CHAPTER 4: Technologies and Test Procedures for Low-Emission Engines

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The new emission standards will require both new engine technologies and new measurement procedures. Section 4.1 documents the technical analysis supporting the feasibility of meeting the Tier 4 emission standards for nonroad diesel engines, including the not-to-exceed standards. Section 4.2 describes the development and characteristics of the new transient duty cycles and Section 4.3 describes issues related to steady-state duty cycles, including the development of new ramped-modal duty cycles and new cycles for transportation refrigeration units.

4.1 Feasibility of Emission Standards

A description of the new emission standards and our reasons for setting those standards can be found in Section II of the preamble to the final rule. This chapter documents the analysis we completed to inform the decisions described in the preamble regarding new emission standards for nonroad diesel engines. This analysis incorporates recent Agency analyses of emission-control technologies for highway diesel engines and expands those analyses with more recent data and additional analysis specific to the application of technology to nonroad diesel engines.[1,2,3]

This section is organized into subsections describing diesel emission-control technologies, issues specific to the application of these technologies to new nonroad engines, specific analyses for engines within distinct power categories (<25 hp and 25-75 hp) and an analysis of the need for low-sulfur diesel fuel (15 ppm sulfur) to enable these emission-control technologies.

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

During the past 15 years, however, more development effort has been put into catalytic exhaust emission-control devices for diesel engines, particularly in the area of particulate matter (PM) control. Those developments, and recent developments in diesel NOx exhaust emission-control devices, make the widespread commercial use of diesel exhaust emission controls feasible. EPA has recently set new emission standards for diesel engines installed in highway vehicles based on the emission-reduction potential of these devices. We believe these devices will make possible a level of emission control for nonroad diesel engines that is similar to that attained by gasoline three-way-catalyst applications. However, without low-sulfur diesel fuel, these technologies cannot be implemented.

Although the primary focus of the Tier 4 emissions program and the majority of the analysis contained in this RIA is directed at the application of catalytic emission control technologies enabled by 15 ppm sulfur diesel fuel, there are also important elements of the program based upon continuing improvements in engine-out emission controls. Like the advanced catalytic based technologies, these engine-out emission solutions for nonroad diesel engines rely upon technologies already applied to on-highway diesel engines. Additionally, these technologies form the basis for the Tier 3 emission standards for some nonroad diesel engines in other size categories. Extensive analysis and discussion of these engine-out emission control technologies can be found in the RIAs associated with the On-Highway Heavy-Duty 2004 emission standards and the Nonroad Tier 2 and Tier 3 emission standards.[4,5,6,7] Those detailed analyses are not repeated here but are a fundamental underpinning of EPA's understanding of engine-out emission controls for diesel engines and the feasibility of applying those controls to nonroad diesel engines in the Tier 4 timeframe.

4.1.1 PM Control Technologies

Particulate matter from diesel engines is made of four components;

- solid carbon soot,
- volatile and semi-volatile organic matter
- inorganic solids (ash) , and
- sulfate.

The formation of the solid carbon soot portion of PM is inherent in diesel engines due to the heterogenous distribution of fuel and air in a diesel combustion system. Diesel combustion is designed to allow for overall lean (excess oxygen) combustion giving good efficiencies and low CO and HC emissions with a small region of rich (excess fuel) combustion within the fuel-injection plume. It is within this excess fuel region of the combustion that PM is formed when high temperatures and a lack of oxygen cause the fuel to pyrolize, forming soot. Much of the soot formed in the engine is burned during the combustion process as the soot is mixed with oxygen in the cylinder at high temperatures. Any soot that is not fully burned before the exhaust valve is opened will be emitted from the engine as diesel PM.

The volatile and semi-volatile organic material in diesel PM is often simply referred to as the soluble organic fraction (SOF) in reference to a test method used to measure its level. SOF is primarily composed of engine oil that passes through the engine with no oxidation or only partial oxidation and condenses in the atmosphere to form PM. The SOF portion of diesel PM can be reduced through reductions in engine oil consumption and through oxidation of the SOF catalytically in the exhaust.

The inorganic solids (ash) in diesel PM comes primarily from metals found in engine oil and to certain extent from engine wear. Ash makes up a very small portion of total PM such that it is often not listed as a PM component and has no impact on compliance with PM emission standards. However, it does impact maintenance of PM filter technologies, as discussed later, because in aggregate over a very long period of time ash accumulation in the PM filter can reach a level such that it must be cleaned from the filter (see section 4.1.1.3.4 below).

The sulfate portion of diesel PM is formed from sulfur present in diesel fuel and engine lubricating oil that oxidizes to form sulfuric acid (H_2SO_4) and then condenses in the atmosphere to form sulfate PM. Approximately two percent of the sulfur that enters a diesel engine from the fuel is emitted directly from the engine as sulfate PM.[8] The balance of the sulfur content is emitted from the engine as SO_2. Oxidation catalyst technologies applied to control the SOF and soot portions of diesel PM can inadvertently oxidize SO_2 in the exhaust to form sulfate PM. The oxidation of SO_2 by oxidation catalysts to form sulfate PM is often called sulfate make. Without low-sulfur diesel fuel, oxidation catalyst technology to control diesel PM is limited by the formation of sulfate PM in the exhaust as discussed in more detail in the discussion below of the need for low-sulfur fuel.

4.1.1.1 In-Cylinder PM Control

The soot portion of PM emissions can be reduced by increasing the availability of oxygen within the cylinder for soot oxidation during combustion. Oxygen can be made more available by either increasing the oxygen content in-cylinder or by increasing the mixing of the fuel and oxygen in-cylinder. Several current technologies can influence oxygen content and in-cylinder mixing, including improved fuel-injection systems, air management systems, and combustion system designs. Many of these PM-reducing technologies offer better control of combustion in general, and better utilization of fuel allowing for improvements in fuel efficiency concurrent with reductions in PM emissions. Improvements in combustion technologies and refinements of these systems is an ongoing effort for highway engines and for some nonroad engines where emission standards or high fuel use encourage their introduction. The application of better combustion system technologies across the broad range of nonroad engines for meeting the new emission standards offers an opportunity for significant reductions in engine-out PM emissions and possibly for reductions in fuel consumption.

In general, the application of these in-cylinder emission control solutions for PM are more successful (reduce PM to a lower level) as engine size increases. This occurs for three reasons: 1) larger engines have a higher volume to surface area within the cylinder reducing the proportion of the in-cylinder volume near a cooler cylinder wall and thus decreasing PM formation in these cool regions; 2) larger engines operate over a narrow engine speed range allowing for better matching of turbomachinery to the engine (i.e., higher boost and more oxygen); and 3) larger engines operate at lower engine speeds reducing oil consumption which contributes to SOF and providing longer residence time for combustion to complete (i.e., at slower speeds the combustion event measured in time is longer). In the Tier 4 program, we are setting an emission standard of 0.075 g/bhp-hr for some nonroad diesel engines >750 hp beginning in 2011. This emission level is approximately 25 percent lower than the level for most current on-highway diesel engines (using 500 ppm sulfur fuel).[A] We are projecting that in-cylinder PM emission control technologies along with 15 ppm sulfur diesel fuel will allow these very large nonroad diesel engines to meet this emission standard. Given the inherent PM control advantage that these larger diesel engines enjoy when compared to the smaller on-highway counterparts and the use of lower sulfur diesel fuel which lowers sulfate PM, we can conclude that the 0.075 g/bhp-hr emission standard is clearly feasible for these engines in 2011.

Another means to reduce the soot portion of engine-out PM emissions from diesel (compression-ignited) engines is to operate the engine with a homogenous method of operation, rather than the typical heterogeneous operation. In homogenous diesel combustion, also called premixed diesel combustion, the fuel is dispersed evenly with the air throughout the combustion system. This means there are no fuel-rich/oxygen-deprived regions of the system where fuel can be pyrolized rather than burned. Rather, combustion occurs globally initiating at an indeterminate number of locations. Because there are no fuel-rich/oxygen deprived regions in homogenous combustion, the carbon (soot) PM emissions are eliminated. The resulting PM emissions are very low, consisting primarily of SOF and sulfate.

Homogenous diesel combustion has been under development for more than twenty years, yet it is still unable to overcome a number of developmental issues.[9,10] Fundamental among these issues is the ability to control the start of combustion.[11] Conventional diesel engines control the start of combustion by controlling the start of fuel injection: injection-timing control. Homogenous diesel combustion systems cannot readily use fuel-injection timing to control the start of combustion because it is difficult to inject fuel into the engine without initiating combustion. If combustion is initiated while the fuel is being injected, the engine will operate under heterogenous combustion resulting in high PM emissions. Techniques used to delay the start of combustion such as decreasing intake air temperatures or reducing the engines compression ratio can lead to misfire, a failure to ignited the fuel at all. Engine misfire results in no engine power and high hydrocarbon (raw fuel) emissions. Conversely, techniques to advance the start of combustion such as increasing intake air temperatures or increasing the engine compression ratio can lead to premature uncontrolled combustion called engine knock. Engine knock causes exceedingly high in-cylinder pressure spikes that can irreversibly damage a diesel engine at all but low-load conditions.

