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Nonroad Diesel Emission Standards

Staff Technical Paper

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Assessment and Standards Division
Office of Transportation and Air Quality
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NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments which may form the basis for a final EPA decision, position, or regulatory action.

Executive Summary

In 1998, EPA adopted more stringent emissions standards for nonroad diesel engines. In that rulemaking, EPA indicated that in 2001 it would review the upcoming Tier 3 portion of those standards (and the Tier 2 emission standards for engines under 50 horsepower) to assess whether or not the new standards were technologically feasible. We are soliciting public comments on this preliminary technical assessment. After reviewing the comments, EPA plans to issue its final assessment early next year on these issues.

When we set the Tier 3 emission standards in 1998, available information indicated that the cooled exhaust gas recirculation (EGR) technology developed for highway diesel engines would be the primary means of compliance with these standards. In conducting our technology review, we have surveyed the recent engineering and scientific literature on advances in diesel emissions control. We have also reviewed information provided by engine manufacturers in support of our 2004 highway standards program, showing the considerable progress they have made in the design of robust EGR systems for use in highway engines. In addition, we have gathered information from engine manufacturers on their design plans for Tier 3 and their testing and development experience with control technologies they are likely to employ. This information shows that cooled EGR is but one of several technologies available to diesel engine manufacturers to meet the Tier 3 emission standards. This widening of technology options comes from the progress of technology development since 1998. In addition, as we acknowledged in the 1998 final rule, we envisioned a Tier 3 program more closely aligned with future highway standards, in particular, achieving comparable control of particulate matter (PM) for nonroad engines. Based on the information we have gathered to date, we reaffirm that the Tier 3 standards in Title 40 of the Code of Federal Regulations (CFR), Part 89, are feasible in the timeframe established in the rule. Based on the information to date, we also reaffirm that the Tier 2 standards for engine under 50 horsepower are likewise feasible. This preliminary assessment is reinforced by certification test data from Tier 1 engines in this power range showing that many of these engines are already meeting the Tier 2 standards.

The 1998 rule did not establish a new Tier 3 program for PM emissions reductions because of critical unresolved issues connected with the appropriate test procedure for characterizing transient operating conditions. Instead, the Agency made a commitment in that rule to establish an effective program for controlling PM emissions beyond the limited control achieved under the Tier 2 standards, and to consider adopting measures to better ensure emissions control in-use. These actions were, at least in part, planned to occur in the context of this technology review. Since the 1998 final rule, the belief that further action is warranted has been reinforced by growing evidence that diesel engine exhaust emissions can cause serious health problems. EPA has recently issued regulations that will dramatically reduce emissions from *highway* diesel vehicles. As a result, *nonroad* diesel engines, already a major source of harmful particulate matter and ozone-forming compounds, will become a dominant mobile source of these emissions in the future.

The Agency has already taken some steps toward dealing with nonroad diesel PM and in-use emissions concerns (such as developing a transient test cycle to better characterize in-use PM emissions). However, we believe a separate rulemaking is the best approach because it is increasingly clear that the most effective means of further reducing emissions of PM (and oxides of nitrogen (NOx), if warranted) is through a "systems" approach that regulates nonroad diesel engines and fuel in a single coordinated program, similar to the approach recently taken to controlling highway vehicle emissions. This approach would continue the pattern followed successfully in the past, in which nonroad emissions reduction programs are modeled after highway programs, with some additional leadtime provided for adaptation of highway technologies to nonroad diesel applications. EPA plans to initiate such a rulemaking with a proposal next year.

1. Introduction

1.1 Purpose

This EPA staff technical paper presents a preliminary staff assessment of the feasibility of upcoming emissions standards for nonroad diesel engines.[a] These standards, referred to as "Tier 3" for engines above 50 horsepower (hp) and "Tier 2" for engines below 50 hp, were adopted in a 1998 rulemaking, but do not begin to take effect until the middle of this decade. EPA announced in the 1998 rule that we planned to perform this assessment to determine the need for any adjustments to the program. We are soliciting public comments on this preliminary assessment. After reviewing the comments, EPA plans to issue a final assessment early next year on these issues.

This paper also discusses continuing air quality concerns caused by nonroad diesel emissions after implementation of the upcoming Tier 3 program. We intend to follow up with a rulemaking to address these concerns next year. Furthermore, that rulemaking will fulfill Agency commitments, made in the 1998 final rule, to establish test procedures and standards levels for controlling PM emissions beyond the limited control achieved under the Tier 2 standards, and to adopt measures to better ensure emissions control in-use. It is important to note that we have not made any final decisions regarding the upcoming rulemaking, and we welcome any and all comments that can help us to develop the best possible program.

1.2 Past EPA Actions

The EPA has taken measures to reduce harmful emissions from nonroad diesel engines in two past regulatory actions. A 1994 final rule, developed under provisions of Section 213 of the Clean Air Act, set initial emissions standards for new nonroad diesel engines greater than 50 hp (59 FR 31306, June 17, 1994). These standards gained modest reductions in NOx emissions and are referred to as EPA's "Tier 1" standards for large nonroad engines. A subsequent final rule published in 1998 set more stringent Tier 2 and Tier 3 standards for these engines, as well as Tier 1 and Tier 2 standards for the nonroad diesel engines under 50 hp (63 FR 56968, October 23, 1998). Nonroad diesel fuel quality is not presently regulated by the EPA.

We also expressed our intent in the 1998 rule to continue evaluating the rapidly changing state of diesel emissions control technology, and to perform a review in the 2001 timeframe of the technological feasibility of the Tier 3 standards, and of the Tier 2 standards for engines rated under 50 hp. This review could then result in additional EPA action to revise the standards upward or downward, as appropriate. The 1998 rule did not establish a new Tier 3 program for PM emissions reductions because of critical unresolved issues connected with the appropriate

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[a] Throughout this staff paper, the term "nonroad diesel engine" refers to compression-ignition engines used in mobile off-highway applications, other than locomotives, underground mining equipment, and large marine engines, which are regulated separately.

test procedure for characterizing transient operating conditions. Instead we made a commitment to pursue resolution of these issues and establishment of a PM control program as part of the 2001 feasibility review process. Therefore the Tier 2 PM standards continue on during the Tier 3 timeframe until changed by the Agency. The 1998 rule also discussed concerns that the advent of electronic engine controls increase the risk that in-use emissions may not be controlled adequately, and indicated that the Agency expected to take action in the future to adopt supplemental measures to better address this issue.

1.3 The Current Situation

We have been engaged in the assessment mentioned above for some time now. A key part of this effort has been meeting with engine manufacturers, equipment manufacturers, and other stakeholders. The meetings held thus far have been extremely helpful, and have provided much of the basis for the technical discussion in the following sections. EPA Docket A-2001-28 includes documentation from these meetings. Some engine manufacturers have also provided written discussions of their views, data, and analyses on this topic, and these too have been put in the docket.

In chapters 3 and 4 of the Regulatory Impact Analysis (RIA) for the 1998 final rule, we described several technologies that we expected would be used to varying degrees in helping to meet the Tier 3 standards (and the Tier 2 standards for engines rated under 50 hp). These technologies included full authority electronic systems and new fuel injection components such as high-pressure unit injectors and common rail fuel systems. Key among the forecast Tier 3 technologies was cooled exhaust gas recirculation, which was believed to have the potential to cut NOx emissions in half. This technology was, at that time, expected to be an essential piece of every engine manufacturer’s design strategy for meeting the heavy-duty *highway* diesel engine standards set in 1997, that take effect in 2004. The 1998 nonroad rule projected the transfer of this technology to most nonroad diesel engines in Tier 3, because the Tier 3 NOx plus nonmethane hydrocarbon (NMHC) standards were intentionally set at comparable levels (and with the anticipation that Tier 3 PM standards would be set at a later point), to take effect a couple of years later.[b]

The development of technology for controlling diesel engine emissions has progressed rapidly in the three years since the 1998 final rule was published. As often happens when a diverse, highly competitive industry tackles challenging new regulatory requirements, the number of potential control options has expanded to include new technologies and more effective application of existing technologies. At this point, we do not believe that cooled EGR will be the only means available to comply with the Tier 3 standards, nor do we believe that any nonroad

[b] Engines in the 50-100 hp category were projected to employ non-cooled, or "hot", EGR systems for reasons of cost, space constraints, less-straightforward technology transfer from the larger highway engines, and our adoption of a somewhat higher Tier 3 NOx+NMHC standard level compared to that of larger engines.

engine designs employing cooled EGR systems will need to rely on them as heavily as was contemplated in the 1998 final rule. The next section presents our technology feasibility assessment of Tier 3 standards in detail. In evaluating Tier 2 standards for engines under 50 hp, we now have substantial test and design data resulting from the Tier 1 program that informs our assessment of the feasibility of these Tier 2 standards. Section 3 presents this assessment in detail.

EPA has taken several steps toward better controlling PM and in-use emissions from nonroad engines. EPA issued guidance in October 1998 on implementation of the defeat device prohibition for electronically-controlled highway and nonroad diesel engines.[1] EPA has also met with engine manufacturers to discuss supplemental regulations to better ensure that excess in-use emissions do not occur. EPA has been working with manufacturers, and has made significant progress, in developing a transient test procedure to better characterize nonroad engine operation in the field and thereby to ensure better control of PM. As discussed earlier, EPA plans to take up these issues in a future rulemaking. The evaluation of Tier 3 and Tier 2 standards in this paper is based on the current regulatory requirements, and does not attempt to evaluate the impact these future actions might have on the already promulgated Tier 3 and Tier 2 standards.

