WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Assessment of Potential Strategies to Reduce Emissions from Diesel Engines in Washington State

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Introduction

Diesel is the dominant fuel used by the commercial transportation sector. Because diesel engines offer important fuel economy, power and durability advantages, they are often the engine of choice for heavy-duty applications. In the United States, approximately 94 percent of all freight is moved by diesel power. Diesel engines also power most non-road equipment including construction and agricultural equipment, marine vessels and locomotives.

While the operational advantages of diesel engines are clear, diesel fuel is a major contributor to particulate matter (PM) emissions. Diesel particulate emissions are of increasing concern as they are small (often less than 2.5 microns in size), and consist of a complex mix of engines oils, sulfates and inorganic materials. These particles have been identified by health experts as contributing to a variety of lung related illnesses including asthma, emphysema and bronchitis. There is also growing evidence that exposure to diesel particulates may increase the risk of cancer in humans. In 1998, the California Air Resources Board declared diesel particulate emissions a toxic air contaminant and a potential cancer risk. In 2000, the U.S. Environmental Protection Agency (EPA) identified diesel PM as a “likely human carcinogen,” and followed this with new stringent standards aimed at reducing emissions from on-road vehicles by as much as 90 percent.

Although the new EPA standards will go a long way to improve diesel emissions in the future, these standards remain a few years off and will primarily impact new engines. However, because of their durability and long life, older uncontrolled diesel engines will continue to make up a significant portion of the heavy duty vehicle fleet for years to come. As a result, efforts are underway to improve emissions from diesel engines already in operation and include a variety of strategies from fuel reformulations to engine retrofits.

The purpose of this report is to identify technologies and actions which can reduce PM emissions in existing diesel engines. Information was gathered through an extensive web-based search, followed up, in some cases, by direct contact with industry representatives and project managers involved in specific diesel reduction programs.

To date, most of the diesel PM reduction efforts have focused on either new engine replacements or retrofitting existing engines with post-combustion emission control equipment. Of primary interest are diesel oxidation catalysts and diesel particulate filters. Diesel oxidation catalysts (DOCs) have been in use for over 20 years in more than 270,000 retrofit applications. They are relatively inexpensive and are robust enough to be used in many non-road applications such as construction and mining equipment. They are not overly sensitive to fuel sulfur content and can achieve PM reductions of 25 percent or more.

Diesel particulate filters (DPFs) also offer retrofit opportunities. However, because these devices require specific engine conditions to operate effectively, they cannot be used in some applications. DPFs work best with newer engines that achieve higher, sustained engine exhaust temperatures. DPFs also require the use of ultra-low sulfur diesel. Although DPFs cost two to three times more than oxidation catalysts, they can achieve PM removal efficiencies in excess of 90 percent.

Low sulfur diesel fuels or alternative fuels can also provide PM control. Reducing the sulfur content of diesel fuels provides a direct fuel-related reduction in particulate matter emissions. More importantly, low sulfur fuel allows the use of emission control technologies which have been proven effective in providing significant PM control. As a result, most diesel PM control programs also include a low sulfur diesel component. Currently, ultra-low sulfur diesel is available in western Washington at a cost premium of 10 to 11 cents per gallon.

Other fuels and fuel technologies that can provide PM benefits include biodiesel, natural gas, diesel/water emulsions and diesel/electric hybrids. Natural gas, biodiesel and diesel/electric hybrid technology are all currently being used in heavy-duty engine applications in Washington. However, natural gas and diesel/electric hybrid applications would typically fall under a new vehicle purchase, although natural gas retrofits or repowering opportunities do exist. While significant emission benefits can be achieved through the use of these technologies when compared to baseline diesel equipment; a more meaningful comparison should include advanced diesel technology engines fueled with ultra-low sulfur diesel. Here, emission benefits may still favor the diesel alternatives, but the degree of benefits is smaller.

In contrast, biodiesel and water/diesel emulsions are direct fuel substitutes that can be used with little or no modifications to an existing diesel engine. For most biodiesel applications, a B20 blend is used, which consists of 80 percent diesel and 20 percent biodiesel. The fuel is available in Washington at a price premium of around $0.20-$0.30 per gallon. PM emission reductions are estimated at about 10 percent or more for B20. Water/diesel emulsion fuels blend about 20 percent water with diesel. A surfactant and additives make up about one percent of the mix and maintain the emulsion. For the most part, this is a proprietary fuel marketed under the name PuriNOx. While there are no current users of PuriNOx in Washington, it is being used successfully in other parts of the country where PM reductions of 40 percent or more have been reported.

Smoke testing and idling restrictions may also provide PM control. A smoke test program uses opacity measurements to identify trucks which emit high levels of smoke. Failing trucks are then targeted for improvements, typically at the owners' expense. Idling restrictions are intended to reduce the idle time of a diesel engine, which in turn reduces diesel engine emissions. This control measurement is being applied in a couple of ways. One is to establish operational guidelines which direct a vehicle driver, such as a school bus or construction equipment operator, to turn their engine off during queuing or other idle periods. This approach is being used extensively in New England states.

Another approach is to employ auxiliary power technologies which allow drivers to turn off their main engines during extended idle periods. In some cases, the power technology is provided independent of the truck through a plug system, often referred to as truck stop electrification. Some of these technologies can reduce engine idle emissions by 90 percent.

While other PM control strategies are available, those discussed appear to be the primary control measures currently being employed around the U.S. Because PM control measures may differ for different applications, this report also looked at some end use applications, including marine engines, buses, agricultural equipment and construction equipment. For the most part, PM control actions are being investigated and applied across sectors. However, small market sectors, such as agricultural equipment, are only just beginning to receive attention, with little to no demonstrated use of specific PM control measures.

1.1 Ultra-Low Sulfur Diesel

Diesel is the dominant fuel used by the commercial transportation sector. In the United States, approximately 94 percent of all freight is moved by diesel power. While diesel fueled engines have a proven track record with respect to power, fuel efficiency and durability, diesel fuel is a major contributor to PM. In 1998, diesel PM was identified by the California Air Resources Board as a toxic air contaminant.

The standard for diesel fuel properties is defined in the American Society for Testing and Materials (ASTM D) 975-93, Standard Specification for Diesel Fuel Oils. The U.S. EPA regulation establishing a baseline diesel fuel category is specified in 40 CFR 79.55c and is based on the ASTM standard. In 1992, the ASTM D975 standard was updated to include a low sulfur fuel specification of 500 parts per million (ppmw) for grades No.1 and No. 2 diesel. To date, the U.S. EPA regulation (40 CFR 80.29) prohibits the sale or supply of diesel fuel for use in on-road motor vehicles having a fuel sulfur content greater than 500 ppmw.

While other fuel properties impact diesel emissions (cetane index, aromatic content), diesel fuel sulfur level has been identified as a major contributor to diesel PM emissions. In May 2000, EPA proposed new, stringent standards designed to reduce emissions from heavy-duty trucks and buses. Key parts of the proposal include:

- Capping diesel fuel sulfur levels at 15 ppmw beginning June 1, 2006 for all highway vehicles; and,
- Establishing a 0.01 g/bhp-hr PM standard to take effect with model year 2007.

Many European countries, as well as some Asian countries, have already adopted low sulfur diesel regulations. Some countries, including Germany, Sweden and Switzerland, are in the process of promoting low sulfur diesel fuels containing no more than 10 ppmw sulfur through a variety of incentives. In Sweden, more than 90 percent of the highway diesel sold today meets the 10 ppmw sulfur level. (1)

EPA rules targeted fuel sulfur content because of sulfur's link to diesel particulate and SOx emissions. Reducing the sulfur content of diesel fuels provides a direct fuel related PM reduction. More importantly, low sulfur fuel allows the use of emission control technologies which have been proven effective in controlling PM emissions.

Currently, the sulfur content of most fuel sold in the U.S. ranges from 350 to 500 ppmw. (2) In Washington State, diesel fuel sold for on-road use averages about 350 ppmw. (3) A number of areas in the country are introducing low sulfur fuels earlier than the deadline set by EPA. Much of this early introduction effort is in response to EPA's Voluntary Diesel Retrofit Program, where low or ultra-low sulfur diesel (ULSD) is a necessary component of the retrofit effort. ULSD is generally considered to contain 15 ppmw sulfur or lower. With the cooperation of Phillips Petroleum, the Puget Sound Clean Air Agency (PSCAA) has helped introduce ultra-low sulfur diesel into Washington State. The fuel is now available at the Phillips refinery located in Ferndale, Washington.

Emissions

The use of low sulfur fuels will impact diesel emissions. An EPA on-road emission model predicts that reducing sulfur content from 141 ppmw to 15 ppmw would reduce diesel PM emissions by about four percent from engines with FTP cycle specific emission rates of 0.1 g/bhp-hr. (4) A reduction in fuel sulfur from 500 ppmw to five ppmw would result in about a 16 percent reduction for similarly designed engines. (4)

A study of fuel sulfur effects completed by the U.S. Department of Energy (DOE) found that engine out PM emissions decreased with lower sulfur fuels. (5) Baseline PM emissions measured over the European Stationary Cycle (ESC or OICA) drive cycle indicated that diesel engine PM emissions decreased by about 29 percent when going from a 350 ppmw sulfur diesel to a three ppmw sulfur diesel. A 1999 study completed by the Manufacturers of Emission Controls Association (MECA) also looked at fuel sulfur effects. MECA noted a 14 percent decrease in PM emissions for a 1998 Detroit Diesel Corporation Series 60 engine when operating on 54 ppmw sulfur fuel versus 368 ppmw sulfur fuel. (6) In California, the ARCO refinery developed an ultra-low sulfur fuel marketed under the name ECD. When compared against a California Air Resources Board (CARB) diesel blend fuel containing 120 ppmw sulfur, the ECD fuel lowered diesel PM emissions by 13 percent on average. (4) New York City Transit test results reported PM emission reductions of 23 percent when using ULSD fuels without any after-treatment. (7)

While lower PM emissions will result from the use of low sulfur diesel fuel alone, the primary emission benefit is achieved when exhaust after-treatment is used. In their study of fuel sulfur effects, DOE found that fuel sulfur had significant effects on particulate filter PM emissions. (5) At three ppmw sulfur, the particulate filters tested achieved PM reductions of 95 percent. With 30 ppmw sulfur fuel, the PM reduction efficiencies dropped to 72 percent. When tested with 150 ppmw sulfur fuel, PM reductions were near zero, and when 350 ppmw sulfur fuel was used, PM emissions actually increased over the baseline.

The effect of sulfur on passive diesel particulate filters (DPF) has prompted regulators and device manufacturers alike to require low sulfur fuels for DPF applications. Johnson Mathey (JM), the manufacturer of the Continuously Regenerating Technology (CRT) Diesel Particulate Filter (DPF), requires a maximum sulfur content of 50 ppm to ensure filter performance and durability. (8) JM also recognizes that DPF performance improves with lower sulfur fuels and that 15 ppm fuels or lower will provide maximum PM removal and filter durability. (9) In their verification protocol for passive DPFs which reduce PM emissions by 85 percent or more, CARB requires that engines must operate with a fuel that has a fuel sulfur content of no more than 15 ppmw. (10)

Although diesel oxidation catalysts (DOCs) can be designed or tailored to operate under higher sulfur concentrations, the use of lower sulfur fuels should improve the devices' particulate reduction efficiency. As a result, some manufacturers recommend a maximum sulfur content of 500 ppmw or less to enhance DOC durability and performance. (4) To minimize the effect of sulphate formation on DOC performance and maximize DOC reduction efficiency, CARB staff has suggested the use of ultra-low sulfur diesel fuels of 15 ppmw. (11)

Cost

EPA estimates that the overall cost associated with lowering the sulfur cap from 500 ppmw to 15 ppmw would be approximately three to four cents. (4,12) In southern California, ARCO produces a 15 ppmw sulfur diesel fuel (ECD-1) at a cost of about five cents per gallon more than typical CARB diesel production costs. (13) In a recent report completed by the U.S. Energy Information Administration on ultra-low sulfur diesel fuel costs, they estimated that some refiners may be able to produce 15 ppmw sulfur diesel at a cost of about 2.5 cents per gallon. (14) However, at the volumes needed to meet demand, costs are generally estimated at 5.4 to 6.8 cents per gallon, and could be higher if supply falls short of demand.

New York City Transit reported that they are paying approximately 11 cents per gallon more for ultra-low sulfur diesel. (15) Locally, the Puget Sound Clean Air Agency is reporting that ultra-low sulfur diesel fuel costs about eight cents per gallon more than conventional diesel. (16) Because the fuel is handled separately, transportation costs currently add another six to seven cents per gallon. This raises the overall cost of ultra-low sulfur diesel to about 15 cents per gallon.

Other issues

Most refiners use a hydrotreating process to de-sulfurize diesel fuels. For the most part, refiners will extend this process to meet the 15 ppmw specification. Diesel fuels that are more difficult to de-sulfurize could be subjected to intense hydrotreating. This process can reduce trace components containing nitrogen and oxygen that provide a natural lubricity. (1) This reduced lubricity could result in excessive engine wear without the addition of a high lubricity additive, like biodiesel. To avoid any problems, ULSD users should make sure that the fuel lubricity meets equipment manufacturers' specifications. The ULSD produced locally by Phillips Petroleum has a minimum of 3,100 grams lubricity (according to the ASTM D6078 Scuffing Load Wear Test) and is in compliance with the ASTM standard for highway diesel. (16)

Additional handling may also be required when using low sulfur fuels. Until low sulfur diesel fuels are mainstreamed, they will need to be kept separate from conventional diesel fuels to prevent blending and/or contamination. Early on, some local users of ULSD experienced minor fuel filter plugging issues when using ULSD; however, the current reformulation appears to be working well. (17)

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1.2 Biodiesel

Biodiesel is a mono-alkyl ester based oxygenated fuel made from vegetable or animal fats. It is commonly produced from oilseed plants such as soybean or canola, or from recycled vegetable oils. Biodiesel has similar properties to petroleum diesel fuel and can be blended with petroleum diesel fuel at any ratio. The most common blend rate is 20 percent biodiesel, 80 percent petroleum diesel. This mixture is referred to as “B20.” Pure or neat biodiesel is termed B100.