Controlled homogenous combustion is possible with a diesel engine under certain circumstances, and is used in limited portions of engine operation by some engine manufacturers. Nissan, a passenger car manufacturer, has developed a modified version of premixed combustion that they call modulated-kinetics, or MK, combustion.[12,13] When operated under MK combustion the PM and NOx emissions of the engine are dramatically decreased. Unfortunately, the range of engine operation for which the MK combustion process can function is limited to low-load conditions. At higher engine loads the combustion process is not stable and the engine reverts to operation with conventional diesel combustion. This dual mode operation allows the engine to benefit from the homogenous combustion approach when

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[A] On-highway diesel engines used in urban buses must meet an even lower PM standard of 0.05 g/bhp-hr.

possible, while still providing the full range of engine operation. Other approaches that are similarly limited to low-load engine operation have been proposed to produce a dual combustion mode engine.[14, 15, 16]

4.1.1.2 Diesel Oxidation Catalyst (DOC)

Diesel oxidation catalyst (DOCs) are the most common form of diesel aftertreatment technology today and have been used for compliance with the PM standards for some highway engines since the early 1990s. DOCs reduce diesel PM by oxidizing a small fraction of the soot emissions and a significant portion of the SOF emissions. Total DOC effectiveness to reduce PM emissions is normally limited to approximately 30 percent because the SOF portion of diesel PM for modern diesel engines is typically less than 30 percent and because the DOC increases sulfate emissions, reducing the overall effectiveness of the catalyst. Limiting fuel sulfur levels to 15ppm allows DOCs to be designed for maximum effectiveness (nearly 100% control of SOF with highly active catalyst technologies) since their control effectiveness is not reduced by sulfate make (i.e., their sulfate make rate is high but because the sulfur level in the fuel is low the resulting PM emissions are well controlled).

DOC effectiveness to control HC and CO emissions are directly related to the “activity” of the catalyst material used in DOC washcoating. Highly active (hence effective) DOCs can reduce HC emissions by 97 percent while low activity catalysts realize approximately 50 percent HC control.[17] Today, highly active DOC formulations cannot be used for NMHC and CO control because the sulfur in current diesel fuel leads to unacceptable sulfate PM emissions, as discussed later in this section. However, with the low sulfur diesel fuel that will be available under this program, DOCs will be able to provide substantial control of these pollutants. We have projected the use of DOCs as part of an overall compliance strategy for engines meeting the interim PM standards in 2008. For those engines, DOC would also provide significant reductions in CO and HC including over the various emission test cycles for these engines. Oxidation catalyst technologies generally (i.e., DOCs and CDPFs) will be an effective tool to ensuring compliance over the NTE provisions of the Tier 4 program and to ensuring compliance with the CO standards under the new test cycles.

Data presented by one engine manufacturer regarding the existing Tier 2 PM standard show that while a DOC can be used to reduce PM emissions when tested on 2,000 ppm sulfur fuel, lowering the fuel sulfur level to 380 ppm enabled the DOC to reduce PM by 50 percent from the 2,000 ppm sulfur fuel.[18] Without the availability of 500 ppm sulfur fuel in 2008, DOCs would be of limited use for nonroad engine manufacturers and would not provide the emission-control necessary for most engine manufacturers to meet the 2008 interim Tier 4 standards. With the availability of 500 ppm sulfur fuel, DOCs can be designed to provide PM reductions on the order of 20 to 50%, while suppressing particulate sulfate reduction.[19] These levels of reductions have been seen on transient duty cycles as well as on highway and nonroad steady-state duty cycles.

DOCs are also very effective at reducing the air toxic emissions from diesel engines. Test data show that emissions of toxics such as polycyclic aromatic hydrocarbons (PAHs) can be reduced by more than 80 percent with a DOC.[20]

DOCs are less effective at controlling the solid carbon soot portion of PM. The solid (soot) typically constitutes 60 to 90 percent of the total diesel PM. Even with 15 ppm sulfur fuel, DOCs would therefore not be able to achieve the level of PM control needed to meet the PM filter based PM emission standards (i.e., PM standards at or below 0.03 g/bhp-hr). As noted above however, DOCs can be effective tools to accomplish emission reductions on the order of 20 to 50 percent even when operated on 500 ppm sulfur diesel fuel and thus may be used by some manufacturers as a means to reduce emissions in order to comply with the 2008 interim Tier 4 standards for engines <75 hp.

4.1.1.3 Catalyzed Diesel Particulate Filter (CDPF)

4.1.1.3.1 CDPF PM and HC Control Effectiveness

Emission levels from a catalyzed diesel particulate filter (CDPF) are determined by several factors. Filtering efficiencies for solid particle emissions like soot are determined by the characteristics of the PM filter, including wall thickness and pore size. Some of these characteristics represent a tradeoff between mechanical strength, weight, size and filtering efficiency. Filtering efficiencies for ceramic based diesel soot filters can be as high as 99 percent with the appropriate filter design.[21] Given an appropriate PM filter design, the contribution of the soot portion of PM to the total PM emissions can be negligible (less than 0.001 g/hp-hr). For some wire mesh or ceramic fiber filter technologies the filtering efficiency is lower, around 70 percent, but the mechanical strength (resistance to thermal and mechanical stress) especially for very large filter sizes is improved.[B,22,23] The level of soot emission control is much less dependent on engine test cycle or operating conditions due to the mechanical filtration characteristics of the particulate filter.

Control of the SOF portion of diesel soot is accomplished on a CDPF through catalytic oxidation. At the elevated temperature of diesel exhaust, the SOF portion of diesel PM consists primarily of gas-phase hydrocarbons which later form particulate matter in the environment when the SOF condenses. Catalytic materials applied to CDPFs can oxidize a substantial fraction of the SOF in diesel PM just as the SOF portion is oxidized by a DOC. However, we believe that for engines with very high SOF emissions the emission rate may be higher than can be handled by a conventionally sized catalyst resulting in higher than zero SOF emissions. If a manufacturer's base engine technology has high oil consumption rates, and therefore high engine-out SOF emissions (i.e., higher than 0.04 g/hp-hr), compliance with the 0.01 g/hp-hr

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[B] There are a number of different ways to measure mechanical strength and toughness. One metric for comparison is tensile strength. Comparing the tensile strength of fiber based filter technologies (approximately 1,000 MPa) to a ceramic filter technology such as Silicon Nitride (5.1 MPa) is illustrative of the higher strength of the fiber based technology.

emission standard may require additional technology beyond the application of a CDPF system alone.[C]

Modern highway diesel engines have controlled SOF emission rates to comply with the existing 0.1 g/hp-hr emission standards. Typically the SOF portion of PM from a modern highway diesel engine contributes less than 0.02 g/hp-hr to the total PM emissions. This level of SOF control is accomplished by controlling oil consumption through the use of engine modifications (e.g., piston ring design, the use of 4-valve heads, the use of valve stem seals, etc.).[24] Nonroad diesel engines may similarly need to control engine-out SOF emissions to comply with the new emission standards. The means to control engine-out SOF emissions are well known and have additional benefits, as they decrease oil consumption reducing operating costs. With good control of engine-out SOF emissions (i.e., engine-out SOF < 0.02 g/hp-hr) and the application of catalytic material to the DPF, SOF emissions from CDPF equipped nonroad engines will contribute only a very small fraction of the total tailpipe PM emissions (less than 0.004 g/hp-hr). Alternatively, it may be less expensive or more practical for some applications to ensure that the SOF control realized by the CDPF is in excess of 90 percent, thereby allowing for higher engine-out SOF emission levels.

The catalytic materials used on a CDPF to promote soot regeneration and to control SOF emissions are also effective to control NMHC emissions including toxic hydrocarbon emissions. CDPFs designed for operation on low-sulfur diesel fuel (i.e., with highly active catalyst technologies) can reduce total hydrocarbon emissions by more than 90 percent.[25] Toxic hydrocarbon emissions are typically reduced in proportion to total hydrocarbon emissions. Table 4.1-1 shows hydrocarbon compound reduction data for two different CDPF technologies.[26]

[C] SOF oxidation efficiency is typically better than 80 percent and can be better than 90 percent. Given a base engine SOF rate of 0.04 g/hp-hr and an 80 percent SOF reduction a tailpipe emission of 0.008 can be estimated from SOF alone. This level may be too high to comply with a 0.01 g/hp-hr standard once the other constituents of diesel PM (soot and sulfate) are added. In this case, engine-out SOF emissions will need to be reduced or the CDPF will need to reduce SOF emissions by more than 90 percent.

