

July 13, 1999

Public Docket No. A-99-06  
U.S. Environmental Protection Agency  
Room M-1500, Waterside Mall  
401 M Street, SW  
Washington, DC 20460

To Whom It May Concern:

On behalf of the State and Territorial Air Pollution Program Administrators (STAPPA) and the Association of Local Air Pollution Control Officials (ALAPCO), we are pleased to provide comments on the U.S. Environmental Protection Agency's (EPA's) Advance Notice of Proposed Rulemaking (ANPRM) on the control of diesel fuel quality, as published in the *Federal Register* on May 13, 1999 (64 FR 26142).

STAPPA and ALAPCO commend EPA for recognizing the need to reduce sulfur in diesel fuel and for issuing this ANPRM announcing the agency's consideration of improvements in diesel fuel quality and seeking comments on the merits of such action. Our associations wholeheartedly agree that reducing sulfur in diesel fuel is imperative. Our commitment to this issue is evidenced by our associations' recent overwhelming adoption of a resolution calling upon EPA to set the most stringent national diesel sulfur standards technologically and economically feasible to ensure maximum emission reductions from existing and emerging light-duty and heavy-duty diesel vehicles and engines. A copy of *STAPPA/ALAPCO's Resolution on Sulfur in Diesel Fuel* is attached.

Specifically, STAPPA and ALAPCO recommend that:

- EPA adopt a national cap on sulfur in nonroad diesel fuel (including that used in locomotives and marine engines) of 500 ppm, to take effect as soon as possible prior to 2004, so that nonroad diesel fuel is subject to the same sulfur standards as currently apply to onroad diesel fuel;
- By 2004, EPA adopt a national cap on sulfur in both onroad and nonroad diesel fuel of no higher than 30 ppm;
- Based on additional study, EPA further lower national standards for sulfur in onroad and nonroad diesel fuel and set appropriate standards for other characteristics affecting diesel fuel quality

and/or emissions, to take effect in 2007;

- In reducing sulfur in diesel fuel, EPA ensure that there will be no adverse impacts on emissions or driveability as a result of changes in other fuel parameters and no increase in the sulfur content of other petroleum fuels; and
- In setting sulfur caps, EPA consider regulatory flexibilities, such as early reduction credits and other economic incentives, to minimize the cost to and compliance burden on affected parties, without significantly affecting the overall benefits of the program in any particular area of the country.

STAPPA and ALAPCO have evaluated the air quality impacts of these recommendations and have concluded that by enabling the use of advanced technologies, such as lean-NO<sub>x</sub> catalysts and adsorbers and particulate filters, such limits on sulfur in diesel fuel will yield enormous reductions in emissions. In fact, the combination of technologically feasible heavy-duty diesel standards and cleaner diesel fuel could achieve NO<sub>x</sub> and PM emission reductions of more than 80 percent. This is equivalent to taking four out of five heavy-duty diesels off the road.

We urge EPA to move ahead with proposal and promulgation of a national low-sulfur onroad and nonroad diesel fuel program for both light-duty and heavy-duty applications consistent with our recommendations and in a time frame that will allow the 30-ppm diesel sulfur cap to take effect in 2004, at the same time that the national low-sulfur gasoline program is implemented. We believe that such a program is essential for several key reasons:

1. Substantial additional control of diesel vehicle emissions is necessary to protect public health and the environment;
2. Reducing sulfur in diesel fuel will decrease emissions of SO<sub>2</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>2.5</sub> precursors and acid rain precursors from existing and future diesel engines;
3. Substantially reducing the sulfur content of diesel fuel can enable the use of currently available advanced control technologies and newly emerging advanced technologies, thus facilitating reductions in ozone precursors and toxic air contaminants from new onroad and nonroad vehicles and engines and potentially achieving further reductions in SO<sub>2</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>2.5</sub> precursors and acid rain precursors;
4. Substantially reducing sulfur in diesel fuel will facilitate significant opportunities to clean up existing onroad and nonroad vehicles and engines; and
5. Clean diesel fuel is spreading to different parts of the world, demonstrating both the environmental benefits and technical feasibility.

In an attachment to this letter ("Additional Comments of the State and Territorial Air Pollution

Program Administrators and the Association of Local Air Pollution Control Officials on the U.S. Environmental Protection Agency's May 13, 1999 Advance Notice of Proposed Rulemaking on Control of Diesel Fuel Quality"), we elaborate on each of these issues.

Once again, we applaud EPA for initiating efforts to control diesel fuel quality and urge the agency to move ahead aggressively to adopt a low-sulfur onroad and nonroad diesel fuel program based on STAPPA and ALAPCO's recommendations. On behalf of our associations, we look forward to working with EPA staff over the next few months as it develops a proposal for diesel fuel quality and encourage the agency to act in a timely manner so that a final rule, applicable to fuel used in both light-duty and heavy-duty diesel vehicles and engines, is promulgated in time for the 30-ppm diesel sulfur cap to take effect in 2004.

Sincerely,

John Elston  
STAPPA Chair  
Mobile Sources and Fuels Committee

Richard H. Baldwin  
ALAPCO Chair  
Mobile Sources and Fuels Committee

## ATTACHMENT

**Additional Comments of the  
State and Territorial Air Pollution Program Administrators  
and the  
Association of Local Air Pollution Control Officials  
on the U.S. Environmental Protection Agency's  
May 13, 1999  
Advance Notice of Proposed Rulemaking on  
Control of Diesel Fuel Quality**

**July 13, 1999**

### **1. Substantial Additional Control of Diesel Vehicle Emissions is Necessary to Protect Public Health and the Environment**

Diesel engines are significant contributors of nitrogen oxides (NO<sub>x</sub>), sulfur dioxide (SO<sub>2</sub>), fine particulate matter (PM<sub>2.5</sub>), PM<sub>2.5</sub> precursors, PM<sub>10</sub>, toxic air pollutants and greenhouse gases and will be an even greater contributor in the future. According to EPA's own projections, mobile sources are responsible for almost one-half of all NO<sub>x</sub> emissions (44 percent nationally) and by 2010, diesel engines will be responsible for 53 percent of mobile source NO<sub>x</sub> emissions. Further, mobile sources are responsible for 20 percent of direct PM<sub>10</sub> emissions and by 2010, EPA projects that diesel engines will account for nearly 70 percent of all mobile source PM<sub>10</sub> emissions. In urban areas, the contribution from diesels is even greater. For example, as noted in the EPA's May 13, 1999 Advance Notice of Proposed Rulemaking on diesel fuel quality, in Atlanta by 2010, mobile sources are expected to account for over 80 percent of all NO<sub>x</sub> emissions (compared to 44 percent nationally) and 60 percent of all direct PM<sub>10</sub> emissions.

Even these estimates may understate the problem. There is substantial evidence that some existing vehicles emit higher amounts of particulate than are currently accounted for in EPA's particulate emissions model. Further, available data suggest that current particulate control technologies that lower the mass of particulate may actually increase the number of particles, but shift the size distribution to a smaller size range; these smaller particles may actually be more hazardous to health than the larger particles they are replacing. Finally, manufacturers have indicated that they are considering the introduction of a new generation of diesel engines for use in light-duty highway vehicles. Even if Tier 2 standards are adopted as proposed, PM emissions from new diesel cars and light trucks would likely be higher than the PM emissions from the gasoline-fueled vehicles they are replacing. Therefore it is likely that diesel PM and NO<sub>x</sub> emissions now and in the future may be higher and more hazardous than EPA's analysis indicates.

Diesel emissions cause or contribute to a host of adverse impacts on health and the environment.

a. Photochemical Oxidants (Ozone)

Ground-level ozone is the prime ingredient of smog, the pollution that blankets many areas during the summer.<sup>1</sup> Ozone is not emitted directly into the atmosphere, but is formed by a reaction of volatile organic compounds (VOCs) and NO<sub>x</sub> in the presence of heat and sunlight. A large number of exceedances of the current ozone standard have already occurred this year with the bulk of the summer still ahead.

Short-term exposures (one to three hours) to high ambient ozone concentrations have been linked to increased hospital admissions and emergency room visits for respiratory problems. Repeated exposures to ozone can exacerbate symptoms and the frequency of episodes for people with respiratory diseases, such as asthma. Other health effects attributed to short-term exposures include significant decreases in lung function and increased respiratory symptoms, such as chest pain and cough. These effects are generally associated with moderate or heavy exercise or exertion. Those most at risk include children who are active outdoors during the summer, outdoor workers and people with pre-existing respiratory diseases, like asthma. In addition, long-term exposures to ozone may cause irreversible changes in the lungs, which can lead to chronic aging of the lungs or chronic respiratory disease.

Ambient ozone also affects crop yield, forest growth and the durability of materials. Because ground-level ozone interferes with the ability of a plant to produce and store food, plants become more susceptible to disease, insect attack, harsh weather and other environmental stresses. Ozone chemically attacks elastomers (natural rubber and certain synthetic polymers), textile fibers and dyes, and, to a lesser extent, paints. For example, elastomers become brittle and crack, and dyes fade after exposure to ozone.

Ozone is also an effective greenhouse gas, both in the stratosphere and the troposphere.<sup>2</sup> That is, ozone absorbs infrared radiation emitting from the earth, captures it before it escapes into space and re-emits a portion of it back toward the earth's surface.

b. Particulate Matter

Particulate matter is the general term for the mixture of solid particles and liquid droplets found in the air. Particulate matter includes dust, dirt, soot, smoke and liquid droplets that are directly emitted into the air from natural and manmade sources, such as windblown dust, motor vehicles, construction sites, factories and fires. Particles are also formed in the atmosphere by

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<sup>1</sup>/ Ozone occurs naturally in the stratosphere and provides a protective layer high above the earth.

<sup>2</sup>/ Intergovernmental Panel on Climate Change (IPCC), Working Group I, "Climate Change 1992 - The Supplementary Report to the IPCC Scientific Assessment," supplement to: Intergovernmental Panel on Climate Change (IPCC), Working Group I, "Policymakers Summary of the Scientific Assessment of Climate Change," Fourth Draft, 25 May 1990.

condensation or the transformation of emitted gases, such as sulfur dioxide, nitrogen oxides and volatile organic compounds.

