

Appendix B. Diesel Engine Emission Control Technologies

A variety of strategies exist for controlling emissions from diesel engines. In developing the Procedure, staff has striven to acknowledge the range of control strategies, and intends for the Procedure to be flexible enough to accommodate all such strategies. The following discussion briefly reviews the more prominent diesel emission control strategies thus far identified and, where appropriate, indicates how the Procedure addresses them.

B.1 Diesel Oxidation Catalyst

A diesel oxidation catalyst (DOC) converts pollutants into harmless gases by means of oxidation. In addition to oxidizing compounds such as carbon monoxide (CO) and gaseous hydrocarbons (HC), oxidation catalysts can reduce the mass of the liquid-phase HCs (unburned fuel and oil) by 90 percent under certain operating conditions. The liquid HCs, or soluble organic fraction (SOF), contribute up to 30 percent of the total PM mass.

There are some potential adverse environmental impacts of DOCs. First, as is the case with most processes that incorporate catalytic oxidation, the formation of sulfates increases at higher temperatures. Depending on the exhaust temperature and sulfur content of the fuel, the increase in sulfate particles may offset the reductions in SOF emissions. Using low sulfur (15 parts per million) diesel fuel can minimize this effect.

Additionally, DOCs and other strategies that involve catalytic action (e.g., passive diesel particulate filters -- see below) can increase the proportion of NO₂ relative to NO, even though total NO_x emissions do not increase. As described in the body of the report, there are concerns with an increase in NO₂, and the proposal includes a limit on NO₂ emissions.

Generally speaking, catalysis can potentially generate other harmful chemical species besides sulfates and NO₂. It was found in a Southwest Research Institute study, for instance, that a DOC significantly increased the nitro-polyaromatic hydrocarbons (nPAH) in diesel exhaust (Pan, 2000). A study by the New York State Department of Environmental Conservation indicates, however, that passive catalyzed DPFs can effectively reduce nPAH emissions (Lanni, 2001). The procedure recognizes the general problem of secondary emissions by allowing for ARB to request additional exhaust analysis beyond criteria pollutant and PM emission measurements, should there be reason for concern.

B.2 Diesel Particulate Filters

In general, a diesel particulate filter (DPF) consists of a porous substrate that permits gases in the exhaust to pass through but traps the PM. DPFs are very efficient in reducing PM emissions; they can typically achieve PM reductions in excess of 90

percent. Most DPFs employ some means to periodically regenerate the filter (i.e., burn off the accumulated PM). These can be divided into two types of systems, passive and active.

B.2.1 Passive Diesel Particulate Filters

A passive DPF is one in which a catalytic material, typically a platinum group metal, is applied to the substrate. The catalyst lowers the temperature at which trapped PM will oxidize to temperatures periodically reached in diesel exhaust. No additional source of energy is required for regeneration, hence the term “passive”.

Field experience has indicated that the success or failure of a passive DPF is primarily determined by the average exhaust temperature at the filter’s inlet and the rate of PM generated by the engine. These two quantities, however, are determined by a host of factors pertaining to both the details of the application and the state and type of engine being employed. As a result, the technical information that is readily accessible can sometimes serve as a guide, but may be insufficient to determine whether a passive DPF will be successful in a given application.

The PM emission level that an engine was initially certified to, for instance, is based on PM generated and measured over a single prescribed test cycle. Testing done by West Virginia University, however, shows that a given diesel truck can generate a wide range of PM emission levels depending on the test cycle chosen (Nine, et al, 2000). How well an engine has been maintained is another factor in determining the actual PM emission rate. The ARB’s informational package for its heavy-duty vehicle inspection programs lists sixteen different common causes of high smoke levels that are related to engine maintenance (ARB, 1999).

With regard to estimating average exhaust temperature in actual use, commonly documented engine characteristics such as the exhaust temperature at peak power and peak torque are insufficient. The exhaust temperature at the DPF’s inlet is highly application dependent, in that the particular duty cycle experienced plays a prominent role, as do heat losses in the exhaust system. Very vehicle-specific characteristics enter the heat loss equation, such as the length of piping exhaust must travel through before it reaches the DPF. Lower average exhaust temperatures can also be the result of operating vehicles with engines that are oversized for the application, as one DPF manufacturer has pointed out.

