way catalysts simultaneously oxidize HC and CO, and reduce NO<sub>x</sub>. Since HC and CO are oxidized during A/F operation slightly lean of stoichiometry, while NO<sub>x</sub> is reduced during operation slightly rich of stoichiometry, there exists a very small A/F window of operation around stoichiometry where catalyst conversion efficiency is maximized for all three pollutants (i.e., less than 1 percent deviation in A/F or roughly  $\pm 0.15$ ). Contemporary vehicles have been able to maintain stoichiometry, or very close to it, by using closed-loop feedback fuel control systems. At the heart of these systems has been a single heated exhaust gas oxygen (HEGO) sensor. The HEGO sensor continuously switches between rich and lean readings. By maintaining an equal number of rich readings with lean readings over a given period, and by limiting the degree to which the exhaust is rich or lean at any point in time, the fuel control system is able to maintain stoichiometry. While this fuel control system is capable of maintaining the A/F with the required accuracy under steady-state operating conditions, the system accuracy is challenged during transient operation where rapidly changing throttle conditions occur. Also, as the sensor ages, its accuracy decreases.

#### *i. Dual Oxygen Sensors*

Many vehicle manufacturers have placed a second HEGO sensor(s) downstream of one or more catalysts in the exhaust system as a method for monitoring the catalyst effectiveness of the federally and California mandated on-board diagnostic (OBD II) system. In addition to monitoring the effectiveness of the catalyst, the downstream sensors can also be used to monitor the primary control sensor and adjust for deterioration, thereby maintaining precise A/F control at higher mileages. Should the front primary HEGO sensor, which operates in a higher temperature environment, begin to exhibit slow response or drift from its calibration point, the secondary downstream sensor can be relied upon for modifying the fuel system controls to compensate for the aging effects. By placing the second sensor further downstream from the hot engine exhaust, where it is also less susceptible to poisoning, the rear sensor is less susceptible to aging over the life of the vehicle. Because of this placement and the decreased susceptibility to aging, we expect the downstream sensor to survive the full life of the vehicle without replacement. As a result, the use of a dual oxygen sensor fuel control system can ensure more robust and precise fuel control, resulting in lower emissions.

By 2007, all vehicle manufacturers are expected to use a dual oxygen sensor system for monitoring the catalyst as part of the OBD system as required by the 2007 rule. As discussed above, most manufacturers also use the secondary HEGO sensor for fuel trim (i.e., minor adjustments) of the fuel control system. We anticipate that all manufacturers will use this secondary sensor for fuel trim.

### *ii. Universal Oxygen Sensors*

The universal exhaust gas oxygen (UEGO) sensor, also called a "linear oxygen sensor", could replace conventional HEGO sensors. Conventional HEGO sensors only determine if an engine's A/F is richer or leaner than stoichiometric, providing no indication of the exact level of the A/F. In contrast, UEGO's are capable of recognizing both the direction and magnitude of A/F transients since the voltage output of the UEGO is "proportional" with changing A/F (i.e., each voltage value corresponds to a certain A/F). Therefore, proportional A/F control is possible with the use of UEGO sensors, facilitating faster response of the fuel feedback control system and tighter control of A/F.

Although some gasoline applications currently use UEGO sensors, discussions with various manufacturers suggest mixed opinions as to the future applicability of UEGO sensors. Because of their high cost, manufacturers claim that it may be cheaper to improve HEGO technology rather than utilize UEGO sensors. An example of this is the use of a "planar" design for HEGO sensors. Planar HEGO sensors (also known as "fast light-off" HEGO sensors) have a thimble design that is considerably lighter than conventional designs. The main benefits are shorter heat-up time and faster sensor response.

### *iii. Individual Cylinder A/F Control*

Another method for tightening fuel control is to control the A/F in each individual cylinder. Current fuel control systems control the A/F for the entire engine or a bank of cylinders. By controlling A/F for the entire engine or a bank of cylinders, any necessary adjustments made to fuel delivery for the engine are applied to all cylinders simultaneously, regardless of whether all cylinders need the adjustment. For example, there is usually some deviation in A/F between cylinders. If a particular cylinder is rich, but the "bulk" A/F indication for the engine is lean, the fuel control system will simultaneously increase the amount of fuel delivered to all of the cylinders, including the rich cylinder. Thus, the rich cylinder becomes even richer having a potentially negative effect on the net A/F.

Individual cylinder A/F control helps diminish variation among individual cylinders. This is accomplished by modeling the behavior of the exhaust gases in the exhaust manifold and using sophisticated software algorithms to predict individual cylinder A/F. Individual cylinder A/F control requires use of an UEGO sensor in lieu of the traditional HEGO sensor, and requires a more powerful engine control computer.

### *iv. Adaptive Fuel Control Systems*

The fuel control systems of virtually all current vehicles incorporate a feature known as "adaptive memory" or "adaptive block learn." Adaptive fuel control systems automatically adjust the amount of fuel delivered to compensate for component tolerances, component wear, varying environmental conditions, varying fuel compositions, etc., to more closely maintain proper fuel

control under various operating conditions.

For most fuel control systems in use today, the adaption process affects only steady-state operation conditions (i.e., constant or slowly changing throttle conditions). Because transient operating conditions have always provided a challenge to maintaining precise fuel control, the use of adaptive fuel control for transient operation would be extremely valuable. Accurate fuel control during transient driving conditions has traditionally been difficult because of inaccuracies in predicting the air and fuel flow under rapidly changing throttle conditions. Air and fuel dynamics within the intake manifold (fuel evaporation and air flow behavior), and the time delay between measurement of air flow and the injection of the calculated fuel mass, result in temporarily lean A/F during transient operation. Variation in fuel properties, particularly distillation characteristics, also increases the difficulty in predicting A/F during transients. These can all lead to poor driveability and an increase in NO<sub>x</sub> emissions.