Scientific studies show a link between particulate matter (alone or in combination with other pollutants in the air) and a series of health effects. Studies of human populations and laboratory studies of animals and humans have established linkages to major human health impacts, including breathing and respiratory symptoms, aggravation of existing respiratory and cardiovascular disease, alterations in the body's defense systems against foreign materials, damage to lung tissue, carcinogenesis and premature mortality.

Particulate matter also causes damage to materials and soiling. Further, it is a major cause of substantial visibility impairment in many parts of the U.S.

Diesel particulate stands out as especially hazardous because of its small size range and chemical characteristics.

#### i. Diesel Particle Size

Particle diameters span more than four orders of magnitude, from a few nanometers to one hundred micrometers. Combustion-generated particles, such as those from motor vehicles, can be as small as 0.01  $\mu\text{m}$  and as large as 1  $\mu\text{m}$ , but are virtually all less than 2.5 microns. Particles produced in the atmosphere by photochemical processes range in diameter from 0.05 to 2  $\mu\text{m}$ . Fly ash produced by coal combustion ranges from 0.1 to 50  $\mu\text{m}$  or more. Wind-blown dust, pollens, plant fragments and cement dusts are generally above 2  $\mu\text{m}$  in diameter.

Motor vehicle particle emissions and the particles formed by the transformation of motor vehicle gaseous emissions tend to be in the fine particle range. Fine particles (those less than 2.5 micrometers in diameter) are of health concern because they easily reach the deepest recesses of the lungs. Scientific studies have linked fine particles (alone or in combination with other air pollutants), with a series of significant health problems, including premature death; respiratory-related hospital admissions and emergency room visits; aggravated asthma; acute respiratory symptoms, including aggravated coughing and difficult or painful breathing; chronic bronchitis; and decreased lung function that can be experienced as shortness of breath.

While all regulation of diesel particulate from vehicles is based on the mass of particulate, several studies in recent years in the United Kingdom, Switzerland and the U.S. have increased the interest in and concern with the number of very small ultrafine particles.<sup>3</sup> Observations that modern

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<sup>3</sup>/"First International ETH Workshop On Nanoparticle Measurement", ETH Zurich, A. Mayer, 7 August 1997, "Characterization of Fuel and Aftertreatment Device Effects on Diesel Emissions", Bagley, Baumgard, Gratz, Johnson and Leddy, HEI Research Report Number 76, September 1996, "UK Research Programme on the Characterization of Vehicle Particulate Emissions (ETSU, September 1997)

engines with reduced particle mass concentrations may actually emit larger number concentrations than older designs raise concerns that the form of future regulations should focus more on the number of particles in addition to or as an alternative to the mass.

Studies are underway to characterize the size distribution of particles in ambient air, as well as to understand the health consequences of these particles. Depending on the results of these studies, future vehicle regulation may focus more on these compounds. This could be mooted, however, to the extent that mass-based standards result in the use of particulate filters or traps as studies consistently show that these devices successfully reduce both the mass and the number of particles.

## ii. Diesel Toxicity

Several prominent bodies have assessed the carcinogenic potential of diesel exhaust. The U.S. National Institute of Occupational Safety and Health (NIOSH) recommended that whole diesel exhaust be regarded as a potential occupational carcinogen based upon animal and human evidence in 1988. The World Health Organization International Agency for Research on Cancer (IARC) concluded in 1989 that there is sufficient evidence of the carcinogenicity of whole diesel engine exhaust in experimental animals and that there is limited evidence of the carcinogenicity of whole diesel exhaust in humans. On that basis, IARC concluded that diesel engine exhaust is probably carcinogenic to humans and classified diesel exhaust in its Group 2A (this category is used when there is limited evidence of carcinogenicity in humans and sufficient evidence of carcinogenicity in animals). Based upon the IARC findings, in 1990, the State of California, under the Safe Drinking Water and Toxic Enforcement Act of 1986 (Proposition 65), identified diesel exhaust as a chemical known to the state to cause cancer. EPA staff twice proposed a conclusion similar to IARC in its draft documents. In 1990, the agency proposed to classify diesel emissions into its category B-1, which is equivalent to IARC Group 2A. A 1994 draft EPA document concluded similarly that there was sufficient animal evidence of carcinogenicity and that the human evidence was limited.

The Health Effects Institute (HEI) evaluated the carcinogenicity of diesel exhaust in 1995. HEI found that the epidemiological data are consistent in showing associations between exposure to diesel exhaust and lung cancer. HEI also found that the carcinogenicity of diesel exhaust had been convincingly demonstrated in rats.

In addition, the classification of diesel exhaust as carcinogenic was made in Germany by the MAK commission (a body established by the ministry for Labor and Social Affairs), which identifies the maximum allowable workplace concentration that may not be exceeded in the workplace. For carcinogenic substances it defines the concentration that can be reached with technical available means without consideration of the cost (in theory). Legally, this classification is only valid for the workplace, but is widely used for other purposes.

Most recently, the California Air Resources Board (CARB) evaluated diesel exhaust as a candidate toxic air contaminant under the state's air toxics identification program. To evaluate

whether or not diesel exhaust causes cancer, the OEHHA reviewed all controlled animal and mutagenicity studies, as well as studies of worker populations exposed to diesel exhaust. In the last decade, seven studies on rats have demonstrated that exposure to diesel exhaust through inhalation causes cancer. In each of these studies, rats were exposed to concentrations of diesel exhaust greater than  $2.5 \text{ mg/m}^3$  ( $2,500 \text{ } \mu\text{g/m}^3$ ) and were observed for periods longer than 24 months.

The report also analyzed over 30 human studies concerning lung cancer risk and workplace exposure to diesel exhaust. Workers who were exposed to diesel exhaust were more likely than others to develop lung cancer. The consistent results are unlikely to be due to chance, confounding or bias, according to CARB.

The report concludes that a reasonable and likely explanation for the increased rates of lung cancer observed in the epidemiological studies is a causal association between diesel particulate exposure and lung cancer.

### c. Nitrogen Oxides

Emissions of nitrogen oxides produce a wide variety of health and welfare effects in addition to contributing to ozone formation. Nitrogen dioxide can irritate the lungs and lower resistance to respiratory infection, such as influenza.  $\text{NO}_x$  emissions are an important precursor to acid rain and may affect both terrestrial and aquatic ecosystems. Atmospheric deposition of nitrogen leads to excess nutrient enrichment problems (“eutrophication”) in the Chesapeake Bay and several other nationally important estuaries along the East and Gulf Coasts.<sup>4</sup> Eutrophication can produce multiple adverse effects on water quality and the aquatic environment, including increased nuisance and toxic algal blooms, excessive phytoplankton growth, low or no dissolved oxygen in bottom waters and reduced sunlight causing losses in submerged aquatic vegetation critical for healthy estuarine ecosystems. Nitrogen dioxide and airborne nitrate also contribute to pollutant haze, which impairs visibility and can reduce residential property values and revenues from tourism.

In order to address all of the above health and environmental concerns, STAPPA and ALAPCO conclude that it is necessary to drastically reduce  $\text{NO}_x$ , PM and  $\text{SO}_x$  emissions from diesel vehicles. Doing so will require a systems approach that utilizes advanced engine designs, advanced and integrated exhaust control technologies and low-sulfur fuel. Low-sulfur fuel achieves three major objectives:

1. It directly reduces emissions of fine particulate and  $\text{SO}_2$ ;
2. It opens up opportunities for significant additional control of PM and  $\text{NO}_x$  from new onroad and nonroad diesel vehicles; and
3. It opens up opportunities for reducing emissions from existing onroad and nonroad diesel

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<sup>4</sup>/In early July, as a result of the build up of nutrients including nitrogen, more than 200,000 fish were reported to have died in two tributaries of the Chesapeake Bay. (New York Times, July 3, 1999)



vehicles and engines.

## 2. Reducing Sulfur in Diesel Fuel Will Decrease Emissions of SO<sub>2</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>2.5</sub> Precursors and Acid Rain Precursors From Existing and Future Diesel Engines

Sulfate particulate and SO<sub>x</sub> emissions, both of which are harmful pollutants, are emitted in direct proportion to the amount of sulfur in diesel fuel. Therefore, lowering the sulfur content of diesel fuel from the current national average of 340 ppm<sup>5</sup> to 30 ppm would reduce these pollutants by approximately 90 percent. Lowering sulfur to even further would, of course, have an even greater impact.

Sulfate PM contributes to PM<sub>10</sub> and PM<sub>2.5</sub> emissions directly with associated adverse health and environmental effects. SO<sub>2</sub>, one fraction of SO<sub>x</sub>, is a criteria pollutant with associated adverse effects. The health and welfare effects of SO<sub>2</sub> emissions from diesel vehicles are probably much greater than those of an equivalent quantity emitted from a utility stack or industrial boiler, since diesel exhaust is emitted close to ground level in the vicinity of roads, buildings and concentrations of people. Further some of the SO<sub>x</sub> is also transformed in the atmosphere to sulfate PM with the associated adverse effects noted above.

Diesel PM, which, as is noted above, has been found by CARB to be a human carcinogen, consists of three primary constituents: a carbonaceous core, a soluble organic fraction (SOF) that sits on the surface of this core and a mixture of SO<sub>x</sub> and water that also sits on the surface of the core. Lowering the sulfur in the fuel lowers the SO<sub>x</sub> fraction of PM, thus lowering the overall mass of PM emitted.

EPA has also established a relationship between sulfur in diesel fuel and particulate emissions.<sup>6</sup> The direct sulfate emissions factor (g/mile) is calculated as follows:

$$DSULV=13.6078*(1.0+WATER)*FDNSTY*SWGHTD*DCNVRT/FE$$

where:

DSULV= the direct sulfate emissions factor for a class and model year of vehicles  
DCNVRT= the fraction of sulfur in the fuel that is converted directly to sulfate (2.0 %)  
FDNSTY= the density of diesel fuel (7.11 lb/gal)  
FE= the fuel economy for the class and model year of the vehicles  
SWGHTD= the weight percent of sulfur in diesel fuel  
WATER= weight ratio of seven water molecules to sulfate, 7.18/98=1.2857

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<sup>5</sup>/Outside of California, Alaska, American Samoa and Guam.