Table 4.1-1 Polyaromatic Hydrocarbon Reductions with a CDPF

Polyaromatic Hydrocarbon Reductions with Catalyzed Diesel Particulate Filters					
Compound	**Baseline**	**DPF-A**	**DPF-B**	**%Red DPF-A**	**%Red DPF-B**
Napthalene	295	50	0	83%	100%
2-Methylnapthalene	635	108	68	83%	89%
Acenapthalene	40	0.8	1	98%	98%
Acenapthene	46	6.7	11	85%	76%
Fluorene	72	29	12	60%	83%
Phenanthrene	169	33	26	81%	85%
Anthracene	10	1	1	90%	90%
Fluoranthene	7.7	0	2	100%	74%
Pyrene	14	0	2	100%	86%
Benzo(a)anthracene	0.22	0	0.01	100%	95%
Chrysene	0.51	0	0	100%	100%
Benzo(b)fluoranthene	0.26	0	0	100%	100%
Benzo(k)fluoranthene	0.15	0	0	100%	100%
Benzo(e)pyrene	0.26	0	0	100%	100%
Perylene	0.01	0	0	100%	100%
Indeno(123-cd)pyrene	0.13	0	0	100%	100%
Dibenz(ah)anthracene	0.01	0	0	100%	100%
Benzo(ghi)perylene	0.32	0	0	100%	100%

The best means to reduce sulfate emissions from diesel engines is by reducing the sulfur content of diesel fuel and lubricating oils. This is one of the reasons that we are limiting sulfur levels in nonroad diesel fuel to 15ppm or less. The catalytic material on the CDPF is crucial to ensuring robust regeneration and high SOF oxidation; however, it can also oxidize the sulfate in the exhaust with high efficiency. The result is that the predominant form of PM emissions from CDPF equipped diesel engines is sulfate PM. Even with 15ppm sulfur diesel fuel a CDPF equipped diesel engine can have total PM emissions including sulfate emissions as high as 0.009 g/hp-hr over some representative operating cycles using conventional diesel engine oils. This level of emissions will meet the new PM emission standard of 0.01 g/hp-hr for engines between 75 hp and 750 hp. We further believe there is room for reductions from this level to provide engine manufacturers with additional compliance margin. Our recently released Highway Diesel Progress Review Report 2 documents progress by a consortium of engine manufacturers, oil companies and other stakeholders to develop a new engine oil formulation with reduced Sulfur, Ash, and Phosphorous (SAP) content for diesel engines. The new engine oil formulation is expected to be ready in 2006. Any reduction in the sulfur level of engine lubricating oils will be beneficial. Similarly, as discussed above, we expect engine manufacturers to reduce engine oil consumption to reduce SOF emissions and secondarily to reduce sulfate PM emissions. While we believe sulfate PM emissions will be the single largest source of the total PM from diesel engines, we believe that with the combination of technology, and the appropriate control of engine-out PM emissions, sulfate and total PM emissions will be low enough to allow compliance with a 0.01 g/hp-hr standard, except in the case of small engines with higher fuel consumption rates, as described later in this section.[D]

CDPFs have been shown to be very effective at reducing PM mass by reducing dramatically the soot and SOF portions of diesel PM. In addition, recent data show that they are also very effective at reducing the overall number of emitted particles when operated on low-sulfur fuel. Hawker, et al, found that a CDPF reduced particle count by over 95 percent, including some of the smallest measurable particles (< 50 nm), at most of the tested conditions. The lowest observed efficiency in reducing particle number was 86 percent. No generation of particles by the CDPF was observed under any tested conditions.[27] Kittelson, et al, confirmed that ultrafine particles can be reduced by a factor of ten by oxidizing volatile organics, and by an additional factor of ten by reducing sulfur in the fuel. Catalyzed PM traps efficiently oxidize nearly all of the volatile organic PM precursors (SOF), and the reduction of diesel fuel sulfur levels to 15ppm or less will substantially reduce the number of ultrafine PM emitted from diesel engines. The combination of CDPFs with low-sulfur fuel is expected to result in very large reductions in both PM mass and the number of ultrafine particles.

Engine operating conditions have little impact on the particulate trapping efficiency of carbon particles by CDPFs, so the greater than 90 percent efficiency for elemental carbon particulate matter will apply to engine operation within the NTE zone and over the regulated transient cycles, as well as to the test modes that comprise the steady-state test procedures such as the ISO C1. However, engine operation will affect the CDPF regeneration and oxidation of SO_2 to sulfate PM (i.e., “sulfate-make”). Sulfate-make will reduce the measured PM removal efficiency at some NTE operating conditions and some steady-state modes, even at the 15 ppm fuel sulfur cap. This increased sensitivity to fuel sulfur is caused by the higher temperatures that are found at some of the steady-state modes. High exhaust temperatures promote the oxidation of SO_2 to SO_3 (which then combines with water in the exhaust, forming a hydrated sulfate) across the precious metals found in CDPFs. The sulfate emissions condense in the atmosphere (as well as in the CFR mandated dilution tunnel used for PM testing) forming PM.

Under contract from the California Air Resources Board, two nonroad diesel engines were recently tested for control of PM emissions with the application of a CDPF over several transient and steady-state test cycles.[28] The first engine was a 1999 Caterpillar 3408 (480 hp, 18 liter displacement) nonroad diesel engine certified to the Tier 1 standards. The engine was tested with and without a CDPF on 12 ppm sulfur diesel fuel. The transient emission results for this engine are summarized in Table 4.1-2. The steady-state emission results are summarized in Table 4.1-3. The test results confirm the excellent PM control performance realized by a CDPF with low-sulfur diesel fuel across a wide range of nonroad operating cycles in spite of the relatively high engine-out PM emissions from this Tier 1 engine. We expect engine-out PM emissions to be lower for production engines meeting Tier 3 standards, which will form the

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[D] We have also set slightly higher PM standards for >750 hp engines predicated on the use of alternative PM filter technologies. These higher levels (standards of 0.02 g/bhp-hr for gensets, and 0.03 g/bhp-hr for mobile machines) are not based on higher sulfate emission rates, as for the <75 hp engines, but instead on slightly less effective PM filtration efficiencies and differing engine out emission rates.

technology baseline for the Tier 4 engines. The engine demonstrated PM emissions of 0.009 g/hp-hr on the Nonroad Transient Cycle (NRTC) from an engine-out emission level of 0.256 g/hp-hr, a reduction of 0.247 g/hp-hr (a greater than 96% reduction). The engine also demonstrated excellent PM performance on the existing steady-state ISO C1 cycle with PM emissions of 0.010 g/hp-hr from an engine-out emission level of 0.127, a reduction of 0.107 g/hp-hr. Thus, this engine would meet the new emission standards for 75-750 hp variable-speed nonroad engines.

Table 4.1-2 Transient PM Emissions for a Tier 1 NR Diesel Engine with a CDPF

1999 (Tier 1) Caterpillar 3408 (480hp, 18l)

	PM [g/bhp-hr]		Reduction
Test Cycle	Engine Out	w/ CDPF	%
Proposed Nonroad TransientCycle (NRTC)	0.256	0.009	96%
Proposed Constant Speed Variable Load Cycle (CSVL)	0.407	0.016	96%
On-Highway U.S. FTP Transient Cycle (FTP)	0.239	0.019	92%
Agricultural Tractor Cycle (AGT)	0.181	0.009	95%
Backhoe Loader Cycle (BHL)	0.372	0.022	94%
Crawler Tractor Dozer Cycle (CRT)	0.160	0.014	91%
Composite Excavator Duty Cycle (CEX)	0.079	0.009	88%
Skid Steer Loader Typical No. 1 (SST)	0.307	0.016	95%
Skid Steer Loader Typical No. 2 (SS2)	0.242	0.013	95%
Skid Steer Loader Highly Transient Speed (SSS)	0.242	0.008	97%
Skid Steer Loader Highly Transient Torque (SSQ)	0.351	0.004	99%
Arc Welder Typical No.1 (AWT)	0.510	0.018	96%
Arc Welder Typical No.2 (AW2)	0.589	0.031	95%
Arc Welder Highly Transient Speed (AWS)	0.424	0.019	96%
Rubber-Tired Loader Typical No.1 (RTL)	0.233	0.010	96%
Rubber-Tired Loader Typical No.2 (RT2)	0.236	0.011	96%
Rubber-Tired Loader Highly Transient Speed (RTS)	0.255	0.008	97%
Rubber-Tired Loader Highly Transient Torque (RTQ)	0.294	0.009	97%

Table 4.1-2 also shows results over a large number of additional test cycles developed from real-world in-use test data to represent typical operating cycles for different nonroad equipment applications (see Section 4.2 for information on these test cycles). The results show that the CDPF technology is highly effective to control in-use PM emissions over any number of disparate operating conditions. Remembering that the base Tier 1 engine was not designed to meet a transient PM standard, the CDPF emissions demonstrated here show that very low emission levels are possible even when engine-out emissions are exceedingly high (e.g., a reduction of 0.558 g/hp-hr is demonstrated on the AW2 cycle).