### v. *Electronic Throttle Control Systems*

As mentioned above, the time delay between the air mass measurement and the calculated fuel delivery presents one of the primary difficulties in maintaining accurate fuel control and good driveability during transient driving conditions. With the conventional mechanical throttle system (a metal linkage connected from the accelerator pedal to the throttle blade in the throttle body), quick throttle openings can result in a lean A/F spike in the combustion chamber. Although algorithms can be developed to model air and fuel flow dynamics to compensate for these time delay effects, the use of an electronic throttle control system, known as “drive-by-wire” or “throttle-by-wire,” may better synchronize the air and fuel flow to achieve proper fueling during transients (e.g., the driver moves the throttle, but the fuel delivery is momentarily delayed to match the inertial lag of the increased airflow).

While this technology is currently used on several gasoline applications, it is considered expensive and those vehicles equipped with the feature are expensive, higher end vehicles. Because of its high cost, it is not anticipated that drive-by-wire technology will become commonplace in the near future.

### c. **Improvements in Fuel Atomization**

In addition to maintaining a stoichiometric A/F ratio, it is also important that a homogeneous air-fuel mixture be delivered at the proper time and that the mixture is finely atomized to provide the best combustion characteristics and lowest emissions. Poorly prepared air-fuel mixtures, especially after a cold start and during the warm-up phase of the engine, result in significantly higher emissions of unburned HC since combustion of the mixture is less complete. By providing better fuel atomization, more efficient combustion can be attained, which should aid in improving fuel economy and reducing emissions. Sequential multi-point fuel injection and air-assisted fuel injectors are examples of the most promising technologies available for improving fuel atomization.

### *i. Sequential Multi-Point*

Typically, conventional multi-point fuel injection systems inject fuel into the intake manifold by injector pairs. This means that rather than injecting fuel into each individual cylinder, a pair of injectors (or even a whole bank of injectors) fires simultaneously, sending fuel into several cylinders. Since only one of the cylinders is actually ready for fuel at the moment of injection, the other cylinder(s) gets too much or too little fuel. With this less than optimum fuel injection timing, fuel puddling and intake manifold wall wetting can occur, both of which can hinder complete combustion. Sequential injection, on the other hand, delivers a more precise amount of fuel that is required by each cylinder to each cylinder at the appropriate time. Because of the emission reductions and other performance benefits “timed” fuel injection offers, sequential fuel injection systems are very common on today’s vehicles and are expected to be incorporated in all vehicles soon.

### *ii. Air-Assisted Fuel Injectors*

Another method used to further homogenize the air-fuel mixture is to use air-assisted fuel injection. By injecting high pressure air into the fuel injector, and subsequently, the fuel spray, greater atomization of the fuel droplets can occur. Since achieving good fuel atomization is difficult when the air flow into the engine is low, air-assisted fuel injection can be particularly beneficial in reducing emissions at low engine speeds. In addition, industry studies have shown that the short burst of additional fuel needed for responsive, smooth transient maneuvers can be reduced significantly with air-assisted fuel injection due to a decrease in wall wetting in the intake manifold.

## **d. Improvements to Exhaust and Exhaust Aftertreatment Systems**

Over the last five years or so, there have been tremendous advancements in exhaust aftertreatment systems. Catalyst manufacturers are progressively moving to palladium as the main precious metal in automotive catalyst applications. Improvements to catalyst thermal stability and washcoat technologies, the design of higher cell densities, and the use of two-layer washcoat applications are just some of the advancements made to catalyst technology. There has also been much development in HC and NO<sub>x</sub> adsorber technology. The advancements to exhaust aftertreatment systems are probably the single most important area of emission control development.

### *i. Catalysts*

As previously mentioned, significant changes in catalyst formulation, size and design have been made in recent years and additional advances in these areas are still possible. Palladium (Pd) is likely to continue as the precious metal of choice for close-coupled applications and will start to see more use in underfloor applications. Some manufacturers, for example, have suggested that they will use Pd/Rh in lieu of tri-metal or conventional Pt/Rh catalysts for underfloor applications. Palladium catalysts, however, are less resistant to poisoning by oil-and fuel-based additives than conventional platinum/rhodium (Pt/Rh) catalysts. Based on current certification trends and

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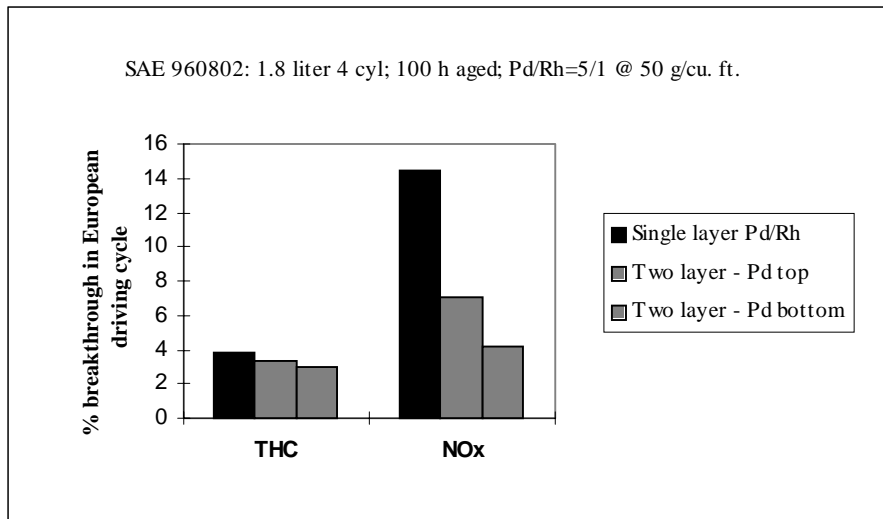
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information from vehicle manufacturers and catalyst suppliers, it is expected that Pd-only and Pd/Rh catalysts will be used in the close-coupled locations while conventional Pd/Rh, Pt/Rh or tri-metal (Pd/Pt/Rh) catalysts will continue to be used in underfloor applications. As palladium technology continues to improve, it may be possible for a single close-coupled catalyst to replace both catalysts. In fact, at least one vehicle manufacturer currently uses a single Pd-only catalyst for one of their gasoline applications. According to MECA, new Pd-based catalysts are now capable of withstanding exposure to temperatures as high as 1100°C and, as a result, can be moved very close to the exhaust manifold to enhance catalyst light-off performance.