<sup>6</sup>/Draft Users Guide To Part5: A Program For Calculating Particle Emissions From Motor Vehicles”, US EPA, February 1995.

13.6078=units conversion factor=(453.592\*3.)/100 where 453.592=the number of grams in a pound, 3=weight ratio of SO<sub>4</sub> to sulfur, and the division by 100 is to correct for the weight percent of sulfur

The gaseous sulfur emission factor is calculated as follows:

$$SOSUB2=9.072 *FDNSTY*SWGHTD*(1 -CNVRT)/FE$$

where the new terms are:

SO<sub>2</sub> = the sulfur emission factor of a vehicle of a given class and model year

9.072 = units conversion factor=(453.592\*2)/100 where 453.592=number of grams in a pound, 2=weight ratio of SO<sub>2</sub> to sulfur, and the division by 100 is to convert for the weight percent of sulfur

Reducing the sulfur content of onroad diesel fuel sulfur to 30 ppm will reduce sulfate PM and SO<sub>2</sub> emissions by 91 percent from current levels. Reducing sulfur further would yield even greater reductions. (For example, lower sulfur to 10 ppm would result in a 97-percent reduction from current levels.) Reducing the sulfur content of nonroad diesel fuel to these levels would result in even greater reductions.

### **3. Substantially Reducing the Sulfur Content of Diesel Fuel Can Enable the Use Of Currently Available Advanced Control Technologies and Newly Emerging Advanced Technologies, Thus Facilitating Reductions in Ozone Precursors and Toxic Air Contaminants from New Onroad and Nonroad Vehicles and Engines and Potentially Achieving Further Reductions in SO<sub>2</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>2.5</sub> Precursors and Acid Rain Precursors**

#### **a. Available Advanced Diesel Control Systems**

##### **i. Flow-Through Oxidation Catalysts**

A flow-through oxidation catalytic converter installed on a vehicle can reduce the SOF of the particulate by as much as 90 percent and total particulate by as much as approximately 25 to 50 percent, depending on the composition of the particulate being emitted.

##### **(1) Operating Characteristics and Control Capabilities**

The concept behind an oxidation catalyst is that it causes chemical reactions without being changed or consumed. An oxidation catalytic converter consists of a stainless steel canister that typically contains a honeycomb-like structure called a substrate or catalyst support. There are no moving parts, just acres of interior surfaces on the substrate coated with catalytic precious metals, such as platinum or palladium. In the case of diesel exhaust, the catalyst oxidizes carbon monoxide (CO), gaseous hydrocarbons (HCs) and the liquid hydrocarbons adsorbed on the carbon particles. The liquid hydrocarbons are referred to as the SOF, or soluble organic fraction, and make up part of the total particulate matter.

The level of total particulate reduction is influenced in part by the percentage of SOF in the particulate. For example, it has been reported that oxidation catalysts could reduce the SOF of the particulate by 90 percent under certain operating conditions, and could reduce total particulate emissions by 40 to 50 percent.<sup>7</sup> Destruction of the SOF is important, since this portion of the particulate emissions contains numerous chemical pollutants that are of particular concern to health experts.

Oxidation catalysts are also effective in reducing particulate and smoke emissions from older vehicles. Under EPA's urban bus rebuild/retrofit program, several manufacturers have certified diesel oxidation catalysts as providing at least a 25-percent reduction in PM emissions. The certification data also indicate substantial reductions in CO and HC emissions. Over 10,000 urban buses have been retrofitted as part of EPA's urban bus rebuild/retrofit program. In addition, several states are moving ahead with voluntary retrofit initiatives for onroad and nonroad heavy-duty diesels. Low-sulfur diesel fuel will maximize the environmental benefits of these initiatives.

Combining an oxidation catalyst with engine management techniques can reduce toxics, NO<sub>x</sub> and PM emissions from diesel engines. This is achieved by making an adjustment to the engine for low NO<sub>x</sub> emissions, which is typically accompanied by increased CO, HC, and particulate emissions; an oxidation catalyst is then used to offset these increases, thereby lowering the exhaust levels for all of the pollutants. Often, the increases in CO, HC and particulate can be reduced to levels lower than otherwise could be achieved. In fact, a system that uses an oxidation catalyst combined with proprietary ceramic engine coatings and injection timing retard to provide over a 40-percent NO<sub>x</sub> reduction while maintaining low particulate emissions has been approved under EPA's urban bus rebuild/retrofit program. This same system has also been approved as reducing PM emissions to below 0.1 g/bhp-hr. Also, two systems employing catalysts and modified engine components (cam shafts and turbochargers) have also been submitted for approval as providing less than 0.1 g/bhp-hr PM emissions.

## (2) Impact of Sulfur in Diesel Fuel on Catalyst Technologies

The sulfur content of diesel fuel is critical to applying catalyst technology. Catalysts used to oxidize the SOF of the particulate can also oxidize SO<sub>2</sub> to form sulfates, which are part of the particulate. This reaction is not only dependant on the level of sulfur in the fuel, but also the temperature of the exhaust gases. Catalyst formulations have been developed that selectively oxidize the SOF while minimizing oxidation of the SO<sub>2</sub>. However, the lower the sulfur content in the fuel, the greater the opportunity to maximize the effectiveness of oxidation catalyst technology. The very low fuel sulfur content (<0.005% wt) available in several European countries has allowed enhanced catalyst performance.

## (3) MECA Catalyst Study

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<sup>7</sup>/ Society of Automotive Engineers (SAE) Technical Paper (SAE No. 900600).

The Manufacturers of Emission Controls Association (MECA) has just completed a test program that further demonstrates the benefits of catalyst technology and the sensitivity of this technology to sulfur in the fuel.<sup>8</sup> This study concludes that “[t]he high activity catalysts provide higher reductions of the soluble organic fraction (SOF) and insolubles, but they also make a significant amount of sulfate. The conversion of sulfur dioxide to sulfate offsets the reduction of other particulate components.”

Reducing the sulfur in the diesel fuel from 368 ppm to 54 ppm reduced the engine out PM emissions from 0.073 g/bhp-hr to 0.063 g/bhp-hr (a 13-percent reduction) and enabled several catalysts to achieve the target of less than 0.05 g/bhp-hr PM; the combination of an oxidation catalyst and a fuel borne catalyst was able to achieve a PM level of 0.036 g/bhp-hr with this fuel.

Even the 54 ppm sulfur in the fuel, however, impairs catalyst performance. MECA demonstrated this by testing one particular catalyst at both 54 ppm sulfur and zero sulfur. With 54 ppm sulfur, the PM emissions were reduced from 0.063 to 0.045, a 29-percent reduction; at zero sulfur, the PM was reduced to 0.038, an additional 11-percent reduction.

Significant reductions of HC, especially toxic hydrocarbons, and CO were also achieved by oxidation catalysts in the MECA test program.

## ii. Diesel Particulate Trap Oxidizers

Diesel particulate trap oxidizers or diesel particulate filters can achieve up to, and in some cases exceed, a 90-percent reduction in particulate. The trap is extremely effective in controlling the carbon core of the particulate and recent evidence indicates it can be very effective in reducing ultrafine PM emissions, which are likely to be the most hazardous to health.

### (1) Operating Characteristics and Control Capabilities

The trap oxidizer system consists of a filter positioned in the exhaust stream designed to collect a significant fraction of the particulate emissions while allowing the exhaust gases to pass through the system. Since the volume of particulate matter generated by a diesel engine is sufficient to fill up and plug a reasonably sized filter over time, some means of disposing of this trapped particulate must be provided. The most common means of disposal is to burn or oxidize the particulate in the trap, thus regenerating, or cleansing, the filter.<sup>9</sup>

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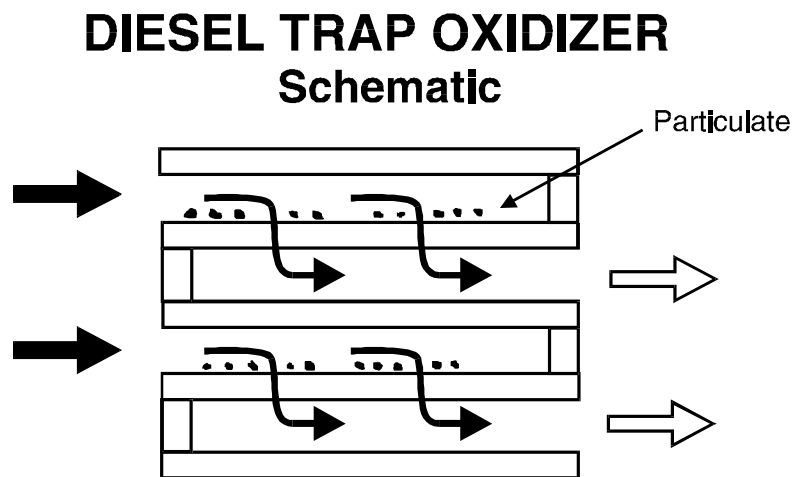
<sup>8</sup>“Demonstration of Advanced Emission Control Technologies Enabling Diesel-Powered Heavy Duty Engines to Achieve Low Emission Levels”, June 1999.

<sup>9</sup>In nonroad applications there has also been use of a disposable filter system. The disposable filter is sized to collect enough particulate for a shift or two of operation while remaining within the engine manufacturers’ back pressure specification and then is removed and appropriately disposed of.

A complete trap oxidizer system consists of the filter and the means to facilitate the regeneration.

Filter Material -- A number of filter materials have been tested, including ceramic monoliths and woven fibers, woven silica fiber coils, ceramic foam, wire mesh, sintered metal substrates and temperature-resistant paper in the case of disposable filters. Currently, the ceramic monoliths, woven fiber and paper filters have been used commercially.