Biodiesel is a domestically produced, renewable motor fuel which is non-toxic and biodegradable. Biodiesel is registered as a fuel and fuel additive with EPA and has passed EPA’s Tier 1 Health Effects Testing under Clean Air Act section 211(b). Neat biodiesel, B100, has also been classified as an alternative fuel by DOE, and meets CARB clean diesel standards. ASTM, the U.S. fuel standard-setting body, recently issued a new specification for biodiesel fuel. Specification D 6751 applies to all biodiesel bought and sold in the U.S. (1)

Emissions

There is a growing body of emission data for biodiesel. Compared to conventional diesel, the use of B100 significantly reduces PM, CO, and HC but increases NOx. (1,2,3) In comparing B20 to conventional diesel fuel, the changes in emissions are directionally the same, but smaller. CARB reports that B100 and B20 reduce PM emissions by 30 percent and 22 percent, respectively, when compared to conventional diesel fuel (CARB iv). The National Biodiesel Board (NBB) indicates similar emissions benefits, and reports PM reductions of 40 percent for B100 and eight percent for B20. In its 2002 draft report on biodiesel emissions, EPA reported an average PM reduction of 10.1 percent for soybean-based B20 fuel, and a two percent increase in NOx emissions. (3) EPA also reported that emissions varied with the type of biodiesel used (soybean, rapeseed, animal fats), and that emission benefits appeared consistent across engine model years.

In a recently completed study on life-cycle emissions from biodiesel and petroleum diesel, DOE concluded that tailpipe PM_{10} emissions are 68 percent lower for biodiesel, while biodiesel life-cycle particulate emissions are 32 percent lower than conventional diesel fuel. (4) A summary of biodiesel emissions is presented in Table 1. Actual emission reductions will vary with application.

Table 1: Biodiesel Emissions Compared to Diesel Fuel

	CARB		NBB	
Pollutants	B100(%)	B20(%)	B100(%)	B20(%)
PM	-30	-22	-40	-8
NOx	+13	+2	+6	+1
PAH	-80	-13	-80	-13

Source: California Air Resources Board; National Biodiesel Board

Blending biodiesel with conventional diesel can be used to reduce the sulfur content of petroleum diesel fuels. Because biodiesel contains zero to one ppmw of sulfur, exhaust emissions of sulfur oxides and sulphates are eliminated. (1) Further, the absence of fuel sulfur suggests that after-treatment technologies such as diesel oxidation catalysts and particulate traps would perform well with biodiesel. In fact, a study conducted by Southwest Research Institute showed that catalyst conversion efficiency of total particulates improved with increased biodiesel content. (5) PM reductions for B20 versus conventional diesel went from five to 15 percent, to ten to 22 percent when an oxidation catalyst was used. Similarly, PM reductions for B100 as compared to conventional diesel fuel averaged 30 to 50 percent, while PM reductions increased to 50 to 60 percent with the addition of a catalyst.

Biodiesel can also be blended with ultra-low sulfur diesel. The Washington Metropolitan Area Transit Authority recently investigated bus emissions resulting from the use of conventional diesel fuel, ULSD), and a blend of 20 percent biodiesel and 80 percent ULSD (BD20). (6) During the ULSD and BD20 tests, the transit bus was equipped with a catalyzed particulate trap. The BD20 fuel showed virtually similar PM reduction efficiencies as the ULSD fuel and reduced PM emissions by greater than 98 percent as compared to the baseline diesel fuel. While showing a slight increase in NOx emissions, the BD20 blend also reduced both carbon monoxide and hydrocarbon emissions by 90 percent over the ULSD fuel.

<u>Cost</u>

The cost of biodiesel depends primarily on the market price for vegetable oils or other feedstock. At a feedstock price of ten cents per pound, a production cost of about one dollar per gallon is projected for a ten million gallon per year (MGY) facility. If the price of feedstock increases to 20 cents per pound, plant production costs increase to as much as two dollars per gallon for a ten MGY plant. (7) Transportation costs will also impact the sale price for biodiesel. Currently, biodiesel sold into Washington markets is shipped from the midwest or east coast. A local biodiesel distributor estimates that transportation or freight charges add about 20 cents per gallon to the price of B100 sold in Washington. (8)

Nationally, B20 costs about 15 to 30 cents above the cost of diesel. (9) B100 costs about 50a cents to one dollar more than conventional diesel fuel. Price will vary locally due to production, transportation and distribution costs, and depending on the volume of fuel purchased. The City of Seattle recently received a price quote from World Energy for B20 fuel. (10) The price for B20 ranged from 0.259 cents per gallon over diesel for 500-2500 gallon lots, to a price premium of 0.199 cents per gallon for 5,001 gallons or more. Currently, the City of Tacoma is getting B20 delivered by mobile refueling for $1.20 per gallon. (11) About 13 cents per gallon of this price is a delivery charge. Lilyblad Petroleum, located in Tacoma, Washington, recently quoted an ex-tax bulk purchase price of $1.60 per gallon B100 fuel. (12).

Biodiesel prices are expected to increase if the current U.S. Department of Agriculture Commodity Credit Corporation (CCC) US Bioenergy Program is stopped. The program provides reimbursements for bioenergy producers for converting targeted commodities into bioenergy. These direct payments to producers were passed on to consumers and reduced the price of biodiesel by over one dollar per gallon. This price cut has been the single biggest contributor to making biodiesel market acceptance possible.

Although biodiesel demands a price premium, it does not require engine modifications, nor does it require any infrastructure changes. To offset biodiesel's higher price, many states have reduced the state fuel tax paid for biodiesel. National energy policy and agricultural legislation is considering similar federal tax incentives for biodiesel blends.

<u>Other issues</u>

Biodiesel fuel offers additional advantages over petroleum diesel. Biodiesel is biodegradable, non-toxic, and has a higher flash-point than petroleum diesel fuel. Biodiesel is also a renewable, domestically produced fuel that can provide local economic benefits. According to an energy lifecycle study completed by DOE, biodiesel yields 3.2 units of fuel energy for every unit of fossil fuel consumed. (4) By comparison, petroleum diesel yields 0.83 units of fuel energy per unit of fossil energy consumed. Because biodiesel is derived from vegetable oils, carbon is also recycled. As a result, biodiesel can reduce carbon dioxide emissions by as much as 78 percent over petroleum diesel. (4)

<u>Availability and use</u> – Currently, more than 12 companies actively produce and market biodiesel fuel. The dedicated production capacity in the U.S. is estimated at around 80 million gallons per year. (1) However, new plants are being proposed throughout the country, including in Washington State, with a typical facility taking approximately one year to come online. Additional production capacity may be available within the oleo-chemical industry, where it is estimated that as much as 200 million gallons of capacity may be available for biodiesel production.

Biodiesel is commercially available in Washington State. Currently, Lilyblad Petroleum, Tacoma, WA, Albina Fuels, Vancouver, WA, and Soundoil.com, Oak Harbor, WA have biodiesel available for delivery or pick-up. The only retail outlet for biodiesel is Dr. Dan's Alternative Fuel Works, in Seattle. Arrangements can also be made for bulk purchase deliveries from national suppliers including World Energy, Chelsea, Massachusetts, and U.S. Pacific Northwest Biodiesel, located in Aloha, Oregon. A list of biodiesel suppliers is available at the National Biodiesel Board website at www.nbb.org.

Handling - Handling of biodiesel is similar to petroleum diesel fuels, with some notable differences. Because of its inherent solvent properties, there may be some material compatibility issues when handling neat biodiesel. Rubber seals and hoses should be replaced as they will degrade after prolonged exposure to biodiesel. Fuel filters should also be checked when first using biodiesel as they may become plugged with accumulated sediments. Also, spills need to be cleaned up quickly, as biodiesel is an effective paint remover.

Biodiesel should not be stored for more than one year to avoid fuel quality problems. In addition, operators should be aware of biodiesel's cold flow properties and take any necessary precautions, including adding pour point depressants in colder climates. Finally, to ensure fuel quality, biodiesel should meet ASTM specification D6751. It is important that biodiesel meets this specification and that the fuel provider guarantees fuel quality in case of engine related problems. A guidebook entitled "Biodiesel and Handling and Use Guidelines" is available online from DOE at http://www.afdc.doe.gov/altfuel/bio_papers.html.

Fuel Economy - Because of its lower British Thermal Unit (BTU) content, engine fuel economy and power are about ten percent lower when running on neat biodiesel, and about two percent lower for a B20 blend. Biodiesel also has excellent lubricity characteristics, and can be added to petroleum diesel fuel in quantities as low as one to two percent to provide significant lubricity improvements meeting or exceeding Original Equipment Manufacturer (OEM) specifications.

Warranty - Although engine manufacturers warranty their engines and not the fuel, most major engine companies have stated formally that the use of biodiesel blends up to 20 percent will not void their parts and workmanship warranties. Some engine companies have already specified that the biodiesel must meet ASTM D-6751 as a condition, while others are still in the process of adopting D-6751 within their company. The National Biodiesel Board maintains a list of engine manufacturer comments on biodiesel use in their engines at www.nbb.org.

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1.3 Fuel/Water Emulsions

Diesel/water emulsions combine about 80 percent diesel, 20 percent water and about one percent surfactants and additives. The additives are included to maintain the emulsion, enhance the lubricity, inhibit corrosion and protect against freezing. The presence of water in the emulsion reduces both PM and NOx, by lowering the combustion temperature and altering the combustion pattern to more completely burn the carbon in the fuel.

The primary producer of diesel/water emulsions is the Lubrizol Corporation. Lubrizol calls its fuel PuriNOx, which is a diesel/water emulsion in which the diesel fuel is the continuous phase and the water is emulsified. These components are mixed in an electronically controlled, automated blending unit to produce a stable, finished fuel. During the blending process the special additive surrounds the water droplets to prevent the water from separating out of the mixture. The encapsulation prevents the water from contacting any metal engine parts, thereby allowing the fuel to perform in a similar fashion to conventional diesel. Lubrizol states that its PuriNOx fuel can be used in existing new and old diesel engines, with and without aftertreatment add-ons and without engine modifications or replacements. Potential applications include centrally fueled on and off-road uses including school bus and transit fleets, construction and agricultural equipment, as well as coastal marine ships and stationary power generators.

Emissions

CARB has verified PuriNOx fuel's ability to reduce both NOx and PM emissions and has issued the Lubrizol Corporation an Interim Verification of Emission Reductions for Alternative Diesel Fuels. In their letter to Lubrizol, CARB staff determined that the use of PuriNOx fuel reduces PM emissions by 62.9 percent using the interim procedure. (1) The Port of Houston is using PuriNOx fuel in its mechanical cranes and docking equipment. (2) PM reductions ranged from a high of 82 percent for a tour boat powered by a 1984 DDC V12 72 engine, to a 3.8 percent increase in a 1958 DDC 4 71 generator engine. The average PM reduction for the emission tests conducted by the Port was 43 percent. The baseline fuel was off-road diesel #2.

The San Francisco Bay Water Transit Authority recently completed a pilot program using PuriNOx in one of its ferry vessels. Emissions testing of the vessel after a period of operation revealed a 42 percent reduction in particulate matter. (3) CARB's recognition of the emission reduction potential of PuriNOx fuel has made it eligible for clean air funding programs in California. The Lubrizol Corporation is in the process of registering PuriNOx fuel with EPA.

Cost

PuriNOx fuel is delivered on-site as a complete fuel product. The Massachusetts Turnpike Authority reported a cost premium for PuriNOx of 15 cents per gallon above

No. 2 diesel. The San Francisco Bay Water Transit Authority paid from 14 to 18 cents per gallon more for PuriNOx fuel. (3)

<u>Other issues</u>

The presence of water in emulsion fuels decreases the volumetric energy content, which causes a reduction in fuel economy. The San Francisco Bay Water Authority (WTA) reported a 15 percent decrease in fuel economy when using PuriNOx fuel (PC), and a power loss of eight to 12 percent. WTA also noted that PuriNOx fuel will "clean out" the fuel delivery system and attention should be given to fuel filter clogging during the early phases of use. (3)

The state of Texas is currently investigating the use of PuriNOx in over 500 pieces of on-road and off-road equipment. Early indications are that they are experiencing power losses of as much as 20 percent for some equipment. (4)

PuriNox is produced by the Lubrizol Corporation and is delivered pre-mixed to the end user. The company has three blender/distributor partners in North America. There are no confirmed reports of PuriNox fuel being used in Washington State.

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2.1 New Engine Technologies

Diesel Engines

Beginning with the 2007 model year, new heavy-duty engines must meet a PM emission standard of 0.01 grams per brake-horsepower-hour(g/bhp-hr). The highway diesel program also establishes standards for nitrogen oxides (NOx) and non-methane hydrocarbons (NMHC) of 0.20 g/bhp-hr and 0.14 g/bhp-hour, respectively. The NOx and NMHC standards are phased in over three years, while the PM standard requires 100 percent compliance starting with model year 2007.

Future off-road diesel engine standards are considerably less stringent than the 2007 on-road standards. However, they will require significant emissions improvements over existing off-road engines. The new off-road PM standards are specific to model year and engine size, but in general, are about 20 to 60 percent lower than current Tier 1 standards. For off-road engines above 175 hp, PM standards will drop from 0.4 g/bhp-hour to 0.15 g/bhp-hour. For the most part, these standards will be phased in through 2005.

Diesel engine emissions are currently controlled through improvements to the basic engine, rather than through the use of after-treatment technologies (the exception being diesel oxidation catalysts). With these control changes, there is usually a tradeoff between NOx improvements and PM improvements. To control NOx emissions, lower combustion temperatures are desirable, while PM emission improvements generally result from higher combustion temperatures.

Currently, diesel emissions are reduced by turbo-charging, after-cooling, high pressure fuel injection, retarding injection timing and optimizing combustion chamber design. (1) Turbochargers reduce both NOx and PM emissions by approximately 33 percent when compared to naturally aspirated engines. (1) Aftercooling with turbocharging provides even larger NOx and PM reductions by decreasing the temperature of the charged air after it is heated by the turbocharger. Retarding injection timing reduces the peak flame temperature, which improves NOx emissions but typically results in higher PM emissions. Combustion chamber improvements and air-fuel injection advancements are ongoing in the industry and result in improved fuel economy and emission reductions.