Time and resource requirements aside, the only way to have “foolproof” verification is therefore to evaluate a passive DPF on each individual vehicle in its own specific application. Of course, such an approach is more time-consuming and resource-intensive than is practical. That responsibility must be left to the emission control system suppliers and their customers. Staff does not presume that the proposed verification procedure will guarantee success, but rather that it will establish a high level of confidence that a given strategy will give real and durable emission reductions in compatible applications.

Passive DPFs have the intrinsic problem that if they do not match the application well and do not regenerate adequately, they can plug up, causing excessive backpressure on the engine. Excessive backpressure can cause the engine to stall, thereby terminating vehicle operation. To address this concern, the procedure requires that DPFs be installed with backpressure monitors that will alert the operator when the backpressure exceeds some pre-set level. With some insight into the state of the DPF, the operator can avoid potentially costly failures.

Even when regenerating properly, adding a DPF to the exhaust system of a vehicle will increase the backpressure by some amount. If more work is required from the engine to push combusted gases out through the exhaust system, a fuel economy penalty can result. The procedure requires that the manufacturer demonstrate that the backpressure caused by its product is within the engine manufacturer's specified limits, and if it is not, that it will nevertheless not cause any damage to the engine. It is noted in passing that test data received from the two verified passive DPF manufacturers show no discernible fuel economy penalty.

B.2.2 Active Diesel Particulate Filters

Unlike passive DPFs, active DPFs use a source of energy beyond the heat in the exhaust stream itself to help regeneration. Active DPF systems can be regenerated electrically, with fuel burners, with microwaves, or with the aid of additional fuel injection to increase exhaust gas temperature. Some active DPFs induce regeneration automatically on-board the vehicle or equipment when a specified backpressure is reached. Others simply indicate to the operator when regeneration is needed, and require the operator to initiate the regeneration process. Some active systems collect and store diesel PM over the course of a full day or shift and are regenerated at the end of the day or shift with the vehicle or equipment shut off. A number of the smaller filters are removed and regenerated externally at a "regeneration station."

Because they have control over their regeneration and are not dependent on the heat carried in the exhaust, active DPFs have a much broader range of application and a much lower probability of getting plugged than passive DPFs. One result of this is that emission control groups for active systems are most likely larger than those for passive filters, depending on the particular system.

While actively regenerated traps do not generally increase NO₂ emissions as passive DPFs may (unless they include catalysis), special attention needs to be given to active traps during regeneration. Spikes in emissions have been observed to occur during regeneration, prompting European researchers involved with the VERT project to require emission measurements over the regeneration period (Mayer, 2001). ARB's verification procedure incorporates the same requirement.

B.2.3 Ash

Filter technology has been identified by ARB staff as potentially generating a new waste stream. As discussed earlier, DPFs are designed to trap diesel particulate matter (PM) to achieve a net decrease in PM emissions. The carbonaceous component of the PM captured by the filter, which is by far the majority, is burned off when the filter regenerates. Any inorganic components are left behind as ash in the filter and accumulate over time. This ash must be cleaned from the filter periodically and properly disposed of.

Ash Production and Composition

Ash that accumulates within a DPF is comprised of inorganic substances carried along in an engine's exhaust stream. The primary source of ash is the combustion of lubrication oil in the engine. The nature of the inorganic additives present in the oil, therefore, determines the composition of the majority of the ash in a DPF. Other sources of ash include material arising from engine wear (small compared to oil ash) and any inorganic fuel additives that may be used. Not considering fuel additives, the rate of ash accumulation within a DPF is primarily a function of the rate at which an engine burns oil.

Ash collected from a diesel engine using typical lubrication oil and no fuel additives is primarily composed of oxides of the following elements: calcium, zinc, phosphorus, silicon, sulfur, and iron. Zinc is the component of primary concern, because it can be considered a hazardous waste depending on its concentration. In Section 66261.24, Title 22, of the California Code of Regulations, identifies two threshold limits for zinc: 250 mg/l for the Soluble Threshold Limit Concentration and 5,000 mg/kg for the Total Threshold Limit Concentration Value. Any ash with zinc levels above these limits is considered a hazardous waste and should be handled accordingly.

Determination of Hazardous Waste

Applicable hazardous waste laws are found in the California Health and Safety Code, Division 20; California Code of Regulations, Title 22, Division 4.5; and Title 40 of the Code of Federal Regulations. Staff recommends requiring manufacturers to notify consumers if a waste stream from their product is known to be a hazardous waste.