All of the technologies function in a similar manner; that is, forcing particulate-laden exhaust gases through a porous media and trapping the particulate matter on the intake side. Excellent filter efficiency has rarely been a problem with the various filter materials listed above, but work has continued with the materials, for example, to 1) optimize high filter efficiency with accompanying low back pressure, 2) improve the radial flow of oxidation through the filter during regeneration and 3) improve the mechanical strength of the filter designs. The figure below shows an example of the filtration mechanism.



Particulate-laden diesel exhaust enters the filter, but because the cell of the filter is blocked at the opposite end, the exhaust cannot exit out the cell. Instead the exhaust gases pass through the porous walls of the cell. The particulate is trapped on the cell wall. The exhaust gases exit the filter through the adjacent cell.

Regeneration -- The exhaust temperature of diesels is not always sufficient to initiate regeneration in the trap. Therefore, a number of techniques have been developed to facilitate combustion of the trapped particulate. Some of these methods include:

1. Using a catalyst-coated trap. The application of a base or precious metal coating applied to the surface of the filter reduces the ignition temperature necessary for oxidation of the particulate;

2. Using a catalyst to oxidize nitric oxide (NO) to NO<sub>2</sub>, which adsorbs on the collected particulate substantially reducing the temperature required to regenerate the filter;
3. Using fuel borne catalyst additives to reduce the temperature required for ignition of the accumulated material;
4. Throttling the air intake to one or more of the cylinders, thereby increasing the exhaust temperature;
5. Using fuel burners, electrical heaters or combustion of atomized fuel by a catalyst to heat the incoming exhaust gas to a temperature sufficient to ignite the particulate;
6. Using periodically compressed air flowing in the opposite direction of the particulate from the filter into a collection bag that is periodically discarded or burned; and
7. Throttling the exhaust gas downstream of the trap. This method consists of a butterfly valve with a small orifice in it. The valve restricts the exhaust gas flow, adding back pressure to the engine, thereby causing the temperature of the exhaust gas to rise and initiating combustion.

Non-catalyzed trap systems appear to have little or no effect on NO<sub>x</sub>, CO or HC emissions. Experience with the catalyzed trap system indicates that HC and CO emissions can be reduced to a considerable degree (in the range of 60-90 percent) with no adverse impact on NO<sub>x</sub> emissions.

The experience with catalyzed traps indicates that there is a virtually complete elimination of odor and the SOF of the particulate.

Trap systems that replace mufflers in retrofit applications have achieved sound attenuation equal to a standard muffler.

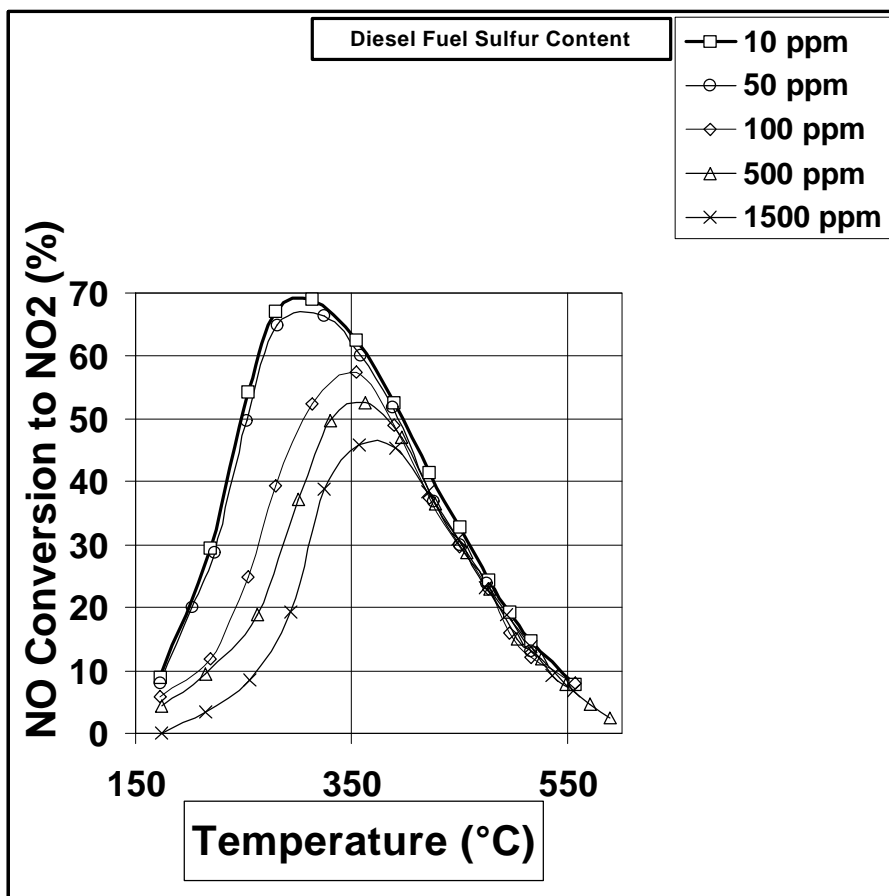
Trap systems do not appear to cause any additional engine wear or affect vehicle maintenance. Concerning maintenance of the trap system itself, manufacturers are designing systems to minimize maintenance requirements during the useful life of the vehicle.

## (2) Impact of Sulfur

Sulfur is not anticipated to impact on the trap itself, but can have a major impact on the regeneration system, depending upon the type selected. For example, the recently developed continuously regenerating trap (CRT) has shown considerable promise for light-duty diesel applications, due to its ability to regenerate even at fairly low exhaust temperatures. The CRT uses NO<sub>2</sub> to assist trap regeneration. NO<sub>2</sub> can oxidize soot collected within the trap at exhaust temperatures as low as 250°C, which is within the typical exhaust temperature range of many light-duty diesel vehicle and truck applications. The NO<sub>2</sub> is produced by oxidizing NO in the exhaust

using a high-platinum-content oxidation catalyst brick located immediately upstream of the ceramic trap-filter.

The CRT is a technology capable of a “step” change in PM emissions, with typical PM reductions exceeding 80 percent. CRT systems are also fairly intolerant of fuel sulfur. SO<sub>2</sub> emissions from combustion of fuel sulfur components significantly impedes oxidation of NO to NO<sub>2</sub>, and can eventually cause trap plugging. The figure below shows the effects of fuel sulfur content on NO oxidation within the CRT by illustrating the efficiency of NO to NO<sub>2</sub> conversion over the oxidation catalyst component of the CRT at different exhaust temperatures and at differing diesel fuel sulfur levels. Inhibition of NO oxidation effectively limits the CRT to use with diesel fuel sulfur levels below 50 ppm.



(3) MECA Diesel Particulate Filter Study

The MECA study noted earlier also evaluated the potential benefits of diesel particulate filters,

as well as the impact of sulfur on their effectiveness.<sup>10</sup> One system was tested using only the 54 ppm sulfur fuel because the manufacturer stipulates that it cannot be used with high-sulfur fuel (see CRT discussion above). This system reduced HC by more than 95 percent, CO by more than 93 percent and PM by 87 percent to a level of 0.008 g/bhp-hr. In addition, since this system relies on a highly active catalyst, the temperature necessary for filter regeneration is low, making it suitable for a broad range of applications.

Another system with a slightly less active catalyst was tested on three fuels: 368 ppm sulfur, 54 ppm sulfur and zero sulfur. With high sulfur PM was reduced to 0.022 g/bhp-hr, a 70-percent reduction. With 54 ppm sulfur, the PM level was reduced below 0.01; with no sulfur in the fuel, the PM was reduced to 0.005 g/bhp-hr. Clearly, lowering the sulfur level in the fuel enables lower PM levels to be achieved over a broader range of applications.

Again, as MECA demonstrated with catalysts but to an even greater degree, diesel particulate filters dramatically reduce toxic hydrocarbon emissions.

## b. Newly Emerging Advanced Technologies

### i. Cooled EGR

The application of electronically controlled exhaust gas recirculation (EGR) to diesel engines reduces combustion temperatures and, therefore, can be an extremely effective means of controlling  $\text{NO}_x$  emissions. EGR systems recirculate a percentage of the engine's exhaust back into the intake air of the engine. Since EGR displaces part of the intake air, it can increase the overall fuel-to-air ratio to a point that can lead to increased PM emissions. Uncooled or "hot" EGR further exacerbates this problem by increasing the temperature of the intake air. The increased temperature decreases air density and further reduces the volume of intake air entering the engine.

Cooled EGR systems use a heat exchanger to cool the recirculated exhaust before it is mixed with intake air. EGR cooling has the potential to reduce or eliminate the increase in intake air temperature and somewhat mitigate (though not eliminate) the PM emissions penalty associated with diesel EGR systems. Cooled EGR also reduces combustion temperatures beyond uncooled EGR, resulting in further decreases in  $\text{NO}_x$  emissions relative to uncooled EGR under certain conditions.  $\text{NO}_x$  emissions reductions of over 40 percent are possible with cooled EGR systems for heavy-duty diesel applications.