In addition to an increased reliance on Pd, catalyst manufacturers have developed “multi-layered” washcoat technologies. Automotive catalysts consist of a cylindrical or oval shaped substrate, typically made of ceramic or metal. The substrate is made up of hundreds of very small, but long cells configured in a shape similar to a honey-comb. The substrate is coated with a substance containing precious metals, rare earth metals, and base-metal oxides, that is known as the catalyst washcoat. Typical washcoat formulations consist of precious metals which either oxidize or reduce pollutants, base-metal oxides, such as alumina, which provide the surface area support for the precious metals to adhere to, and base components (rare earth metals) such as lanthanum, ceria, and zirconia, which act as promoters and stabilizers, and encourage storage and reduction of oxygen. Conventional catalysts have a single layer of washcoat and precious metals applied to the catalyst substrate. More advanced catalysts use multi-layered washcoats with two or more layers of different combinations of washcoat and precious metals. The washcoat can be applied to the substrate such that one layer can be applied on top of another. The use of multi-layered washcoat technology allows precious metals that have adverse reactions together to be separated such that catalyst durability and emission reduction performance are significantly enhanced. For example, Pd and Rh can have adverse reactions when combined together in a single washcoat formulation. A multi-layer washcoat architecture that uses Pd and Rh could have the Pd on the bottom layer and the Rh on the top layer. Rh is particularly used at reducing NO<sub>x</sub>. It is generally preferable to reduce NO<sub>x</sub> in the top layer while CO and HC are still present and then oxidize CO and HC in the bottom layer. Figure III.B-1<sup>p</sup> illustrates the impact coating architecture (multi-layered washcoat technology) can have on emission performance.

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<sup>p</sup> Figure III.B-1 shows “% breakthrough in European driving cycle” on the y-axis; this can be defined as the percentage of emissions that pass through the catalyst without being converted to H<sub>2</sub>O, CO<sub>2</sub>, and N<sub>2</sub> during the European test cycle.



**Figure III.B-1. Impact of Coating Architecture on HC and NOx Emissions**

Manufacturers have also been developing catalysts with substrates which utilize thinner walls in order to design higher cell density, low thermal mass catalysts for close-coupled applications (improves mass transfer at high engine loads and increases catalyst surface area as well as speeding up light-off during cold starts). The greater the number of cells there are, the more surface area that exists for washcoat components and precious metals to adhere to, resulting in more precious metal sites available for oxidizing and reducing pollutants. Cell densities of 600 cells per square inch (cps) have already been commercialized, and research on 900 and 1200 cps catalysts has been progressing. Typical cell densities for conventional catalysts are 400 cps.

We have projected that, in order to meet the proposed 2007 heavy-duty gasoline emission standards, catalyst volumes would have to increase. Current heavy-duty gasoline applications have catalyst volumes slightly lower than the corresponding engine displacement. We believe that most heavy-duty gasoline vehicles would likely need to increase catalyst volumes on the order of ten percent. As mentioned above, higher cell density substrates effectively provide more surface area for pollutant conversion, therefore catalyst volumes may not need to be increased as significantly if higher cell density substrates are used.

We have also projected that some level of increased catalyst loading would be necessary to meet the proposed 2007 heavy-duty gasoline standards. Typical catalyst loadings for current heavy-duty gasoline applications are four grams/liter (g/L) of catalyst volume. We believe that, based on input from catalyst suppliers and vehicle manufacturers, catalysts meeting the proposed 2007 standards would need loadings more on the order of five g/L. However, catalyst suppliers have also indicated to us that they and vehicle manufacturers are constantly working on ways to reduce the amount of precious metal loading ( a process they refer to as “thrifting”). Thrifting is achieved in several ways. One of the most common is matching the catalyst to the attributes of the vehicle. By



working in unison, vehicle manufacturers and catalyst suppliers are able to thrift or reduce the amount of precious metal used in a given application by attempting to optimize the vehicle fuel control strategy, exhaust mass flow rate, and exhaust temperature with various catalyst parameters, such as catalyst location, substrate design, cell density, oxygen storage capability, and precious metal and base metal dispersion, to name a few. Other methods of thrift are the constant improvements being made to washcoat architecture - that is, constant improvement to the materials used in the washcoat formulation so that the precious metals and other components better adhere to the substrate surface. Finally, improvements to washcoat application processes can also significantly improve catalyst performance while allowing thrift of precious metals. Improvements to processes consist of advancements to the process used to coat the substrate with washcoat materials - allowing precious metals, base metals, and ceria to be better dispersed. Better dispersion means that rather than relatively large "clumps" of precious metals unevenly dispersed throughout the catalyst surface, many smaller precious metal sites are dispersed uniformly throughout the catalyst surface increasing the chance for pollutants to come into contact with the precious metal and react into a harmless emission. Therefore, as thrift continues, it is possible that precious metal loading may actually decrease rather than increase.