2. Tier 3 Technology Assessment

In 1998 we set new Tier 3 NOx+NMHC emission standards for nonroad diesel engines between 50 and 750 horsepower.[c] The schedule we set for introduction of these new standards included a gradual phase-in that limited impacts on engine and equipment manufacturers. The emission levels of these standards were set based largely on our belief that manufacturers of nonroad engines would be able to apply emission control technologies developed for highway engines. The NOx+NMHC standards set for Tier 3 did include provisions that reflect unique nonroad concerns. Specifically, the NOx+NMHC standard was set at a less stringent level when compared to the comparable highway standard, in order to account for differences in aftercooler performance. Similarly, the standards are phased-in over a number of years according to horsepower rating. This will allow for a gradual transfer of highway technologies such as cooled EGR systems to nonroad engines. These highway technologies are already in limited production and are expected to be in widespread use by 2003, a full three to six years before they will be needed for nonroad engines. The resulting emission standards for Tier 3, in grams per horsepower-hour (g/hp-hr), are shown in Table 2-1.

Table 2-1
Nonroad Tier 3 Emission Standards (g/hp-hr)

Engine Power	Model Year	NMHC+ NOx	Carbon Monoxide (CO)	PM *
50≤hp<100	2008	3.5	3.7	0.30
100≤hp<175	2007	3.0	3.7	0.22
175≤hp<300	2006	3.0	2.6	0.15
300≤hp<600	2006	3.0	2.6	0.15
600≤hp<750	2006	3.0	2.6	0.15

* Tier 2 standards carry over into Tier 3

The following sections describe the fundamentals of diesel engine combustion, pollutant formation, pollutant control technologies and the resulting engine changes that we expect can be applied by engine manufacturers in order to comply with the Tier 3 standards. The following sections make clear that highway emissions control technologies are rapidly being developed and transferred to nonroad engines in many ways, not all of which could have been anticipated during the 1998 rulemaking process. This rapid development and the fact that the Tier 3 standards do not begin to phase in for four more years (fully phasing in in seven years) support our continued

[c] The 1998 rule also established new Tier 2 PM standards for nonroad engines, but not Tier 3 PM standards. The Tier 2 PM standards continue into Tier 3 absent further action by EPA.

belief that engine manufacturers will be able to comply with the Tier 3 standards through the continued advancement of existing highway diesel engine technologies.

2.1 Combustion Fundamentals and Pollution Formation

Diesel combustion consists of a complicated series of events, both physical and chemical, which can be altered through engine design and operation. The sequence and rate at which these events occur are strongly related to the kinds and quantities of pollutants formed during combustion. The following sections will describe the combustion and pollutant formation processes so that the means of controlling emissions discussed in this paper can be better understood.

2.1.1 Diesel Combustion Background

The typical diesel engine used in nonroad applications operates on a four-stroke cycle consisting of the intake stroke, the compression stroke, the power (or combustion) stroke, and the exhaust stroke. The combustion event provides the energy for engine operation. It starts at the end of the compression stroke and continues through the first half of the power stroke. Near the end of the piston compression stroke, fuel is injected into the cylinder at high pressure and mixes with the contents of the cylinder (air + residual combustion gases + EGR gases if EGR-equipped). This period of premixing is referred to as ignition delay. Ignition delay ends when the premixed cylinder contents self-ignite due to the high temperature and pressure produced by the compression stroke in a relatively short, homogenous, premixed combustion event. Immediately following premixed combustion, diesel combustion becomes primarily nonhomogeneous and diffusion-controlled (the rate of combustion is limited by the rate of fuel and oxygen mixing). During this phase of combustion, fuel injection continues creating a region that consists of fuel only. The fuel diffuses out of this region and air is entrained into this region creating an area where the fuel to air ratio is balanced (i.e., near stoichiometric conditions) to support combustion.[d] The fuel burns primarily in this region. One way to visualize this phenomenon is to roughly divide the cylinder contents into fuel-rich and fuel-lean sides of the reaction-zone where combustion is taking place as shown in Figure 2-1. As discussed in the following subsections, the pollutant rate of formation in a diesel engine is largely defined by these combustion regions and how they evolve during the combustion process.[2]

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[d] Stoichiometric conditions: the amount of air and fuel is balanced at the theoretical, or chemically correct, level to give complete combustion without any unburned fuel or oxygen remaining. The ratio of the actual air-to-fuel (A/F) ratio to the ideal stoichiometric ratio is often referred to as lambda (λ). In this nomenclature, $\lambda = 1$ represents an ideal balance, $\lambda > 1$ indicates an excess of air (oxygen) and $\lambda < 1$ indicates an excess of fuel.

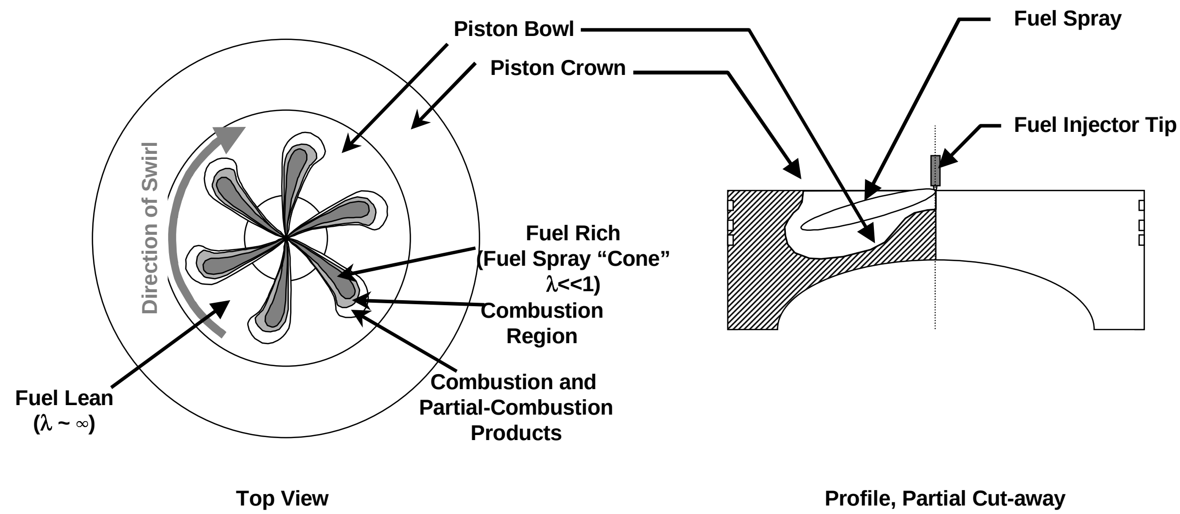

Figure 2-1
Diesel Combustion Schematic

2.1.2 NOx Formation Background

NOx is formed in diesel engines from molecular nitrogen (N_2) and oxygen (O_2) in the stoichiometric combustion region of the diffusion-controlled diesel combustion process described in the previous section. At the high temperatures present in the combustion zone, a fraction of the nitrogen and oxygen can dissociate, forming radicals which can then combine through a series of reactions to form nitric oxide (NO), the primary NOx constituent. Nitrogen dioxide (NO_2), the other NOx constituent, is formed from NO in the flame region. The NOx formation rate has a strong exponential relationship to temperature. Therefore high temperatures result in high NOx formation rates.[3] Any changes to engine design that can lower the peak temperature realized during combustion, the partial pressures of dissociated nitrogen and oxygen, or the duration of time at these peak temperatures can lower NOx emissions. Most of the NOx emission control technologies discussed in the following sections reduce NOx emissions by reducing the peak combustion temperature.

Researchers have investigated the limits of diffusion-controlled stoichiometric combustion in order to determine the minimum NOx emission rate possible from conventional diesel engine combustion (this includes the use of EGR, which is discussed later in this paper).[4,5] The researchers found that there is a minimum peak combustion temperature below which the conventional diesel diffusion-controlled combustion process can not be maintained. Based on this observation, experimental data, and theoretical NOx formation rates, a minimum "practical" NOx emission rate for conventional diesel combustion was estimated at approximately one-half of the Tier 3 NOx+NMHC standard. A theoretical limit of conventional diesel combustion was estimated at approximately one-fourth of the Tier 3 standard. The researchers suggest that reductions in NOx emissions below these levels will require NOx removal aftertreatment systems or a fundamentally different form of diesel engine combustion. While new technologies are rapidly being developed for highway engines to reduce NOx emissions below the levels discussed here (e.g., NOx adsorbers and Homogenous Charge Compression Ignition (HCCI)) it is unclear to what degree these advanced technologies will be available for application to nonroad diesel engines. The NOx adsorber technology requires low sulfur diesel fuel (< 15 parts per million (ppm) sulfur) in order to ensure durability.[6] The various forms of HCCI being investigated for highway applications do not currently provide NOx control beyond 50% engine load, making its use for nonroad applications uncertain.[7]

2.1.3 PM Formation Background

PM emitted from diesel engines is a multi-component mixture composed chiefly of elemental carbon (or soot), semi-volatile organic compounds, sulfate compounds (primarily sulfuric acid) and associated water.

During diffusion-controlled combustion, fuel diffuses into a reaction zone and burns. Products of combustion and partial products of combustion diffuse away from the reaction zone where combustion occurs. At temperatures above 1,300 K, fuel compounds on the fuel-rich side of the reaction zone can be pyrolized[e] to form elemental carbon particles.[8] Most of the elemental carbon formed (80% to 98%) is oxidized during later stages of combustion, most likely by hydroxyl radicals formed during combustion.[9,10] The remaining elemental carbon agglomerates into complex aggregate chain soot particles and leaves the engine as a component of PM emissions.

From this description, the formation of soot during combustion and emission of soot as PM following the combustion event can be summarized as being dependent upon three primary factors:

1. Temperature
2. Residence time
3. Availability of oxidants

Thus, in-cylinder control of PM is accomplished by varying engine parameters that affect these variables while balancing the resultant effects on NOx emissions and fuel consumption.