#### (1) Impact of Sulfur

One of the primary drawbacks to the use of cooled EGR systems is the potential for

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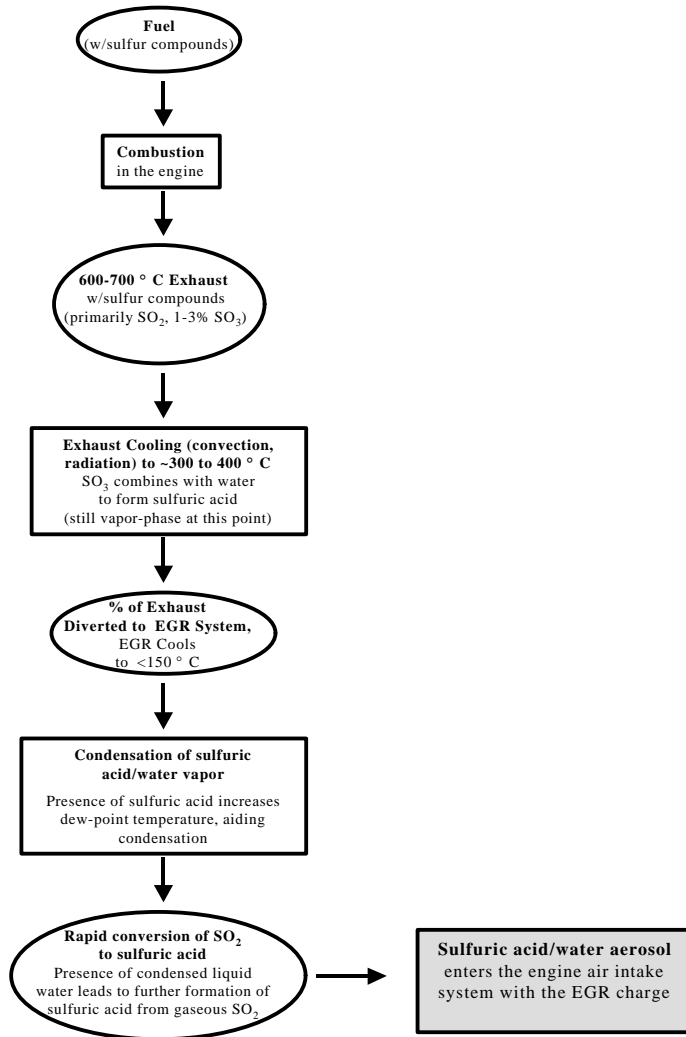
<sup>10</sup>/"Demonstration of Advanced Emission Control Technologies Enabling Diesel-Powered Heavy Duty Engines to Achieve Low Emission Levels," June 1999.



condensation of sulfuric acid, either in the heat exchanger or immediately downstream of the heat exchanger within the EGR system, and resultant corrosion-related durability problems associated with the introduction of sulfuric acid into the intake system. The effects of EGR cooling on engine durability have not yet been fully investigated. Current passenger car diesel applications have not yet needed high rates of cooled EGR to meet light-duty on-highway diesel NO<sub>x</sub> requirements for either the U.S. or other markets. Considerable work has been done on heavy-duty cooled EGR stems from an emissions and performance perspective, but only limited information is available on potential durability problems associated with these systems.<sup>11</sup> The condensation of sulfuric acid and its entrainment into the intake air is represented in the schematic below.

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<sup>11</sup>/ Kreso, A.M. et al. *A Study of the Vapor- and Particle-phase Sulfur Species in the Heavy-duty Diesel Engine EGR Cooler*. SAE Technical Paper Series, No. 981423, 1998, Leet, J.A. et al. *EGR's Effect on Oil Degradation and Intake System Performance*. SAE Technical Paper Series, No. 980179, 1998, McKinley, T.L. *Modeling Sulfuric Acid Condensation in Diesel Engine EGR Coolers*. SAE Technical Paper Series, No. 970636, 1997.

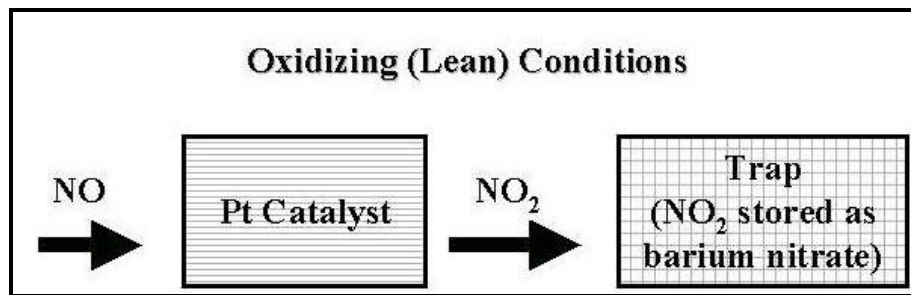


Sulfuric acid aerosol is extremely nonvolatile. Even after considerable dilution with intake air, the aerosol will remain in the form of sulfuric acid/water droplets in the air intake system. The entrainment of this corrosive aerosol poses problems for materials durability for the EGR cooler, the engine intake system and other engine systems. Acid aerosol formation may also increase the frequency of oil changes, due to increased acidification of engine lubricating oil.

Current diesel fuel sulfur levels appear to limit EGR cooling to temperatures above 140° to 150°C for most operating conditions to minimize sulfuric acid aerosol formation. This would ultimately limit the potential to further reduce both NO<sub>x</sub> and PM emissions from engines utilizing more aggressive EGR cooling strategies.

ii. NO<sub>x</sub> Storage Catalysts

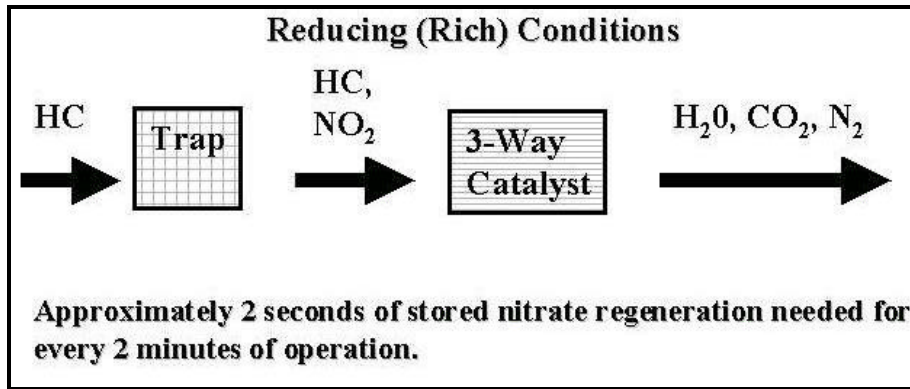
NO<sub>x</sub> storage catalysts are probably the best example of a diesel emissions control capable of “step” reductions in emissions if diesel fuel sulfur levels are considerably reduced. A generalized schematic of their operation is provided below. This catalyst system employs a high-platinum (Pt) content catalyst for oxidation of NO to NO<sub>2</sub>.<sup>12</sup> The NO<sub>2</sub> is then stored using one of a number of barium compounds, such as barium nitrate. For durations of approximately two seconds every two minutes, diesel fuel is either sprayed into the exhaust or fuel is injected into the cylinder after combustion to provide the necessary HC to remove the NO<sub>x</sub> from the storage components. The NO<sub>x</sub> is then reduced over a standard three-way catalytic converter. The average NO<sub>x</sub>-reduction potential for this technology over the light-duty Federal Test Procedure (FTP) is 50 to 75 percent, with a fuel consumption penalty of approximately 3 to 5 percent.<sup>13</sup>



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<sup>12</sup>In the absence of an oxidation catalyst, total NO<sub>x</sub> in diesel exhaust is primarily NO (typically >80%) with lesser amounts of NO<sub>2</sub>.

<sup>13</sup>Wall, J.C., Cummins Engine Co., *Diesel Fuel Composition for Future emissions Regulations*. Panel discussion, SAE International Fall Fuels and Lubricants Meeting and Exposition, October 21, 1998.



(1) Impact of Sulfur

Unfortunately, the chemistry for sulfate storage in such systems is similar to the desired nitrate storage. Sulfur dioxide from combustion of fuel sulfur compounds is oxidized to  $\text{SO}_3$  by the platinum catalyst and stored as barium sulfate. Purging sulfate from the storage components requires significantly longer periods of fuel-rich conditions and significantly higher temperatures ( $600^\circ$  to  $700^\circ\text{C}$ ). The extended periods of high exhaust temperatures necessary for sulfate purging from the storage components of the catalyst would be difficult to achieve, even for many heavy-duty diesel applications. Extended high temperature operation would also have a detrimental impact on the useful life of the  $\text{NO}_x$  storage components of the system. Creation of the necessary fuel-rich environment would pose a significant fuel consumption penalty and would increase PM and HC emissions levels.

Without sulfate purging, fuel sulfur levels of 350 ppm result in near complete deactivation of  $\text{NO}_x$  storage within 20 hours of operation.  $\text{NO}_x$  storage catalysts are clearly not a viable  $\text{NO}_x$  exhaust aftertreatment control at current diesel fuel sulfur levels. Diesel engines employing  $\text{NO}_x$  storage catalyst systems will probably be limited to the use of diesel fuels with less than 30 to 50 ppm sulfur.<sup>14</sup> Even at such fairly low sulfur levels, additional development of catalyst components that reduce sulfur poisoning of the  $\text{NO}_x$  storage components and less frequent, lower temperature sulfate purging cycles may still be needed.

iii. Lean- $\text{NO}_x$  Catalysts

Various types of active (requiring a post-combustion fuel injection event) and passive (no post-injection) lean- $\text{NO}_x$  catalysts are in production or are under investigation for reduction of  $\text{NO}_x$  emissions in lean exhaust environments, such as those present in diesel exhaust. Lean- $\text{NO}_x$  catalysts typically reduce  $\text{NO}_x$  efficiently over a fairly narrow range of catalyst temperatures. There are both “high” and “low” temperature varieties of lean- $\text{NO}_x$  catalysts. Low temperature, platinum-based

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<sup>14</sup>/Wall, J.C., Cummins Engine Co., *Diesel Fuel Composition for Future emissions Regulations*. Panel discussion, SAE International Fall Fuels and Lubricants Meeting and Exposition, October 21, 1998.

lean-NO<sub>x</sub> catalysts using zeolites for support, catalyst promotion and adsorption of NO<sub>x</sub> and HC would be typical of a lean-NO<sub>x</sub> catalyst technology for light-duty diesel vehicles with catalyst temperatures primarily in the 200° to 300°C range. High-temperature lean-NO<sub>x</sub> catalyst formulations are under investigation primarily for highly-loaded, heavy-duty diesel engine applications. High-temperature lean-NO<sub>x</sub> catalysts are primarily base metal catalysts that are only effective at exhaust temperatures exceeding 300°C.

A number of new common rail fuel injection systems are capable of injecting fuel after combustion to provide additional hydrocarbons for use as a NO<sub>x</sub> reductant with active lean-NO<sub>x</sub> catalysts. One example is the introduction of an active lean-NO<sub>x</sub> catalyst system for a European light-duty diesel application.<sup>15</sup> Although active Pt-zeolite catalyst systems have higher NO<sub>x</sub> removal efficiencies than similar passive catalyst systems, NO<sub>x</sub> removal efficiencies are still only in the range of 15 to 35 percent on average, and significantly below that of NO<sub>x</sub> storage catalyst systems. It is more likely that low-temperature systems like the Pt-zeolite lean-NO<sub>x</sub> catalyst systems will be used for incremental NO<sub>x</sub> reduction for light-duty applications in combination with other technologies, such as cooled EGR.