The largest source of HC emissions continues to be cold start operation where the combination of rich A/F operation and the ineffectiveness of a still relatively cool catalyst results in excess HC emissions. One of the most effective strategies for controlling cold start HC emissions is to reduce the time it takes to increase the operating temperature of the catalyst immediately following engine start-up. The effectiveness or efficiency of the catalyst increases as the catalyst temperature increases. One common strategy is to move the catalyst closer to the exhaust manifold where the exhaust temperature is greater (e.g., a close-coupled catalyst). In addition to locating the catalyst closer to the engine, retarding the spark timing and increasing idle speed are other possible approaches. Retarding spark timing causes combustion to occur later in the power stroke allowing more heat to escape into the exhaust manifold during the exhaust stroke and has negligible impact on fuel economy.<sup>9</sup> Increased idle speed leads to a greater amount of combustion per unit time, providing a greater quantity of heat for heating the exhaust manifold, headpipe, and catalyst.

### *ii. Secondary Air Injection*

Secondary injection of air into exhaust ports after cold start (e.g., the first 40-60 seconds) when the engine is operating rich, coupled with spark retard, can promote combustion of unburned HC and CO in the exhaust manifold and increase the warm-up rate of the catalyst. By means of an electrical pump, secondary air is injected into the exhaust system, preferably in close proximity of the exhaust valve. Together with the oxygen of the secondary air and the hot exhaust components of HC and CO, oxidation ahead of the catalyst can bring about an efficient increase in the exhaust temperature which helps the catalyst to heat up quicker. The exothermic reaction that occurs is dependent on several parameters (secondary air mass, location of secondary air injection, engine

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<sup>9</sup> SAE 2000-01-1957 (available June 2000).

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A/F ratio, engine air mass, ignition timing, manifold and headpipe construction, etc.), and ensuring reproducibility demands detailed individual application for each vehicle or engine design.

### *iii. Heat Managed Exhaust Systems*

Insulating the exhaust system is another method of furnishing heat to the catalyst to decrease light-off time. Similar to close-coupled catalysts, the principle behind insulating the exhaust system is to conserve heat generated in the engine to aid the catalyst warm-up. Through the use of laminated thin-wall exhaust pipes, less heat will be lost in the exhaust system, enabling quicker catalyst light-off.

### **e. Improvements in Engine Calibration Techniques**

Of all the technologies discussed above, one of the most important emission control strategies is not hardware-related. Rather, it is software related and, more specifically, involves the algorithms and calibrations contained within the software that are used in the power-train control module (PCM) which control how the various engine and emission control components and systems operate. Advancements in software along with refinements to existing algorithms and calibrations can have a major impact in reducing emissions. Confidential discussions between manufacturers and EPA have suggested that manufacturers believe emissions can be further reduced by improving and updating their calibration techniques.

As computer technology and software continues to advance, so does the ability of the automotive engineer to use these advancements in ways to better optimize the emission control systems. For example, as processors become faster, it is possible to perform calculations more quickly, thus allowing for faster response times for controlling engine parameters, such as fuel rate and spark timing. As the PCM becomes more powerful with greater memory capability, algorithms can become more sophisticated. Manufacturers have found that as computer processors, engine control sensors and actuators, and computer software become more advanced, and, in conjunction with their growing experience with developing calibrations, as time passes, their calibration skills will continue to become more refined and robust, resulting in even lower emissions.

Manufacturers have suggested to us that perhaps the single most effective method for controlling NO<sub>x</sub> emissions will be tighter A/F control which could be accomplished with advancements in calibration techniques without necessarily having to use advanced technologies, such as UEGO sensors. Manufacturers have found ways to improve calibration strategies such that meeting federal cold CO requirements and complying with stringent light-duty LEV and NLEV standards has not required the use of advanced hardware, such as electrically heated catalysts or HC adsorbers as some had originally predicted they would need.

Since emission control calibrations are typically confidential, it is difficult to predict what advancements will occur in the future, but it is clear that improved calibration techniques and strategies are a very important and viable method for further reducing emissions.

**2. Current Certification Emission Levels for Heavy-Duty Gasoline Vehicles & Engines**

Gasoline engine manufacturers are producing heavy-duty engines equipped with substantial emission controls. Table III.B-2 provides a list of some key technologies currently being used for heavy-duty engine emissions control. Comparing Table III.B-2 to Table III.B-1 makes clear that the technologies expected for compliance with the proposed 2007 model year heavy-duty gasoline standards are already being used. Manufacturers have introduced improved systems as they have introduced new or revised engine models. These systems can provide very good emissions control and many engines are being certified to levels of less than half the current standards. Many of these technologies have been carried over from light-duty applications.

**Table III.B-2. Key Technologies  
Currently Used on Heavy-Duty  
Gasoline Engines**

Sequential Fuel Injection/electronic control
3 way catalyst
Pre- and Post-catalyst heated exhaust gas oxygen sensors
Electronic EGR
Secondary air injection
Improved electronic control modules

We believe that the most promising overall emission control strategy for heavy-duty gasoline engines is the combination of a three-way catalyst and closed loop electronic control of the air-fuel ratio. Control of the air-fuel ratio is important because the three-way catalyst is only effective if the air-fuel ratio is at a narrow band near stoichiometry. For example, for an 80 percent conversion efficiency of HC, CO, and NO<sub>x</sub> with a typical three-way catalyst, the air-fuel ratio must be maintained within a fraction of one percent of stoichiometry. During transient operation, this minimal variation cannot be maintained with open-loop control. For closed-loop control, the air-fuel ratio in the exhaust is measured by an oxygen sensor and used in a feedback loop. The throttle position, fuel injection, and spark timing can then be adjusted for given operating conditions to result in the proper air-fuel ratio in the exhaust. Most, if not all, engines have been equipped with closed loop controls. Some engines have been equipped with catalysts that are achieving catalyst efficiencies in excess of 90 percent. This is one key reason engine and vehicle certification levels are very low. In addition, electronic control can be used to adjust the air-fuel ratio and spark timing to adapt to lower engine temperatures, therefore controlling HC emissions during cold start

operation.