The combination of organic compounds (volatile and semi-volatile) that contribute to PM are often referred to as the volatile organic fraction (VOF), or the soluble organic fraction (SOF), depending upon the test procedure used to measure the compounds. The test procedure used to demonstrate compliance with the PM emission standard does not differentiate between the various components of PM. Sulfate PM and VOF are formed after cooling and air-dilution of the exhaust. Formation of sulfate PM is a function of fuel sulfur content. In the absence of post-combustion treatment of the exhaust (i.e., aftertreatment), approximately 1 to 3 % of fuel sulfur

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[e] Pyrolysis is a high-temperature decomposition that strips hydrogen from the hydrocarbon fuel molecules.

is converted to sulfate, while the remainder is emitted as gaseous sulfur dioxide(SO_2). Post-combustion treatment of the exhaust using platinum catalysts can oxidize the VOF thereby lowering PM emissions. VOF emissions are also reduced by the same in-cylinder emission control strategies used to reduce hydrocarbon (HC) emissions. But, this can also oxidize up to 50% or more of the SO_2 to sulfate PM, depending on the exhaust temperature and the platinum content of the catalyst. VOF emissions are also reduced by the same in-cylinder emission control strategies used to reduce hydrocarbon (HC) emissions.

2.1.4 The NOx vs. PM Trade-Off

Diesel engine emission control technology performance is often characterized by its "NOx vs. PM trade-off". This trade-off refers to the fact that, under many conditions, control technology designed to reduce one pollutant (e.g., NOx) will do so while increasing production of another pollutant (e.g., PM). For example lower oxygen content (lowering the air-to-fuel ratio) lowers NOx formation but increases PM formation. Diesel engine designers must balance this trade-off in order to accomplish compliance with both the NOx and PM standards. In the case of the Tier 3 emission standards, since the NOx+NMHC standard is reduced substantially while the PM standard remains at the Tier 2 level, we would expect there to be a shift in how design engineers trade off NOx and PM emissions. The lack of restrictive Tier 3 PM standards makes it directionally easier for manufacturers to meet the relatively more restrictive NOx+NMHC standard by changing the balance of the NOx vs. PM trade-off from the Tier 2 engine designs.

2.1.5 Hydrocarbon Formation Background

Hydrocarbon (HC) emissions from diesel engines primarily occur due to fuel and lubricant trapped in crevices (e.g., at the top ring land and the injector sac) which prevents sufficient mixing with air for complete combustion. Fuel-related HC can also be emitted due to "overmixing" during ignition delay, a condition where fuel in the induced swirl-flow has mixed beyond the lean flammability limit.[11] Higher molecular weight HC compounds (primarily lubricant related compounds) adsorb to soot particles or nucleate and thus contribute to semi-volatile organic PM. Lower molecular weight HC compounds (chiefly fuel related compounds) are primarily emitted in the gas phase. Under some cold-start conditions, fuel-related HC is emitted as a concentrated, condensed aerosol ("white smoke"). Hydrocarbons can be controlled in-cylinder by reducing the size and number of crevices, and by reducing ignition delay. Post-combustion treatment of hydrocarbons can be accomplished via oxidation over precious-metal and base-metal catalysts.

2.2 Emission Control Technologies

The following sections describe some of the emission control technologies available to diesel engine manufacturers. The technologies described here have all been applied in one form or another to highway diesel engines. Most of the technologies described in these sections can be applied directly to similar nonroad diesel engines. There are a few technologies (e.g., cooled EGR) that have unique issues when applied to nonroad diesel engines. We discuss those issues in a separate section following this discussion.

The RIA documents for the recent heavy-duty highway 2004 standards technology review rule and for the Tier 3 nonroad emission standards contain additional information regarding the effectiveness of several of the technologies discussed here, primarily cooled EGR systems.[12,13] The reader should refer to these previous rulemaking documents for additional information on diesel emission control technologies relevant to the Tier 3 emission standards.

2.2.1 Charge Air Cooling

Lowering the intake manifold temperature (and therefore the initial temperature of the gases entering the combustion chamber-- air and possibly recirculated exhaust), lowers the peak temperature of combustion and thus NOx emissions. The NOx reduction realized from lowering the intake manifold temperature can vary depending upon the engine design but one estimate suggests NOx emissions can be reduced by five to seven percent with every 10°C decrease in intake manifold temperature.[14] Typically the intake manifold temperature is lowered by cooling the intake gases through a heat exchanger located between the turbocharger compressor outlet and the intake manifold. This type of heat exchanger is commonly called an aftercooler since it cools the gases after they are heated by the compression work done by the turbocharger compressor.

While aftercooling reduces NOx emissions, it was initially developed to improve the specific power output of an engine by increasing the density of air entering the combustion chamber. There are two kinds of aftercooling strategies– air-to-water or air-to-air. Air-to-water aftercoolers use engine coolant to lower the intake air temperature. This method, however, can only reduce the temperature of the compressed intake air to the operating temperature of the engine and significantly adds to the heat load on the cooling system. The temperature of the intake air after compression by the turbocharger is approximately 150°C. An air-to-water aftercooler can only cool the intake charge air to approximately 90°C.

Air-to-air aftercoolers use a stream of outside air flowing through a separate heat exchanger to cool the intake air. An air-to-air aftercooler can cool the compressed intake air to a temperature approaching that of the ambient air. Air-to-air aftercoolers are widely used with highway engines. However, nonroad engines historically have not incorporated air-to-air aftercooling. Over time, equipment manufacturers are expected to modify their designs to make space for air-to-air aftercooling technology. While introducing air-to-air aftercooling requires a greater degree of engine and equipment modification, the benefits for improved fuel efficiency, greater engine durability, higher power density, and better control of NOx emissions make a compelling case for their widespread use in the long term.[15]

Air-to-air aftercoolers can be somewhat less effective when used on nonroad applications because of the lack of ram-air cooling[f] in most nonroad applications. The lack of ram-air cooling can result in lower aftercooler performance in nonroad applications than for highway vehicles. The resulting increase in intake charge temperature will reduce the NOx reduction effectiveness of diesel engine used in nonroad applications as compared to highway applications. This fact is one of the reasons why we set a less stringent Tier 3 NOx+NMHC standard for nonroad engines compared to the "equivalent" heavy-duty 2004 highway NOx+NMHC standard.

2.2.2 Fuel Injection Rate Shaping and Multiple Injections

Historically the relationship between combustion system design and fuel system operation were fixed functions of the basic engine design and were thus optimized at a single operating point (or designed as a compromise between several important operating points). At all other operating points, emission performance was compromised when compared to ideal operation. These older systems, still in wide-spread use on nonroad engines, have limited emission control flexibility.

The most recent advances in fuel injection technology are the systems that use rate shaping or multiple injections to vary the delivery of fuel over the course of a single combustion event. These systems are beginning to be used extensively on light and medium heavy-duty diesel trucks, a class of engines commonly carried over to nonroad engine applications. Igniting a small quantity of fuel initially limits the characteristic rapid increase in pressure and temperature that leads to high levels of NOx formation. Injecting most of the fuel into an established flame then allows for a steady burn that limits NOx emissions. Rate shaping may be done either mechanically or electronically. Rate shaping has been shown to reduce NOx emissions by up to 20 percent.[16]

For electronically controlled engines, multiple injections may be used to shape the rate of fuel injection into the combustion chamber. Recent advances in fuel system technology allow high-pressure multiple injections to be used to reduce NOx by 50 percent with no significant penalty in PM. Two or three bursts of fuel can come from a single injector during the injection event. The most important variables for achieving maximum emission reductions with optimal fuel economy using multiple injections are the delay preceding the final pulse and the duration of the final pulse.[17]

Advanced common rail fuel systems are being developed and introduced for both

[f] "Ram-air" cooling refers to ambient air pushed through the air-to-air aftercooler due to the speed of the vehicle. For a highway truck traveling at 60 miles per hour, the cooling realized by the air flowing over the aftercooler can be substantial. Since nonroad equipment is often stationary (e.g., a generator set) or travels at a slow speed (e.g., a tractor working in a field) this effect is not very strong for nonroad engines. Nonroad equipment commonly uses an engine mounted fan to impart additional air flow through the aftercooler and radiator in order to compensate for the lack of ram air.

highway and nonroad diesel engines. These fuel systems allow fuel injection rates (as determined by fuel pressure) and multiple fuel injection events to be changed based upon any engine operating condition. This flexibility allows engine designers to tailor the fuel injection system operation across the entire range of engine operation. The ability to tailor fuel system control parameters (injection timing, injection pressure, injection rate and injection duration/quantity) across the range of diesel engine operation removes these historic compromises allowing for substantial improvements in engine performance and emissions.[18,19]

The dramatic improvements in engine performance and emission controls promised by these new technologies has led to rapid introductions of common rail fuel systems to nonroad engines, well in advance of the rate we would have predicted only a few years ago. John Deere announced that many of its new Tier 2 compliant engines will utilize Denso common rail fuel systems.[20] Similarly, Caterpillar is expanding the use of its Hydraulic Electronic Unit Injector (HEUI) fuel system in nonroad engines in order to meet the more restrictive Tier 2 standards while reducing fuel consumption by five to 10 percent.[21]

2.2.3 Injection Timing Retard

Delaying the start of fuel injection and thus the start of combustion can significantly reduce NOx emissions from a diesel engine. The effect of injection timing on emissions and performance is well established.[22,23,24,25] Delaying the start of combustion by retarding injection timing aligns the heat release from the fuel combustion with the portion of the power (or combustion) stroke of the engine cycle after the piston has begun to move down. This means that the cylinder volume is increasing and that work (and therefore heat) is being extracted from the hot gases. The removal of this heat through expansion lowers the temperature in the combustion gases. NOx is reduced because the premixed burning phase is shortened and because cylinder temperature and pressure are lowered. Timing retard increases HC, CO, PM, and fuel consumption, however, because the end of injection comes later in the combustion stroke, where the time for extracting energy from fuel combustion is shortened, and the cylinder temperature and pressure are too low for more complete oxidation of PM. Many of these tradeoffs with injection timing retard can be changed through the application of new technologies such as common rail fuel systems and EGR as discussed elsewhere in this section.

2.2.4 Exhaust Gas Recirculation

EGR reintroduces or retains a fraction of the exhaust gases into the cylinder. The use of EGR decreases NOx formation in three different ways:

1. *Thermal Effects Due to Mass:* EGR can thermally reduce peak combustion temperature: Increasing the mass of the cylinder contents by increasing carbon dioxide (CO_2) and water vapor concentrations reduces peak cylinder temperatures during combustion.[26] At higher engine loads (with increased fuel injection quantities) with EGR, increased turbocharger boost pressures are necessary to prevent increased soot formation due to low air-to-fuel ratios. The increased boost

pressure further increases the mass of cylinder contents.