The results summarized in the two tables support the feasibility of the NTE provisions in this rulemaking. In spite of the Tier 1 baseline of this engine, there are only three test results with emissions higher than the permissible limit for the NTE standards. The first, in Table 4.1-2, shows PM emissions of 0.031 over the AW2 cycle, but from a very high baseline level of nearly 0.6 g/hp-hr. We believe that simple improvements to the engine-out PM emissions as needed to comply with the Tier 2 emission standard would reduce these emission below the 0.02 level required by the NTE standard. There are two other test points in Table 4.1-3 that are above the

NTE standard, both at 10 percent engine load. However, both test points are outside the NTE zone, which excludes emissions for engine loads below 30 percent. It is important to note that, although the engine would not be constrained to meet NTE standards under these conditions, the resulting reductions at both points are still substantially greater than 96 percent.

Table 4.1-3 Steady-State PM Emissions from a Tier 1 NR Diesel Engine w/ CDPF

1999 (Tier 1) Caterpillar 3408 (480hp, 18l)				
Engine Speed	Engine Load	PM ([g/bhp-hr]		Reduction
%	%	Engine Out	w/ CDPF	%
100	100	0.059	0.010	83%
100	75	0.103	0.009	91%
100	50	0.247	0.012	95%
100	25	0.247	0.000	100%
100	10	0.925	0.031	97%
60	100	0.028	0.011	61%
60	75	0.138	0.009	93%
60	50	0.180	0.010	95%
60	25	0.370	0.007	98%
60	10	0.801	0.018	98%
91	82	0.091	0.006	93%
80	63	0.195	0.008	96%
63	40	0.240	0.008	97%
0	0	--	--	--
	ISO C1 Composite	0.127	0.011	91%

The second engine tested was a prototype engine developed at Southwest Research Institute (SwRI) under contract to EPA.[29] The engine, dubbed Deere Development Engine 4045 (DDE-4045) because the prototype engine was based on a John Deere 4045 production engine, was also tested with a CDPF from a different manufacturer on the same 12 ppm diesel fuel. The engine is very much a prototype and experienced a number of part failures during testing, including to the turbocharger actuator. Nevertheless, the transient emission results summarized in Table 4.1-4 and the steady-state results summarized in Table 4.1-5 show that substantial PM reductions are realized on this engine as well. The emission levels on the NRTC and the ISO C1 duty cycles would meet the PM standard of 0.01 g/hp-hr once the appropriate rounding convention is applied.[E] Note also that measured emissions over the transient highway FTP cycle are higher than for either of the new nonroad transient duty cycles. This suggests that developing PM-compliant engines on the new nonroad transient cycles may not be substantially different from developing compliant technologies for highway engines.

[E] The rounding procedures in ASTM E29-90 are applied to the emission standard. The emission results are therefore rounded to the same number of significant digits as the specified standard, i.e., 0.014 g/hp-hr is rounded to 0.01 g/hp-hr, while 0.015 g/hp-hr would be rounded to 0.02 g/hp-hr.

Table 4.1-4 Transient PM Emissions for a Prototype NR Diesel Engine with a CDPF

EPA Prototype Tier 3 DDE-4045 (108hp, 4.5l)

Test Cycle	PM [g/bhp-hr] Engine Out	PM [g/bhp-hr] w/ CDPF	Reduction %
Proposed Nonroad TransientCycle (NRTC)	0.143	0.013	91%
Proposed Constant Speed Variable Load Cycle (CSVL)	0.218	0.018	92%
On-Highway U.S. FTP Transient Cycle (FTP)	0.185	0.023	88%
Agricultural Tractor Cycle (AGT)	0.134	0.008	94%
Backhoe Loader Cycle (BHL)	0.396	0.021	95%
Crawler Tractor Dozer Cycle (CRT)	0.314	0.008	97%
Composite Excavator Duty Cycle (CEX)	0.176	0.009	95%
Skid Steer Loader Typical No. 1 (SST)	0.288	0.012	96%
Skid Steer Loader Typical No. 2 (SS2)	0.641	0.013	98%
Skid Steer Loader Highly Transient Speed (SSS)	0.298	0.011	96%
Skid Steer Loader Highly Transient Torque (SSQ)	0.536	0.014	97%
Arc Welder Typical No.1 (AWT)	0.290	0.018	94%
Arc Welder Typical No.2 (AW2)	0.349	0.019	95%
Arc Welder Highly Transient Speed (AWS)	0.274	0.019	93%
Rubber-Tired Loader Typical No.1 (RTL)	0.761	0.014	98%
Rubber-Tired Loader Typical No.2 (RT2)	0.603	0.012	98%
Rubber-Tired Loader Highly Transient Speed (RTS)	0.721	0.010	99%
Rubber-Tired Loader Highly Transient Torque (RTQ)	0.725	0.009	99%

As with the results from the Caterpillar engine, the two low-load (10 percent load) steady-state emission points (see Table 4.1-5) have some of the highest brake specific emission rates. However, these rates are not high enough to preclude compliance with the steady-state emission cycle. The test points are also not within the NTE zone and still show substantial levels of PM reduction.

Table 4.1-5 Steady-State PM Emissions for a Prototype NR Diesel Engine w/CDPF

EPA Prototype Tier 3 DDE-4045 (108hp, 4.5l)

Engine Speed %	Engine Load %	PM [g/bhp-hr] Engine Out	PM [g/bhp-hr] w/ CDPF	Reduction %
100	100	0.178	0.012	93%
100	75	0.116	0.006	95%
100	50	0.126	0.006	96%
100	25	0.218	0.013	94%
100	10	0.470	0.029	94%
60	100	0.045	0.007	84%
60	75	0.062	0.014	78%
60	50	0.090	0.009	90%
60	25	0.146	0.019	87%
60	10	0.258	0.046	82%
91	82	0.094	0.004	95%
80	63	0.099	0.006	94%
63	40	0.136	0.011	92%
0	0	--	--	--
	ISO C1 Composite	0.129	0.010	92%

The new NTE requirement, unlike the nonroad transient cycle (NRTC) or the existing ISO C1 cycle, is not a composite test. In fact, several of the individual modes within the C1 cycle test fall within the NTE zone. As discussed above, CDPFs are very efficient at capturing elemental carbon PM (up to 99 percent), but sulfate-make under certain operating conditions may exceed the standard of 0.01 g/hp-hr over the NRTC or C1 duty cycles, which is part of the reason the NTE standard for PM is greater than the PM standards that apply for testing over the NRTC and C1 duty cycles.

In this rulemaking, we are making changes to the test procedures for nonroad CI engines. The switch to the test procedures specified in part 1065 and part 86 (from those specified in part 89) will generally improve the repeatability of emission measurements. These changes do not change our analysis of the feasibility to comply with the Tier 4 standards as they are designed to improve accuracy and repeatability and as such do not adversely impact stringency. Also, as described in section III.G.3 of the preamble, we are considering in a separate proceeding additional changes to the part 1065 regulations to further improve the test procedures. Like the changes finalized in this rulemaking, these planned changes will not impact stringency only accuracy and repeatability, and thus, will not impact feasibility.