All HD gasoline engines are equipped with three-way catalysts. Engines may be equipped with a variety of different catalyst sizes and configurations. Manufacturers choose catalysts to fit their needs for particular vehicles. Typically, current federal vehicle catalyst systems<sup>f</sup> on are a single converter or two converters in series or in parallel. A converter is constructed of a substrate, washcoat, and catalytic material. The substrate may be metallic or ceramic with a flow-through design similar to a honeycomb. A high surface area coating, or washcoat, is used to provide a suitable surface for the catalytic material. Under high temperatures, the catalytic material will increase the rate of chemical reaction of the exhaust gas constituents. Catalyst systems on HD vehicles tend to have fairly low precious metal loading and catalyst volumes are typically 80 to 90 percent of engine volumes. Precious metal loadings have tended to be in the range of 1 to 4 g/L, and we expect most precious metal loadings to be up to 4 g/L for the 2004 standards.

Significant changes in catalyst formulation have been made in recent years and additional advances in these areas are still possible. Platinum, Palladium and Rhodium (Pt, Pd, and Rh) are the precious metals typically used in catalysts. Historically, platinum has been widely used. Today, palladium is being used much more widely due to its ability to withstand very high exhaust temperatures. In fact, some HD vehicles currently are equipped with palladium-only catalysts. Other catalysts contain all three metals or contain both palladium and rhodium. Some manufacturers have suggested that they will use Pd/Rh in lieu of tri-metal or conventional Pt/Rh catalysts for underfloor applications. Improvements in substrate and washcoat materials and technology have also significantly improved catalyst performance.

Tables III.B-3 and III.B-4 provide certification results from the 2000 model year for various engines and vehicles. The engine data is EPA certification data and the vehicle data is California Medium-duty Vehicle certification data. The tables provide an indication of the emission levels that have been achieved through the application of these technologies.

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<sup>f</sup> In contrast to some California LEV program medium-duty vehicles which have close-coupled catalysts.

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**Table III.B-3. 2000 Model Year Vehicle Certification Data (gram/mile)<sup>1</sup>**

<i>Mfr</i>	<i>Same Eng Fam.</i>	<i>Model<sup>2</sup></i>	<i>Engine Size (liters)</i>	<i>GVWR (lbs.)</i>	<i>NOx (g/mi)</i>	<i>HC<sup>3</sup> (g/mi)</i>	<i>Stds</i>	<i>Sales Area<sup>4</sup></i>
Daimler Chrysler	Y	Ram 3500 Cab Chassis 4WD	5.9	11000	0.48	0.16	Tier1	CA
	Y				0.4	0.097	LEV	CA
		Ram 2500 P/U 4WD	5.9	8800	0.2	0.084		
	Y	Ram 2500 P/U 2WD	8.0	8800	0.41	0.2	Tier1	CA
		Ram 3500 P/U 4WD	8.0	10500	0.34	0.19		
	Y	Ram 3500 P/U 2WD	8.0	11000	0.56	0.22	Tier1	CA
					0.66	0.26		
					0.72	0.24		
					0.67	0.23		
	Y	B3500 Van 2WD	5.2	8700	0.29	0.14	Tier1	FA
Ram 2500 Cab Chassis 4WD		5.9	8800	0.4	0.15			
Ford	Y	Excursion 4WD	5.4	8900	0.38	0.1675	LEV	CA
	Y	E350 2WD	5.3	9300	0.34	0.147	LEV	CA
					0.34	0.147	LEV	CF
	Y		6.8	9300	0.35	0.1615	LEV	CA
	Y	F350 4WD	6.8	11000	0.34	0.1421	LEV	CA
	Y	E250 Strip Chassis 2WD	4.2	8600	0.19	0.1003	LEV	CA
					0.19	0.1003	LEV	CF
	Y		E250 Econoline 2WD	4.2	8600	0.22	0.12	Tier1
		0.21				0.11		
General Motors	Y	K3500 P/U 4WD	5.7	10000	0.66	0.24	Tier1	CA
	Y		7.4		0.6	0.18	Tier1	CA
	Y	K2500 Silverado 4WD	6.0	8600	0.61	0.13	Tier1	CA
		K2500 Suburban 4WD	6.0	8600	0.67	0.17	Tier1	CA

<sup>1</sup> The boldfaced entries show emission levels at or below the proposed 2007 HD gasoline standards.

<sup>2</sup> Some of these models may be Tier 2 medium-duty passenger vehicles.

<sup>3</sup> Tier 1 HC levels are NMHC; LEV HC levels are NMOG.

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**Table III.B-4. 2000 Model Year Engine Certification Data (g/bhp-hr)<sup>1</sup>**

<i>Mfr</i>	<i>Same Engine Family</i>	<i>Engine Size (liters)</i>	<i>Service Class</i>	<i>NOx (g/bhp-hr)</i>	<i>HC (g/bhp-hr)</i>	<i>NMHC (g/bhp-hr)</i>
DaimlerChrysler	Y	5.9	<14k	1.291	0.18	
	Y	8.0	<14k	1.14	0.13	
Ford	Y	5.4	CFF/ULEV	0.66	0.10	
	Y		<14k	0.66	0.10	
	Y	6.8	CFF/ULEV	0.48	0.13	
	Y		all	0.48	0.13	
	Y		<14k	0.48	0.12	
General Motors	Y	4.3	Fed <14k	0.9	0.2	
	Y	5.7	Fed CFF/LEV	2.7	0.3	0.2
	Y		50 State <14k	2.0	0.2	n/a
	Y	6.0	Fed CFF/LEV	1.7	0.3	0.2
	Y		50 State <14k	0.52	0.2	n/a
	Y	7.4	Fed CFF/LEV	1.7	0.6	0.5
	Y		50 State <14k	3.7	0.6	
	Y		50 State >14k	0.8	0.5	
	Y			3.7	0.6	

<sup>1</sup> The boldfaced entries show those current vehicles having at least one exhaust constituent within 20 percent of the proposed 2007 standards.