2. *Dilution Effect*: A fraction of the air within the cylinder is replaced with inert exhaust, primarily CO_2 and water vapor. This reduces the amount of molecular oxygen available for dissociation into atomic oxygen, an important step in NOx formation via what is know as the Zeldovich mechanism.[27]

3. *Chemical Dissociation Effect:* Although perhaps of less significance than thermal and dilution effects, the high temperature dissociation of CO_2 and water vapor is highly endothermic, and thus can reduce temperatures via absorption of thermal energy from the combustion process.[28]

EGR can be implemented in a variety of ways:

1. *External high pressure loop EGR*: In this case exhaust from the exhaust manifold (upstream of, or integral with, the turbocharger exhaust turbine) is routed into the intake manifold (downstream of the turbocharger compressor and the aftercooler). Under many conditions the intake manifold is at a higher pressure than the exhaust manifold. Therefore some means of driving EGR flow is necessary, such as a venturi, intake throttle, pump, or some combination of these components. One disadvantage of this approach is that it reduces exhaust energy available to drive the turbocharger.

2. *External low pressure loop EGR:* In this case, exhaust is routed from downstream of the turbocharger exhaust turbine to the inlet of the turborcharger compressor. This approach is generally not favored for diesel engines since the turbocharger compressor and aftercooler are subject to fouling from PM and other exhaust constituents.

3. *Internal EGR:* This can be accomplished via adjustments to valve timing events that result in increased retention of residual exhaust within the cylinder. It can also be accomplished by introducing a separate exhaust valve opening event that allows exhaust from adjacent cylinders to be drawn into the cylinder from the exhaust manifold.

There are both cooled (engine-coolant heat exchanger) and uncooled varieties of external EGR, and at least one source has investigated expansion cooling of internal EGR through use of early intake valve closing (a variant of the Miller-Atkinson cycle).[29]

One of the drawbacks of hot EGR is that the high temperature of the EGR increases the intake manifold temperature substantially. This has two negative effects. The first is reduced intake charge density which lowers the fresh air/fuel ratio for a given level of turbocharger boost. The lower air/fuel ratio can result in higher PM emissions if the boost pressure is not increased to compensate for the lower intake charge density. Even if the boost pressure is increased, the additional pumping work done by the turbocharger can cause an increase in fuel consumption. The second negative effect of the high intake manifold temperature is that it decreases the effectiveness of the EGR. NOx is a strong function of temperature, and any increases in the intake charge temperature will result in higher NOx production during the combustion process. The impact of the temperature is smaller than the overall impact of the EGR so the net effect is still a reduction in NOx, but lowering the intake charge temperature would lead to an even greater NOx reduction. For these reasons, a number of highway manufacturers are using cooled EGR to meet the 2004 highway emission standards and we anticipate this technology may be applied to some nonroad applications.[30]

Exhaust gas recirculation reduces the air-fuel ratio at a given engine load by two mechanisms: dilution of the fresh air charge and increased charge temperature. These mechanisms can be countered by higher intake manifold pressures. Higher intake manifold pressures would also be necessary to maintain power density and air-fuel ratios sufficient to prevent excessive PM increases. The additional pressure would increase the charge density and maintain the desired air-fuel ratio. To accomplish this EGR equipped engines are likely to use turbomachinery capable of operating at higher pressure ratios. The higher pressure ratios will also increase the compressor discharge temperature and require additional aftercooler heat rejection to reduce the fresh air charge temperature back to previous non-EGR levels.

2.2.5 Induced Mixing/Charge Motion

Inducing turbulent mixing is one means of increasing the likelihood of soot particles interacting with oxidants within the cylinder. Turbulent mixing can be induced or increased by a number of means including increased (high) injection pressure, multiple/split injections, intake port/valve design and piston bowl design.

When diesel fuel is injected into the cylinder during combustion the high pressure fuel spray causes increased motion of the air and fuel within the cylinder. This increased motion leads to great air and fuel interaction and reduced particulate matter emissions. Increasing fuel injection pressure increases the velocity of the fuel spray and therefore increases the mixing introduced by the fuel spray.

Multiple injection/split injection has been shown to significantly reduce particulate emissions, most notably in cases that use retarded injection timing or a combination of injection timing retard and EGR to control NOx.[31,32,33,34] The typical diffusion-burn combustion event is broken up into two events. A main injection is terminated, then followed by a short dwell period with no injection, which is in turn followed by another short injection event, see Figure 2-2. The second pulse of injected fuel induces late-combustion turbulent mixing. The splitting of the injection event into two events aids in breaking up and entraining the "soot cloud" formed from the first injection event into the bulk cylinder contents. Sufficient control of the post injection event would likely require the use of either a high-pressure common rail or HEUI fuel injection system.

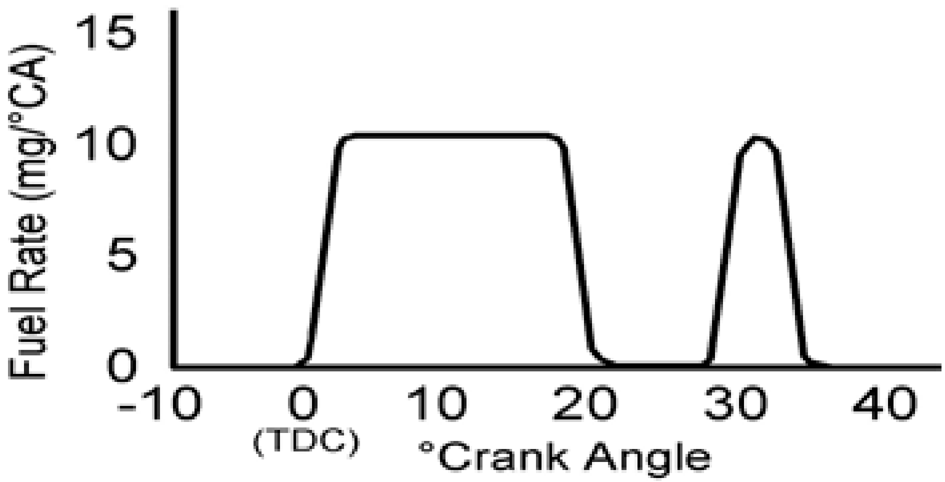
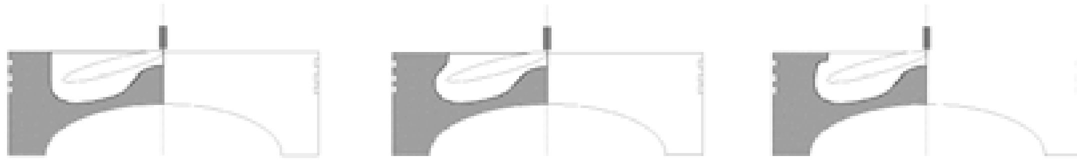


Figure 2-2
An example of using multiple fuel injection events to induce late-combustion mixing and increase soot oxidation for PM control
(Adapted form *Pierpont, Montgomery and Reitz, 1995*).

Increasing the turbulence of the intake air entering the combustion chamber (i.e., inducing swirl) can reduce PM by improving the mixing of air and fuel in the combustion chamber. Historically, swirl was induced by routing the intake air to achieve a circular motion in the cylinder. Manufacturers are, however, increasingly using "reentrant" piston designs in which the top surface of the piston is cut out to allow fuel injection and air motion in a smaller cavity in the piston to induce additional turbulence. Manufacturers are also changing to three or four valves per cylinder, which reduces pumping losses and can also allow for intake air charge motion. The effect of swirl is often engine-specific, but some general effects may be discussed.

At low loads, increased swirl reduces HC, PM, and smoke emissions and lowers fuel consumption due to enhanced mixing of air and fuel. NOx emissions might increase slightly at low loads as swirl increases. At high loads, swirl causes slight decreases in PM emissions and fuel consumption, but NOx may increase because of the higher temperatures associated with enhanced mixing and reduced wall impingement.[35] A higher pressure fuel system can be used to offset some of the negative effects of swirl, such as increased NOx, while enhancing the positive effects such as a reduction in PM.[36] Intake air turbulence such as “swirl” can be induced using shrouded intake valves or by use of a helical-shaped air intake port.[37] Swirl is important in promoting turbulent mixing of fuel and soot with oxidants, but can reduce volumetric efficiency.

Piston bowl design can be used to increase turbulent mixing. One example of this is the reentrant piston bowl shown in Figure 2-3. Reentrant bowl designs induce separation of the flow over the reentrant “ledge” of the piston and help to maintain swirl through the compression stroke and into the expansion stroke.[38]



(A) (B) (C)

Figure 2-3
Schematic examples of a straight-sided piston-bowl (A), a reentrant piston bowl (B), and a deep, square reentrant piston bowl (C).

2.2.6 Control of Air-to-Fuel Ratio

Availability of oxidants (primarily oxygen) is highly dependent on the overall air-to-fuel ratio at which the engine is operated. Thus soot formation/oxidation and PM emissions are a strong function of the overall A/F ratio of the engine. Temporary conditions of fuel-rich air-to-fuel ratio can occur on turbocharged engines when the engine power demand increases sharply. This is because the fuel system can increase fueling immediately but the turbocharger takes some time to increase air flow. A well known example of this is emission of black smoke when an older diesel vehicle (without A/F control) accelerates from a stoplight. Electronic control of fuel injection can limit the injected quantity of fuel until sufficient air supply (i.e., boost pressure) can be obtained. Electronic wastegate control and electronically controlled, variable geometry turbochargers (VGT) can also be used to improve turbocharger response and improve PM emissions under such transient conditions. Electronic control of EGR is also necessary to prevent temporary conditions of overly fuel-rich air-to-fuel ratios.