As diesel engine improvements reach their limit, NOx and PM emission control will most likely require aftertreatment devices to achieve new, stringent emission standards. Diesel oxidation catalysts have been used in some engines since the 1990s to reduce PM emissions. These devices have proven effective at reducing PM emissions by 25 percent or more, are robust and require little or no maintenance.

Diesel oxidation catalysts will not allow engine manufacturers to meet the 2007 emission standards. (2) The catalyzed diesel particulate filter and the continuously regenerating diesel particulate filter (DPF) have demonstrated their effectiveness in reducing particulate emissions to 2007 standards. When coupled with ultra-low sulfur diesel, DPFs have achieved PM reductions of greater than 95 percent and have engine-out PM emission levels of 0.008 g/bhp-hour. In their review of diesel engine technology developments necessary to meet 2007 standards, EPA identified DPFs (when coupled with ultra-low sulfur diesel) as the leading technology for PM compliance. (2) While meeting NOx standards is proving problematic, all of the engine manufacturers surveyed by EPA indicated that they could meet 2007 PM standards. (2) In fact, one engine manufacturer was identified as already selling vehicles with catalyzed diesel particulate filters that met 2007 PM standards.

Although EPA reports that catalyst-based emission control technologies represent the most viable path for reducing PM and NOx emissions to levels below the 2004 standards, they also suggested that emerging in-cylinder emission control technologies may provide valuable synergistic benefits for compliance with 2007 standards. (2) Both Toyota and Nissan have been developing new combustion technologies that break the traditional NOx versus PM tradeoff and produce very low emissions of both. Nissan utilizes two distinct combustion modes. When engine torque is greater than 40 percent, the engine operates using conventional diesel combustion. At lower operating loads, the engine is operated with a low-temperature premixed combustion approach. Using this latter approach, engine PM and NOx emissions are reduced by more than 90 percent. Toyota is also developing a low temperature combustion technology that gives very low engine-out NOx and PM emissions.

Natural gas

Natural gas is a gaseous fuel composed mostly of methane, with smaller amounts of propane, ethane, helium, carbon dioxide and water. While natural gas is considered an effective alternative to diesel fuel, it is not as convenient to use as a liquid fuel. Natural gas must either be compressed to 3000-3600 pounds per square inch (psi), or liquefied through super cooling (-327.2 degrees F). In either case, refrigeration or compression equipment is required for refueling purposes.

Compression is the most common method for delivering natural gas for vehicle use. Currently, there are over 1,200 compressed natural gas (CNG) stations in the U.S. Because of its lower fuel density, CNG is not considered a practical fuel for long distance, heavy-duty truck applications such as Class 7 and 8 trucks. CNG is being used successfully in shorter range, heavy duty applications such as street sweepers and refuse trucks, and has a long history of use in many medium-duty applications such as school bus and transit fleets. For longer range applications, liquefied natural gas (LNG) is the preferred fuel. While LNG infrastructure is fairly limited at present, it is slowly being developed, primarily in southern California and Arizona. Still, it takes about 1.7 times the volume of LNG to provide an equivalent amount of energy to a gallon of diesel.

Because natural gas has a very high octane rating, it does not readily ignite in diesel engines. As a result, most heavy duty natural gas engines use a spark-ignition, four-stroke cycle to achieve combustion. However, original equipment manufacturers are developing natural gas engines that employ the more efficient, diesel combustion cycle. Cummins Westport, Inc., of Vancouver, British Columbia, is currently developing a 15 liter, 400-hp, high-pressure, direct-injection (HPDI) engine called the ISX-G. (3) This engine compresses air, unmixed with fuel, like a conventional diesel. The system then injects a small amount of diesel pilot fuel, followed by natural gas, which is stored on-board as LNG. Unlike other "dual-fuel" engines, the ISX-G technology is unique in that it preserves the diesel cycle's high compression ratio and apparently produces diesel-like torque and fuel efficiency. Cummins Westport, Inc. expects that this technology will be able to meet future emission standards.

Emissions

Natural gas engines are typically considered cleaner than petroleum fueled engines. However, all engines are becoming cleaner as engine manufacturers are required to meet stricter emission standards. Therefore, when comparing diesel versus natural gas emissions, it is important to make sure that like technologies are being considered.

A case in point is a recent study conducted by CARB. In the spring of 2002, CARB released the results of a study on transit bus emissions. (4) The study compared the emissions of a state-of-the-art diesel bus running on ultra-low sulfur diesel and equipped with particulate trap technology to an older, natural gas bus that employed no after-treatment controls. The preliminary results indicated the natural gas buses were found to discharge more mutagenic emissions, particulate mass, hydrocarbons and carbon monoxide.

Natural gas industry advocates argued that the results were unfairly comparing state-of-the-art diesel technology with older natural gas technology. As a result, CARB completed a follow-up study that investigated the emissions of currently manufactured natural gas buses equipped with oxidation catalysts. (5) The CARB study found that the oxidation catalyst-equipped CNG buses produced very low toxic emissions. Further, in terms of total PM mass, the study showed that CNG with or without oxidation catalysts is "significantly superior" to the current and "conventional" diesel bus, including the catalyst-equipped bus fueled with ultra-low sulfur diesel. (5)

In August 2002, DOE published the results of a multiple year study of United Parcel Service (UPS) trucks operating on CNG. (6) Although most of the CNG technology used by UPS is early production equipment, emission testing indicated that the CNG trucks had much lower emissions than diesel trucks of a similar age. Chassis dynamometer tests revealed that the CNG trucks had 95 percent lower particulate emissions, 75 percent lower emissions for CO, and 49 percent lower NOx emissions.

North Thurston Public Schools, located in Lacey, WA, is currently purchasing four new CNG-powered buses. Each bus is powered by a Cummins 230 hp, 5.9G natural gas engine with catalyst. The engine was certified for PM emissions of 0.02 g/bhp-hour. The equivalent ISB diesel engine manufactured by Cummins has a PM certification of 0.09 g/bhp-hour, an increase of about 78 percent. It should be noted that PM emissions from the diesel engine would be reduced significantly if retrofitted with a catalyzed diesel particulate filter.

Cost

Natural gas powered buses and trucks cost more than conventional diesel powered vehicles. The North Thurston Public School CNG powered school buses manufactured by BlueBird have a price premium of approximately $23,000. The Port of Seattle is paying approximately $40,000 more for a CNG option on a New Flyer of America 40 foot, low-floor coach powered by an 8.3 L Cummins natural gas engine. The Port of Seattle purchase of a natural gas powered street sweeper manufactured by Elgin under the model name Crosswind J will cost about $46,000 more than an equivalent diesel model.

Natural gas powered fleets may also be required to install refueling equipment due to the limited availability of natural gas fueling stations. A time-fill compressed natural gas refueling network appropriate for a school bus fleet could cost $100,000 or more. A commercial sized CNG station capable of fast filling vehicles is estimated to cost upwards of $300,000, while the state of New York identified a cost of five million dollars for a fuel station capable of refueling 30 buses per hour. (7) Maintenance shops and garages may also require costly safety modifications such as the addition of spark arrestors and methane detection equipment.

Hybrid electric

An emerging alternative to conventional diesel engines is the electric hybrid system. Hybrid buses typically utilize an electric drive coupled in series or operating in parallel with a combustion engine and traction battery.

Hybrid technology allows the use of a smaller internal combustion engine which is designed to operate near its optimum efficiency, thereby minimizing engine emissions and maximizing fuel economy. Typically, a hybrid system also employs regenerative braking which transforms kinetic energy into electric energy, again improving fuel economy. To a fleet operator, hybrid technology is attractive because it does not require the development of new refueling infrastructures or modifications to existing maintenance areas.

Emissions

New York City Transit (NYCT) operates a small but growing fleet of diesel/hybrid buses. Emissions testing on NYCT's original fleet of ten 1998 Orion VI hybrid buses was conducted by West Virginia University using a mobile chassis dynamometer. (8) On the Commercial Business Test cycle, the hybrid buses produced 50 percent lower PM emissions and 36 percent lower NOx emissions as compared to the NovaBUS RTS diesel buses operated by NYCT. Additional emission testing was completed on the new Orion VII diesel hybrid buses and the conventional Orion V diesel buses, with and without catalyzed diesel particulate filters. The new hybrid bus had 49 percent lower NOx and 93 percent lower PM than the Orion V diesel bus without the particulate filter. The new hybrid bus had 49 percent lower NOx, and 60 percent lower PM than the Orion V bus equipped with a diesel particulate filter.

Cost

The 1998 NYCT hybrid buses cost an average of $465,000 each. (8) An NYCT diesel bus costs about $290,000, or $175,000 less. The next generation of Orion VII hybrid buses purchased by NYCT cost $385,000 per bus, or about $95,000 more than the average NYCT diesel bus.

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2.2 Diesel Oxidation Catalyst

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

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

<u>Emissions</u>

In their 1999 review of heavy-duty diesel retrofits, EPA summarized emissions data for 60 heavy-duty diesel two- and four-stroke engines utilizing DOC technology. (3) Table 2 presents these results, which ranged from 19 to 50 percent reduction in total PM, with an average PM reduction of 33 percent.

Table 2: Diesel Oxidation Catalyst Use in Heavy Duty Diesel

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

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

In developing the California Diesel Risk Reduction Program, CARB also reviewed a number of products and technologies that were reported to reduce diesel particulate emissions. (2) While much of this information was based on manufacturer provided data, it provides a reasonable summary of DOC technology at that time. The PM reductions identified are similar to those reported by EPA's 1999 study of diesel retrofit technologies. CARB reported achievable emission reductions resulting from DOC use ranging from 16 to 30 percent, depending on product and test cycle. A summary of the CARB analysis is presented in Table 3.

Table 3: Diesel Oxidation Catalyst PM Emission Test Results

Test	Engine type	PM Control Efficiency
ISO 8178-D2	Ford-150 hp	8%
ISO 8178-D2	Ford-150 hp	21%
8-mode steady- state	1979 Deutz F6L-912W	16%
Transient cycle-bulldozer	Cummins TD-25G 450 Hp	24%
FTP	1992 Cummins L-10 280 Hp	30%
FTP	1998 DDC Series 60 400Hp	5 separate DOCs- 23%, 25%, 5%, 29%, 27%.

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

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

Cost

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

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

Other issues

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

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

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

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

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

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

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2.3 Diesel Particulate Filters

One of the leading technologies for meeting future PM emission standards is the diesel particulate filter, or DPF. These devices generally consist of a wall-flow type filter positioned in the exhaust stream of a diesel vehicle. As the exhaust gases pass through the system, particulate emissions are collected and stored. Because the volume of diesel particulates collected by the system will eventually fill up and even plug the filter, a method for controlling trapped particulate matter and regenerating the filter is needed.

For many diesel engines, the exhaust gas temperature is insufficient to regenerate the filter. For filter regeneration to work effectively, exhaust temperatures need to exceed about 500 degrees C for non-catalyzed systems, and 250 to 300 degrees C for catalyzed systems. (1) Some diesel particulate filters use a "passive" approach, and do not require an external or active control system to dispose of the accumulated soot. Passive filters are installed in place of the muffler. At idle or low power operations, particulate matter is collected on the filter. As the engine exhaust temperatures increase, the collected material is then burned or oxidized by the exhaust gas, thus cleansing or "regenerating" the filter. To ensure filter regeneration, various strategies (or combinations) are used. Regeneration methods include:

- Coating the filter substrate with a base or precious metal, thereby reducing the temperature needed for oxidation of the diesel particulate matter.
- Installing a catalyst upstream of the filter, again lowering the exhaust temperature needed to burn off the particulates.
- Using fuel-borne catalysts to reduce the burn-off temperature of the collected particulates.
- Installing fuel burners, electrical heaters or some other active method to heat the exhaust gas to a high enough temperature to ensure PM oxidation.

While limited to primarily off-road applications, another strategy which avoids filter regeneration altogether is to use a disposable particulate trap. The disposable system is sized to collect diesel particulate matter over a set period of operation. When full, the system is removed from the vehicle and replaced with a new unit.

Emissions

The effectiveness of DPFs is well documented. CARB reports PM emission reductions of 85 to 97 percent for various types of catalyzed diesel particulate filters. (2) EPA reports conservative estimates of 80 percent PM reductions for base metal catalyzed particulate filters, and more than 90 percent PM reductions for precious metal catalyzed particulate filters. (3) A year-long study of trucks and buses equipped with passive diesel particulate filters was recently completed by a consortium of equipment manufacturers and researchers. (1) The test vehicles included grocery trucks, tanker trucks, refuse trucks, school buses and transit buses. For all five of these fleets, the test vehicles retrofitted with DPFs and operated using ultra-low sulfur fuels achieved PM emission reductions of more than 90 percent when compared with control vehicles equipped with factory mufflers and operated on typical California diesel. (1) New York transit buses equipped with catalyzed diesel particulate filters achieved similar emission results. Even after 12 months of operation, PM reductions of more than 90 percent were measured. (4)

Both EPA (http://www.epa.gov/otaq/retrofit/retroverifiedlist.htm)and CARB (http://www.arb.ca.gov/diesel/verifieddevices/verdev.htm) maintain a list of diesel particulate filters that have been verified to achieve an expected level of PM emission reductions. Switzerland has also done extensive testing of particulate trap systems and maintains a list of tested and approved trap technologies for construction equipment. The VERT Filter-list is recognized by CARB and can be found at (http://www.akpf.org/pub/filterliste_en_2002.pdf).

Cost

The Manufacturers of Emission Controls Association (MECA) estimates catalyzed diesel particulate filter costs of $3,300 to $5,000. The California Air Resources Board provides a range of cost from $5,000 to $7,500 for a 100 hp engine, $6,900 to $9000 for a 275 hp engine, $10,500 for a 400 hp engine, and over $32,000 for a 1,400 hp engine. (2) A 1999 study of diesel particulate control devices for the underground mining industry provided an estimated cost of $30 to $50 per hp for DPFs. (5) New York City Transit noted that the catalyzed diesel particulate filters used on their buses cost approximately $5,000 to $6,000 per bus, while the City of Seattle estimated an installed cost of $7,500 per DPF. (3, 6)

Installation of DPFs can range from an hour and a half to a full day. 2,3) CARB estimates installation costs of $167 to $518, and annual maintenance costs of $156 to $312.(2) In a study completed on grocery trucks retrofitted with DPFs, exhaust system repair costs were 0.015 cents per mile higher for retrofit trucks over the first ten months of operation. (7) As in all cases, actual costs will vary depending on the application and the manufacturer. Some applications may require backpressure monitoring devices, while others may require muffler wraps, which may increase costs. DPFs are heavier and larger in diameter than a muffler, so modifications to the exhaust system may also be required.