**3. Current Gasoline Vehicles vs. the Proposed 2007 Heavy-Duty Gasoline Complete Vehicle Standards**

We are proposing standards that are comparable to the California LEV-II program LEV standards. The proposed 2007 NOx level for 8,500 to 10,000 pound vehicles would be 0.2 g/mi and the proposed 2007 NOx level for 10,000 to 14,000 pound vehicles would be 0.4 g/mile. The NMHC standards being proposed are 0.195 and 0.23 g/mile for the 8,500 to 10,000 pound and 10,000 to 14,000 pound vehicles, respectively. The boldfaced entries in Table III.B-3 show current certification emission levels at or below the proposed 2007 HD gasoline standards. While most of

these vehicles do not have both exhaust constituents below the proposed 2007 standard, these data demonstrate that many current vehicles are very close to meeting the proposed 2007 standards without having the regulatory requirement. In fact, several vehicles (those with both emission levels in boldface text) could actually comply with the proposed 2007 standards using their current certification levels.

#### **4. Current Incomplete Gasoline Vehicles vs. the Proposed 2007 Heavy-Duty Gasoline Engine Standards**

We are proposing a NO<sub>x</sub> standard of 0.20 g/bhp-hr and a NMHC standard of 0.14 g/bhp-hr. The boldfaced entries in Table III.B-4 show those current engines having at least one exhaust constituent within 20 percent of the proposed 2007 standards. While no engines have both exhaust constituents within 20 percent of the proposed standards, the data demonstrate that current engines can be designed to be near the proposed 2007 standards despite current standards of 4.0 g/bhp-hr NO<sub>x</sub> and 0.9 g/bhp-hr NMHC. Based on industry input, we believe that manufacturers will continue the process of replacing their old engines with more advanced engines over the next several years. As new and more advanced engines are introduced, we anticipate that they will be capable of achieving the 2007 standards.

#### **5. Technological Feasibility of the Proposed 2007 Heavy-Duty Gasoline Standards**

We project that the proposed 2007 heavy-duty gasoline standards would require the application of advanced engine and catalyst systems similar to those projected for their light-duty counterparts. The technologies and emission control strategies that will be used for medium-duty passenger vehicles (MDPVs), which have a GVWR greater than 8,500 pounds, should also apply directly to heavy-duty gasoline vehicles. Historically, manufacturers have introduced technology on light-duty gasoline applications and then applied those technologies to their heavy-duty gasoline applications. The proposal allows manufacturers to take this same approach for 2007. In other words, we expect that manufacturers would meet the proposed 2007 standards through the application of technology developed to meet light-duty Tier 2 standards for 2004.

Improved calibration and systems management will be critical in optimizing the performance of the engine with the advanced catalyst system. Precise air/fuel control must be tailored for emissions performance and must be optimized. Calibration refinements may also be needed for EGR system optimization and to reduce cold start emissions through methods such as spark timing retard. We also project that electronic control modules with expanded capabilities would be needed on some vehicles and engines.

We also expect increased use of other technologies in conjunction with those described above. We expect some increased use of air injection to improve upon cold start emissions. We may also see air-gap manifolds, exhaust pipes, and catalytic converter shells as a means of

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improving upon catalyst light-off times, thereby reducing cold start emissions. Other, non-catalyst related improvements to gasoline emission control technology include, as already stated, higher speed computer processors which enable more sophisticated engine control algorithms and improved fuel injectors providing better fuel atomization and improved fuel combustion.

For engines, the biggest concern will be the thermal durability of the catalyst systems due to the heavier loads typical of the larger, more commonly engine certified, systems. However, there is less emphasis on cold start emissions on the engine certification test procedure than the chassis test procedure. As a result, there may be less use of close-coupled catalysts for engine certified systems, although we have assumed the same implementation of that technology for vehicles and engines.

Catalyst system durability is a key issue in the feasibility of the standards. Historically, catalysts have deteriorated when exposed to very high temperatures and this has long been a concern for heavy-duty work vehicles. Manufacturers have often taken steps to protect catalysts by ensuring exhaust temperatures remain in an acceptable range. Catalyst technologies in use currently are much improved over the catalysts used only a few years ago. The improvements have come with the use of palladium, which has superior thermal stability, and through much improved washcoat technology. The use of rhodium with palladium will also enhance performance of the catalyst. The catalysts have been shown to withstand temperatures typically experienced in heavy-duty applications. Manufacturers also continue to limit exhaust temperature extremes not only to protect catalyst systems but also to protect the engine. EPA's proposed requirements would allow manufacturers to take necessary steps to protect engine and emission control systems from high temperatures. Nonetheless, we are assuming that 2007 model year heavy-duty gasoline vehicles and engines would require up to a 25 percent increase in precious metal loadings over the estimated 2004 loadings (i.e., 5 g/L versus 2004 levels of 4 or 4.5 g/L) to ensure acceptable catalyst durability characteristics while meeting the proposed standards.