2.2.7 Diesel Oxidation Catalyst

The flow-through oxidation catalyst reduces HC and PM emissions by oxidizing both gaseous (volatile) hydrocarbons and the semi-volatile portion of PM known as the volatile organic fraction (VOF) forming carbon dioxide and water. The VOF consists of hydrocarbons adsorbed to the carbonaceous solid particles and heavy hydrocarbons that under atmospheric conditions will condense to form liquid aerosols. The soot or elemental carbon portion of the PM remains largely unaffected by the catalyst. Although engine design improvements have reduced VOF emissions, VOF can still comprise a significant fraction of the total PM mass.

Diesel oxidation catalysts (DOCs) can also oxidize sulfur species in the exhaust to form sulfate PM. At higher exhaust temperatures, catalysts have a greater tendency to oxidize sulfur dioxide to form sulfates, which contribute to total PM emissions. Catalyst manufacturers have been successful in developing catalyst formulations that minimize sulfate formation.[39] Catalyst manufacturers have also adjusted the placement of the catalyst to a position where the needed VOF reduction is achieved, but sulfate formation is minimized.[40] Nonroad fuel with sulfur concentrations higher than 0.05 weight percent will limit the effectiveness of diesel oxidation catalysts but as shown by at least one manufacturer, DOCs can be used to reduce PM emissions as part of a Tier 3 compliant emission strategy (see Figure 2-4).[41]

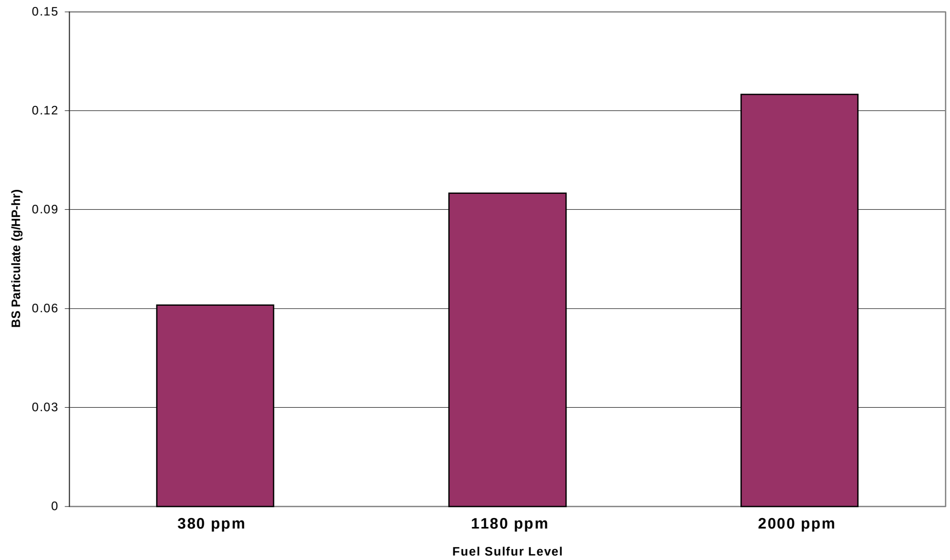


Figure 2-4
Nonroad Tier 3 Particulates as a Function of Fuel Sulfur 8 Mode C1 Cycle, Oxidation Catalyst Equipped Diesel Engine

2.2.8 Control of Oil Consumption

Reducing oil consumption not only decreases maintenance costs, but also VOF and PM emissions. Reducing oil consumption has been one of the primary ways that highway diesel engines have complied with the PM standard since 1994. Oil consumption through the combustion chamber can be reduced through improvements in piston ring design and through the use of valve stem seals. Piston rings can be designed to "scrape" oil from the cylinder liner surface back into the crankcase reducing the amount of oil consumed during combustion from the cylinder. Valve stem seals can be used to reduce oil leakage from the lubricated regions of the engines valvetrain into the intake and exhaust ports of the engine. Engine designs that incorporate these technologies have reduced VOF and PM emissions.

2.3 Diesel Emission Control Systems Capable of Tier 3 Compliance

The preceding sections describe the fundamentals of emission formation in diesel engines and the control technologies used to reduce these harmful emissions. The control technologies identified here are all well known and represent existing control technologies applied either to highway or nonroad diesel engines. The application of these technologies to nonroad engines does not require new invention or substantial changes to the technologies. Many of the technologies discussed here are strongly interrelated, with changes in one area potentially leading to synergistic improvements in others (e.g., advanced common rail fuel systems can allow for reduced NOx and PM emission while improving fuel economy). The integration of these technologies into a single emission control system design can allow for substantial reductions in diesel engine emissions. We do not believe that a single emission control technology alone will be applied in order to meet the Tier 3 emission standards. Rather we believe, based on the substantial test data provided in the following section, that a number of different systems approaches incorporating many of the technologies discussed here can be used to comply with the Tier 3 standards. In this section, we have included examples of engine designs which incorporate the previously discussed emission control technologies into total emission control systems in order to demonstrate the emission control capability needed to meet the Tier 3 standards. These examples serve to show that a systems approach incorporating existing technologies can achieve compliance with the Tier 3 standards.

2.3.1 Optimized Engine Systems Using Cooled EGR

The use of EGR for NOx control is a well established technology for gasoline engines and is experiencing growing acceptance for highway diesel engines. Cooled EGR systems for diesel engines are in current production for light-duty vehicles in the U.S. and Europe as well as for some heavy-duty transit bus applications in the U.S.[42] Several diesel engine manufacturers including Cummins, Detroit Diesel, and Mack have indicated that cooled EGR will be the primary technology used to comply with the heavy-duty highway 2004 engine standards. These same manufacturers are expected to have cooled EGR engines in production starting in 2002, more than four years earlier than the start of the Tier 3 phase-in.[43]

One example of the emission control systems these companies will use is the system Cummins has announced it will introduce in late 2002 compliant with the heavy-duty highway emission standards set for 2004. This engine uses a high pressure loop (exhaust manifold to intake manifold) cooled EGR system, an advanced high pressure common rail fuel system, improved turbocharger system, a centrally located fuel injector, and combustion system enhancements. This system incorporates a jacket water cooled EGR cooler and a variable geometry turbocharger to drive and control the EGR rate.[44] Lower power ratings (similar to typical nonroad engine ratings) use a conventional turbocharger with a wastegate. With this emission control system, the engine is able to meet the heavy-duty highway transient certification cycle and the Supplemental Emissions Test standards of 2.5 g/hp-hr NOx+NMHC, 0.1 g/hp-hr PM.[45] This engine also has to meet a Not-To-Exceed (NTE) zone cap of 3.12 g/hp-hr NOx+NMHC and 0.125 g/hp-hr PM. The NTE zone includes six of the eight nonroad certification modes (see Figure 2-5). The six that are included in the NTE region are the most heavily weighted test modes in terms of the total emission and work used to calculate the nonroad composite emission rate. Therefore, if an engine is compliant at those six modes it is highly likely to be compliant with the eight mode composite level. Since this engine is compliant with the NTE limit, it is likely that this highway engine would be compliant with the nonroad Tier 3 emission standards. In fact, the emissions level would likely be close to 2.5 g/hp-hr NOx+NMHC (well under the Tier 3 standard) over the non-road certification composite. This is because compliance with the Supplemental Emissions Test standards includes testing at 13 steady-state test modes which are similar or in some cases coincident with the nonroad emission test modes. If this same engine were sold in a nonroad application for Tier 3, it may even be possible to calibrate the engine with less reliance on cooled EGR while still meeting the Tier 3 standard.

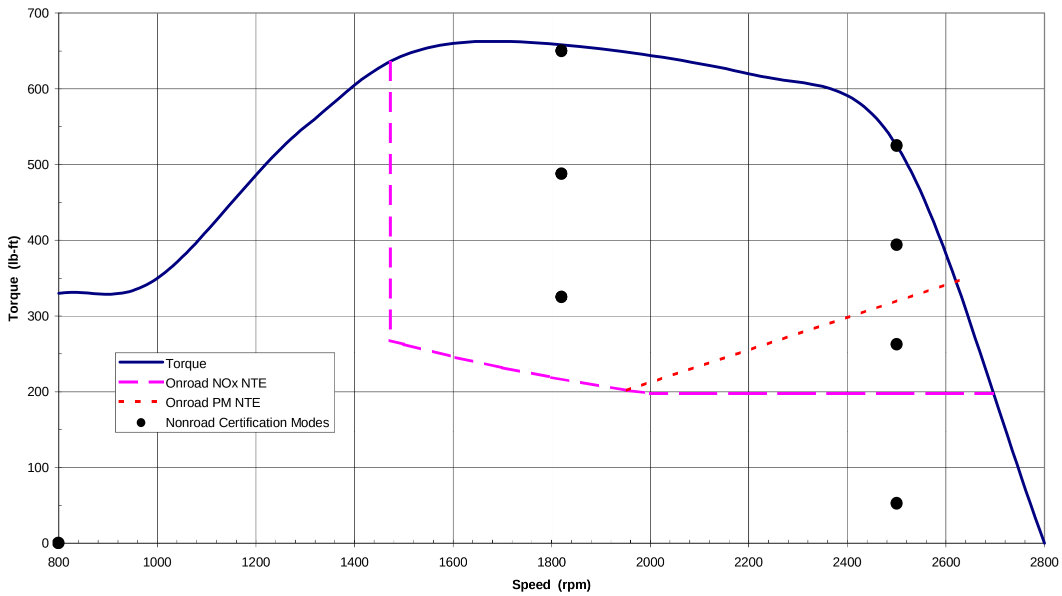


Figure 2-5
Map of Engine Operating Range (Torque vs Speed)

The emission control system described here represents the kind of technology that we anticipated would be used to meet the Tier 3 emission standards when we set the standards in 1998. We continue to believe that this approach can be used to meet the Tier 3 emissions standards, but we no longer are assuming that this will be the only way that emission control technologies will be combined in order to meet the Tier 3 standards. The following sections detail two more approaches that we believe some manufacturers could use to comply with the emission standards.