Other issues

Older engines - DPF performance is affected by the rate of PM generated by the engine. (8) In general, engines built prior to the 1994 emission standards of 0.1g/bhp-hour PM exhibit excessive PM emissions for DPF applications. (9) Because DPFs must be able to capture and “store” a certain quantity of soot, 1993 and older engines will likely overload the filters’ soot carrying capacity and cause significant performance problems. (9) The New York City Transit retrofitted 25 Detroit Diesel 6V92 DDEC engines with catalyzed DPFs. After a few weeks of operation, the filters began to plug and DPF performance was compromised. Transit officials concluded that the plugging was caused by excessive particulate emissions resulting from the older engines. (3) Recently, CARB issued an advisory to transit agencies which stated that there are no verified devices at this time that reduce PM by 85 percent or more for transit bus engines older than 1994. (10)

Exhaust temperature - Diesel particulate filters are also very sensitive to exhaust gas temperatures and fuel sulfur content. For most continuously regenerating catalyzed particulate filters to work properly, an engine must operate at around 300 degrees C for 30 percent of the duty cycle, or 30 minutes. (3) The CRT catalyzed diesel particulate filter system manufactured by Johnson Mathey requires an average exhaust temperature of at least 270 degrees C for 40 percent of the engine duty cycle. (11)

Exhaust gas temperatures are highly application dependent. Excessive heat loss in the exhaust system can cause lower exhaust gas temperatures, as can oversized engines that are operated low on their torque/power curve. Although many diesel applications generate sufficient exhaust gas temperatures for successful DPF operations, device manufacturers and regulators recommend that certain vehicle applications be equipped with data loggers to continuously monitor exhaust back pressure and temperature. (4) Once it is determined that sufficient exhaust gas temperatures exist for filter regeneration, the monitoring can be stopped.

Unlike passive DPFs, active DPFs have an external source of heat to complete regeneration. Active DPFs employ a variety of approaches for regeneration including fuel burner, electricity, microwaves or fuel injection. Some systems do it automatically when a specified backpressure is achieved, while others require operator assistance to initiate the process. (8) CARB staff suggests that active systems have a much broader range of application since they are not dependent on the exhaust gas reaching a critical burn-out temperature. (8) A recent report issued by the Engine Manufacturers Association (EMA) states that passive diesel particulate filters are not suitable for many non-road mobile machinery applications. Instead, EMA argues that off-road applications require an active, automatic regeneration filter system. (12) EMA points out that no such system exists today that is mature enough to meet commercial viability.

Low sulfur fuels - Fuel sulfur content also affects the performance of passive DPFs. DOE recently concluded a study examining the effects of sulfur on diesel particulate filters. (13) Two passive regeneration systems were tested: a catalyzed DPF (the filter is directly coated with a catalyst) and a continuously regenerating DPF (a catalyst is located upstream of the filter). DOE found that DPFs cease to reduce PM emissions with fuels containing 150 ppm sulfur and become a source of PM emissions with 350-ppm sulfur fuels. Overall, baseline PM emissions increased as the fuel sulfur level increased. At three ppm sulfur, both devices reduced PM emissions by 95 percent; and at 30 ppm sulfur, the PM reduction efficiencies of both devices dropped to around 72 percent.

The effect of sulfur on DPFs has prompted regulators and device manufacturers alike to require low sulfur fuels for DPF applications. Johnson Mathey (JM), the manufacturer of the CRT Diesel Particulate Filter, requires a maximum sulfur content of 50 ppm to ensure filter performance and durability. (14) JM also recognizes that DPF performance improves with lower sulfur fuels and that 15 ppm fuels or lower will provide maximum

PM removal and filter durability. (9) In their verification protocol for passive DPFs which reduce PM emission by 85 percent or more, CARB requires that engines operate with a fuel that has a fuel sulfur content of no more than 15 ppm by weight. (11)

Maintenance - Some increase in backpressure resulting from the addition of a DPF should be expected. With higher back pressure comes a fuel economy penalty. If backpressure becomes too great, an engine can stall or even be damaged. To avoid backpressure problems due to excessive ash build-up in the filter, DPF manufacturers have prescribed maintenance schedules for filter cleaning. Johnson Mathey and Englehard both recommend performing filter maintenance approximately once each year or every 60,000 miles. To ensure DPF durability and performance, CARB requires the installation of a backpressure monitor and indicator light on vehicles retrofitted with verified passive DPF systems. (11) CARB has also noted that test data received from two verified passive DPF manufacturers shows no discernible reduction in fuel economy due to the addition of the devices. (8)

The ash that accumulates within a DPF is largely inorganic substances, with the primary source being the combustion of engine lube oil. The ash generally consists of phosphorus, sulfur, calcium and zinc. (1) High levels of zinc could create a problem with disposal, as the ash may be considered a hazardous waste depending on the concentration of zinc. Local waste disposal regulations should be checked prior to ash disposal.

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3.1 Smoke Testing or Emission Inspection Programs

The 1990 Clean Air Act required EPA to develop light duty vehicle inspection and maintenance standards (I/M) to help control vehicle emissions. Program implementation of these standards was relegated to the states. A growing concern over health related PM effects motivated some states to extend I/M programs to include heavy duty diesel vehicles (HDDV). Currently, 17 states, including Washington, have some type of diesel I/M program (Colorado 2002).

HDDV I/M programs may employ a roadside measurement of the amount of visible smoke being emitted from a vehicle's exhaust system under some specified test conditions. In addition, some jurisdictions require annual or semi-annual inspections of HDDVs which are performed at fleet maintenance facilities or centralized inspection sites.

The roadside smoke opacity test is often carried out at weigh stations, custom inspection facilities or any other suitable site which allows easy access to and from the highway. Tests are random in that they are unannounced and are held at varying inspection sites. Vehicles are selected for opacity testing based on visual observation of the vehicles as they approach the test site. High smoke emitters are flagged for inspection, with selection based on inspector experience. The roadside test usually applies to all HDDVs, regardless of origin, and is free of charge. Failing the test may result in a fine, which is often waived or reduced if the owner furnishes proof that the reason for failure has been corrected.

Annual or periodic programs operate similar to the light duty I/M test. Here, HDDV operators are required to complete a smoke test within a jurisdiction, are charged for the testing, and can be fined or denied registration renewals until the reason for failure is fixed or at least attempted to be fixed. Unlike roadside testing, periodic testing does not single out high emitters for testing. Instead, all vehicles (with the possible exception of newer vehicles up to the latest three or four model years) need to show that they can pass inspection.

Proponents of periodic inspections argue that this approach captures all registered vehicles within a given jurisdiction and encourages vehicle owners to consistently maintain their vehicles with respect to smoke emissions. Proponents of roadside inspections argue that roadside testing targets only the gross emitters and can be moved around to areas where dirty vehicles are observed to operate. Further, roadside testing treats all smoking vehicles the same and does not discriminate between vehicles registered in and out of state.

Because HDDVs often move between jurisdictions and states, a push was made to develop a standardized protocol for smoke testing. In 1997, the EPA Office of Mobile Sources issued a "Guidance to States on In-Use Smoke Test Procedure for Highway Heavy-Duty Diesel Vehicles." This document provides guidance on how to conduct smoke tests using the SAE Recommended Practice J1667, Snap-Acceleration Smoke Test

Procedure. J1667 was developed in 1996 with the help of the engine manufacturers, trucking industry, smoke testing equipment manufacturers and state and federal regulators (http://www.arb.ca.gov/msprog/hdvip/saej1667.pdf).

The test is performed on a vehicle when it is standing still and in neutral. The engine is accelerated without any external load to the maximum governed speed. A smoke meter is placed at the end of the exhaust pipe and the opacity of the smoke is measured. The opacity is expressed in percent of light reduction, and is the degree to which the exhaust obscures a beam of light shining through it.

EPA recommends that states employ J1667 opacity failure points (the point at which the vehicle fails a smoke test) of 55 percent for pre-1991 vehicles and 40 percent for 1991 and later model year vehicles.

Emissions

Actual emission benefits resulting from smoke testing programs have not been well documented. The goal of smoke testing is to reduce visible, black exhaust smoke. While it is commonly accepted that less smoke means lower particulates, a reduction in the opacity of the particulate matter does not necessarily result in a reduction in its total mass (Canada EPS 2000). The Colorado Diesel Stakeholder Group noted that the continued use of opacity as a surrogate measurement tool to identify high-emitting vehicles should be reevaluated. At best, opacity levels identify some but not all high-emitting engines (Colorado 2002).

Recently, Energy and Environment Analysis, Inc (EEA) was contracted by the state of Colorado to quantify the emissions benefits of smoke testing of heavy duty vehicles (EEA, 2001). Although their research sample was small (only 26 vehicles total), EEA did come up with some interesting observations. Their primary conclusion was that the standard opacity cut-points of 55 percent for pre-1991 vehicles and 40 percent for later vehicle models may not be appropriate, at least for the state of Colorado. EEA argued that the cut-points, initially developed by the state of California, are too high, and were originally set conservatively because of California's requirement of zero errors of a vehicle being failed incorrectly.

EEA found that, for pre-1991 vehicles failing at a 45 percent opacity cutpoint (instead of the standard 55 percent), repair reduced PM emissions by 45 to 50 percent. For 1991 and newer vehicles (all of which failed the 40 percent opacity cutpoint), repairs produced a greater than 40 percent reduction in opacity and a 25 to 30 percent reduction in emissions of PM (EEA.) EEA also found that NOx levels went up but still remained within the established standards, and that aldehyde and PAH emissions were reduced dramatically following repair. The average cost of repair was $1,088.

Early work by various researchers suggests that there is some correlation between smoke opacity and PM emissions. Based on their study results, however, EEA indicated that smoke opacity is at best a poor predictor of PM emissions. They suggested that driving cycle CO and THC emissions are correlated much more strongly with PM and that an improved I/M test procedure based on tailpipe measurement of CO and THC be developed (EEA).

Costs

Smoke testing costs are difficult to assess as it depends on what is counted as cost. Costs could include:

- program administration costs;
- administrative costs to fleets, including annual labor costs to complete the inspections; and
- costs to fleet or vehicle owners which could include vehicle down time, vehicle repair costs, testing fees, testing fines, and annual increased maintenance costs due to voluntary repairs done in order to avoid failing the test.

California's Heavy Duty Vehicle Roadside Inspection Program has an estimated total program cost of about $5.6 million per year, or $280 per vehicle inspected (Colorado 2002). Of this amount, vehicle owners pay about $1.9 million for increased maintenance and lost opportunity costs, and the state pays about $3.7 million to annually inspect the vehicles (not counting Highway Patrol costs). Between June 1998 and September 2001, 64,648 visual inspections were performed. During this time frame, the fail rate was 4,538 vehicles, or about seven percent. Program managers indicate that they inspect about 20,000 vehicles annually, which equates to about 1,400 vehicle failures per year at a seven percent fail rate (Colorado 2002).

California also conducts a periodic inspection program. Here, all fleets of two or more California-registered HDDVs (about 291,600) are subject to an annual self-inspection using the snap acceleration test. A four model year exemption is allowed, which is estimated at 26 percent of the fleet. The state audits the fleets for compliance, with less than one percent of the fleets requiring formal action (Colorado 2002). State costs for auditing are $0.5 million annually. The cost of self testing is estimated at $18.1 million per year. The annual program cost is estimated at $84 per vehicle inspected. In addition, vehicle repairs resulting from inspection programs are estimated to improve fuel economy and effectively offset the costs of repair to the operator.

In 1997, CARB estimated that the cost-effectiveness of the HDDV smoke test program in reducing criteria pollutants was superior to other emission control programs. In fact, the HDDV smoke test program was estimated to be between 2.4 and 4.7 times more cost-effective than other control method (Canada 2000). Current estimates by CARB suggest that the programs cost about $1.05 per pound of emission reduction (tri-national HDDV smoke test workshop-3/2002).

Other issues

In a recent workshop sponsored by the Northeast States for Coordinated Air Use Management and CARB, participants raised some common themes concerning heavy duty vehicle emission testing (tri-nat workshop). These issues included a need to better correlate opacity and PM (and NOx); a need to revisit current opacity cut-points; and a need to develop new, advanced emission testing methods (loaded test, chassis test, on-board diagnostics) for use with new engine technologies.

Representatives from a number of organizations had concerns with the current opacity cut-points. Some felt that the current levels may be allowing too many potentially polluting vehicles to pass the smoke test. The state of Colorado has lowered their cut-points to below the accepted EPA standard and California is investigating the need for more restrictive cut-points as well. While the current snap-idle test appeared to be acceptable to the majority of participants, a need for advanced testing methods was raised in response to newer engines. Some participants argued that with newer engines, visible smoke was not necessarily a good indicator of particulate emissions, and as a result, spot or road-side inspections were going to lose their effectiveness.

Smoke testing is primarily a tool to reduce visible smoke emissions from heavy duty diesel vehicles. The relationship between opacity and PM is not fully understood; however, it appears that lowering opacity should provide PM emission reductions. The Colorado Diesel Stakeholder Work Group observed that, although high opacity readings indicate high PM emissions, low opacity does not necessarily indicate low PM emissions. They further acknowledged that the lack of quantitative emissions data makes it difficult to judge the effectiveness of their HDDV Inspection and Maintenance program in reducing diesel emissions. However, they concluded that the program provides undeniable benefits as an incentive for good maintenance and as a deterrent to vehicle tampering (Colorado 2002).