#### (1) Impact of Sulfur

An approximately 25-percent reduction in catalyst NO<sub>x</sub> efficiency due to adsorption of sulfur compounds has been reported after 40,000 miles of roadway aging in a light-duty application at a nominal 500 ppm fuel sulfur limit. Sulfate PM emissions (primarily sulfuric acid), rather than sulfur poisoning, will probably be a more pressing issue with respect to fuel sulfur content. Conversion efficiencies for fuel sulfur to sulfuric acid of up to 20 percent are possible with Pt-zeolite lean-NO<sub>x</sub> catalysts.

High-temperature base metal catalysts reduce NO<sub>x</sub> emissions by up to 30 percent over the heavy-duty FTP cycle. One such catalyst is the Cu ZSM5 catalyst. Similar to low temperature systems, they will likely be used for incremental NO<sub>x</sub> reduction in combination with cooled EGR for heavy-duty diesel engine applications. One exception might be to meet new off-cycle NO<sub>x</sub> emissions requirements for heavy-duty diesel engines. Base-metal catalysts can provide very high (>50 percent) NO<sub>x</sub> reduction efficiencies at high load conditions and, thus, might be used to reduce high-load off-cycle NO<sub>x</sub> emissions without the fuel consumption penalties of retarded fuel injection timing strategies or the PM penalties associated with high rates of EGR at high loads. It is not clear whether or not long term exposure to SO<sub>2</sub> poses a significant problem for this technology.

#### c. Selective Catalytic Reduction

Selective catalytic reduction (SCR) for NO<sub>x</sub> control is currently available for stationary diesel

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<sup>15</sup>Peters, A., et al., *Catalytic NO<sub>x</sub> Reduction on a Passenger Car Diesel Common Rail Engine*. SAE Technical Paper Series, No. 980191, 1998.

engines and has been proposed for mobile light- and heavy-diesel applications. SCR uses ammonia as a reducing agent for NO<sub>x</sub> over a catalyst composed of precious metals, base metals and zeolites. The ammonia is supplied by introducing a urea/water mixture into the exhaust upstream of the catalyst. The urea/water mixture is typically stored in a separate tank that must be periodically replenished. NO<sub>x</sub> reductions of 70 to 90 percent are possible using such systems.

Control of the quantity of urea injection into the exhaust, particularly during transient operation, is an important issue with SCR systems. Injection of too large of a quantity of urea leads to a condition of “ammonia slip,” whereby excess ammonia formation can lead to both direct ammonia emissions and oxidation of ammonia to produce (rather than reduce) NO<sub>x</sub>. There are also a number of potential hurdles to overcome with respect to a major emission control system that requires frequent replenishing in order to function. This raises issues related to supply, tampering and the possibility of running the urea tank dry. There is currently no wide-spread distribution system in the U.S. for supplying the necessary water/urea mixtures for diesel vehicles and trucks.

Packaging of the urea supply within the constraints of modern light-duty vehicles may also be particularly challenging. Packaging of SCR systems does not appear to be a major problem for heavy-duty truck applications.

i. Impact of Sulfur

These systems appear to be tolerant of current U.S. onroad diesel fuel sulfur levels.

d. Conclusions Regarding the Use of Advanced Technologies with High-Sulfur Fuel

Most of the most successful or promising systems to reduce NO<sub>x</sub>, PM and toxics from diesel engines would benefit from low-sulfur or even zero-sulfur fuel. Use of these technologies could likely enable manufacturers of light-duty vehicles to achieve EPA’s recently proposed Tier 2 standards. Heavy-duty engine manufacturers could likely go well beyond the 2004 requirements and achieve levels in the range of 1.0 grams/bhp-hour for NO<sub>x</sub> and 0.01 for PM while simultaneously reducing toxic emissions and ultrafine particles. Comparable reductions would seem feasible for nonroad vehicles and engines.

Some promising technologies, such as SCR, appear to be tolerant of today’s onroad sulfur levels, but these systems address only one portion of the problem -- NO<sub>x</sub> emissions -- while doing nothing to lower PM, toxics or ultrafines. Further it remains to be seen whether such systems would be practical in moving vehicles. A urea distribution network and infrastructure is just one of the hurdles to be overcome.

Achieving the very low levels of NO<sub>x</sub>, PM, toxics and ultrafines, which all categories of diesels will need to do in the future, presents a very strong challenge to the vehicle industry. In meeting this challenge they deserve to be provided with the quality of fuel that maximizes opportunities for success in all vehicle applications. As STAPPA and ALAPCO have resolved, this means 30 ppm maximum sulfur in the 2004 timeframe and even lower levels sulfur shortly thereafter.

#### 4. Substantially Reducing Sulfur in Diesel Fuel Will Facilitate Significant Opportunities To Clean Up Existing Onroad and Nonroad Vehicles and Engines

As noted earlier, a flow-through oxidation catalytic converter installed on a vehicle can reduce the SOF of the particulate by as much as 90 percent and total particulate by as much as approximately 25 to 50 percent, depending on the composition of the particulate being emitted. Smoke emissions from older vehicles can also be reduced by over 50 percent and a catalyst can virtually eliminate the obnoxious odor of diesel exhaust. Furthermore, reductions of 60 to 90 percent of CO and HC emissions can be achieved. As a result, the diesel oxidation catalyst has become a leading retrofit control strategy in both the onroad and nonroad sectors throughout the world. Using a flow-through oxidation converter on diesel-powered vehicles is not a new concept. Oxidation converters have been installed on nonroad vehicles around the world for over 20 years and have been installed on urban buses in the U.S. for over two years, with over 8,000 urban buses having been retrofitted, as well as over 1,000 highway trucks.

As also noted above however, the performance of these converters can be significantly advanced if low-sulfur fuel is available.

Diesel particulate trap systems have also been retrofitted to existing vehicles. Second-generation regeneration systems, which are less complex, are emerging for this application. These systems rely on fuel additives like cerium, or platinum catalysts placed in front of the filter, or catalysts coated directly on the filter to initiate the regeneration process. Catalyst integrated trap systems, such as the CRT, which dramatically lower CO, HC, PM, ultrafines and toxics, are extremely sensitive to sulfur.

##### a. Retrofit Experience in Europe

Programs are underway in Sweden and London.

##### i. Swedish Retrofit Program

From January 1, 1991, environmental classifications were introduced for diesel fuel in Sweden with tax relief for both sulfur content and composition. These were further revised in January 1992 to the classifications summarized below.

<b>Fuel Characteristic</b>	<b>Urban Diesel 1</b>	<b>Urban Diesel 2</b>	<b>Standard</b>
<b>Max. Sulfur, %</b>	<b>0.001</b>	<b>0.005</b>	<b>0.2</b>
<b>Max. Aromatics, %</b>	<b>5</b>	<b>20</b>	<b>-</b>

<b>Fuel Characteristic</b>	<b>Urban Diesel 1</b>	<b>Urban Diesel 2</b>	<b>Standard</b>
<b>Max. PAH, %</b>	<b>0.02</b>	<b>0.1</b>	<b>-</b>
<b>Distillation:</b>			
<b>IBP (min) ° C</b>	<b>180</b>	<b>180</b>	<b>-</b>
<b>10% (min)</b>	<b>-</b>	<b>-</b>	<b>180</b>
<b>95% (max)</b>	<b>285</b>	<b>295</b>	<b>**</b>
<b>Density (kg/m<sup>3</sup>)</b>	<b>800-820</b>	<b>800-820</b>	<b>#</b>
<b>Cetane Number</b>	<b>50</b>	<b>47</b>	<b>##</b>
<b>Tax Rate (\$/m<sup>3</sup>)<sup>(1)</sup></b>	<b>126</b>	<b>165</b>	<b>199</b>

Notes:

\* In addition to the urban grades, one summer and three winter standard grades are specified

\*\* 95% distillation varies with grade:

Summer; 370; Winter: 340

# Density varies with grade

Summer: 820-860 kg/m<sup>3</sup>

Winter: 800-845 (-26 C); Winter:800-840 (-32 and -38 C grades)

## 45 to 49

(1) 1994 tax rates exclude added value tax

Virtually all of the diesel fuel now sold in Sweden -- onroad and nonroad -- is Urban 1 and, thus, has very low levels of sulfur, less than 10 ppm. This has enabled retrofit programs to be put in place for both onroad and nonroad vehicle categories. Stockholm, Goteborg and Malmo, the three largest cities in Sweden, have placed restrictions on the types of heavy-duty vehicles that can be used in their most heavily polluted central areas. To be used in these areas, all heavy-duty diesel vehicles have to comply with the EURO 2 standards after January 1, 1999. A general exemption is applicable for all vehicles that are eight years or younger, because it has been determined that it would be too costly to replace all these vehicles. A special exemption can be issued for older vehicles if they are retrofitted with approved kits that reduce PM by 80 percent and HC by 60 percent, with no increase in NO<sub>x</sub> or noise. Up to now, about 3,000 units have been installed, the majority being CRT filters. These filters require low-sulfur fuel to be used. Test results with a typical system are summarized below.

Test Results With The UNIKAT AZ90 - V18

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	With Test 1	With Test 2	Without Test 1	Without Test 2	Reduction
CO	0.11	0.07	1.77	1.68	-95%
HC	0.05	0.03	0.59	0.62	-93%
NO <sub>x</sub>	6.24	6.07	6.37	6.26	-3%
PM	0.01	0.01	0.25	0.24	-98%

Beginning January 1, 1999, the three Swedish cities have also introduced a system to reduce the emissions from nonroad engines, such as construction equipment and tractors. The system is applicable to all kinds of applications, from lawn mowers and hedge cutters to big excavators.

Within each city's borders, substantial construction work is going on and some part of the work is carried out under the responsibility of the municipality. In order to be selected by the municipality, the contractor must assure the use of only new engines fulfilling the latest emission requirements or agree to retrofit older engines with either an oxidizing catalytic converter or an oxidizing catalytic converter in combination with a particle filter.