2.3.2 Caterpillar's ACERT

Caterpillar has announced that it will produce engines compliant with the Tier 3 emission standards using existing highway diesel engine technologies. The new engines being developed by Caterpillar will be marketed under the trade name "Advanced Combustion Emissions Reduction Technology" or "ACERT." Caterpillar indicated in a letter to the EPA that it is "prepared to license the ACERT technology, including related patents, to Caterpillar's engine competitors."[46] Caterpillar has provided data for a mid-range industrial engine (Caterpillar 3126) that meets the Tier 3 standards (Figure 2-6 shows three compliant calibrations of the ACERT system).[47] Caterpillar describes ACERT as a combination of proven hardware components integrated in a systems approach to meet emissions and performance goals. The engines use open-loop electronic engine controls, the HEUI fuel system, a variable geometry turbocharger, valve event control, and a diesel oxidation catalyst (DOC). While Caterpillar did not identify a specific NOx or PM reduction associated with each of the technologies in the ACERT system, the following discussion describes how the identified technologies may work in the ACERT strategy.

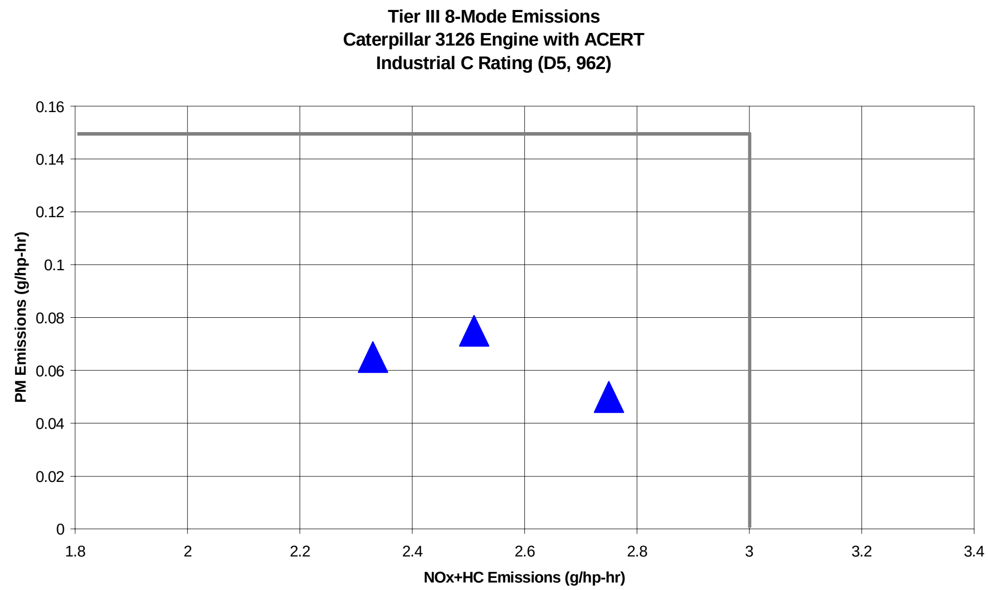


Figure 2-6
Tier 3 Emissions Caterpillar 3126 ACERT Engine

Caterpillar has stated that the HEUI injection system used with ACERT has the ability to accurately and independently control the number of fuel injection events, fuel injection pressure and the injected quantity. Multiple injections allow the use of a late "post-injection" event for PM control, which can allow further injection timing retard for NOx control. Caterpillar has stated that the VGT used within ACERT is used to allow the electronic control system to regulate intake air pressure. The use of VGT in concert with electronic control of injection timing and injection quantity can extend A/F and PM control over a broader range of engine operating conditions, thus reducing PM emissions while maintaining NOx control. Control of valve events can be used to reduce NOx emissions by allowing a degree of internal EGR either by retaining more residual gases in cylinder or by allowing exhaust flow-reversal. Control of valve events can also be used to provide a degree of expansion cooling of the cylinder contents. Caterpillar has not commented on the potential use of valve event control for reducing NOx emissions.

The diesel oxidation catalyst used by Caterpillar provides additional HC control, which will likely improve the ability to meet the Tier 3 NMHC+NOx standard. Using a diesel oxidation catalyst may also provide a reduction in the semi-volatile organic compounds that contribute to PM. Caterpillar provided emissions data showing that over the range of fuel sulfur levels required for in-use testing under Tier 3, sulfate-make with the DOC selected was sufficiently low to allow compliance with the Tier 3 PM emission standard (see Figure 2-4).

2.3.3 Hot EGR and Combustion System Optimization

Under contract with EPA, Southwest Research Institute (SwRI) has been working to evaluate a variety of means to reduce emissions from a typical nonroad engine, with engineering support from a number of engine/component manufacturers. For this work a Tier 1 compliant John Deere 4045H Powertech diesel engine was used as a baseline for emissions improvement and development. The engine, as delivered by John Deere, has a displacement of 4.5 liters, and is equipped with a turbocharger, an aftercooler, two valves per cylinder and a mechanical direct injection fuel system.[48] John Deere has recently announced improvements to this engine that include the use of four valves per cylinder, an electronic fuel system, and higher capacity electronics.[49] This new improved engine was not available for use at the time the test program was started.

One step in the work at SwRI included the addition of an external hot EGR system controlled by an EGR valve and variable nozzle turbocharger (a particular type of VGT) with an electronically controlled fuel system to the engine. This testing demonstrated NOx + HC emission levels of 4.0 g/hp-hr with a PM level of 0.12 g/hp-hr over the nonroad test cycle.[50] The NOx reduction performance realized in this step of the development work was limited in part by limitations on the amount of EGR that could be achieved with the test configuration. Additional EGR flow could be achieved through the use of an intake-side venturi, an integral EGR turbo pump, or other intake flow control strategies. From the testing at SwRI, additional EGR flow to reduce NOx at rated and peak torque operating conditions could be expected to significantly reduce NOx emissions.

An additional design iteration of the engine by SwRI included the use of cooled EGR and air-to-air aftercooling. This engine demonstrated NOx+HC emissions of 3.3 g/bhp-hr and PM emissions of 0.10 g/bhp-hr over the nonroad test cycle, using fuel sulfur and aftercooling levels appropriate to nonroad engine applications. The significant NOx and PM emission reductions demonstrated in this test program were accomplished without the use of a common rail fuel system which would be expected to allow for further reductions in NOx and PM control due to the added flexibility it would provide in controlling injection pressure (rate) and multiple injection events.

The various design iteration steps of the development program at SwRI are documented in Figure 2-7.

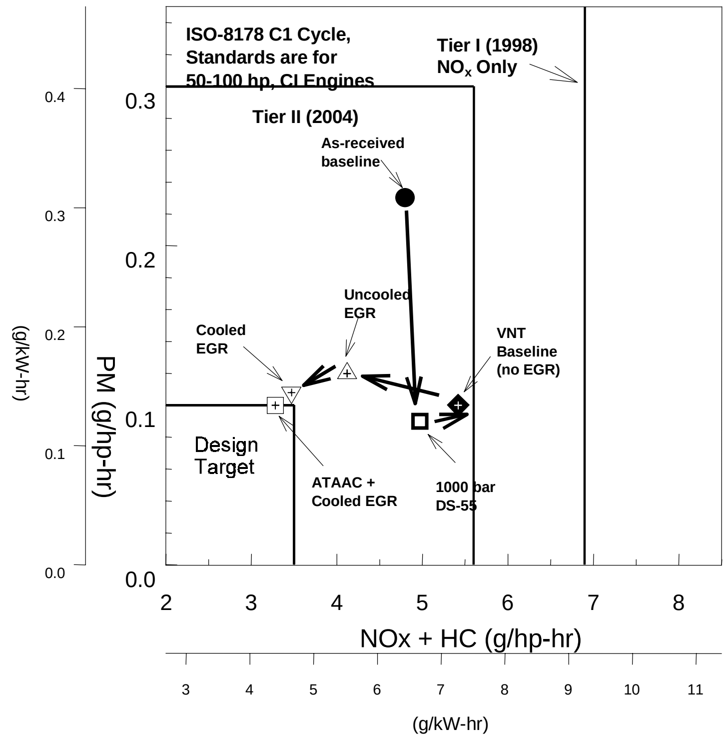


Figure 2-7
Technology Sequence for SwRI Engine

John Deere has been investigating a number of system solutions to develop nonroad engines compliant with the Tier 3 emission standards. One approach that John Deere has focused on is a system incorporating a high pressure fuel injection system with injection rate shaping capabilities, a diesel oxidation catalyst (to lower HCs and PM), and hot EGR (either internal or external).[51] This technology development approach is consistent with the types of systems solutions considered in this paper.

2.4 Special Considerations

The Tier 3 emission standards were developed based upon our assessment that emission control technologies developed for highway diesel trucks could be applied to nonroad engines and equipment. We see considerable evidence that this transfer of technology is already occurring with the introduction of Tier 2 compliant engines (e.g., the use of common rail fuel systems, air-to-air aftercooling and advanced electronics), and we continue to believe that highway technology transfer will enable Tier 3 emission compliant engines. However, we have always recognized that there are differences between highway vehicles and nonroad equipment that must be considered in evaluating engine technologies. These differences include acceptable levels of heat rejection, limited aftercooler performance without ram-air for nonroad, and equipment packaging constraints. In large part due to these differences, the Tier 3 standards were set at a less stringent level when compared to the corresponding highway engine standards. The standards are both numerically less restrictive and also defined under less restrictive test conditions (i.e., nonroad has a simple eight mode steady-state test cycle, highway engines must meet a demanding transient emission test including both cold and hot cycles). We continue to believe that these less stringent standards appropriately account for the unique nonroad engine and equipment issues as discussed in the following sections.

2.4.1 Nonroad Fuel Quality (Sulfur)

Diesel fuel sold for use in nonroad equipment is not currently regulated by EPA. Typical nonroad diesel fuel meets ASTM specification D975 which sets a maximum sulfur level of 5,000 ppm. Fuel meeting this standard commonly has a sulfur level of up to 3,000 ppm. For this reason, as well as for reasons of convenience and availability, many nonroad equipment users choose to operate their equipment on fuel sold for highway vehicle use. Highway diesel fuel is regulated and has a maximum sulfur content of 500 ppm with a typical average sulfur level of 300 ppm. Nonroad engines and equipment are designed to operate on the maximum fuel sulfur level that may be encountered during the vehicle's life (e.g., 5,000 ppm). Sulfur in diesel fuel can cause increased corrosion of engine components, accelerated deterioration of engine lubricating oil, accelerated engine wear and increases in PM emissions. Consideration of these issues is given in nonroad engine designs and maintenance schedules.