We believe that manufacturers will be able to achieve the proposed emission levels by optimizing all of these technologies. Advanced catalyst systems have already shown potential to reduce emissions to close to the proposed levels. Some current California vehicles in the 8,500-10,000 pound range are certified to levels below 0.2 g/mile NO<sub>x</sub>. California tested an advanced catalyst system on a vehicle loaded to a test weight comparable to a heavy-duty vehicle test weight and achieved NO<sub>x</sub> and NMOG levels of 0.1 g/mile and 0.16 g/mile, respectively. Furthermore, the California vehicle with the advanced catalyst had not been optimized as a system to take full advantage of the catalyst's capabilities.

In a light-duty truck technology demonstration program performed for our Tier 2 rulemaking effort, we found that a combination of calibration changes and improvements to the catalyst system resulted in heavy light-duty truck (LDT4) NO<sub>x</sub> emission levels well below, and NMHC/NMOG emissions slightly below, the Tier 2 intermediate useful life standards (0.05 g/mi NO<sub>x</sub> and 0.075 g/mi NMOG). The catalyst improvements consisted of increases in volume and precious metal loading, and higher cell-densities than those found in the original hardware.



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The most significant difference between LDT4s (the heaviest of the light-duty classification) and medium-duty passenger vehicles (MDPV), which had been heavy-duty gasoline vehicles prior to our Tier 2 rule, is that MDPVs have a vehicle weight up to 800 pounds more than LDT4s. MDPVs will also be typically equipped with larger displacement engines. The potential impact of these differences is higher engine-out emissions than typical LDT4s. These higher engine out emissions may be expected due to both the larger engine displacement, and the greater load that the engine will be operated under due to the extra weight. However, neither of these preclude manufacturers from applying the same basic emission control technologies and strategies as used by light-duty vehicles and trucks. The only difference will likely be the need for larger catalysts with higher precious metal loadings than found in current systems.

We believe that test weight should not have a significant impact on emissions. We are currently testing a Ford Excursion as part of an EPA technology demonstration program. Preliminary baseline results with a green (i.e., “new”) catalyst indicate that emission levels are approximately at, or slightly above, the proposed 2007 heavy-duty standards. However, once the aged advanced catalyst system is installed and modifications are made to optimize EGR and start-up spark retard, in conjunction with air injection, we are confident that emission levels will fall far below the proposed 2007 heavy-duty standards. We have also tested the Excursion at loaded vehicle test weight (curb weight + 300 lb) and again at adjusted loaded vehicle weight (curb + half payload) and found that the engine-out and tailpipe emission results for NMHC and NO<sub>x</sub> were the same for the two test weights. In other words, the additional weight (approximately 700 lbs) had no impact on emission performance. In fact, this is borne out in the data shown in Table III.B-3, which shows that the DaimlerChrysler 8.0L engine used in the Ram 2500 Pickup (GVWR = 8,800 lbs) and the Ram 3500 Pickup (GVWR = 10,500 lbs) both have very similar emission levels despite having different payloads and, therefore, different test weights. The heavier vehicle actually had slightly lower emissions. This is also true with the Ford 6.8L engine used in the E350 (GVWR = 9300 lbs) and in the F350 (GVWR = 11,000 lbs): both vehicles have essentially the same emission levels. This is significant because the majority of the heavy-duty vehicles falling under the proposed 2007 heavy-duty standards are large panel vans and pick-up trucks which typically weigh the same or less than MDPVs.

We believe that the proposed standards would require manufacturers to focus some effort on engine-out emissions control, and that engine-out NO<sub>x</sub> levels in the 6 to 8 g/bhp-hr are reasonably achievable. Since some engines are already in this range, we believe that future engines will deliver even lower engine out emissions. Recalibration of engine systems, including the EGR system and perhaps some modest hardware changes to those systems, would be necessary. EGR plays a key role in reducing engine-out NO<sub>x</sub> and system redesign may allow more effective use of this technology.

Lastly, the proposed averaging, banking, and trading (ABT) program can be an important tool for manufacturers in implementing the proposed standard. The proposed program would allow manufacturers to comply with the more stringent standards by introducing emissions controls over a longer period of time, as opposed to during a single model year. Manufacturers plan their product

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introductions well in advance. With ABT, manufacturers can better manage their product lines so that the new standards do not interrupt their product introduction plans. Also, the program also allows manufacturers to focus on higher sales volume vehicles first and use credits for low sales volume vehicles. We believe manufacturers have significant opportunity to earn credits in the pre-2007 time frame.

This discussion highlights our proposed finding that there are numerous proven and existing technologies available that should allow heavy-duty gasoline vehicles to meet our proposed 2007 heavy-duty gasoline standards. Therefore, we believe that these technologies, combined with low sulfur gasoline, ABT, and considerable leadtime before 2007 implementation, should make the proposed 2007 heavy-duty standards technologically feasible for heavy-duty gasoline vehicles.

### C. Feasibility of the Proposed Evaporative Emission Standards

We are proposing new evaporative emission standards for heavy-duty vehicles and engines. The proposed standards are shown in Table III.C-1. These standards would apply to heavy-duty gasoline-fueled vehicles and engines, and methanol-fueled heavy-duty vehicles and engines. Consistent with existing standards, only the standard for the three day diurnal test sequence would apply to liquid petroleum gas (LPG) fueled and natural gas fueled HDVs.

**Table III.C-1. Proposed Heavy-Duty Evaporative Emission Standards for the 2007+ Model Year\***  
(grams per test)

Category	3 Day Diurnal + Hot Soak	Supplemental 2 Day Diurnal + Hot Soak**
8,500 - 14,000 lbs	1.4	1.75
>14,000 lbs	1.9	2.3

\* Does not include medium-duty passenger vehicles, and does not apply to diesel fueled vehicles.

\*\* Does not apply to LPG or natural gas fueled HDVs.