Since actions of the end user can influence the composition of ash and other waste streams, it is also the responsibility of the owner/operator/maintenance provider of the engine using the diesel emission control system to determine if the waste stream is classified as hazardous according to Section 66261.3, Title 22 of the California Code of Regulations. If a waste stream is determined to be hazardous, the hazardous waste generator (as defined in 22 CCR, § 66262.10) must comply with all appropriate County, State and Federal Regulations. This can include application for state and/or federal generator identification numbers, proper handling, storage and management of the hazardous waste stream, and proper disposal and treatment of the hazardous waste stream.

Excluded Recyclable Material

Section 25143.2 of the Health and Safety Code allows for wastes that can be reused or recycled to be treated accordingly. This option might be open to some waste streams, especially those containing precious metals and/or other reclaimable components.

B.3 Fuel Additives

Fuel additives are essentially any substance added to the fuel. Additives can reduce the total mass of particulate matter (PM), with variable effects on CO, NO_x and HC production. Use of some additives alone shows 15 percent to 50 percent mass reductions in PM. The reduction can be as high as 99 percent when used with a DPF. Some additive-based systems reduce polynuclear aromatic hydrocarbons by around 80 percent. Additives can range from less than 10 parts per million (ppm) to greater than 100 ppm in the fuel. Additives can significantly decrease soot combustion temperatures facilitating DPF regeneration. Mixed data exist regarding fuel economy. Some studies show a fuel economy improvement ranging from five to seven percent, while others show an equivalent fuel penalty. Most additives are fairly insensitive to fuel sulfur content and will work with a range of sulfur concentrations as well as different fuels and other fuel additives (HEI, Attachment A; DieselNet, 2000.02b; Mayer, 1999).

An additive added to diesel fuel in order to aid in soot removal in diesel particulate filters by decreasing the ignition temperature of the carbonaceous exhaust is called a fuel borne catalyst (FBC). These can be used in conjunction with both passive and active filter systems. As noted in the body of the report, FBC can improve fuel economy, aid other system's performance, aid other retrofit systems, and decrease mass PM emissions. FBC/diesel particulate filters systems are in wide spread use in Europe in both on-road and off-road, mobile and stationary applications (DieselNet 2000.02b).

The following sections describe properties of some of the more common additives that staff has encountered in its research.

B.3.1 Cerium based additives:

Description: When used with appropriate filters, regeneration tends to be smooth, high local peak temperatures inside the trap do not occur and engine backpressure remains approximately constant. Typical concentrations for Cerium additives can range from around 20 ppm up to 100 ppm. However, at the highest concentrations, there can be some problems with backpressure increases and filter plugging depending on the system and application. Lower level cerium additives tend to avoid this problem provided that periodic trap regeneration occurs. There is evidence supporting the increase of nano-particulate matter (Mayer, 2002). This is related to additive concentration with appreciable increases in nano-particulate formation with higher additive concentrations. For instance, 100 ppm cerium reduces the balance temperature of a trap system from 537-557 °C to 432 °C. Used in conjunction with a filter, PM mass emissions are reduced from 70 to 98 percent and NO_x is either

unchanged or reduced. Use of cerium additives can increase fuel consumption by 4.7 percent in some circumstances (DieselNet 2000.02; Mayer, 1999; Mayer, 1998; Lemaire, 1999; HEI, Attachment A; Mayer, April 1998).

Current Use: Cerium based additives are in wide spread use in Europe and VERT approved when used with DPFs. A cerium based additive is part of Peugeot's new filter based system and, in addition to on-road applications, cerium additives are used off-road in construction and forklift applications (Mayer, 2002; Lemaire, 1999).

Environmental Fate and Transport: Crops can take up cerium. Cerium has affinity for humic substances that may alter its availability in aquatic systems. Current fate and transport studies are limited and may not adequately address long term environmental exposure risks to both humans and other organisms (Molycorp Inc., 1995; HEI, 2001).