3.2 Idling Restrictions

Over the road (Class 7 and 8) trucks, construction equipment, and school bus and transit fleets are often idled during normal operations. Idling truck engines are used to provide electrical power for non-driving operations, to provide heat or air conditioning for the sleeper cab, to keep the engine warm during cold weather and to provide electrical power for in-truck appliances. School buses are idled during student pick-ups, deliveries and in bus parking yards, while construction equipment is idled during routine operations as equipment is staged for use.

EPA has identified idling as a major contributor to PM emissions. PM emission rates will vary based on vehicle type, age, fuel used, maintenance and a variety of other factors. However, EPA has calculated fleet average emissions of particulate matter smaller than 10 microns in size (PM_{10}) resulting from idling for light, medium and heavy duty trucks and buses. Table 1 presents idle emission factors for PM, for HDDV, based upon gross vehicle weight (GVW). (1)

Table I
Idling Vehicle Emissions

Engine Size	PM_{10} Emissions
Light/medium Heavy Duty Diesel Vehicles (8501-33,000 lbGVW)	2.62 g/hr
Heavy Heavy Duty Diesel Vehicles (33,001+ lb GVW)	2.57 g/hr
Heavy Duty Diesel buses (all buses, urban and city)	2.52 g/hr

Source: EPA 420-F-98-014

There are various approaches that can be taken to minimize idling emissions. Idling restrictions are probably the most direct method for reducing emissions or exposure. A number of school districts are considering or have established idling guidelines or regulations. (2,3) These include:

- shutting off engines during student loading and unloading periods;
- limiting idling times for engine warm-up, or alternatively, installing block heaters;
- priority scheduling lowest emission buses and optimizing bus routes;
- providing a conditioned space for bus drivers to wait; and
- powering flashing lights without running the main engine.

Construction activities can also be controlled to minimize air quality impacts. Construction site guidelines could include:

- requiring equipment to be properly tuned;
- turning off diesel equipment not actively in use;

- turning off dump trucks that are idling to load or unload for more than five minutes;
- establishing a staging zone away from the public for trucks that are waiting to load or unload; and
- locating equipment away from sensitive receptors such as fresh air intakes.

Improving the emissions characteristics of idled vehicles through retrofit actions, repowering, alternative fuels or replacement will also reduce PM emissions resulting from idling.

Idling restrictions are more difficult when dealing with over-the-road trucks. Because these trucks are usually idled to maintain driver comfort or vehicle requirements, shutting down the engine may not be an acceptable solution. Manufacturers of idle control equipment and the trucking industry are currently researching various approaches to reduce idling emissions. A list of currently available idle reduction technologies are maintained by EPA at www.epa.gov/otaq/retrofit/idlingtech.htm .

Nationally, there are about 458,000 combination trucks traveling at least 500 miles per day. (4) While accurate idling statistics are not available, the industry estimates trucks idle approximately six hours per day, for a total of 1,830 hours per year. (4) At this rate, U.S. trucks are consuming in excess of 840 million gallons of diesel fuel annually while idling. Using the EPA idle emissions factors, PM emission rates resulting from truck idling amount to approximately 15 grams per day per truck, or about 169 pounds of particulate matter per truck per year.

Operating heavy duty diesel engines at idle to provide space heating, ventilation and air conditioning to the sleeper compartment is very inefficient. Over 85 percent of the energy in diesel fuel is wasted in cab heating during the winter, and as much as 94 percent of diesel fuel energy is lost for summertime air-conditioning needs. (5)

The primary technologies being developed to reduce truck idling are direct-fire heaters, auxiliary power units and truck stop electrification. While direct-fire heaters are very efficient when compared to idling a truck engine, these devices cannot provide cooling and AC/DC power, both of which contribute significantly to truck idling. Auxiliary power units (APUs) are typically small, truck-mounted systems that include an internal combustion engine, a compressor and an alternator. They are generally diesel powered, but development of fuel cell APUs is underway. The units are integrated into the truck's operating system to allow for independent operation, or as a back-up alternative to the main engine.

Truck stop electrification is another option to reduce truck idling. This technology is currently being developed in various parts of the U.S. Some systems provide only electrical power to the truck via a service outlet. Cooling, heating and other appliance needs are met by retrofitting the truck with the necessary electrical equipment. Other technologies provide fully external services which are independent of the truck. One such provider is IdleAire Technologies Corporation of Knoxville, Tennessee. IdleAire has developed an advanced truck stop electrification system that brings HVAC (heating, venting, and air conditioning) to the cab and sleeper compartment via an external device. The company installs a heating, ventilating and air conditioning unit at each truck parking space beside or above the truck. HVAC is delivered to the truck by a microprocessor-controlled system that connects to the truck. It also provides 110 AC electric power for in-cab appliance needs including phone, television and internet service, and an additional 110 AC outlet for engine block heating. An IdleAire system is currently being installed in 32 truck parking spaces at a truck stop located in New York City. (5)

Emissions

Emission benefits of idling reduction technologies are currently being evaluated. EPA estimates that an auxiliary power unit will result in an 88 percent reduction from the baseline emissions of an idling truck. (6) EPA also estimates an 80 to 90 percent reduction in baseline emissions from an idling truck using advanced truck stop electrification technology. Argonne National Laboratories estimated PM emission reductions of approximately 73 percent for an auxiliary power unit, and about a 98 percent reduction for truck stop electrification (see Table 2). (4) The IdleAire advanced truck stop electrification project in New York State is expected to reduce truck idling PM emissions by 98 percent, according to project sponsors. (5)

Table 2
Estimated Emissions from Truck Cab/Sleeper and Engine Block Heating

Technology	NOx g/hr	PM10 g/hr	CO2 g/hr
Idling	56.7	2.57	10.397
Direct-fired heater	0.264	na	1,456
APU	11.6	0.69	1,871
Electrification	6.04	0.035	3,014

Source: Argonne National Labs-Analysis of Technology Options to Reduce the Fuel Consumption of Idling Trucks. Data are estimates only.

Costs

Idling reduction technology costs are summarized in Table 3. (7) Equipment costs range from about $1,400-$2,000 for a small cab heater to more than $7,000 from APU with an inverter to allow use of 110-V applications. While the high cost of the equipment, particularly the APU, may deter truck operators, some manufacturers offer a lease/purchase plan for their units.

Because of the high initial cost of truck stop electrification and the uncertainty of use, development of these sites has been slow. The South Coast Air Quality Management district has a program for truck stop operators that will generate mobile source emission reduction credits for truck stop electrification. Other areas in the country are also looking at some type of private/public partnership to get these projects started.

Table 3
Idling Technology Cost/Benefit Analysis

Technology	Initial Cost	Fuel Savings/yr @1.50/gal	Maint. Savings/yr	Operating Charge
Direct- fired heater	$2,000	$1,152	$513	
APU	$7,000	$2,880	$1,339	
Truck stop electrification (TSE)	$75K 30 spaces; $2.5K per truck	$3,600	$1,539	$3,000 annual usage fee/ truck cost $1.25/hr
Advanced TSE	$300 K 30 spaces	$3,600	$1,539	3,000 annual usage fee/ truck cost $1.25/hr

Source: EPA Power Point Presentation, Long Duration Truck Engine Idling, Paul Bubbosh, June 5, 2002 Albany, NY.

Operations

Engine manufacturers often recommend that an engine idle for three to five minutes before driving after the vehicle stops. However, most newer diesel engines will stay warm for several hours after they have been running, thereby avoiding restarting difficulties. Older vehicles may have more difficulty restarting, so manufacturers' recommendations should be checked.

Idling typically consumes about one gallon of diesel fuel per hour. Idling technologies can save from $1,152 to as much as $3,600 in annual fuel costs. Letting an engine idle also does more damage to an engine than starting and stopping, causing twice the wear on internal parts compared to driving at regular speeds. (2) Because of the reduced wear and tear on the engine, maintenance savings may result from the use of idling technology. Depending on the technology, payback periods could be as little as one or more years.

The high cost to develop truck stop electrification and the uncertainty of use has limited their development. However, because of the societal benefits achieved by truck stop electrification projects, public/private partnerships may be the way these projects overcome current obstacles. A number of public entities in New York State are currently trying this approach and have partnered with a private TSE manufacturer to determine its viability.

Each technology does have drawbacks. Direct-fired heaters cannot supply cooling or power, while APUs are fairly large and heavy, and have a high initial cost. However, both of these technologies go with the truck and benefits accrue wherever they are operated. The major drawback for truck stop electrification is its high cost, and that if developed, it will be limited to specific locations. Because of this, truck stop electrification siting will probably be restricted to high use areas such as multi-modal freight loading and staging areas and overnight truck stops along major urban corridors.

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3.3 **Diesel Emission Reduction Programs**

Texas Emissions Reduction Plan (TERP)

TERP was created in 2001 by the 77th Texas Legislature to provide grants and other incentives for improving air quality throughout the state. The program was authorized in Senate Bill 5, and is administered by the Texas Natural Resource Conservation Commission (TNRCC).

The program is designed to reduce NOx emissions from on and off-road diesel powered vehicles in select Texas counties. Eligible activities include:

- lease or purchase of low emission non-road equipment (>50Hp);
- repowering or retrofitting of diesel powered engines;
- demonstration of new technology;
- non-diesel infrastructure activities; and
- use of qualifying low emission fuels.

Eligible projects are restricted to specific counties in violation of federal emission standards. Projects also must meet a cost-effectiveness criterion and cannot exceed a cost of $13,000 per ton of NOx reduced.

TERP is funded through a number of fees and surcharges, and not from general revenue. The original revenue was expected to be about $130 million per year; however, the Texas courts determined that collecting fees for registration of out-of-state vehicles was unconstitutional. As a result, in Fiscal Year 2002 (September 2001 thru August 2002) the revenue received was about $20.5 million. The Texas legislature will consider the funding issues during their spring session. The fees include:

- a one percent surcharge on the retail sale, lease, or rental of new or used construction equipment;
- a 2.5 percent surcharge on the retail sale or lease of pre-1997 on-road diesel vehicles over 14,000 lbs;
- a 10 percent surcharge based on the total fees imposed on the registration of truck-tractor and commercial motor vehicles;
- a $10 fee on the inspection of commercial motor vehicles; and
- a $225 fee for inspection/registration of a vehicle from out-of-state (ruled unconstitutional and never collected).

The Carl Moyer Program

The California legislature allocated a one-time appropriation of $16 million dollars to fund the Carl Moyer program through the 2001-2002 Fiscal Year. Previously, $25 million in CARB’s1998-99 fiscal year budget, $19 million in its 1999-2000 fiscal year budget, and $50 million in its 2000-2001 fiscal year budget were allotted for Carl Moyer Program incentive grants, as a means to reduce emissions from heavy-duty engines.

The incentives are grants that cover the incremental cost of cleaner on-road, off-road, marine, locomotive and stationary agricultural pump engines, as well as forklifts, airport ground support equipment, and Auxiliary Power Units. Beginning in summer 1999, grants became available through participating air pollution control and air quality management districts. The incentive program focuses on reducing emissions of smog-forming oxides of nitrogen (NOx), but will also reduce particulate emissions.

Lower Emission School Bus Program

CARB received an appropriation in their 2000-2001 Budget of $50 million to establish a Lower-Emission School Bus Program. In the 2001-2002 Budget, an additional $16 million was received. CARB staff, in coordination with the California Energy Commission and the local air pollution control districts, developed program guidelines that establish criteria for the purchase of new school buses and retrofits of existing school buses to reduce particulate matter emissions. The goal of the program is to replace older buses with safe and clean new buses and clean up in-use buses. All California school districts are eligible. Bus project funding will be split between alternative fuels and new clean diesel technologies. Half of the clean diesel technology funding will be directed toward the retrofit of buses with particulate filters that achieve 85 percent reduction in PM. School districts are only responsible for a 25 percent match of a new bus purchase cost, with a maximum share of $25,000.

The State of Georgia Tax Credit

A tax credit is available to anyone who installs diesel particulate emission reduction equipment (which can include equipment that provides for heat, air conditioning, light,and communications for the driver's compartment of a commercial motor vehicle) at any truck stop, depot, or other facility. The tax credit is ten percent of the total of the cost of the diesel particulate emission reduction technology equipment and its installation costs. It is good for the taxable year in which the taxpayer first places the equipment in use. See Georgia Code Section 48-7-40.16, Official Code of Georgia Annotated.

Oregon Non-point Source Pollution Control Facilities Tax Credit

The State of Oregon offers a tax credit for Oregon taxpayers who purchase a "pollution control facility" (includes any equipment or device) used to reduce or control air pollution. The tax credit applies to retrofit technologies verified by the EPA's Voluntary Retrofit Diesel Program. Information about the application procedures, fees, and assessment of cost can be found by following this link to Oregon's Pollution Control Facilities Tax Credit Program.

Sacramento Emergency Clean Air Transportation Program

The Sacramento Emergency Clean Air Transportation Program (SECAT) provides $70 million in transportation funds to clean up the region's heavy-duty diesel truck fleet by 2005, with most of the work to be done by 2002. The SECAT program is authorized by the state legislature in bill AB2511. It is funded by $50 million set aside by the Governor, and $20 million in local transportation funds (from the Congestion Mitigation Air Quality, or CMAQ fund) allocated by the Sacramento Area Council of Governments (SACOG) Board of Directors to match the state funding.

New York Clean-Fueled Bus Program

The Clean-Fueled Bus Program is administered by the New York State Energy Research and Development Authority (NYSERDA). The program provides funding for the incremental cost of a clean-fueled bus over a diesel bus. Eligible participants include transit authorities, state agencies, state universities, municipalities, and school bus fleets. Applications are evaluated primarily on emission reductions per program dollar, whether the bus will operate in a "nonattainment" area (an area that has failed to attain one or more national ambient air quality standard), and the volume of petroleum displaced. The program was created through the 1996 New York State Clean Water/Clean Air Bond Act and sustained by budget appropriations. The program's primary goal is the reduction of NOx and PM_{10} emitted in the operation of the New York bus fleet. NYSERDA is responsible for developing and administering the program. The program leverages private sector funding by providing funding to cover the incremental cost of clean-fueled buses over a diesel bus. The entire program has funded 538 buses at a program cost of $25 million. Leveraged costs are estimated at $150 million.