The use of cooled EGR to comply with the Tier 3 emission standards may be more difficult when compared to highway applications due to the higher fuel sulfur level typical of nonroad diesel fuel. Sulfur is an issue since it forms corrosive sulfuric acid (H_2SO_4) in diesel exhaust. During combustion sulfur is oxidized 97-99% to sulfur dioxide (SO_2) and trace amounts of sulfate (SO_3).[52] SO_3 also forms in the exhaust manifold as equilibrium thermodynamics begin to favor its formation below ~730°C. However, reaction kinetics limit the SO_3 formation rate.[53] In diesel exhaust SO_3 immediately reacts with water vapor to form aqueous sulfuric acid (~73% H_2SO_4 by wt.), and this acid begins to condense from about 80 to 145°C , depending upon engine operating conditions and fuel sulfur content.[54] [55] [56] Although the acid's concentration is strong, the acid at this point only accounts for ~0.5% of the fuel sulfur. However, once the exhaust cools below the water vapor dew point (~30 to 80°C), SO_2, which accounts for nearly all of the fuel sulfur, will begin to react significantly with condensed water to form H_2SO_4.[57] Since nonroad fuel has six times the sulfur content, the rate of acid condensation will increase by a similar amount relative to highway.[58]

The increase in condensation rate is significant since the increased fuel sulfur content increases a nonroad engine's exposure to sulfuric acid. The acid impacts the engine in at least three ways: direct corrosion of engine components, secondary wear from corrosion byproducts, and acidification of the engine oil. Condensation can occur in the EGR cooler, after the EGR is mixed with the fresh air in the intake system, and on the cylinder walls. Studies have shown that increased fuel sulfur levels (350 ppm to 13,300 ppm) increase engine wear significantly, particularly in conjunction with EGR.[59] Material selection will be key to making cooled EGR work with nonroad fuel.

In the EGR cooler, condensation can occur over a wide range of operating conditions.[60] Condensation in the cooler is a function of the acid/water dewpoint temperature which is influenced by sulfur concentration, pressure, and the air-fuel ratio of the engine. Increasing sulfur concentration, increasing pressure, and decreasing air-fuel ratio all increase the dewpoint temperature and the likelihood of condensation.[61] The fuel sulfur level is not an engine design parameter, but pressure and air-fuel ratio can be manipulated by the engine designers. Unfortunately, these factors tend to work against each other such that higher air-fuel ratios require higher pressures and vice versa, so that this trade-off, while it will certainly play into the engine optimization, will not be able to completely eliminate condensation in the EGR cooler. Lower coolant temperatures also increase the condensation rate.[62] A simple solution to this could be to turn EGR off until the coolant temperature has reached its normal operating temperature. In any case, condensation will still occur in the EGR cooler. Work has already been done for EGR coolers that shows materials are available that provide suitable corrosion resistance.[63] Higher grade stainless steels and fabrication methods (e.g., laser welding rather than brazing) will allow EGR coolers to live in this corrosive environment.

Direct corrosion of the engine components also occurs in the cylinder. Acid condensation can corrode the piston, rings, and liner. The most damaging corrosion occurs at the top ring reversal area of the liner. Due to the slow piston speed in this area, lubrication is poor, making the liner surface finish critical for oil control. The liner surface finish is carefully selected and controlled to hold oil and provide lubrication for the rings. The top ring reversal area is the liner area most exposed to high pressure combustion products, including acids. Corrosion in this area compromises the surface finish causing loss of lubrication and further accelerated wear. Therefore it is very important to select the ring and liner materials to be corrosion resistant. In addition to careful selection of the basic materials, plasma sprays can be used to provide corrosion resistance. Tests have shown these sprayed on coatings (like FFS, a material containing 434 stainless steel and Ni-BN) to be effective in reducing formic acid corrosion of iron liners.[64]

Condensation can also occur when the EGR is mixed with the lower temperature fresh air in the engine intake system. The same factors influence the dewpoint temperature and condensation rate as in the EGR cooler, with the addition of the fresh air temperature. The fresh air temperature is a function of the ambient temperature, engine load (boost level and compressor efficiency), and aftercooler efficiency. As discussed previously, the aftercooler efficiency of nonroad equipment is not likely to be as high as found in highway equipment due to the lack of ram air. Consequently, the fresh air temperature will be higher than on highway. This will reduce the condensation rate somewhat compared to highway engines at similar conditions. What this means is that the condensation rate will not quite scale directly with the fuel sulfur content but will be somewhat less depending on the particular engine and equipment.

Since condensation will be occurring in the intake system downstream of the EGR introduction point, the materials that it comes in contact with will need to be corrosion resistant.[65]

Corrosion in the intake system is particularly troublesome because it can accelerate cylinder kit wear. As the intake system corrodes, the corroded materials can flake off and find their way into the engine. Some of these corrosion products, like aluminum oxide, are very good abrasives that can rapidly abrade the cylinder liner and rings. To prevent this, coatings or materials can be used to reduce or eliminate the exposure of corrosion susceptible materials. Stainless steels or improved corrosion resistant aluminum materials might be used in place of aluminum castings in the intake system, for instance**.**

Should nonroad engine and equipment manufacturers choose to use cooled EGR as part of a Tier 3 engine emission strategy, we believe that they may have to make some changes in material selection and maintenance intervals compared to similar highway engines due to the high sulfur content of nonroad diesel fuel. However, we understand that the identification of these material changes will come as a natural extension of the extensive work already done by highway engine manufacturers and their suppliers to develop cooled EGR systems.[66] It may be possible given the rapid progress of highway EGR system development that no changes will be necessary due to the very high quality and durability levels expected of highway diesel engines. Additionally, the use of low sulfur highway diesel fuel is a common practice for many users of nonroad equipment and would for those users reduce any increased maintenance levels expected when compared to highway engines.

2.4.2 Nonroad Equipment Design Impacts

Although assessing the feasibility of new emission standards primarily centers on the emission control technologies available to engine designers, there is an additional concern as well, stemming from how these emission controls might alter equipment designs. New engine or aftertreatment characteristics that could compromise the functionality or safety of nonroad equipment, or that may result in the need for sweeping redesigns of equipment models in too short a leadtime period, impact the feasibility of emission standards.

These impacts on equipment manufacturers were thoroughly considered in the RIA for the 1998 rulemaking that set the Tier 3 standards. As a result, a number of special flexibility measures were adopted in that final rule specifically to mitigate these impacts. For example, equipment manufacturers may exempt a certain portion of their production from the need to use engines meeting the new standards. This exemption allowance spans seven years to cover both Tier 2 and Tier 3 product introductions.

The physical impacts that the use of new emission controls may have on equipment designs essentially fall into two broad categories– (1) increased heat rejection and fuel consumption (resulting in larger heat exchangers, cooling fans, and fuel tanks), and (2) packaging changes to accommodate engine and heat exchanger profile changes or the addition of exhaust emission control devices.

Some manufacturers have expressed a belief that the potential Tier 3 technologies discussed in Section 2.2 will result in added heat rejection and a resulting need for larger, possibly relocated, heat exchangers and cooling fans.[67] Cooling of the exhaust gas flow in a cooled EGR system, for example, requires the use of an additional cooling unit. It is not evident that this increased heat rejection would be associated with an overall increase in fuel consumption and need for larger fuel tanks, however, because the addition of EGR to accomplish NOx control can allow engine designers to advance injection timing from the retarded timing strategies used for NOx control in Tier 2 engines, thereby recovering some of the efficiency loss associated with timing retardation. This, in fact, has been projected for highway diesel engine designs that use cooled EGR to meet the 2004 model year standards.[68] [g]

Even though cooled EGR systems have the potential for an increase in heat rejection, Caterpillar expects that its ACERT technology for Tier 3 will result in at most a slight increase in heat rejection compared to Tier 2 engines.[69] Caterpillar is also projecting that the use of ACERT technology in nonroad diesels will not reduce fuel economy, reliability, or performance.[70]

It seems clear that some packaging impacts will result from Tier 3 technologies. Although highway engine design experience indicates that EGR plumbing in itself may not greatly alter the engine profile, adding an EGR cooler could result in additional equipment redesign in applications with engine compartments tightly constrained by functional or safety objectives. ACERT technology, too, may involve additional equipment design engineering to accommodate aftertreatment devices and other changes.

Although these potential equipment impacts may result in added engineering effort to match equipment to Tier 3 engines, they are not more severe than what was envisioned in the feasibility assessment undertaken in the 1998 rule. In fact, the advent of ACERT technology, with the expectation of little to no increase in heat rejection, provides an additional path to minimizing equipment impacts not envisioned in 1998. The fact that Caterpillar makes not only engines, but also equipment using those engines in a large variety of applications, reinforces the expectation that this technology is being developed with the needs of equipment designers in mind.

The 1998 rule set a multi-tier schedule of emission standards extending through most of this decade, thus helping engine and equipment manufacturers to plan product redesigns. The RIA expressed the expectation, based on manufacturers' comments, that equipment redesigns for Tier 2 would be made with Tier 3 needs in mind, so that further changes for Tier 3 would be minimized.[71] Nevertheless, we developed the flexibility provisions in the final rule to extend to both tiers in order not to constrain manufacturers redesign strategies. For example, we provided a 7 year period, spanning Tier 2 and Tier 3 phase-in dates, in which the equipment manufacturer exemption allowance provisions could be used. In fact, some Tier 2 engine redesigns have been accomplished with very little change to parameters that affect equipment designs, highlighting

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[g] The reason that fuel efficiency can be maintained even though more engine heat is rejected to a heat exchanger is that less heat would leave the engine through the exhaust gases, a likely phenomenon with cooled-EGR systems.

the value of this flexible approach.[72] The fact that the final rule had envisioned an added PM control requirement for Tier 3, a requirement not included in this paper's feasibility assessment, reinforces our belief that the rule's conclusion of Tier 3 feasibility with respect to equipment impacts is still appropriate.