The new NTE requirements apply not only during standard laboratory conditions, but also during the expanded ambient temperature, humidity, and altitude limits defined in the regulations. We believe the new NTE PM standard is technologically feasible across this range of ambient conditions. As discussed above, CDPFs are mechanical filtration devices, and ambient temperature changes will have minimal effect on CDPF performance. Ambient altitude will also have minimal, if any, effects on CDPF filtration efficiencies, and ambient humidity should have no effect on CDPF performance. As discussed above, particulate sulfate make is sensitive to high exhaust gas temperatures; however, at sea-level conditions, the NTE requirements apply up to ambient temperatures that are only 14˚F greater than standard test cell conditions (100˚F under the NTE standards, versus 86˚F for C1 laboratory conditions). At an altitude of 5,500 feet above sea level, the NTE standards apply only up to an ambient temperature within the range of standard laboratory conditions (i.e., 86˚F). These small or non-existent differences in ambient temperature should have little effect on the sulfate make of CDPFs, and as can be seen in Tables 4.1-3 and 4.1-5 above, even when tested at an engine operating test mode representative of the highest particulate sulfate generating conditions (peak-torque operation) with 12 ppm sulfur diesel fuel, the results show the engine would easily meet the NTE PM standard. Based on the available test data and the expected impact of the expanded, but constrained, ambient conditions under which engines must comply with the NTE standards, we conclude that the NTE PM standard for engines > 75 hp is technologically feasible (including engines >750 hp), provided low-sulfur diesel fuel (15 ppm or lower) is available. Although we do not have data available specific to the application of wire or fiber mesh filter technologies on diesel engines >750 hp, the same filtration principles and control mechanisms apply to this technology as to the ceramic technology described here. A discussion of the technical feasibility for engines with rated power lower than 75 hp is given in Sections 4.1.4 and 4.1.5.

4.1.1.3.2 CDPF Regeneration

Diesel particulate filters (DPFs) control diesel PM by capturing the soot portion of PM in a filter media, typically a ceramic wall flow substrate, and then by oxidizing (burning) it in the oxygen-rich atmosphere of diesel exhaust. The SOF portion of diesel PM can be controlled through the addition of catalytic materials to the DPF to form a catalyzed diesel particulate filter (CDPF).[F] The catalytic material is also very effective to promote soot burning. This burning off of collected PM is referred to as "regeneration." In aggregate over an extended period of operation, the PM must be regenerated at a rate equal to or greater that its accumulation rate, or the DPF will clog.

For a non-catalyzed DPF the soot can regenerate only at very high temperatures, in excess of 600˚C, a temperature range that occurs infrequently in normal diesel engine operation (exhaust temperatures for many engines might never reach 600˚C). With the addition of a catalytic coating to make a CDPF, the temperature necessary to ensure regeneration is decreased significantly to approximately 250˚C, a temperature within the normal operating range for most diesel engines.[30]

The catalytic materials that most effectively promote soot and SOF oxidation, however, are significantly impacted by sulfur in diesel fuel. Sulfur both degrades catalyst oxidation efficiency (i.e., poisons the catalyst) and forms sulfate PM. Both catalyst poisoning by sulfur and increases in PM emissions due to sulfate make influence our decision to limit the sulfur level of diesel fuel to 15 ppm as discussed in greater detail in the discussion below of the need for low-sulfur diesel fuel.

Filter regeneration is affected by catalytic materials used to promote oxidation, sulfur in diesel fuel, engine-out soot rates, and exhaust temperatures. At higher exhaust temperatures, soot oxidation occurs at a higher rate. Catalytic materials accelerate soot oxidation at a single exhaust temperature compared with non-catalyst DPFs, but even with catalytic materials increasing the exhaust temperature further accelerates soot oxidation.

Having applied 15 ppm sulfur diesel fuel and the best catalyst technology to promote low-temperature oxidation (regeneration), the regeneration balance of soot oxidation equal to or greater than soot accumulation over aggregate operation simplifies to the following question: are the exhaust temperatures high enough on aggregate to oxidize the engine-out PM emission rate?[G] The answer is yes, for most highway applications and many nonroad applications, as demonstrated by the widespread success of retrofit CDPF systems for nonroad equipment and the use of both retrofit and original equipment CDPF systems for highway vehicles.[31,32,33]

[F] With regard to gaseous emissions such as NMHCs and CO, the CDPF works in the same manner with similar effectiveness as the DOC (i.e., NMHC and CO emissions are reduced by more than 80 percent).

[G] If the question was asked, "without 15 ppm sulfur fuel and the best catalyst technology, are the exhaust temperatures high enough on aggregate to oxidize the engine-out PM emission rate?" the answer would be no, for all but a very few highway or nonroad diesel engines.

However, it is possible that for some nonroad applications the engine-out PM emission rate may exceed the soot oxidation rate even with low-sulfur diesel fuel and the best catalyst technologies. Should this occur, successful regeneration requires that either engine-out PM emission rates be decreased or exhaust temperatures be increased, both feasible strategies. In fact, we expect both to occur as highway-based technologies are transferred to nonroad engines. As discussed earlier, engine technologies to lower PM emissions while improving fuel consumption are continuously being developed and refined. As these technologies are applied to nonroad engines driven by both new emission standards and market pressures for better products, engine-out PM emissions will decrease. Similarly, techniques to raise exhaust temperatures periodically for initiating soot oxidation in a PM filter have been developed for highway diesel vehicles as typified by the PSA system used on more than 400,000 vehicles in Europe.[34]

During our 2002 Highway Diesel Progress Review, we investigated the plans of highway engine manufacturers to use CDPF systems to comply with the HD2007 emission standards for PM. We learned that all diesel engine manufacturers intend to comply through the application of CDPF system technology. We also learned that the manufacturers are developing means to raise the exhaust temperature, if necessary, to ensure that CDPF regeneration occurs.[35] These technologies include modifications to fuel-injection strategies, modifications to EGR strategies, and modifications to turbocharger control strategies. These systems are based upon the technologies used by the engine manufacturers to comply with the 2004 highway emission standards. In general, the systems anticipated to be used by highway manufacturers to meet the 2004 emission standards are the same technologies that engine manufacturers have indicated to EPA that they will use to comply with the Tier 3 nonroad regulations (e.g., electronic fuel systems).[36] In a manner similar to highway engine manufacturers, we expect nonroad engine manufacturers to adapt their Tier 3 emission-control technologies to provide back-up regeneration systems for CDPF technologies to comply with the new emission standards. We have estimated costs for such systems in our cost analysis.

4.1.1.3.3 Current Status of CDPF Technology

More than one emission control manufacturer is developing CDPFs. In field trials, they have demonstrated highly efficient PM control and promising durability. A recent publication documents results from a sample of these field test engines after years of use in real-world applications.[37] The sampled CDPFs had on average four years of use covering more than 225,000 miles in applications ranging from city buses to garbage trucks to intercity trains, with some units accumulating more than 360,000 miles. When tested on the highway FTP cycle, they continued to demonstrate PM reductions in excess of 90 percent.

Another program evaluating CDPFs in the field is the ARCO Emission Control Diesel (EC-D) program.[H] In that program, a technology validation is being run to evaluate EC-D and CDPFs using diesel vehicles operating in southern California. The fuel's performance, impact

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[H] EC-D is a diesel fuel developed recently by ARCO (Atlantic Richfield Company) from typical crude oil using a conventional refining process and having a fuel sulfur content less than 15 ppm.

on engine durability and vehicle performance, and emission characteristics are being evaluated in several fleets in various applications. The program is still ongoing, but interim results have been made available.[38] These interim results have shown that vehicles retrofitted with CDPFs and fueled with EC-D (7.4 ppm sulfur) emitted 91 percent to 99 percent less PM compared with the vehicles fueled with California diesel fuel (121 ppm sulfur) having no exhaust filter equipment. Further, the test vehicles equipped with the CDPFs and fueled with EC-D have operated reliably during the program start-up period and no significant maintenance issues have been reported for the school bus, tanker truck and grocery truck fleets that have been operating for over six months (approximately 50,000 miles).[39] These results from on-highway diesel engines are significant because in form and function the engines are virtually the same as those used for nonroad diesel applications. In fact, in many cases on-highway diesel engines have directed nonroad counterparts that are virtually identical. Further, even for nonroad engines which may differ in physical size or horsepower range, the underlying chemistry and filtration efficiency of CDPFs is the same.

Even with the relatively mature state of the CDPF technology, progress is still being made to improve catalytic-based soot regeneration technologies and to develop system solutions to ensure that even under the most extreme conditions soot regeneration can be ensured. Improvements in catalytic soot oxidation are important because more active soot oxidation can help to improve fuel economy and to ensure robust soot regeneration. A PM filter with a more effective soot oxidation catalyst would be expected to have a lower average soot loading and therefore would be less restrictive to exhaust flow, thus decreasing the pressure drop across the PM filter and leading to better fuel economy. Improved effectiveness in oxidizing soot will also further ensure that excessive soot loading that might lead to PM filter failure will not occur.

A paper presented at a recent conference of the Society of Automotive Engineers (SAE) documented design improvements in catalyzed diesel particulate filters with improved soot oxidation effectiveness. The paper showed that changes in where catalytic materials were coated within a PM filter system (on an upfront flow-through catalyst, on the surface of the PM filter or a combination of both) influenced the effectiveness of the catalyst material to promote soot oxidation.[40] This kind of system analysis suggests that there remain opportunities to further improve how diesel particulate filters are designed to promote soot oxidation and that different solutions may be chosen dependent upon expected nonroad equipment operation (expected exhaust temperature history), packaging constraints and cost.