When several contractors are bidding for the same assignment, the contractor with the most modern engines/machines will win, even if that entails a higher cost. That is, the municipality is, to a certain extent, prepared to pay extra money for reducing the emissions in the city area.

The base requirement is that the heavy-duty vehicles (i.e., trucks used for transport during the construction work) shall fulfill the requirements for the "Environmental Zones," and the diesel fueled engines used in the remaining nonroad applications shall fulfill at least EU/USA Step 1 for nonroad engines.

Diesel engines not fulfilling the base requirements (EU/USA Step 1) must be equipped with a catalytic converter. Diesel engines fulfilling those requirements must, however, install an after-treatment device after they are eight years old. For certain applications, the most polluting machines, a particle filter must be installed. No engine is allowed on the construction site even if equipped with a catalytic converter if it is more than 14 years old. No engine will be allowed, even if equipped with a particle filter, if it is more than 16 years old.

The requirements for approval are as follows:

	<u>Pollutant</u>	<u>Emission Reduction</u>
<u>Particle Filter:</u>	Diesel Particulate Matter	80 %
<u>Catalytic Converter:</u>	Hydrocarbons	80 %

For all applications regardless of engine used, no increase in NO<sub>x</sub> or noise is acceptable.

So far, 13 catalytic converters in the power range 5-560 kW, and 15 combinations of converters and filters in the power range 10-330 kW, all from four different suppliers, are approved. The Swedish Motor Test Center, which is responsible for certifying systems, is expecting more devices to be approved in the near future.

For both onroad and nonroad retrofit applications, a very clean fuel ( the Swedish Class 1 city diesel with 0.001% sulfur) is used.

ii. London

An initial experiment was carried out with an older bus using the fuel that was typical at that time (about 0.2 Wt. % sulfur) and a CRT system; very rapidly the filter was blocked. Subsequently, a very clean fuel similar to the Swedish Class 1 city diesel with 0.001% sulfur was tried and the very clean fuel was found to substantially reduce visible smoke on these older engines. Further, the particulate mass was reduced by approximately 25 to 30 percent. When an oxidation catalyst was added, the overall PM reduction was about 40 percent with CO, HC and NO<sub>x</sub> reductions of about 80 percent, 8 percent and 8-9 percent, respectively.

Based on these very good results, no visible smoke and reductions of PM, CO, HC and NO<sub>x</sub>, 300 old buses were fitted with catalysts and operated on city diesel for a year under typical London driving conditions. The systems were found to be durable with none of the ceramic substrates cracking or breaking; based on laboratory testing of two buses, the emissions performance only deteriorated by about 10 percent. Based on this, additional buses are being fitted with oxidation catalysts. Approximately 1,000 buses have been fitted to date. Some of these buses are still equipped with their old engines while others have new Euro 2 engines. Approximately 73 percent of them are operating on fuel with sulfur levels below 50 ppm; many of these fuels are averaging 10 ppm sulfur.<sup>16</sup> Both the old and the new engines are achieving approximately 40 percent reductions in PM, 80-90 percent reduction in HC and 5-10 percent reductions in NO<sub>x</sub>.

London Bus Test Results (grams/kilometer)

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<sup>16</sup>/All diesel fuel sold in the UK will have less than 50 ppm sulfur before the end of this year.

Technology	Fuel Sulfur	Catalyst	CRT	HC	CO	NO <sub>x</sub>	CO <sub>2</sub>	PM10
Euro 2 Diesel	0.05%	No	No	0.64	1.35	15.0	1386	0.23
Euro 2 Diesel	0.001	No	No	0.63	1.38	14.2	1351	0.157
Euro 2 Diesel	0.001	Yes	No	0.328	0.274	13.41	1288	0.083
Euro 2 Diesel	0.001	No	Yes	0.136	0.203	11.93	1282	0.022

Most of the new systems are a modular design so that, if needed, filters or traps can be added at a later date.

Tests have also been carried out to determine the impact of these systems on ultrafine PM, (i.e., PM in the size range of 100 nanometers or less). Consistent ultrafine PM reductions of 30 to 50 percent are being measured with the catalysts.

**5. Clean Diesel Fuel is Spreading To Different Parts of the World, Demonstrating Both The Environmental Benefits and Technical Feasibility**

The quality and composition of diesel fuel can have important effects on pollutant emissions. The area of fuel effects on diesel emissions has seen a great deal of study in the last few years, and a large amount of new information has become available. These data indicate that fuel variables, such as the sulfur content and the fraction of aromatic hydrocarbons contained in the fuel, the volatility of the diesel fuel (85 or 90 percent distilled temperatures) and the use of fuel additives, may have a significant impact on emissions.

a. Volatility

Diesel fuel consists of a mixture of hydrocarbons having different molecular weights and boiling points. As a result, as some of it boils away on heating, the boiling point of the remainder increases. This fact is used to characterize the range of hydrocarbons in the fuel in the form of a "distillation curve" specifying the temperature at which 10 percent, 20 percent, etc. of the hydrocarbons have boiled away. A low 10 percent boiling point is associated with a significant content of relatively volatile hydrocarbons. Fuels with this characteristic tend to exhibit somewhat higher HC emissions than others. Formerly, a relatively high 90 percent boiling point was considered to be associated with higher particulate emissions. More recent studies have shown that this effect is spurious -- the apparent statistical linkage was due to the higher sulfur content of these high-boiling

fuels.

In a Dutch study, however, the test fuels were composed of two sets at clearly different 85 or 90 percent boiling points, among which sulfur content varied independently. A highly significant effect of 85 or 90 percent boiling point temperatures was found, in addition to a significant effect of sulfur and a probably significant effect of aromatics contents. A typical effect of a 20°C change in 85 percent boiling point is 0.05 g/kWh at present particulate levels. As mentioned earlier, this may be related to generally higher 85 or 90 percent points, which in the test fuels went up to 350° or 360° C. Commercial diesel fuels in Europe show values up to about 370° C.

#### b. Aromatic Hydrocarbon Content

Aromatic hydrocarbons are hydrocarbon compounds containing one or more "benzene-like" ring structures. They are distinguished from paraffins and naphthenes, the other major hydrocarbon constituents of diesel fuel, which lack such structures. Compared to these other components, aromatic hydrocarbons are denser, have poorer self ignition qualities, and produce more soot in burning. Ordinarily, "straight run" diesel fuel produced by simple distillation of crude oil is fairly low in aromatic hydrocarbons. Catalytic cracking of residual oil to increase gasoline and diesel production results in increased aromatic content, however. A typical straight run diesel might contain 20 to 25% aromatics by volume, while a diesel blended from catalytically cracked stocks could have 40-50% aromatics.

Aromatic hydrocarbons have poor self ignition qualities, so that diesel fuels containing a high fraction of aromatics tend to have low Cetane numbers. Typical Cetane values for straight run diesel are in the range of 50-55; those for highly aromatic diesel fuels are typically 40-45, and may be even lower. This produces more difficulty in cold starting, and increased combustion noise, HC and No<sub>x</sub>, due to the increased ignition delay.

Increased aromatic content is also correlated with higher particulate emissions. Aromatic hydrocarbons have a greater tendency to form soot in burning, and the poorer combustion quality also appears to increase particulate SOF emissions. Increased aromatic content may also be correlated with increased SOF mutagenicity, possibly due to increased polynuclear aromatic (PNA) and nitro-PNA emissions. There is also some evidence that more highly aromatic fuels have a greater tendency to form deposits on fuel injectors and other critical components. Such deposits can interfere with proper fuel/air mixing, greatly increasing PM and HC emissions.

Polycyclic aromatic hydrocarbons (PAH) are included in the great number of compounds present in the group of unregulated pollutants emitted from vehicles. Exhaust emissions of PAH (here defined as three ringed and larger) are distributed between particulate- and semi-volatile phase. Some of these compounds in the group of PAH are mutagenic in the Ames test and in some cases even cause cancer in animals after skin painting experiments. Because of this fact, it is of importance to limit the emissions of PAH from vehicles, especially in densely populated high traffic urban areas. An important factor affecting the emissions of PAH from vehicles is selection of fuel and fuel

components. A linear relationship exists between fuel PAH input and emissions of PAH. The PAH emission in the exhaust consists of uncombusted through fuel input PAH and PAH formed in the combustion process. By selecting of diesel fuel quality with low PAH contents ( 4 mg/l, sum of PAH) the PAH exhaust emissions will be reduced by up to approximately 80 percent, compared to diesel fuel with PAH contents larger than 1 g/l (sum of PAH). By reducing fuel PAH contents in commercial available diesel fuel the emissions of PAH to the environment will be reduced.<sup>17</sup>

### c. Other Fuel Properties

Other fuel properties may also have an effect on emissions. Fuel density, for instance, may affect the mass of fuel injected into the combustion chamber, and thus the air/fuel ratio. This is because fuel injection pumps meter fuel by volume, not by mass, and the denser fuel contains a greater mass in the same volume. Fuel viscosity can also affect the fuel injection characteristics and, thus, the mixing rate. The corrosiveness, cleanliness and lubricating properties of the fuel can all affect the service life of the fuel injection equipment -- possibly contributing to excessive in-use emissions if the equipment is worn out prematurely.

Studies carried out in Sweden have indicated that significant environmental benefits can result from the careful formulation of diesel fuels. Two of the more important studies are summarized below.

The EC 1 diesel is the Swedish Environmental Class 1 diesel according to the specification summarized above. The EPEFE fuel is the base fuel used in the EPEFE-study; somewhat better than current market fuel. The test was carried out on a Volvo FH 12 with engine type D12A 420. Test cycles used were the Braunschweig bus cycle and the ECE R 49 tests. The R 49 test was simulated on a chassis dynamometer.<sup>18</sup>

The EC1 diesel fuel with low aromatic content, low content of polycyclic aromatic hydrocarbons, low sulfur content, lower density and low 95 percent distillation point gave about 10 percent lower NO<sub>x</sub> and particulate emissions and, above all, six times lower content of polycyclic aromatic compounds, 60 times lower content of nitropyrenes in exhaust emission and much lower biological long term effect (three to eight times lower as tested with the Ames test) than the EPEFE reference diesel fuel.