2.5 Tier 3 Technology Assessment Conclusions

In 1998, when we set the Tier 3 emission standards, we did so with the belief that the technologies being developed for highway diesel engines (especially cooled EGR) could be carried over and applied to nonroad diesel engines. Since that time we have followed developments in both the highway and nonroad diesel engine markets and have observed continued advancements in emission control technologies. Moreover we have observed an increasing rate of highway engine technologies (especially electronic fuel system technologies) being applied to nonroad engines.

While we did predict that highway engine technologies could be applied to nonroad engines, the effectiveness of such an approach and the preferred technology paths developing from it are different from what we had assumed. In 1998 we assumed that cooled EGR would be the primary technology used by all engine manufacturers to comply with the Tier 3 standards. We no longer believe that cooled EGR will be the preferred technology for all engine manufacturers. It now appears that there are several different system approaches incorporating existing technologies (as detailed in the preceding sections) available to diesel engine manufacturers which will allow for compliance with the Tier 3 emission standards. The fact that diesel engine manufacturers have identified multiple system solutions to Tier 3 compliance reinforces our assessment that the Tier 3 emission standards are feasible.

As described in the sections above, the application of highway engine technologies to nonroad engines can enable substantial reductions in NOx+NMHC emissions to the levels required by the Tier 3 emission standards. While some changes to the technologies may be required in order to address unique nonroad issues, the fact that the Tier 3 emission standards do not begin to phase-in until 2006 (fully phased-in in 2008), leads us to conclude that there is ample lead time for these design enhancements to occur. In addition, the fact that a nonroad engine and equipment manufacturer (Caterpillar) has provided evidence that it can meet the Tier 3 standards four years in advance of 2006 provides us with additional assurance that the standards are feasible. For all of these reasons, we continue to believe these standards are technologically feasible.

3. Tier 2 Under 50 hp Technology Assessment

Nonroad diesel engines with power ratings under 50 hp were not regulated in our 1994 rulemaking that set the first Tier 1 standards. Instead, Tier 1 standards for these engines were set in the 1998 rulemaking and took effect in 1999 and 2000 (phased in by horsepower). Tier 2 standards were also set for these small engines in the 1998 rule, to phase in over 2004-2005 (Table 3-1). These Tier 2 standards were set at stringency levels comparable to the Tier 2 standards for larger nonroad engines, which in turn were based on conventional in-cylinder control technologies already in-use in highway engines, but with allowance made in the standards levels for aspects of design and operation unique to small engines, such as the priority put in this market on simple, low-cost, non-electronic designs. Shorter useful life requirements were also adopted. Even with these allowances made, we felt that it was appropriate to include the small Tier 2 engines in the technology review because at the time of the 1998 rulemaking these engines had never been regulated by EPA, and we expected that a review undertaken after Tier 1 designs and certification test results became available would be beneficial.

Table 3-1
Small Nonroad Engine Tier 2 Standards (g/hp-hr)

Engine Power	Model Year	NMHC+ NOx	CO	PM
hp<11	2005	5.6	6.0	0.60
11≤hp<25	2005	5.6	4.9	0.60
25≤hp<50	2004	5.6	4.1	0.45

We have reviewed the latest certification testing data available in our publicly available certification database for Tier 1 engines in the under 50 hp class, consisting of 220 engines certified for the 2001 model year. Although Tier 2 standards do not take effect until 2004 at the earliest, many of these Tier 1 engines are already meeting the Tier 2 standards levels, as shown in Table 3-2. Although more indirect injection (IDI) engines meet the Tier 2 levels than direct injection (DI) engines, there is appreciable compliance demonstrated in both categories and across a broad range of power ratings and manufacturers.[h] The certification test results are presented in detail in a memo to docket A-2001-28.[73]

Among the engines that do not already meet the Tier 2 standards, roughly half of both the DI and the IDI engines do comply with the PM standard and exceed the NOx+NMHC standard by only 10 percent or less. All 220 engines demonstrated compliance with the Tier 2 carbon monoxide standard level. We believe that this test data, provided on engines already marketed

[h] DI engines inject diesel fuel directly into the combustion chamber. IDI engines employ a pre-mixing side chamber, which allows lower injection pressures. Both types of engines are common in the small nonroad diesel market and were considered in the 1998 rule in its analysis of standards feasibility.

using conventional technologies of proven durability, combined with the 3 to 4 years of leadtime remaining before Tier 2 implementation, shows conclusively that the Tier 2 small engine standards are feasible.

Table 3-2
Tier 1 Engine Compliance With Tier 2 Standards

	Tier 2 Compliant Engine Families	Total Engine Families	Percent Tier 2 Compliant
<11 hp			
IDI	9	12	75%
DI	4	18	22%
IDI+DI	13	30	43%
11-25 hp			
IDI	44	50	88%
DI	3	16	19%
IDI+DI	47	66	71%
25-50 hp *			
IDI	44	55	80%
DI	7	60	12%
IDI+DI	54	124	44%

* For this hp category, the sum of IDI and DI engines does not equal the indicated total number of engines because the certification information for 9 engines did not specify the fuel system.

4. Dealing With Future Air Quality Impacts

Nonroad diesel emissions contribute to air pollution known to have a wide range of adverse health and welfare impacts. Emissions from nonroad diesels contribute a substantial percentage of the precursors or direct components of ambient concentrations of ozone, PM, sulfur and nitrogen compounds, aldehydes, and substances known or considered likely to be carcinogens. EPA has concluded that diesel exhaust is likely to be carcinogenic to humans by inhalation at occupational and environmental levels of exposure.[74] Nonroad diesel engine emissions also contribute to adverse environmental effects including visibility impairment, acid rain, nitrification and eutrophication of water bodies.

Today, ground-level ozone and particulate matter remain a pervasive pollution problem in the United States. In 1999, 90.8 million people (1990 census) lived in the 31 areas designated as nonattainment areas under the 1-hour ozone national ambient air quality standards (NAAQS).[75] Studies of 6 to 8 hour exposures showed health effects from prolonged and repeated exposures, at moderate levels of exertion, to ozone concentrations as low as 0.08 ppm.[76] Prolonged and repeated ozone concentrations at these levels are common in areas throughout the country, and are found in areas that are exceeding, and areas that are not exceeding, the 1-hour ozone standard.[77] For example, 153 million people, or 87 percent of the total population in counties evaluated (176 million), lived in areas with 2 or more days with concentrations of 0.09 ppm or higher in 1998, including areas currently meeting the 1-hour NAAQS.[78]

The most recent PM_{10} monitoring data indicate that 14 of the designated PM_{10} nonattainment areas with a 1999 population of 23 million violated the PM_{10} NAAQS between 1997 and 1999.[i] In addition, there are 25 unclassifiable areas that have recently recorded ambient concentrations of PM_{10} above the PM_{10} NAAQS. Current 1999 $PM_{2.5}$ monitored values, which cover about a third of the nation's counties, indicate that at least 40 million people live in areas where long-term ambient fine particulate matter levels are at or above 16 $\mu g/m^3$.[79] This 16 $\mu g/m^3$ threshold is the low end of the range of long term average $PM_{2.5}$ concentrations in cities where statistically significant associations were found with serious health effects, including premature mortality.[80]

Future inventory projections suggest that adverse health effects caused by air pollution will continue in the future unless additional emission reductions are achieved. Emissions of NOx, VOC, PM, and SOx from all source categories (i.e., mobile, area, stationary) that contribute to ambient concentrations of ozone, diesel PM, and fine particulate matter are projected to begin increasing between 2010 and 2025 as economic growth overtakes expected emission reductions from current control programs. Since the 1998 nonroad diesel engine rulemaking, the belief that further action is warranted has been reinforced by growing evidence that diesel engine exhaust causes serious health problems. EPA has recently put in place

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[i] PM_{10} is PM with a diameter of less than 10 microns. $PM_{2.5}$ is PM with a diameter of less than 2.5 microns.

programs to dramatically reduce emissions from highway diesel vehicles.   As a result, nonroad diesel engines, already a major source of harmful particulate matter and ozone-forming compounds, will become a dominant mobile source of these emissions in the future.

Section 213 (a)(3) of the Clean Air Act requires EPA to establish nonroad engine standards that provide for the "greatest degree of emission reduction achievable through the application of technology which the Administrator determines will be available for the engines or vehicles to which such standards apply, giving appropriate consideration to the cost of applying such technology within the period of time available to manufacturers and to noise, energy, and safety factors associated with the application of such technology". In light of the progress being made in the development of technologies to reduce emissions from highway diesel engines and the continuing concerns about nonroad diesel impacts on air quality discussed above, we believe it may be appropriate to move the control of nonroad emissions beyond the Tier 3 program. Considering the information gathered in conducting the recent highway diesel engine and fuel rulemaking, we also believe that a similar "systems" approach is likely to be the most cost-effective way to pursue this goal. The systems approach recognizes that significant further reductions in nonroad emissions will require fuel quality improvements and so it entails adopting nonroad fuel and engine changes in a single coordinated program.

There are many possible ways of pursuing future standards for nonroad engines and fuels. For example, one manufacturer has suggested that aftertreatment-based PM standards be introduced in 2009, along with 15 ppm sulfur fuel, with more stringent NOx standards beginning to take effect in 2012.[81] This implementation schedule may be later than appropriate under the provisions of the Clean Air Act, but a standards-setting approach along these lines may merit consideration. In any approach taken, consideration would need to be given to appropriate leadtime periods, phase-in and other flexibility provisions, test cycles, in-use emissions control measures, coordination with highway fuel and engine regulations, State Implementation Plan emission reduction needs, and international harmonization goals. We would also expect the rulemaking to consider the interaction between the existing and new standards, including any ways in which a coordination of requirements under these sets of standards might be appropriate.

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