Alhough highly effective catalytic soot oxidation, enabled by clean diesel fuel (15 ppm S), suggests that PM filters will regenerate passively for most vehicle and many nonroad equipment applications, there remains the possibility that for some conditions active regeneration systems (backup systems) may be desirable.[I] For this reason, some vehicle manufacturers have

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[I] We are defining backup regeneration to include any number of methods for raising exhaust temperatures in order to promote PM filter regeneration. These could include changes to engine management to change engine operation and raise exhaust temperature, any external mechanism to add heat into the exhaust, or a combination of engine management to increase hydrocarbon (fuel) emissions from the engine in order to oxidize those emissions across a diesel oxidation catalyst (DOC) and thus raise exhaust temperatures.

developed systems to help ensure that PM soot regeneration can occur under all conditions. One example of this is a current production product sold in Europe by PSA/Peugeot. On diesel powered Peugeot 607 passenger cars (a Ford Taurus-sized passenger car) a PM filter system is installed that includes mechanisms for engine-promoted soot oxidation. The vehicle estimates soot loading from several parameters, including exhaust backpressure and can periodically promote more rapid soot oxidation by injecting additional fuel late in the combustion cycle. This fuel is injected so late in the cycle that it does not contribute to engine power but instead is combusted (oxidized) across an oxidation catalyst in front of the PM filter. The combustion of the fuel across the catalyst increases the exhaust temperature substantially, encouraging rapid soot oxidation. Peugeot has sold more than 400,000 passenger cars with this technology and expects to expand the use of the system across all of its diesel vehicle lines.[41] Other European vehicle manufacturers indicated to EPA during our progress review, that they intend to introduce similar technologies in the near future. They noted that this was not driven by regulation but by customer demand for clean diesel technologies. The fact that manufacturers are introducing PM filter technologies in advance of mandatory regulations suggests that the technology is well developed and mature.

The potential for synergistic benefits to the application of both PM filters and NOx adsorbers was highlighted in the HD2007 Regulatory Impact Analysis, but at that time little was known as to the extent of these synergistic benefits.[42] Toyota has developed a combined diesel particulate filter and NOx adsorber technology dubbed DPNR (Diesel Particulate NOx Reduction). The mechanism for synergistic PM soot regeneration with programmed NOx regeneration was recently documented by Toyota in a SAE publication. The paper showed that active oxygen molecules created both under lean conditions as part of the NOx storage function and under rich conditions created by the NOx regeneration function were effective at promoting soot oxidation at low temperatures.[43] This suggests that the combination of a NOx adsorber catalyst function with a diesel particulate filter can provide a more robust soot regeneration system than a PM filter-only technology.

4.1.1.3.4 CDPF Maintenance

Inorganic solid particles present in diesel exhaust can be captured by diesel particulate filters. Typically these inorganic materials are metals derived from engine oil, diesel fuel or even engine wear. Without a PM filter these materials are normally exhausted from the engine as diesel PM. While the PM filter is effective at capturing inorganic materials it is not typically effective at removing them, since they do not tend to be oxidized into a gaseous state (carbon soot is oxidized to CO_2 which can easily pass through the PM filter walls). Because these inorganic materials are not typically combusted and remain after the bulk of the PM is oxidized from the filter they are typically referred to as ash. While filtering metallic ash from the exhaust is an environmental benefit of the PM filter technology it also creates a maintenance need for the PM filter to remove the ash from the filter periodically.

The maintenance function for the removal of ash is relatively straightforward, and itself does not present a technical challenge for the industry. We have estimated cost for ash removal as one of the costs of this rule (see RIA Chapter 6). However, both the industry and EPA would like to see ash-related PM filter maintenance reduced as much as possible. EPA has specific guidelines for acceptable maintenance intervals for nonroad diesel engines with CDPFs intended to ensure robust emission-control technologies (3,000hrs for engines <175 hp and 4,500hrs for engines ≥175hp). Nonroad engine manufacturers are similarly motivated to improve reliability to minimize end-user maintenance costs. The issue of ash accumulation was raised consistently during our progress review visits with the industry. The industry is investigating several ways to address this issue including means to improve ash tolerance and to reduce the amount of ash present in diesel exhaust.

For most current PM filter designs ash accumulates at the end of the inlet passages of the PM filter. As more ash is accumulated, the effective filter size is reduced because the ash fills the end of the passage shortening the effective filter length. Increasing PM filter size to tolerate higher levels of ash accumulation is one simple approach to address ash. This approach, though effective, is undesirable due to the added cost and size of the resulting PM filter. Several companies are investigating means to develop PM filter mechanisms that are more ash-tolerant. These approaches include concepts to increase storage area within the filter itself and concepts that promote self-cleaning of the filter, perhaps driven by engine and vehicle vibrations during normal vehicle operation. Our recent Highway Diesel Progress Review Report 2 described two such systems recently introduced for on-highway applications. For light-duty vehicle applications the technologies are described as fit for life, meaning that ash cleaning maintenance will not be necessary over the life of a light-duty diesel vehicle. For heavy-duty diesel engines (and for nonroad diesel engines >250 hp) the technologies are expected to increase the interval between ash cleaning by 50 percent.

In addition to concepts to improve ash handling, possibilities exist to decrease the amount of ash present in diesel exhaust. The predominant source of ash in diesel exhaust is inorganic materials contained in engine oil (oil ash). A significant fraction of the ash in engine oil is from additives necessary to control acidification of engine oil due in part to sulfuric acid derived from sulfur in diesel fuel. As the sulfur content of diesel fuel is decreased, the need for additives to neutralize the acids in engine oil should also decrease. The concept of an engine oil with less ash content is often referred to as “low-ash oil.” Several technical programs are ongoing to determine the impact of changes in oil ash content and other characteristics of engine oil on exhaust emission-control technologies and engine wear and performance. Historically, as engine technologies have changed (often due to changes in emission regulations) engine oil formulations have also changed. These changes have been accomplished through industry consensus on oil specifications based on defined test protocols. This process of consensus definition has begun to develop engine oils specifications for highway diesel engines for the 2007 model year. This engine oil will also be appropriate for application to nonroad diesel engine designed with the same technologies (i.e., an engine oil specification designed for highway HD2007 engines would also be appropriate for use with Tier 4 engines).

It may also be possible to reduce the ash level in diesel exhaust by reducing oil consumption from diesel engines. Diesel engine manufacturers over the years have reduced engine oil consumption to reduce PM emissions and to reduce operating costs for engine owners. Further improvements in oil consumption may be possible to reduce ash accumulation rates in PM filters. If oil accumulation rates could be halved and engine oil ash content similarly decreased, the PM filter maintenance interval would be increased four-fold. Current retrofit PM filter ash maintenance intervals can range from 50k miles to more than 200k miles.[44]

4.1.2 NOx Control Technologies

Oxides of nitrogen (NO and NO_2, collectively called NOx) are formed at high temperatures during the diesel combustion process from nitrogen and oxygen present in the intake air. The NOx formation rate is exponentially related to peak cylinder temperatures and is also strongly related to nitrogen and oxygen content (partial pressures). NOx control technologies for diesel engines have focused on reducing emissions by lowering the peak cylinder temperatures and by decreasing the oxygen content of the intake air.