Health Risks: Although cerium has low acute toxicity, long term health and environmental effects are less well understood. Inhalation is thought to be the primary method of exposure to cerium from diesel exhaust. However, other routes of entry might include direct contact with the additives and ingestion. The form cerium takes can also influence its biological and environmental fate. Cerium oxide is the primary form found in the exhaust although cerium can also form salts. Oxides and hydroxides of cerium are poorly soluble in body fluids and are slow to clear from the organism. Nitrates, phosphates and chlorides have intermediate solubility and have clearance times up to several weeks. Sulfates and sulfides are easily soluble and clear from an organism within days. Cerium can affect the respiratory tract and associated lymph nodes (inhalation exposure) and once in the circulatory system can partition to the skeleton, liver, kidney and spleen. Studies subjecting animals to large dosages of cerium show evidence of neurological effects, possibly due to cerium competing with calcium binding sites in the brain. Long term human exposure to cerium is correlated with rare earth pneumoconiosis, but the precise role of cerium in this disease is not well characterized due to confounding metal aerosols (HEI, Attachment A; HEI, 2001; DieselNet, 2002.02b; Mayer, 1998; Mayer, 1999). Effects of nano-particulate cerium oxide are unknown (Mayer, 2002). However, projections show the environmental exposure to cerium from fuel additives will be orders of magnitude below occupational exposure limits. Further research is necessary to identify the size of emitted particles containing cerium, potential developmental and neurotoxic effects of cerium particles, the effects of engine aging and regeneration on emissions of cerium and the chronic effects of inhaled cerium particles in emissions on target organs (HEI, 2001; HEI, Attachment A).

B.3.2 Copper Based Additives

Description: Copper will decrease PM emissions, lower the soot combustion temperature and facilitate filter regeneration. As with other additives, when used in conjunction with DPFs, the higher the additive concentration the greater the filter pressure drop due to ash accumulation and the greater the operating costs of the system. Copper platinum blends dropped balance temperature for trap systems from 537-557 °C to 347 °C. There are significant problems with copper-based additives.

They can cause severe fouling of fuel injectors and cyclic soot loading of the filter yielding high temperature peaks during regeneration. Some ceramic fiber wound filters were determined to be incompatible with copper based additives as the high regeneration temperatures caused glazing of the copper and oil ash resulting in bonding of the fibers and decreased filter durability. Copper-based additives result in dioxin and furane emissions (DieselNet, 2000.02b; Mayer, 1998; Mayer, 1999).

Fate and Transport: Some fate and transport studies address environmental risks from copper. Copper is toxic to certain species, but more importantly, copper additives result in the deleterious secondary emissions of furanes and dioxins. This precludes them from further consideration (DieselNet, 2000.02b; Mayer, 1998).

B.3.3 Platinum Based Additives:

Description: The most common platinum additives are actually bi-metallic additives consisting of Platinum in conjunction with another metal. Platinum additives lower balance temperature for traps facilitating regeneration. Platinum/cerium blends display a synergistic effect and drop balance temperatures from 537-557 °C to 327 °C and are typically used at low dosage levels (less than 10 ppm). The low dosage results in decrease nano-particulate formation as compared to additives with higher effective concentrations (HEI, Attachment A; DieselNet, 2000.02b). However, at this low concentration, it is possible that any increase in nano-particulate is masked by soot (Mayer, 2002). Data for the one additive used alone show 25 percent reduction in particulate emissions as well as 35 percent reductions in hydrocarbons and 11 percent reductions in carbon monoxide. When used in conjunction with an oxidation catalyst reductions up to 50 percent are achieved and this number increased to 95 percent when the additive was coupled with a DPF. Up to a 20 percent decrease in NO_x for certain fuel/technology/additive combinations have been reported. Fuel economy benefits of five to seven percent have been reported for heavy-duty diesel engines. Without a filter, six percent of the metal input is released from the engine after 1000 hours of high load; a filter reduces the release of metal to less than one percent (DieselNet, 2000.02b; HEI, Attachment A; Mayer, 1999; Valentine, 2002; Mayer, 1998, Valentine et al, 2000; Khair, et al, 1999; Fanick et al, 2001; Vincent et al, 2001).

Current Use: Platinum based additives are in use in Europe with DPF systems for both on and off road applications and stationary sources (Valentine, 2002).

Fate and Transport: Studies show an increase in platinum group element concentrations in ambient air and dust since the introduction of catalytic converters. Catalytic converters contribute more platinum into the environment than other industrial sources. Levels up to 130 µg/kg are found in dust samples collected in Germany. Normal levels found in the earth's crust are on the order of 5 µg/kg. Platinum is found in all particulate matter size ranges and has the potential of airborne transport (HEI, Attachment A; Zereini, 200; Veltz, 1996; Artelt, 1999; Artelt, 1998, DieselNet, 2000.02b).