Massachusetts State Revolving Fund-Diesel Retrofit Program

The state of Massachusetts is operating a number of diesel retrofit programs. For the most part these programs are driven by regulatory actions which mandate compliance, although federal CMAQ funds have been used to offset some project costs. In the state's largest retrofit program, the Central Artery Project, the Massachusetts Turnpike Authority requires project contractors to share the cost of installing retrofit devices on their equipment. Similarly, for all state funded water and sewer projects, contractors must show that they will retrofit part of their fleet before they are eligible to bid.

4.1 School Buses

In a recent study, Yale University identified that children were at particular risk from exposure to school bus diesel emissions. The Yale study found that children's exposure to airborne particulates in tested buses was sometimes five to15 times higher than background levels of particulate matter smaller than s.5 microns in size ($PM_{2.5}$). The Yale investigators also considered that children were more susceptible to adverse respiratory effects following exposure to fine particulate emissions, and that bus idling behavior, queuing practices and bus ventilation were significant factors in the rate of exposure.

The Union of Concerned Scientists (UCS) estimates that nationally, school buses release 3,000 tons of particulate matter, 95,000 tons of smog-forming pollutants and 11 million tons of greenhouse gas emissions. On average, a single school bus is estimated to produce more than 14 pounds of particulate matter per year, or more than twice the emissions released by a new, standard diesel engine. UCS concluded that older school bus fleets were responsible for emitting the most pollution.

Washington's publicly owned school bus fleet consists of about 9,026 school buses, of which 8,559 are diesel powered, and the remaining 468 operate on gasoline or other fuels. This is a significant change from 1991, when Washington school districts operated a total of 7,111 buses, of which 4,559 were diesel-powered units, 2,273 were gasoline powered, and 279 were alternative fueled buses.

Washington also operates one of the older bus fleets in the country. Currently, Washington school districts operate 187 buses that were built prior to 1977, and 2,841 buses built prior to 1990. Buses built prior to 1977 do not meet current safety standards for crash and roll-over protection. Older buses also exhibit higher emission rates. This is due in part to mechanical deterioration, but also because earlier bus engines were certified to less stringent emission standards.

Emission reduction options

School districts are chronically under-funded. Consequently, school transportation programs have limited resources for fleet improvements. Diesel particulate emissions are a growing health concern, however, and school districts need to take action. These actions can range from low- or no-cost measures such as proper maintenance and idling restrictions, to higher cost actions such as particulate trap retrofits or new engine purchases.

Bus idling restrictions

A number of school districts, particularly in the northeastern United States, have instituted bus idling restrictions. These restrictions include:

- Bus engines should be turned off immediately upon reaching destinations, unless the stop is of short duration.
- Buses should not be turned on until fully loaded, especially when queued up for loading and unloading. Exceptions should include conditions that would compromise student safety, such as extreme weather conditions or idling in traffic.
- Buses should be retrofitted with batteries to operate flashing equipment to allow for safe operations when shut off.
- At school bus yards, idling times during morning and afternoon warm-up should follow manufacturer recommendations (typically three to five minutes), while block heaters should be used in colder climates.
- School districts should schedule the newest, lowest emission buses for the longest routes, and investigate the use of bus routing software to minimize trips.

Emission savings - On average, a bus will emit 2.52 grams of PM_{10} for every hour it is idling. While cold starts will offset some of these savings, limiting idle time will result in significant PM reductions and limit students' and drivers' exposure rates to particulates.

Cost - None. Idling restrictions can save fuel. The average diesel engine burns about one gallon of fuel for each hour it idles. Thus, if a district operates 25 buses and each bus reduces its idle time by 30 minutes per day, the district would save $2,250 per year at one dollar per gallon of diesel fuel.

Users - School districts in New England, including Connecticut and Massachusetts, have instituted bus idling restrictions.

Diesel oxidation catalysts

A diesel oxidation catalyst (DOC) is a pollution control device that consists of a canister containing a honeycomb-like structure coated with a catalyst. As the exhaust gases traverse the catalyst, carbon monoxide, gaseous hydrocarbons and liquid hydrocarbon particles (unburned fuel and oil) are oxidized, thereby reducing harmful emissions.

An oxidation catalyst retrofit consists of either an in-line engine muffler replacement or an add-on control device. The size of the DOC will need to be matched to engine displacement and the exhaust system. Installation can take as little as one and one half hours to three or four hours depending on the application. Oxidation catalysts require very little maintenance, do not increase engine fuel use, and do not shorten engine life or adversely affect vehicle drivability. Manufacturers claim that the useful life of the device will vary with the application and can range from 4,000 to 10,000 operating hours.

Although DOCs can be designed or tailored to operate under high sulfur concentrations, lower sulfur fuels improve the devices' particulate reduction efficiency. As a result, some manufacturers recommend a maximum sulfur content of 500 ppm or less to enhance DOC durability and performance. To maximize DOC performance and reduction efficiency, CARB suggests the use of ultra-low sulfur diesel fuels of 15 ppmw.

Emissions - EPA summarized emissions data for 60 heavy-duty diesel two and four stroke engines utilizing DOC technology. The devices achieved particulate emission reductions ranging from 19 to 50 percent, with an average PM reduction of 33 percent. Emission results will vary and retrofit device performance should be verified. To date, EPA has verified PM reductions of 25 percent for three manufacturers of DOCs (http://www.epa.gov/otaq/retrofit/retroverifiedlist.htm).

Cost - CARB reported DOC costs ranging from $2,100 for a 275 hp engine to as much as $20,000 for a 1,400 hp engine. The Manufacturers of Emissions Controls Association (MECA) reports DOC costs of $425 to $1,150 per device. The Everett School District, located in Everett, Washington, is currently paying $2,500 per DOC for school bus retrofits.

Use - Over 250,000 off-road engines have been retrofitted with DOCs. In addition, over 20,000 DOCs have been installed on school buses, transit buses and highway trucks in the U.S. and Europe. Locally, Everett School District is retrofitting six buses with oxidation catalysts.

Diesel particulate traps

These devices generally consist of a wall-flow type filter positioned in the exhaust stream of a diesel vehicle. As the exhaust gases pass through the system, particulate emissions are collected and stored. The stored particulates are either actively removed (oxidized) by an external thermal source, or passively removed using a catalytic reaction which "regenerates" the filter.

Diesel particulate filters (DPFs) are heavier and larger in diameter than a muffler, so modifications to the exhaust system may be required during installation. Installation can take from a couple of hours to a full day depending on the application. DPF applications are limited by certain equipment and operational constraints. In general, engines built prior to the 1994 emission standards of 0.1g/bhp-hr PM exhibit excessive PM emissions for DPF applications to work effectively.

DPFs are also sensitive to exhaust gas temperatures and fuel sulfur content. For most continuously regenerating catalyzed particulate filters to work properly, an engine must operate at around 300 degrees C for 30 percent of the duty cycle. Engine datalogging may be required for certain applications to ensure that a satisfactory temperature regime is achieved. High fuel sulfur content also affects the performance and durability of DPFs. Manufacturers recommend a maximum sulfur content of 50 ppmw. CARB requires a maximum sulfur content of 15-ppmw to ensure filter performance and durability.

Emissions - The California Air Resources Board reports PM emission reductions of 85 to 97 percent for various types of catalyzed diesel particulate filters. EPA reports conservative estimates of 80 percent PM reductions for base metal catalyzed particulate filters, and more than 90 percent PM reductions for precious metal catalyzed particulate filters.

Cost - The Manufacturers of Emission Controls Association (MECA) estimates the cost of catalyzed diesel particulate filters at $3,300 to $5,000. The City of Seattle estimated an installed cost of $7,500 per DPF application. CARB estimates installation costs of $167 to $518, and annual maintenance costs of $156 to $312.

Users - Over 50,000 DPFs have been retrofitted to heavy duty diesel vehicles worldwide. EPA is anticipating more than 100,000 engine retrofits to be completed by the end of 2002, the majority of which will be refitted with DPFs.

Ultra-low sulfur fuel (ULSD)

In May 2000, EPA proposed new, stringent standards designed to reduce emissions from heavy-duty trucks and buses. A key part of the proposal includes capping diesel fuel sulfur levels at 15 ppmw beginning June 1, 2006 for all highway vehicles. Reducing the sulfur content of diesel fuels provides a direct fuel-related PM reduction. More important, ultra-low sulfur fuel allows the use of emission control technologies which have been proven effective in controlling PM emissions.

In Washington State, diesel fuel sold for on-road use averages about 350 ppmw. Ultra-low sulfur fuel (ULSD, <15 ppmw) is available in Washington, and can be purchased through the Phillips Petroleum refinery located in Ferndale. Additional handling will be required when using low sulfur fuel, as ULSD will need to be kept separate from conventional diesel fuels to prevent blending and/or contamination. Users of ULSD will also need to track fuel lubricity to ensure it meets engine manufacturers' specifications.

Emissions - ULSD emission benefits will vary with the application. An EPA on-road emission model predicts that reducing sulfur content from 141 ppmw to 15 ppmw would reduce diesel PM emissions by about four percent. According to CARB, a reduction in fuel sulfur from 500 ppmw to five ppmw would result in about a 16 percent reduction for similarly designed engines.

The primary emission benefit of using ULSD is that it improves the performance of after-treatment equipment. The U.S. Department of Energy found that at three ppmw sulfur fuel, the particulate filters tested achieved PM reductions of 95 percent. This dropped to 72 percent PM removal with 30 ppmw sulfur fuel, and near zero with 150 ppmw sulfur fuel. Higher sulfur fuels will also damage particulate trap filters.

Cost - EPA estimates that the overall cost associated with lowering the sulfur cap from 500 ppmw to 15 ppmw would be approximately three to four cents. Locally, ultra-low sulfur diesel fuel costs about eight cents per gallon more than conventional diesel. Because the fuel is handled separately, transportation costs currently add another six to seven cents per gallon, raising the overall cost of ultra-low sulfur diesel to about 15 cents per gallon.

Users - Ultra-low sulfur diesel fuel has been in use in both the U.S and Europe for a number of years, and will be mandated in the U.S. starting in 2006. ULSD is available in Washington from the Phillips Petroleum refinery located in Ferndale.

Biodiesel

Biodiesel is a mono-alkyl ester based oxygenated fuel that is commonly produced from oilseed plants such as soybean or canola, or from recycled vegetable oils. It is a domestically produced, renewable motor fuel that is non-toxic and biodegradable and can be blended with petroleum diesel fuel at any ratio. The most common blend rate is 20 percent biodiesel, 80 percent petroleum diesel. This mixture is referred to as "B20." Pure or neat biodiesel is termed B100. Biodiesel is registered as a fuel and fuel additive with EPA and has passed EPA's Tier 1 Health Effects Testing under Clean Air Act section 211(b).

The American Society of Testing and Materials recently issued a new specification for biodiesel fuel. Specification D 6751 applies to all biodiesel bought and sold in the U.S and ensures that biodiesel meets specific quality standards. Handling of biodiesel is similar to petroleum diesel fuels, with some notable differences. Because of its inherent solvent properties, material compatibility issues may exist when using biodiesel fuel. A guidebook entitled "Biodiesel Handling and Use Guidelines" covers these and other issues in detail and is available from the U.S. Department of Energy at http://www.afdc.doe.gov/altfuel/bio_papers.html.

Emissions - Biodiesel fuel exhibits lower PM, CO, and HC emissions than petroleum diesel, but increases NOx emissions. CARB reports that B100 and B20 reduce PM emissions by 30 percent and 22 percent, respectively, when compared to conventional diesel fuel. The National Biodiesel Board indicates similar emission benefits, and reports PM reductions of 40 percent for B100 and eight percent for B20.

Cost - Nationally, B20 costs about 15 to 30 cents above the cost of diesel (DOE). B100 costs about 50 cents to one dollar more than conventional diesel fuel. Price will vary locally due to production, transportation and distribution costs, and on the volume of fuel purchased. Lilyblad Petroleum, located in Tacoma, Washington, recently quoted an ex-tax bulk purchase price of $1.60 per gallon of B100 fuel.

Use - Biodiesel is being marketed across the country and in Washington State. Biodiesel users in Washington include the cities of Tacoma and Seattle, and Mt. Rainier National Park.

4.2 Marine Engines

A 1999 inventory study by the Puget Sound Clean Air Agency estimated that tugboats operating in King, Pierce, Snohomish and Kitsap counties consume approximately 52.5 million gallons of fuel per year, and account for as much as seven percent of the NOx generated in the four-county region. In total, commercial marine vessels (tugboats, ferries, ships, military and fishing) operating in the four-county area were estimated to consume about 111.6 million gallons of fuel per year. While PM emissions were not determined as part of this study, the large quantity of fuel consumed by commercial marine vessels would indicate that they are a significant contributor to regional PM emissions.

New engine standards

Until recently, marine engines did not need to meet strict emission standards. In 1997, the International Marine Organization (IMO) adopted pollution standards for ships, referred to as MARPOL Annex VI. The IMO set NOx emission limits for marine diesel engines, but did not set emission standards for PM. In 1999, the EPA set emission standards for new commercial marine diesel engines at or above 37 kilowatts (kW). The standards for small and medium-duty marine engines are based on similar standards adopted for non-road engines (40 CFR Part 89). These standards are referred to as Tier 2 and set a maximum PM emission limit of 0.20 g/kwh (kilowatt-hr) for smaller engines, up to 0.50 g/kwh for large engines below 30 liters per cylinder (see Table 1). EPA is currently setting standards for "Category 3" engines which are used in large ocean going vessels. These standards apply to engines at or above 30 liters per cylinder and should be finalized by January 2003.