4.1.2.1 In-Cylinder NOx Control Technologies

Several technologies have been developed to accomplish these objectives, including fuel-injection timing retard, fuel-injection rate control, charge air cooling, exhaust gas recirculation (EGR) and cooled EGR. The use of these technologies can result in significant reductions in NOx emissions, but are limited due to practical and physical constraints of heterogeneous diesel combustion.[45]

Our recent Highway Diesel Progress Review Report 2, investigated the extent to which in-cylinder NOx control technologies had advanced. The report noted that a number of diesel engine manufacturers introduced cooled EGR systems on their heavy-duty diesel engines in 2002 compliant with the 2004 emission standards for NOx and NMHC of 2.5 g/bhp-hr. The engines circulate a portion of the exhaust gases through a heat exchanger cooling the exhaust before reintroducing the gases into the engine intake manifold. The systems control NOx emissions by providing a diluent (spent exhaust gases) reducing the oxygen content of the intake air and recirculated exhaust mixture. Engine manufacturers have now demonstrated that these systems can be further refined to allow NOx emissions compliant with the 2007 NOx averaging level of approximately 1.2 g/bhp-hr. To reduce NOx emissions below 1.2 g/bhp-hr engine manufacturers will likely need to increase EGR rates (use higher levels of EGR), thus we are referring to such refinements for on-highway 2007 diesel engines as high flow EGR. Although there are nonroad specific challenges to applying similar technologies to nonroad diesel engines (most notably the lack of ram-air for cooling), the fundamental NOx control technologies are applicable to all diesel engines. We are confident based on the continuing development of on-highway technologies for in-cylinder NOx control using cooled EGR or ACERT^{TM} that nonroad diesel engines between 25 and 75 hp and mobile machine nonroad engines >750 hp will be able to comply with their respective Tier 4 standards (i.e., 3.5 g/bhp-hr NOx+NMHC for 25-50 hp engines, the same standard certified using the NRTC and NTE for 50-75 hp engines, and 2.6 g/bhp-hr NOx for >750 hp engines), including the NRTC (with cold-start) and the NTE standards all of which are similar in difficulty to the heavy-duty FTP (with cold-start) and the NTE standards for on-highway engines. For additional discussion of these emission control technologies and the impact of the NTE and cold-start, see the RIA for the on-highway HD 2004 emission standards and the RIA for the Tier 2/3 emission standards.[46,47]

A new form of diesel engine combustion, commonly referred to as homogenous diesel combustion or premixed diesel combustion, can give very low NOx emissions over a limited range of diesel engine operation. In the regions of diesel engine operation over which this combustion technology is feasible (light-load conditions), NOx emissions can be reduced enough to comply with the 0.3 g/hp-hr NOx emission standard.[48] Some engine manufacturers are already producing engines that utilize this technology over a narrow range of engine operation.[49] Unfortunately, it is not possible today to apply this technology over the full range of diesel engine operation. We believe that more engine manufacturers will utilize this alternative combustion approach in the limited range over which it is effective, but will have to rely on conventional heterogenous diesel combustion for the bulk of engine operation. See Section 4.1.1.1 for additional discussion of homogenous diesel combustion and PM emission control.

4.1.2.2 Lean-NOx Catalyst Technology

Lean-NOx catalysts have been under development for some time, and two methods have been developed for using a lean NOx catalyst depending on the level of NOx reduction desired though neither method can produce more than a 30 percent NOx reduction. The “active” lean-NOx catalyst injects a reductant that serves to reduce NOx to N_2 and O_2 (typically diesel fuel is used as the reductant). The reductant is introduced upstream of, or into, the catalyst. The presence of the reductant provides locally oxygen-poor conditions that allow the NOx emissions to be reduced by the catalyst.

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

Active lean-NOx catalysts have been shown to provide up to 30 percent NOx reduction under limited steady-state conditions. However, this NOx control is achieved with a fuel economy penalty upwards of 7 percent due to the need to inject fuel into the exhaust stream.[50] NOx reductions over the transient highway FTP cycle are only on the order of 12 percent due to excursions outside the optimum NOx reduction efficiency temperature range for these devices.[51] Consequently, the active lean-NOx catalyst does not appear to be capable of enabling the significantly lower NOx emissions required by the Tier 4 NOx standards.

The “passive” lean-NOx catalyst uses no reductant injection. The passive lean-NOx catalyst is therefore even more limited in its ability to reduce NOx because the exhaust gases normally contain very few hydrocarbons. For that reason, today’s passive lean-NOx catalyst is capable of best steady-state NOx reductions of less than 10 percent. Neither approach to lean-

NOx catalysis listed here can provide the significant NOx reductions necessary to meet the Tier 4 standards.

4.1.2.3 NOx Adsorber Technology

NOx emissions from gasoline-powered vehicles are controlled to extremely low levels through the use of the three-way catalyst technology first introduced in the 1970s. Three-way-catalyst technology is very efficient in the stochiometric conditions found in the exhaust of properly controlled gasoline-powered vehicles. Today, an advancement upon this well-developed three-way catalyst technology, the NOx adsorber, has shown that it too can make possible extremely low NOx emissions from lean-burn engines such as diesel engines.[J] The potential of the NOx adsorber catalyst is limited only by its need for careful integration with the engine and engine control system (as was done for three-way catalyst equipped passenger cars in the 1980s and 1990s) and by poisoning of the catalyst from sulfur in the fuel. The Agency set stringent new NOx standards for highway diesel engines beginning in 2007 predicated upon the use of the NOx adsorber catalyst enabled by significant reductions in fuel sulfur levels (15 ppm sulfur or less). The final rule includes similarly stringent NOx emission standards for nonroad engines from 75-750 hp and for certain engines >750 hp, again based on using technology enabled by a reduction in fuel sulfur levels.

NOx adsorbers work to control NOx emissions by storing NOx on the surface of the catalyst during the lean engine operation typical of diesel engines. The adsorber then undergoes subsequent brief rich regeneration events where the NOx is released and reduced across precious-metal catalysts. The NOx storage period can be as short as 15 seconds and as along as 10 minutes depending upon engine-out NOx emission rates and exhaust temperature. Several methods have been developed to accomplish the necessary brief rich exhaust conditions necessary to regenerate the NOx adsorber technology including late-cycle fuel injection, also called post injection, in exhaust fuel injection, and dual bed technologies with off-line regeneration.[52,53,54] This method for NOx control has been shown to be highly effective when applied to diesel engines but has some technical challenges associated with it. Primary among these is sulfur poisoning of the catalyst, as described in Section 4.1.2.3.4.2 below.

4.1.2.3.1 How do NOx Adsorbers Work?

As noted, the NOx adsorber catalyst is a further development of the three-way catalyst technology developed for gasoline powered vehicles more than twenty years ago. The NOx adsorber enhances the three-way catalyst function through the addition of storage materials on the catalyst surface that can adsorb NOx under oxygen-rich conditions. This enhancement means that a NOx adsorber can allow for control of NOx emissions under lean-burn (oxygen-rich) operating conditions typical of diesel engines.

[J] NOx adsorber catalysts are also called, NOx storage catalysts (NSCs), NOx storage and reduction catalysts (NSRs), and NOx traps.

Three-way catalysts reduce NOx emissions as well as HC and CO emissions (hence the name three-way) by promoting oxidation of HC and CO to water and CO_2 using the oxidation potential of the NOx pollutant, and, in the process, reducing the NOx emissions to atomic nitrogen, N_2. Said another way, three-way catalysts work with exhaust conditions where the net oxidizing and reducing chemistry of the exhaust is approximately equal, allowing the catalyst to promote complete oxidation/reduction reactions to the desired exhaust components, carbon dioxide (CO_2), water (H_2O) and nitrogen (N_2). The oxidizing potential in the exhaust comes from NOx emissions and from oxygen (O_2) that is not consumed during combustion. The reducing potential in the exhaust comes from HC and CO emissions, which are products of incomplete combustion. Operation of the engine to ensure that the oxidizing and reducing potential of the combustion and exhaust conditions is precisely balanced is referred to as stoichiometric engine operation.

If the exhaust chemistry varies from stoichiometric conditions emission control is decreased. If the exhaust chemistry is net "fuel-rich," meaning there is an excess of HC and CO emissions in comparison to the oxidation potential of the NOx and O_2 present in the exhaust, the excess HC and CO pollutants are emitted from the engine. Conversely, if the exhaust chemistry is net "oxygen-rich" (lean-burn), meaning there is an excess of NOx and O_2 in comparison to the reducing potential of the HC and CO present in the exhaust, the excess NOx pollutants are emitted from the engine. It is this oxygen-rich operating condition that typifies diesel engine operation. Because of this, diesel engines equipped with three-way catalysts (or simpler oxidation catalysts) have very low HC and CO emissions while NOx (and O_2) emissions remain almost unchanged from the high engine-out emission levels. For this reason, when diesel engines are equipped with catalysts (diesel oxidation catalysts (DOCs)) they have HC and CO emissions that are typically lower, but have NOx emissions that are an order of magnitude higher, than for gasoline engines equipped with three-way catalysts.

The NOx adsorber catalyst works to overcome this situation by storing NOx emissions when the exhaust conditions are oxygen-rich. Unfortunately the storage capacity of the NOx adsorber is limited, requiring that the stored NOx be periodically purged from the storage component. If the exhaust chemistry is controlled such that when the stored NOx emissions are released the net exhaust chemistry is at stoichiometric or net fuel-rich conditions, then the three-way catalyst portion of the catalyst can reduce the NOx emissions in the same way as for a gasoline three-way catalyst equipped engine. Simply put, the NOx adsorber works to control NOx emissions by storing NOx on the catalyst surface under lean-burn conditions typical of diesel engines and then by reducing the NOx emissions with a three-way catalyst function by periodically operating under stoichiometric or fuel-rich conditions.