These proposed standards represent more than a 50 percent reduction in the numerical standards as they exist today. Nonetheless, the proposed evaporative emission standards appear to be feasible now. Many designs have been certified that already meet these standards. A review of 1998 through 2000 model year certification data indicates that nearly all evaporative system families in the 8,500 to 14,000 pound range comply with the proposed 1.4 g/test standard, while all evaporative system families in the over 14,000 pound range comply with the proposed 1.9 g/test standard. Table III.C-2 summarizes the 1998 through 2000 model year evaporative emission certification data.

**Table III.C-2. 1998-2000 Model Year Evaporative Emission Certification Data (grams/test)**

<i>Manufacturer</i>	<i>Category (GVWR)</i>	<i>3 Day Diurnal Emissions (grams/test)*</i>
DaimlerChrysler	<14k	0.74
		0.64
		0.64
		1.01
		1.06
Ford	<14k	1.17
		1.80
	>14k	1.17
		1.80
General Motors	<14k	0.67
		0.78
		0.85
		1.03
		1.29
		1.57
		1.69
		1.74
	>14k	0.67
		0.73
		0.85
		1.03
		1.29
		1.57
1.69		
1.74		

\* The boldfaced entries show emission levels at or below the proposed HD gasoline evaporative standards.

Therefore, we believe that the proposed evaporative emission standards would not require the development of new materials or, in many cases, even the new application of existing materials. There are two approaches to reducing evaporative emissions for a given fuel. One is to minimize the potential for permeation and leakage by reducing the number of hoses, fittings and connections. The second is to use less permeable hoses and lower loss fittings and connections. Manufacturers are already employing both approaches. Fluoropolymer materials can be added as liners to hose and component materials to yield large reductions in permeability over such conventional materials as monowall nylon. In addition, fluoropolymer materials can greatly reduce the adverse impact of alcohols in gasoline on permeability of evaporative components, hoses and seals. Alcohols, present

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in about 10 percent of gasoline sold in the U.S., cause swelling of conventional materials which leads to increases in permeability and can also lead to tearing and leakage in situations where the materials are constrained in place, such as with gaskets and O-rings. Due to the common presence of alcohols such as ethanol in the gasoline pool and its adverse affect on materials and emissions durability, we believe material upgrades such as those discussed above are necessary to ensure that the benefits are captured in-use. Today's proposed standards would likely ensure their consistent use and discourage manufacturers from switching to cheaper materials or designs to take advantage of the large safety margins they have under current standards.

Additionally, most manufacturers are moving to "returnless" fuel injection systems. Through more precise fuel pumping and metering, these systems eliminate the return line in the fuel injection system. The return line carries unneeded fuel from the fuel injectors back to the fuel tank. Because the fuel injectors are in such close contact with the hot engine, the fuel returned from the injectors to the fuel tank has been heated. This returned fuel is a significant source of fuel tank heat and vapor generation. The elimination of the return line also reduces the total length of hose on the vehicle though which vapors can permeate, and it reduces the number of fittings and connections through which fuel can leak.

Steel fuel tanks and steel fuel lines have essentially zero losses due to permeation, but are vulnerable to leakage at joints and interfaces. Manufacturers are moving toward plastic fuel tanks for their lighter weight and greater ability to be molded to odd shapes. However, plastic tanks are permeable and are also susceptible to seepage and higher permeability at areas where connections and welds are made. Materials and manufacturing techniques exist to reduce these losses.

To estimate the per vehicle cost of an improved evaporative system, our Tier 2 rulemaking analysis looked at the incremental cost for an average current model year light-duty vehicle with a steel fuel tank (certified at ~ 1.0 g) to go from a certification level of 1.0 grams per test to a level of about 0.5 grams per test on the three day test cycle.<sup>53</sup> The reductions of the individual items are shown in Table III.C-3. The items in the table are ranked in order of decreasing cost effectiveness. Since the evaporative test procedure measures evaporative emissions each day over a three day period and then uses the highest day, gram per day numbers in the table are a reasonable proxy for grams per test data.

Table III.C-3. Potential Evaporative Improvements and Their Costs to Manufacturers <sup>54</sup>

<i>Emission Source</i>	<i>Baseline Vehicle (grams/day)</i>	<i>Improved Vehicle (grams/day)</i>	<i>Change (grams/day)</i>	<i>Cost (\$/vehicle)</i>	<i>Cost Effectiveness Ranking (Cost/Change)</i>
Fuel cap seal	0.10	0.01	0.09	0.20	1
Fuel pump assembly seal	0.10	0.01	0.09	0.40	2
Fuel and vapor line	0.23	0.01	0.22	1.25	3
Fuel rail/manifold connectors	0.06	0.02	0.04	0.40	4
Canister improvements	0.12	0.04	0.08	1.00	5
Fill tube clamps	0.06	0.02	0.04	0.60	6
Fuel and vapor line connectors	0.18	0.06	0.12	2.20	7
Fill tube/fill neck connector	0.20	0.10	0.10	5.00	8
Allowance for non-fuel emissions	0.20	0.20	0	-----	-----

Table III.C-3 shows that a manufacturer can choose from a range of improvements, and attain significant reductions in evaporative emissions. By selecting the first five items from the table, the manufacturer can achieve a reduction in evaporative emissions of about 0.5 g/day for a total cost of about three to four dollars per vehicle. While these figures were based on a passenger car, we believe it is reasonable to assume the same sort of results for heavy-duty gasoline vehicles since the same basic components are used. Non-fuel emissions may be higher for larger vehicles, but our evaporative standard for >14k vehicles (1.9 gpt) and <14k vehicles (1.4 gpt) is higher to include a larger allowance for non-fuel losses.

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