Table 1
EPA Marine Engine Emission Standards

Category	Displacement (liters/cylinder)	Start date	NOx + HC (g/kW-hr)	PM (g/kW-hr)	CO (g/kW-hr)
1	power ≥ 37 kW disp. <0.9	2005	7.5	0.40	5.0
1	0.9 ≤ disp. < 1.2	2004	7.2	0.3	5.0
1	1.2 ≤ disp. < 2.5	2004	7.2	0.2	5.0
1	2.5 ≤ disp. < 5.0	2007	7.2	0.2	5.0
2	5.0 ≤ disp < 15	2007	7.8	0.27	5.0
2	15 ≤ disp < 20 and, power < 3300kw	2007	8.7	0.5	5.0
2	15 ≤ disp < 20 and, power ≥ 3300kw	2007	9.8	0.5	5.0
2	20 ≤ disp < 25	2007	9.8	0.5	5.0
2	25 ≤ disp < 30	2007	11.0	0.5	5.0

Retrofits/re-powering

Over 100 marine vessels have been qualified under California's Carl Moyer Program to reduce NOx and PM emissions. The vast majority of these projects have involved replacing older two-stroke diesel engines with newer, electronically controlled diesel engines. A few project sponsors, like the Water Transit Authority in San Francisco, have looked at fuel switching or at adding after-treatment equipment, but re-powering appears to be the focus of most Carl Moyer marine projects.

In a July 2002 study completed by CALSTART, marine emission control options for passenger ferries serving San Francisco Bay were examined. The study assumes that all existing engines are EPA Tier 2 compliant. The study then looked at six emission control options for the ferries including humid air motor, injection timing delay, catalyst-based diesel particulate filter (CF), selective catalytic reduction (SCR), SCR and CF, and natural gas. The options examined were primarily focused on NOx reductions, but include PM savings as well.

A humid air motor (HAM) is basically a device that adds water to the intake air in order to cool it. This increases air density and lowers the charge-air temperature, resulting in lower NOx emissions. While fairly easy to implement, it can cause corrosion of engine parts, and smoke and PM emissions typically increase. Injection timing delay (ITD) is a fairly simple control strategy that reduces the pressure at auto-ignition by retarding the timing of fuel injection. This lowers the peak flame temperature and reduces NOx, but can also increase fuel consumption and PM emissions. Catalyzed diesel particulate filters (CF) have been shown effective in land based applications for controlling PM, but are only just being examined for marine applications. Selective catalytic reduction is a post-combustion strategy that uses ammonia or urea as a reducing agent for NOx over a precious metal catalyst. SCR technology imposes space and weight requirements but can be used with high sulfur fuels and achieves significant NOx reductions and lower PM emissions.

A summary of the emission control options is presented in Table 2. In general, the study concluded that "although none of the low-emission technologies examined in this study are commercially available in the U.S. for ferries, all of them are currently in use in other transportation modes and no serious impediments to commercialization currently exist."

Table 2
Emission Control Options

Action	PM emission reductions	Capital cost ($/kW)	Operating cost (non-fuel, $/kW-yr)	Fuel penalty
HAM	-1%	32	1	3%
ITD	+11%	0	1	4%
CF	-90%	20	18	1%
SCR	-40%	71	20	2%
SCR&CF	-94%	91	38	3%
Natural gas	-90%	165-202	0	NA

Source: *Passenger Ferries, Air Quality, and Greenhouse Gases: Can System Expansion Result in Fewer Emissions in the San* Francisco Bay Area, CALSTART, July, 23, 2002.

CARB recently completed a matrix of emission control technologies for ocean-going marine vessels. The matrix is in draft form and CARB requests that it not be cited at this time. However, it can be accessed at http://www.arb.ca.gov/msprog/offroad/marinevess/documents/matrix.pdf.

Fuels

Because of the high volume of fuel consumed, commercial marine businesses often arrange deals with local refiners to produce tailored marine fuels specific to their application. Often these fuels involve less refining (leaving more sulfur in the fuel) and are lower cost than other diesel fuels. While commercial marine engines may use either distillate fuel, residual fuel, or a mixture of these fuels, a 1999 EPA study found that the most common fuel consumed by tugboats, ferries, and fishing boats is marine distillate fuel A, or DMA.

The ASTM specification for DMA requires a sulfur content not to exceed 1.5 percent by mass, or 15,000 ppmw. By comparison, on-road diesel has a maximum sulfur content of 0.05 percent or 500 ppmw. In Washington State, on-road diesel has a typical sulfur content of 350 ppmw. In their study, EPA tested over 195 samples of DMA collected from 27 U.S. ports. The average sulfur content for DMA was reported to be 0.36 percent, or 3,600 ppmw, and ranged as high as 1.66 percent sulfur.

The use of low sulfur diesel fuels or alternative diesel fuels offers an opportunity for reducing PM emissions from commercial marine engines. Unlike marine engine retrofits or re-powering (both of which can require detailed analysis and high initial investment costs), low sulfur and alternative diesel fuels can be readily substituted for most marine applications. This, of course, assumes that fuel supply issues can be overcome, including higher fuel costs and fuel availability and distribution issues.

In general, the lower the sulfur content of a fuel, the lower the PM emissions. EPA reported that a reduction in fuel sulfur from 500 ppmw to five ppmw would result in about a 16 percent reduction in PM emissions. A study of fuel sulfur effects completed by the U.S. Department of Energy indicated that diesel engine PM emissions decreased by about 29 percent when going from a 350 ppmw sulfur diesel to a three ppmw sulfur diesel. Similarly, a 1999 study completed by the Manufacturers of Emission Controls Association noted a 14 percent decrease in PM emissions for a 1998 Detroit Diesel Corporation Series 60 engine when operating on 54 ppmw sulfur fuel versus 368 ppmw sulfur fuel.

The potential for PM reductions should be even greater than those cited if current marine diesel fuel consumed in Washington has as high a fuel sulfur content as that reported by EPA for DMA. In addition, low sulfur fuel would allow the use of post combustion control equipment including diesel oxidation catalysts and diesel particulate filters. Ultra-low sulfur diesel (ULSD) costs as much as 15 cents per gallon more than on-road diesel, and would cost even more when compared against marine diesel fuels. Low sulfur, on-road diesel fuel would cost less than ULSD and could also provide significant PM emission benefits if the marine diesel fuel currently used in Washington waters is high in sulfur.

Other fuels are also being explored for marine applications. CARB reports that B100 and B20 reduce PM emissions by 30 percent and 22 percent, respectively, when compared to conventional diesel fuel. The National Biodiesel Board indicates similar emission benefits, and reports PM reductions of 40 percent for B100 and eight percent for B20. The San Francisco Bar Area Water Transit Authority (WTA) recently completed on-board testing of biodiesel in one of their passenger ferries, powered by a Detroit Diesel 12V-7122-7000, 360 horsepower diesel engine. While NOx emissions increased for almost all engine settings, operation on B100 fuel achieved PM emission reductions of between 50 and 60 percent when compared to standard off-road diesel.

The WTA also tested a water emulsion fuel produced by Lubrizol under the name PuriNOx. When operating on PuriNOx fuel, the WTA found that PM was reduced by 42 percent, while opacity was reduced by 75 percent. The Port of Houston also completed testing of PuriNOx fuel in a passenger ferry application. PM reductions for the ferry averaged 80 percent when operating on the PuriNOx fuel as compared to off-road diesel fuel.

Both biodiesel and PuriNOx would cost considerably more than current marine diesel fuels. PuriNOx costs about 15 cents per gallon more than on-road diesel, while biodiesel costs could range from 15 to 20 cents per gallon more for B20, up to one dollar more for B100. The Washington State Ferries is currently planning to run a trial fuels program in January 2003. The Rhododendron ferry, stationed out of Tacoma, will be the platform for the fuels test, which will look at biodiesel blends.

4.3 Locomotives

The U.S. locomotive fleet consists of over 20,000 units. The dominant motive power is diesel-electric, with engines ranging in size from about 2000 hp for switching operations, to 4000 hp engines designed for passenger and line-haul operations. Locomotives have a typical service life of 40 years, and are often overhauled five or more times during this period.

Emission Standards

Three separate sets of federal emission standards have been adopted for locomotives. The first set of standards (Tier 0) applies to locomotives and locomotive engines originally manufactured from 1973 through 2001. The second set of standards (Tier 1) applies to locomotives and locomotive engines originally manufactured from 2002 through 2004. The final set of standards (Tier 2) applies to locomotives and locomotive engines originally manufactured in 2005 and later. In all cases, locomotives and locomotive engines will be required to meet the applicable standards at the time of original manufacture and at each subsequent remanufacture. In addition to the exhaust emission standards, this final rule establishes smoke opacity standards for all locomotives and locomotive engines. Because of their small number, locomotives manufactured before 1973 are exempt.

Exhaust Emission Standards for Locomotives				
	Gaseous and Particulate Emissions (g/bhp-hr)			
Tier and duty-cycle	HC	CO	NOx	PM
Tier 0 line-haul duty-cycle	1.00	5.0	9.5	0.60
Tier 0 switch duty-cycle	2.10	8.0	14.0	0.72
Tier 1 line-haul duty-cycle	0.55	2.2	7.4	0.45
Tier 1 switch duty-cycle	1.20	2.5	11.0	0.54
Tier 2 line-haul duty-cycle	0.30	1.5	5.5	0.20
Tier 2 switch duty-cycle	0.60	2.4	8.1	0.24

PM control measures

A unique feature of the locomotive program is that it includes emission standards for remanufactured engines, including all those that were originally built since 1973. Regulation of the remanufacturing process is critical because locomotives are generally remanufactured five to 10 times during their total service lives, which is typically 40 years or more. As a result, there exists a built-in mechanism for improving locomotive emissions from existing stock.

Significant efforts are underway to improve the emissions of new locomotive engines. Much of this activity is focused on improvements in fuel injector pressure, injection timing, injection nozzles, aftercooling, and changes in combustion chamber designs. There is also interest in converting locomotives to alternative fuels, including liquefied natural gas (LNG) and hybrid operations. In California, LNG rail operations are an option currently being developed in parts of the state for NOx and PM control. A local company, Energy Conversions Inc of Fife, WA, has developed a dual fuel, natural gas locomotive engine which has been used by Burlington Northern for line haul operations.

RailPower Technologies Corp, of Vancouver, Canada, is working with Union Pacific to demonstrate a hybrid, battery powered locomotive used for switching operations. Called the "Green Goat," the locomotive uses energy stored in a bank of lead-acid batteries to power its traction motors and a small 100 hp motor keeps the batteries charged. The Green Goat could reduce fuel consumption by 30 percent over traditional switchers and reduce particulate emissions by as much as 85 percent. Results of the demonstration program should be available by late 2003.

Locomotive emission improvements could also result from the use of low sulfur diesel fuel. Southwest Research Institute recently evaluated exhaust emissions from six late-model locomotive engines using diesel fuels of varying sulfur content. (2) Two types of locomotives were evaluated: three 4,000 hp, General Motors EMD SD70MAC locomotives and three 4,400 hp General Electric DASH9-44CW locomotives. These engines were operated on CARB diesel, on-highway diesel with a sulfur level of 330 ppm, and two high-sulfur nonroad fuels measuring 4,760 ppm and 3,190 ppm sulfur, respectively. The latter, lower sulfur nonroad fuel better represents locomotive fuels used in California.

For the three EMD locomotives, the CARB fuel reduced composite PM emissions by an average of three percent from levels for on-highway diesel, and by an average of 16 percent from levels for the high sulfur fuel containing 4,760 ppm sulfur. PM emissions were reduced by 13 percent between the on-highway diesel and the high sulfur fuel. In the GE locomotives, using CARB fuel also reduced the composite PM emissions by an average of three percent compared to on-highway diesel, and by an average of 39 percent compared to the 4,760 ppm sulfur nonroad fuel. PM emissions were reduced by 38 percent between on-highway diesel and the 4,760 ppm sulfur fuel. When using the 3,190 ppm sulfur fuel, PM emissions were reduced by 27 and 25 percent respectively, when compared to CARB diesel and on-highway diesel.

Reducing locomotive idling presents another opportunity for controlling PM emissions. Tests conducted by the Southwest Research Institute (SwRI) determined that locomotives can significantly reduce exhaust emissions by using an auxiliary power unit (APU) to power on-board electrical and environmental systems instead of continuously idling the locomotive's main engine. (3) SwRI monitored switcher locomotive operations over a period of year and found that switcher locomotives typically idle about 60 percent of their operational time. Besides idling to maintain onboard power and heating and cooling requirements, engine idling also occurred to avoid the difficulties associated with cold-engine startup.

SwRI estimates that the use of an APU could produce an 84 percent reduction in PM emissions when compared to main-engine idle emissions. Stand-by or idling emissions from locomotives average about 33 grams per hour of particulate matter. APU operations also reduce other criteria pollutants, as well as provide an 83 percent reduction in fuel consumption during idle. This is equivalent to a savings of approximately 15,600 gallons of fuel per year, or about $12,000.

The locomotive industry is also beginning to examine the use of particulate filters for controlling particulate emissions. In California, demonstration projects examining the feasibility of particulate traps for switcher applications are underway, with results available in late 2004. Issues surrounding the demonstration project include space constraints for diesel particulate filter (DPF) placement and whether engine duty cycles will support DPF use. Because of the high idle time of these engines, excessive exhaust loading of the filter is also a concern. However, unlike over the road applications, locomotives have ancillary electrical energy available during normal operations which could power an active filter regeneration system.

References

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2. Steven Fritz, *Diesel Fuel Effects on Locomotive Exhaust Emissions,* SWRI, October, 2000.
3. Personal Communication, Steven Fritz, Southwest Research Institute, March 13, 2003.

4.4 Construction Equipment

According to the Manufacturers of Emission Control Association, off-road construction equipment has over 20 years of experience with diesel oxidation catalysts (DOCs), with over 250,000 off-road engines retrofitted. The underground mining industry is one of the leading industries employing diesel emission controls. In a 1999 report, the industry concluded that DOCs are effective at reducing PM and toxic diesel emissions from underground mining equipment. The report further states that diesel particulate filters (DPFs) were first commercialized in underground mines, and that DPFs have been successfully used in targeted engine applications where exhaust gas temperatures were sufficiently high over a sustained period to complete filter regeneration.

The Big Dig project in Massachusetts has retrofitted over 120 pieces of construction equipment with emission controls. Oxidation catalyst retrofits are currently the “control system of choice,” although some diesel particulate filters are being utilized. Some of the reasons cited for choosing DOCs are: lower costs, no significant power losses, no additional operation and maintenance costs, and the ability to use conventional on-road diesel fuels. The Big Dig project is also using idling restrictions to minimize emissions and public exposure.