Health Risks: Platinum is toxic to some species and the effect of nano-particulate platinum fraction is poorly understood. There is evidence that an inverse correlation exists between the diameter of the platinum particles and solubility. Platinum salts are known allergens at concentrations found in occupational settings. The United Kingdom's Department of Health reviewed platinum based diesel fuel additives and concluded there were minimal human health risks from FBCs. Bioavailability studies show platinum partitioning to the lungs, lung macrophages, blood, liver, gastrointestinal tract and kidneys depending on the route of exposure. Additionally bioavailability studies shows a significant fraction of ultrafine platinum particles are bioavailable. Long term ramifications of increased environmental platinum levels are inconclusive (Mayer, 2002; Veltz, 1996; Artelt, 1999; Artelt, 1998; Zereini, 2001; DieselNet, 2000.02b; HEI, Attachment A; Toxicity, Mutagenicity and Carcinogenicity Report, 1996)

B.3.4 Manganese Based Additives:

Description: Methylcyclopentadienyl manganese tricarbonyl (MMT) is one of the better documented manganese based fuel additives. It has been used in gasoline in the United States and Canada and can be used with a variety of fuel types. MMT reduces NOx by as much as 20 percent in some applications, and also acts as an octane booster and smoke abator. Although the US EPA determined that MMT does not cause failures of emission control devices or systems, the EPA requested a battery of tests to better characterize potential health effects (HEI, Attachment A, National Round Table on the Environment and Economy, 2001)

Health Risks: Use of this additive, as well as any manganese based fuel additive, increases manganese species in the environment. Long term exposure to high levels of manganese results in manganism, a neurological condition similar to Parkinson's disease. Reproductive and respiratory effects have been reported, with evidence showing inhaled manganese is more toxic than ingested manganese. However, Health Canada repeatedly determined that there was no evidence to indicate a hazard to human health. Some researchers have challenged this conclusion on the grounds that long term health effects and environmental fate and transport are poorly understood (HEI, Attachment A; National Round Table on the Environment and Economy, 2001)

B.3.5 Iron Based Additives:

Description: These include ferrocene derivatives, and iron blend FBCs. Typical dosing concentrations are 10 ppm to 20 ppm. Older testing was done with doses of 60 and 120 ppm. As with other high concentration FBC's, use of additives at this level ppm increases nano-particulate emissions by up to two orders of magnitude. Iron based additives, used without a filter at low ppm concentrations, can result in a 20 percent in PM. Iron based additives are compatible with most engines and exhaust after treatment systems, although some iron additives might be problematic with some technologies. Iron additives increase octane, allow for a shorter burn out time of the soot, and lower the ignition temperature of soot down to about 350 °C. Up to 99.9 percent of fine particulates are retained in the system when the additive is used with a filter.

Reductions in both particle mass and number are seen when used in conjunction with DPF. In addition to PM reductions, there is a decrease in PAH's and no increased NOx emissions. Platinum/iron blends can reduce balance temperatures from 537 °C – 557 °C to 357 °C. Results from studies with traps show soot filtration efficiencies greater than 90 percent with normal regeneration of the filter. Most of the iron ash is retained in the filter with a 0.85 percent increase in fuel consumption (DieselNet, 2000.02b; HEI, Attachment A; Werner, 2002).

Current usage: Iron based products are in use in construction vehicles/building machinery in Germany, Austria and Switzerland for greater than 5 years. Additionally, several hundred city buses, garbage trucks, forklifts and cleaning machinery have used these additives for the last several years (Werner, 2002).

Environmental Fate and Transport: Ferrocene will biodegrade given long time periods. Swedish EPA considers this product (in gasoline) as presenting no environmental hazard over conventional gasoline (Werner, 2002).

Health Risks: Ferrocene has relatively low toxicity. Based on EU requirements, it is listed in the lowest toxicity class. There is no evidence of carcinogenicity or neurotoxic effects. Emission testing showed no general trends save an increase in iron in the exhaust. Chronic exposure studies showed no significant effect on the subjects (HEI, Attachment A; DieselNet, 2000.02b; Werner, 2002).

B.4 Alternative Diesel Fuels

A basic definition of an alternative diesel fuel is a fuel that can be used in a diesel engine without modification to the engine and that is not just a reformulated diesel fuel. For example, alternative diesel fuels may include emulsified fuels, biodiesel fuels, Fischer Tropsch fuels, or a combination of these fuels with regular diesel fuel. The emissions effects of these fuels can vary widely.