The second study was carried out on four vehicles (two trucks and two buses) and two engines (nonroad). They were tested with a typical market diesel fuel and an EC1 diesel fuel. The

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<sup>17</sup>/ All diesel fuel sold in the UK will R. Westerhom, Stockholm University (1995). Fuel-Related PAH Emissions from Heavy-Duty Vehicles.

<sup>18</sup>/K. Grägg, Swedish Motor Vehicle Testing Company, Motortestcenter (1995), Chemical characterization and Biological Testing of Exhaust Emissions from a Truck fueled with EC 1 and EPEFE Reference Fuel.

NO<sub>x</sub> emissions of the two buses and the two trucks were 5-10 percent lower with the EC1 fuel. The PM emission were 10-15 percent lower.

The emissions of PAC decreased by about 80 percent and the biological activity of the exhaust as tested with the Ames mutagenicity test decreased by about 80-90 percent. Concerning the two nonroad engines, the PM emissions were reduced with about 20 percent, but the NO<sub>x</sub> emissions were not reduced. No unregulated emission tests were performed on the engines.<sup>19</sup>

#### d. Fuel Additives

Several generic types of diesel fuel additives can have a significant effect on emissions. These include Cetane enhancers, smoke suppressants and detergent additives. In addition, some additive research has been directed specifically at emissions reduction in recent years.

Cetane enhancers are used to enhance the self ignition qualities of diesel fuel. These compounds (generally organic nitrates) are generally added to reduce the adverse impact of high aromatic fuels on cold starting and combustion noise. These compounds also appear to reduce the aromatic hydrocarbons' adverse impacts on HC and PM emissions, although PM emissions with the Cetane improver are generally still somewhat higher than those from a higher quality fuel able to attain the same Cetane rating without the additive. In the Dutch study cited earlier, no significant effect of ashless Cetane improving additives could be detected on NO<sub>x</sub> or particulates.

Smoke suppressing additives are organic compounds of calcium, barium or (sometimes) magnesium. Added to diesel fuel, these compounds inhibit soot formation during the combustion process and, thus, greatly reduce emissions of visible smoke. Their effects on the particulate SOF are not fully documented, but one study has shown a significant increase in the PAH content and mutagenicity of the SOF with a barium additive. Particulate sulfate emissions are greatly increased with these additives, since all of them readily form stable solid metal sulfates, which are emitted in the exhaust. The overall effect of reducing soot and increasing metal sulfate emissions may be either an increase or decrease in the total particulate mass, depending on the soot emissions level at the beginning and the amount of additive used.

Detergent additives (often packaged in combination with a Cetane enhancer) help to prevent and remove coke deposits on fuel injector tips and other vulnerable locations. By thus maintaining new engine injection and mixing characteristics, these deposits can help to decrease in-use PM and HC emissions. A study for CARB estimated the increase in PM emissions due to fuel injector problems from trucks in use as being more than 50 percent of new-vehicle emissions levels. A significant fraction of this excess is unquestionably due to fuel injector deposits.

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<sup>19</sup>K. Grägg, Swedish Motor Vehicle Inspection Company, Motortestcenter (1995), The Effects on the Exhaust Emissions of Changing to a Low-Aromatic, Low PAC and Low-Sulfur Diesel Fuel.

e. U.S. Regulations

Beginning in October 1993, EPA regulations applicable to diesel fuels used in onroad vehicles limited the sulfur content to 500 ppm and required either a minimum Cetane number of 40 or a maximum aromatic content of 35 percent by volume. These changes have tended to raise the Cetane number and reduce the aromatic content of U.S. diesel fuels used in onroad vehicles.

f. California

In California, all diesel fuel used in onroad and nonroad vehicles must comply with CARB regulations limiting the sulfur and aromatic content of the fuel. These CARB regulations, which took effect in October 1993, specify that diesel fuel sulfur content cannot exceed 500 ppm and that the aromatic hydrocarbon content cannot exceed 10 percent by volume, except in fuels that are covered by a certified alternative formulation.

Alternative diesel fuel formulations with aromatic levels higher than 10 percent can be certified as being equivalent to a 10 percent aromatic fuel and legally marketed in California. The determination of equivalence is based on a comparison of NO<sub>x</sub> and PM emissions, as well as an assessment of the SOF of the PM emissions. In California, the diesel fuel market is dominated by certified alternative formulations. The limited data publicly available regarding alternative California formulations that have been certified are shown below, along with the specification of a 10 percent reference fuel. As indicated, the alternative formulations compensate for higher aromatic and polycyclic aromatic levels with lower sulfur levels and higher Cetane number levels, with the latter being achieved through the use of nitrogen-based additives.

Specifications of California Certified Alternative Diesel Formulations Compared to a 10% Aromatic Reference Fuel					
Property	Reference	Chevron (001)	Chevron (003)	Chevron (006)	ARCO (007)
Max. Aromatics (vol. %)	10	19	19	15	21.7
Max. Sulfur (PPM)	500	54	196	200	33
Max. Polycyclics (vol. %)	1.4	2.2	4.68	3.6	4.6
Max. Nitrogen (PPM)	10	484	466	340	20
Min. Cetane Number	48	58	59	55	55.2

g. Comparison of Properties of Federal and California Diesel Fuels

The table below presents fuel property data for federal onroad diesel fuels produced at non-California refineries during the summer of 1996 and California diesel fuels produced at California refineries during the same period.<sup>20</sup> As shown, the cleaner California fuel differs from the federal fuel in that it has lower density; contains lower levels of aromatics, Polycyclic aromatics and sulfur; and has a higher Cetane number.

Average Properties of Federal and California Diesel Fuels (Summer 1996)		
Diesel Fuel Property	Federal	California
Spec. Gravity	0.853	0.842
T10 (1F)	431	440
T50 (1F)	510	531
T90 (1F)	606	623
Aromatics (vol %)	32.3	18.2
Polycyclic Aromatics (vol%)	5.2	2.8
Sulfur (ppm)	350	140
Nitrogen (ppm)	-	109
Cetane Number	44.1	53.8

h. European Union

The European Union has enacted regulations establishing maximum values for several diesel fuel properties beginning in 2000, as shown below. Again, these regulations are generally attempting to achieve a reduction in diesel fuel sulfur and polycyclic aromatic content, a reduction in density and T95 temperature, and an increase in Cetane number. In addition, a further reduction in fuel sulfur levels will be required beginning in 2005. Further requirements for diesel fuel composition that would take effect in the 2005 timeframe are scheduled to be proposed by the end of 1999.

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<sup>20</sup>Final Report, 1996 American Petroleum Institute/National Petroleum Refiners Association Survey of Refining Operations and Product Quality, July 1997.



European Union Specifications for Diesel Fuel Composition			
Property	Average	2000 Limit	2005 Limit
Cetane Number	-	51 (min)	-
Sulfur (PPM)	300	350 (max)	50 (max)
Polycyclic Aromatics (vol%)	6	11 (max)	-
Density (g/cm - 60 °F)	-	0.845 (max)	-
T95 (°F)	-	680 (max)	-

i. Finland and Sweden

Both Finland and Sweden adopted specifications for “reformulated” diesel fuels in the early 1990s. These specifications are presented below. It should also be noted that the level of fuel taxes applied to these fuels is substantially lower than applied to conventional diesel fuels. These tax incentives have been provided to encourage the use of these fuels, since they would generally be more expensive than conventional diesel fuels.

Finnish and Swedish Reformulated Diesel Fuel Specifications			
Diesel Fuel Property	Finland	Sweden	
		Urban 1	Urban 2
Density (g/cm <sup>3</sup> )	-	0.80-0.82	0.80-0.82
IBP (°F - min)	-	356	356
T90 (°F - max)	-	545	563
Aromatics (vol % - max)	20	5	20
Polycyclic Aromatics (vol% - max)	-	0.02	0.1
Sulfur (PPM – max)	50	10	50
Cetane Number/Index (min)	47	50	47

j. World-Wide Diesel Fuel Specifications Proposed by Engine and Vehicle Manufacturers

In addition to the diesel fuel regulations summarized above, recommended specifications for diesel fuels sold worldwide have been published by a group of trade associations representing vehicle

and engine manufacturers.<sup>21</sup> These recommendations include three sets of specifications for diesel fuels, which apply to:

1. Markets with no or minimal requirements for emissions control;
2. Markets with stringent requirements for emissions controls (e.g., U.S. Tier 1 or EU-Stage 1 and 2); and
3. Markets with advanced requirements for emissions controls (e.g., California LEV and ULEV, EU-Stage 3 and 4).

The table below presents the recommended specifications for each type of fuel for those properties most closely associated with emissions. Based on that table, engine and vehicle manufacturer recommendations call for the same directional changes in diesel fuel properties as are occurring in several locations. In addition, they also indicate that larger changes in all of these fuel properties are needed to comply with more stringent emission standards, even though compliance may also require substantial advances in engine design and emission control system technologies.

World-Wide Diesel Fuel Specifications Recommended by Engine and Vehicle Manufacturers			
Diesel Fuel Property	Emissions Control Requirements		
	Minimal	Stringent	Advanced
Density (g/cm <sup>3</sup> )	0.820-0.860	0.820-0.850	0.820-0.840
T95 (°F – max)	698	671	644
FBP (°F – max)	-	689	662
Aromatics (vol % - max)	-	25	15
Polycyclic Aromatics (vol% - max)	-	5	2
Sulfur (PPM - max)	5,000	300	30
Cetane Number (min)	48	53	55
Cetane Index (min)	45	50	52

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<sup>21</sup>/World-Wide Fuel Charter, Recommendations for World-Wide Fuels Harmonization, December 1998.

k. Conclusions Regarding Clean Diesel Fuel

1. There is a clear worldwide trend toward lower and lower levels of sulfur in diesel fuel.
2. Other diesel fuel properties, such as volatility, aromatic content and additives, can also have positive or negative effects on diesel vehicle emissions and require careful study and analysis.