The Engine Manufacturers Association recently issued a joint report with the European Association of Internal Combustion Engines Association. The report investigated the feasibility of DPFs for non-road equipment and concluded that catalyzed diesel particulate filters do not meet the unique demands of off-road engines, and instead suggests the need for active DPF technology. Taking a contrary position, the Swiss government has tested and approved a number of particulate trap systems for retrofitting off-road diesel engines. They report over 50,000 successful DPF applications for off-road equipment.

Fuel switching is also being considered for off-road applications. Beyond the use of low sulfur diesel fuels, off-road applications have used or are using biodiesel fuels and water emulsion diesel fuels. The state of Texas is particularly interested in the latter fuel, and has over 500 pieces of equipment operating on PuriNOx at this time. A summary of PM reduction measures is presented on the following pages.

Measure	PM reductions	Cost	Issues
Idling restrictions • Turn off diesel construction equipment not in active use and dump trucks that are idling for 5 minutes or more. • Establish a staging zone for trucks that are waiting to load/unload to minimize public exposure to emissions. • Restrict morning warm-ups to 3-5 minutes (check w/manufacturer) • Locate equipment away from sensitive receptors such as fresh air intakes to buildings.	Up to 2.52 g PM per hour of idling	No capital costs, may be some operational costs due to scheduling and staging.	One gallon of diesel fuel is consumed for every hour of idling.
Diesel Oxidation Catalysts (DOC)	25-50% reduction	$1500-$3000 or more.	Long history of use in construction and mining industries. Does not require low sulfur fuels. Works well with older, high-emitting engines.
Diesel Particulate Filters (DPF)	85%-97% reduction	$3300-$15,000	Requires low sulfur fuels of less than 50 ppmw sulfur-performs best with ULSD. Not suitable for engines older than 1993. Some construction equipment has unique duty cycles and lower exhaust temperatures which may prevent DPF regeneration. The Engine Manufacturers Association position is that passive particulate filters are not yet suitable for most off-road applications.

Measure	PM reductions	Cost	Issues
Ultra-low sulfur fuel (15 ppmw sulfur content)	4%-16% reduction	$0.05-$0.15 per gallon	Available in Washington through Phillips Petroleum. Necessary for DPF operations.
Biodiesel	B100: 30%-40% reduction B20: 8%-22% reduction	B100: $0.50-$1.00/gallon over diesel. B20: $0.15-$0.30 over diesel	Available in Washington. Some material compatibility issues. Does not require engine retrofit. Has demonstrated use in construction applications, particularly in sensitive riparian areas.
PuriNOx	Up to 62% reduction in PM	$0.15-$0.20 above standard diesel	Works well in construction applications. Does not require engine retrofits. Sole source fuel purchase as only one producer. Up to 20% power loss.
Natural gas	>90% PM reduction compared to conventional diesel. Comparable PM emissions to new generation diesels w/ULSD and DPFs.	No engine development in this area.	New purchase. Needs access to NG refueling station. Construction equipment is not a target market for natural gas engine development.
Hybrid Electric	50% PM reduction	$95,000 or more for bus application.	Construction equipment is not a target market for hybrid development at this time

4.5 Agricultural Equipment

A 1997 census of Washington State agriculture estimates that there are more than 54,800 wheeled tractors operating on Washington farms. (1) About 33,180 tractors are powered by 40 horsepower (hp) or larger engines, with about 25,230 of these engines rated at 40 to 99 hp, and approximately 7,950 tractors powered by 100 hp or larger engines. The majority of these tractors, or about 47,860, were manufactured prior to 1993, with the balance of 6,975 tractors manufactured between 1993 through 1997. In addition to wheeled tractors, the census estimated Washington farm equipment included an additional 5,450 grain and bean combines, 8,173 mower conditioners, and 7,892 pickup bailers. Again, the majority of this equipment was estimated to be more than five years old.

While the Washington census did not differentiate equipment by fuel type, nationally, about two-thirds of farm equipment is diesel powered. In addition to mobile farm equipment, many farms also operate irrigation pumps. California estimates that farm tractors and irrigation pumps are responsible for 97 percent of all agricultural PM emissions. For Washington State, irrigation pumping is not as significant a source of agricultural PM emissions as in California, due to the large federal hydroelectric/irrigation projects operating in this state.

PM Control Measures

Like all off-road engines, new agricultural equipment must meet new federal or state of California nonroad emission standards. However, existing agricultural equipment is only just coming under review for PM control. Most of this activity is occurring in California, which has recently begun to target irrigation pumps and tractors for NOx and PM emission control. To date, California control efforts have focused only on new engine replacement for tractors, and engine replacement and some limited fuel switching for irrigation pumps.

New engine replacement: While California's programs are mainly directed at curbing NOx emissions, PM emission reductions are also recognized. The primary strategy for improving existing irrigation and tractor emissions is to replace existing uncertified engines built prior to 1996 with new, off-road emission certified diesel engines. In the Sacramento area, irrigation pump replacements are averaging around $7,000 to $12,000 for a 100-150 hp pump, and PM savings are estimated at 25 percent or more. (2) For tractors, engine replacement costs are around $25,000 to $30,000, with similar PM benefits expected.

While not yet available, repowering of existing agricultural engines may also be a future option. Both Caterpillar and Cummins off-road engine divisions are focusing efforts on remanufacturing or reconditioning uncertified engines to meet Tier 1 standards. (3) Once verified, it is expected that these engines would also qualify for California incentive programs.

Fuel switching: For irrigation pumps, fuel switching is an option for improving emissions. Ideally, switching to electricity is an excellent emission control measure. However, the expense of stringing power lines coupled with high California electricity costs has limited this option. Instead, switching out pumps to propane operations has gained some interest in California, but there is little available information on the costs or benefits of this measure to date.

Substituting low sulfur diesel for off-road diesel is also an option for controlling agricultural PM emissions. While this measure is not being used in California since it does not provide NOx benefits, it could represent a possible option in Washington. Diesel fuel sold for use in nonroad equipment is currently unregulated by EPA and can reach sulfur levels of 3,000 to 5,000 ppm. As previously discussed, low sulfur fuel can provide direct PM emissions benefits. How much benefit would depend on the average sulfur content of fuel currently used by Washington’s agricultural sector, and the sulfur content of the replacement fuel. It is likely that for reasons of convenience and availability, many agricultural equipment users may already operate their equipment using on-road diesel. In those cases, the PM savings from a lower sulfur fuel would be reduced.

Biodiesel is also a possible PM control option for agricultural applications. Substituting a 20 percent biodiesel blend for diesel can provide PM reductions of 10 percent or more. While the cost of retail biodiesel currently limits its viability for on-farm use, there is a growing interest by Washington’s agricultural community in developing an oil seed industry. If this market develops locally, the cost and availability of biodiesel for powering farm equipment becomes more attractive and could represent a viable option for PM control.

Retrofit control devices: In California, retrofitting existing agricultural equipment with diesel oxidation catalysts or particulate filter technologies is not being done at this time. The agricultural sector has only just started to receive attention from California regulators and the focus is on replacing older engines with newly certified engines.

There is also some concern that the typical agricultural equipment duty cycle, which is characterized as low speed, low exhaust temperatures and significant idle time, does not meet the ideal operational profile of retrofit devices. While it is expected that diesel oxidation catalysts should work with most agricultural applications, agricultural equipment duty cycles may not be compatible with the use of passive, diesel particulate filter devices. In addition, the lack of ultra-low sulfur fuels for agricultural use also inhibits the introduction of particulate filter technologies in this sector.

The use of retrofit control devices and an understanding of where they work best in an agricultural setting should increase as California begins to develop new non-road rules in its upcoming SIP. Until then, there does not appear to be much activity in this area. Citing zero market demand for agricultural equipment retrofits, at least one device manufacturer confirmed this trend and is focusing commercialization efforts on other larger and more numerous on-road and non-road applications.

References

1. *1997 Census of Agriculture-Washington State and County Data*, Volume 1, Part 47, U.S. Department of Agriculture, March, 1999.
2. Personal Communication, Tom Swenson, Sacramento Air Quality Management District, March 18, 2003.
3. Personal Communication, Jackie Laurenco, California Air resources Board, March, 31, 2003.

4.6 Logging Equipment

There are 2,796 logging trucks registered in Washington State. (1) These trucks operate both in the forests and on the highways, as they transport logs to mills and transshipment sites. In addition to logging trucks, there are a number of off-road vehicles that operate primarily in the forests. These include conventional, heavy duty dump trucks and bulldozers, as well as more specialized equipment such as loaders and skidders. Loaders are similar to excavators, with a log grapple replacing a bucket on the boom. This equipment is used to load logs both in the forest and in log yards, and is either tracked or mounted on rubber tires. Skidders are unique to logging operations. They are articulated in the middle to allow for steering through logged areas and are mounted on rubber tires. Skidders are used to haul logs out of a cut, are equipped with a log grapple, blade or winch and are powered by a 100 to 175 hp diesel engine.

PM Control Measures

Logging trucks are Class 8 trucks. (2) They are often powered by 400 to 500 horsepower diesel engines, and in limited cases may be equipped with a self-loading boom. Because of the off road demands placed on these trucks, some of the mechanical equipment, in particular the drive train and braking system, may be more robust than that of an on-road truck. (2)

PM control measures that have been demonstrated for over-the-road, Class 8 trucks should work for logging trucks. However, because logging trucks have unique operational requirements, the experiences gained from on-road Class 8 truck projects may not be directly transferable. In a literature review of retrofit projects and in talking with retrofit device manufacturers, there are no reported retrofits of logging trucks with either oxidation catalysts or diesel particulate filters. Therefore, a demonstration project designed to determine the feasibility of retrofitting these trucks with PM devices, such as DOCs or DPFs, is needed. Issues of concern include potential backpressure problems and filter overloading.

There is also no reported use of diesel oxidation devices or particulate filters with off-road logging equipment. While some of this equipment is unique to logging, experiences gained from other off-road applications such as the Big Dig project, should provide direction. Even so, logging equipment and operations are sufficiently different from construction projects that retrofit technologies should be demonstrated prior to wide-scale use.

As with other on-road and off-road applications, the use of low sulfur fuels in logging equipment could provide some PM benefits. However, many of these logging sites are isolated and there may be practical difficulties in maintaining a low sulfur diesel supply. Similarly, biodiesel or diesel emulsions could also provide PM reductions, but face the same fuel supply issues as low sulfur diesel. Logging trucks, which consume the majority of their fuel while traveling on paved roads, should not face the same fuel supply constraints and could be more amenable to the use of these fuels. Other alternative fuel technologies, such as natural gas or hybrid electric diesel, have not been looked at for logging equipment.

Logging trucks may also queue up during off-loading of logs. This may occur in port areas where idling is an unwelcome source of emissions. Anti-idling regulations, similar to those adopted by some construction projects, may be an appropriate and beneficial control measure in those instances.

References

1. Personal Communication, Washington State Department of Licensing, March 3, 2003.
2. Personal Communication, Paccar, March 4, 2003.

4.7 Commercial and Industrial Equipment

Commercial and industrial equipment cover a wide variety of applications, including stationary engines for power generation or as prime movers, loading equipment such as forklifts, airport ground support equipment, transport refrigeration units, and a host of other equipment designed for specific tasks. For many of these applications, diesel engines are dominant and are a contributing factor to PM emissions.

<u>PM Control Measures</u>

Stationary diesel fueled engines are used for power generation and as prime movers for driving commercial or industrial processes. In a December 2001 study commissioned by the California Energy Commission, five out of a total of 13 emission control technologies investigated were chosen for back-up generator applications. (1) The control measures were selected based on a number of criteria, including emission reduction potential and cost-effectiveness. The approved technologies included water emulsion diesel fuels, ultra-low sulfur diesel, diesel particulate filters, oxidation catalysts and selective catalytic reduction.

Because operating hours for standby generators are low, the cost per ton for PM control is significantly higher than for applications with longer operating times. Given this situation, the water emulsion and ultra-low sulfur diesel fuels were identified as the most cost-effective PM control measures examined, offering expected PM reductions of 25 to 63 percent for water emulsion diesels, and 10 percent for ultra-low sulfur diesel. Of the retrofit technologies examined, diesel particulate filters were expected to achieve 85 to 90 percent PM reductions, with oxidation catalysts providing 20 to 50 percent lower PM emissions. While the retrofit technologies were considered viable control measures, the study concluded that their higher costs made them somewhat less cost-effective than the fuels approach. However, the study also noted that a particular drawback of water emulsion fuels is the five to 15 percent power loss associated with their use.

Specialized vehicles, such as forklifts and airport ground support equipment, are also considered commercial and industrial equipment. More and more, indoor air quality issues are forcing operators of indoor powered equipment, like forklifts, to look at air quality control measures, particularly alternative fuels. Propane, compressed natural gas (CNG) and electricity are all viable fuels for powering forklifts, with compressed natural gas and electricity providing the best emissions profile. Because many of these applications operate long hours, the payback for alternative fuel forklift conversions are often two to three years or less. For example, the freight company USF Reddaway, of Clackamas, Oregon, recently converted 24 forklifts and 17 yard spotters to CNG operations. (2) For an investment cost of $320,000, USF estimated a first year savings of nearly $130,000 in fuel and refueling labor costs.

Airport ground support equipment is used to transport freight, to support maintenance and repair functions, and to provide power to various service functions. This equipment includes tugs for airplane hook-up and pushback, air conditioning tugs that provide power to the aircraft, forklifts and lifts, belts and container loaders and other equipment. In response to air quality requirements, most of the major airports including Dallas-Fort Worth, Chicago O'Hare, New York JFK and Altanta-Harstfield, are converting ground support equipment to either CNG or electricity. For electricity, on-site PM reductions are 100 percent. CNG particulate matter emissions are also substantially reduced when compared to diesel, but less than that achieved by electric powered equipment. Locally, the Seattle-Tacoma International airport is also converting part of their vehicle fleet to CNG, but has not yet extended the program to their ground support equipment.

References

1. California Energy Commission, *Emission Reduction Technology Assessment for Diesel Backup Generators in California*, prepared by Arthur D. Little, P500-01-128, December, 2001.
2. Oregon Office of Energy, Case Study: Natural-gas Vehicles at USF Reddaway Reduce Emissions, Costs and Accidents, September, 2000.