In general, alternative diesel fuels need to follow the same procedure as other emission control strategies. The major exception is that alternative diesel fuels must undergo a more extensive test procedure which includes 21 transient FTP tests on the base fuel and the same on the test fuel. Those fuels are alternated according to one of three testing sequences found in the procedures. Fewer tests are required if cold starts are included. A second additional requirement for fuels is that applicability, description, and fuel parameters need to be included with the application. Staff has harmonized these requirements with the interim procedure for alternative diesel fuels conducted through with the ARB's Stationary Source Division (SSD). Although the SSD verification by itself would not be acceptable for the diesel emission control strategy program, the emission reductions may be claimed for other programs. The data from the alternative diesel fuel program may be used in the emission control strategies program.

As with other strategies, the effect of the fuel on the engine durability must be demonstrated. The levels of reduction would be granted in the same manner as other

diesel emission control strategies. As is the case for other strategies, the verification would cover a specific group of engines or engine families. Extension of the verification may be sought after initial verification by supplementing the data supporting the original verification with additional data and engineering analysis.

B.5 NOx Control Strategies

Although not as mature as PM control strategies in general, significant research into NOx control strategies that may be suitable for retrofit use is being conducted and a number of NOx control strategies for diesel engines are nearing commercial readiness. A sampling of NOx control technologies are briefly described below. As noted in the staff report, the verification procedure is appropriate for verifying NOx reductions equal to or greater than 15 percent.

B.5.1 Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is one of the most effective engine control methods for reducing NOx emissions. Spent combustion gases recirculated back into the intake system serve as a diluent to lower the oxygen concentration and to also increase the heat capacity of the air/fuel charge. Cooling the exhaust gas that is to be recirculated can be used to minimize combustion temperatures. This reduces peak combustion temperature and the rate of combustion, thus reducing NOx emissions. Typical NOx reductions are about 50 percent. However, PM emissions may increase and fuel economy may decrease. The proper balance of EGR and temperature may provide the characteristics necessary for decreasing NOx emissions without increasing PM emissions. It is anticipated that cooled EGR would be an integral part of the engine manufacturers' effort to meet the lower NOx emission requirements in October 2002. Recently, hundreds of EGR systems which include diesel particulate filters have been successfully installed on existing Swedish urban buses, giving 50 percent NOx reductions and over 90 percent PM reductions (STT Emtec product literature).

B.5.2 Selective Catalytic Reduction Systems

Selective catalytic reduction (SCR) systems use a reductant, usually ammonia or urea, to convert NOx to nitrogen and oxygen. These systems are common in stationary sources and are also used on a few mobile sources in Europe. In this system, the reductant is injected into the exhaust upstream of the catalyst. As the exhaust gases, along with the reductant, pass over a catalyst applied to either a ceramic or metallic substrate, NOx emissions can be reduced by more than 70 percent (MECA, 2000). In addition, staff estimates that PM emissions could be reduced by 25 percent and HC emissions by 50 to 90 percent in SCR systems. SCR retrofit systems are expected to be available for urban bus applications within two to three years.

B.5.3 NOx Adsorbers

NOx adsorbers, also called NOx traps, are one of the newest emission control strategies under development. They employ catalysts to which NOx in the exhaust stream adsorbs when the engine runs lean. After the adsorber has been fully saturated with NOx, the system is regenerated with released NOx being catalytically reduced when the engine runs rich. NOx reductions in excess of 80-90 percent have been reported (Majewski, 2001). A prerequisite for proper functioning of this new technology is low-sulfur fuel.

B.5.4 Reprogramming of Defeat Devices

Some NOx reductions may be achieved through reprogramming of engines with defeat devices. In October 1998, some heavy-duty engine manufacturers and the U.S. EPA settled a court case regarding the use of an illegal emission defeat device. Engine manufacturers had installed engine control software to artificially increase NOx emissions during steady highway cruising in order to maintain high fuel economy at highway speeds. The settlement required engine manufacturers to lower NOx emissions by upgrading existing heavy-duty engines and disabling the engine control software. Although the consent decree does produce NOx emission reductions, the scope of the decree is relatively limited in that it is only applicable to those on-road engines that had the devices originally. Early reprogramming does yield NOx emission reductions that could be verified.