The NOx storage process can be further broken down into two steps. First the NO in the exhaust is oxidized to NO_2 across an oxidation promoting catalyst, typically platinum. Then the NO_2 is further oxidized and stored on the surface of the catalyst as a metallic nitrate (MNO_3). The storage components are typically alkali or alkaline earth metals that can form stable metallic nitrates. The most common storage component is barium carbonate ($BaCO_3$), which can store NO_2 as barium nitrate ($Ba(NO_3)_2$) while releasing CO_2. For the NOx storage function to work, the NOx must be oxidized to NO_2 prior to storage and a storage site must be available (the device cannot be "full"). During this oxygen-rich portion of operation, NOx is stored while HC and CO emissions are oxidized across the three-way catalyst components by oxygen in the exhaust. This can result in near zero emissions of NOx, HCs, and CO under the net oxygen-rich operating conditions typical of diesel engines.

The NOx adsorber releases and reduces NOx emissions under fuel-rich operating conditions through a similar two step process, referred to here as NOx adsorber regeneration. The metallic nitrate becomes unstable under net fuel-rich operating conditions, decomposing and releasing the stored NOx. Then the NOx is reduced by reducing agents in the exhaust (CO and HCs) across a three-way catalyst system, typically containing platinum and rhodium. Typically, this NOx regeneration step occurs at a significantly faster rate than the period of lean-NOx storage such that the fuel-rich operation constitutes only a small fraction of the total operating time. Since this release and reduction step, NOx adsorber regeneration, occurs under net fuel-rich operating conditions, NOx emissions can be almost completely eliminated. But for some of the HC and CO emissions, "slip"(failure to remove all of the HC and CO) may occur during this process. The HC and CO slip can be controlled with a downstream "clean-up" catalyst that promotes their oxidation or potentially by controlling the exhaust constituents such that the excess amount of the HC and CO pollutants at the fuel-rich operating condition is as low as possible, that is, as close to stoichiometric conditions as possible.

The difference between stoichiometric three-way catalyst function and the newly developed NOx adsorber technology can be summarized as follows. Stoichiometric three-way catalysts work to reduce NOx, HCs and CO by maintaining a careful balance between oxidizing (NOx and O_2) and reducing (HCs and CO) constituents and then promoting their mutual destruction across the catalyst on a continuous basis. The newly developed NOx adsorber technology works to reduce the pollutants by balancing the oxidation and reduction chemistry on a discontinuous basis, alternating between net oxygen-rich and net fuel-rich operation to control the pollutants. This approach allows lean-burn engines (oxygen-rich operating), like diesel engines, to operate under their normal operating mode most of the time, provided that they can periodically switch and operate such that the exhaust conditions are net fuel-rich for brief periods. If the engine/emission-control system can be made to operate in this manner, NOx adsorbers offer the potential to employ the highly effective three-way catalyst chemistry to lean-burn engines.

4.1.2.3.2 NOx Adsorber Regeneration Mechanisms

NOx adsorbers work to control NOx emissions by storing the NOx pollutants on the catalyst surface during oxygen-rich engine operation (lean-burn engine operation) and then by periodically releasing and reducing the NOx emissions under fuel-rich exhaust conditions. This approach to controlling NOx emissions can work for a diesel engine provided that the engine and emission-control system can be designed to work in concert, with relatively long periods of oxygen-rich operation (typical diesel engine operation) followed by brief periods of fuel-rich exhaust operation. The ability to control the NOx emissions in this manner is the production basis for lean-burn NOx emission control in stationary power systems and for lean-burn gasoline engines. As outlined below, we believe there are several approaches to accomplish the required periodic operation on a diesel engine.

The most frequently mentioned approach for controlling the exhaust chemistry of a diesel engine is through in-cylinder changes to the combustion process. This approach roughly mimics the way in which lean-burn gasoline engines function with NOx adsorbers. That is, the engine itself changes in operation periodically between "normal" lean-burn (oxygen-rich) combustion and stoichiometric or even fuel-rich combustion to promote NOx control with the NOx adsorber catalyst. For diesel engines this approach typically requires the use of common rail fuel systems, which allow for multiple fuel-injection events, along with an air handling system that includes exhaust gas recirculation (EGR).

The normal lean-burn engine operation can last from as little time as 15 seconds to more than three minutes as the exhaust NOx emissions are stored on the surface of the NOx adsorber catalyst. The period of fuel-lean, oxygen-rich, operation is determined by the NOx emission rate from the engine and the storage capacity of the NOx adsorber. Once the NOx adsorber catalyst is full (once an unacceptable amount of NOx is slipping through the catalyst without storage) the engine must switch to fuel-rich operation to regenerate the NOx adsorber.

The engine typically changes to fuel-rich operation by increasing the EGR rate, by throttling the fresh air intake, and by introducing an additional fuel-injection event late in the combustion cycle. The increased EGR rate works to decrease the oxygen content of the intake air by displacing fresh air that has a high oxygen content with exhaust gases that have a much lower oxygen content. Intake air throttling further decreases the amount of fresh air in the intake gases again lowering the amount of oxygen entering the combustion chamber. The combination of these first two steps serves to lower the oxygen concentration in the combustion chamber, decreasing the amount of fuel required to reach a fuel-rich condition. The fuel is metered then into the combustion chamber in two steps under this mode of operation. The first, or primary, injection event meters a precise amount of fuel to deliver the amount of torque (energy) required by the operator demand (accelerator pedal input). The second injection event is designed to meter the amount of fuel necessary to achieve a net fuel-rich operating condition. That is, the primary plus secondary injection events introduce an excess of fuel when compared with the amount of oxygen in the combustion chamber. The secondary injection event occurs very late in the combustion cycle, so it does not generate additional torque. This is necessary so the switching between the normal lean-burn operation and this periodic fuel-rich operation is transparent to the user.

Additional ECM capability will be necessary to monitor the NOx adsorber and determine when the NOx regeneration events are necessary. This can be done in a variety of ways, though they fall into two general categories: predictive and reactive. First, the predictive method estimates or measures the NOx flow into the adsorber in conjunction with the predicted adsorber performance to determine when the adsorber is near capacity. Then, upon entering optimal engine operating conditions, the system performs a NOx regeneration. This particular step is similar to an on-board diagnostic (OBD) algorithm waiting for proper conditions to perform a functionality check. During the NOx regeneration, sensors determine how accurately the predictive algorithm performed, and adjust it accordingly. Second, the reactive method is envisioned to monitor NOx downstream of the NOx adsorber and detection of NOx slippage triggers a regeneration event. This method is dependent on good NOx-sensor technology. This method also depends on the ability to regenerate under any given engine operating condition, since the algorithm reacts to indications that the adsorber had reached its NOx storage capacity. In either case, we believe these algorithms are not far removed from the systems that will be used by nonroad manufacturers to meet Tier 3 emission standards and will be virtually identical to the systems used by highway engine manufacturers to comply with the HD2007 emission regulations. When used in combination with the sophisticated control systems that will be available, we expect that NOx regeneration events can be seamlessly integrated into engine operation such that the operator may not be aware that the events are taking place.

Using this approach of periodic switching between normal lean-burn operation and brief periods of fuel-rich operation all accomplished within the combustion chamber of a diesel engine is one way in which an emission-control system for a diesel engine can be optimized to work with the NOx adsorber catalyst. This approach requires no new engine hardware beyond the air handling and advanced common rail fuel systems that many advanced diesel engines will have already applied to meet the Tier 3 NOx standard. For this reason an in-cylinder approach is likely to appeal to engine manufacturers for product lines where initial purchase cost or package size is the most important factor in determining engine purchases.

Another approach to accomplish the NOx adsorber regeneration is through the use of a so-called “dual-bed” or “multiple-bed” NOx adsorber catalyst system. Such a system is designed so the exhaust flow can be partitioned and routed through two or more catalyst “beds” operating in parallel. Multiple-bed NOx adsorber catalysts restrict exhaust flow to part of the catalyst during its regeneration. By doing so, only a portion of the exhaust flow need be made rich, reducing dramatically the amount of oxygen needing to be depleted and thus the fuel required to be injected to generate a rich exhaust stream. One simple example of a multiple bed NOx adsorber is the dual-bed system in Figure 4.1-1. In this example, the top half of the adsorption catalyst system is regenerating under a low exhaust flow condition (exhaust control valve nearly closed), while the remainder of the exhaust flow is bypassed to a lower half of the system. A system of this type has the following characteristics:

- Half of the system operates with a major flow in an “adsorption mode,” where most of the exhaust is well lean of stoichiometric ($\lambda > 1$ or $>>1$, typical diesel exhaust), NO is converted to NO_2 over a Pt-catalyst, and stored as a metallic nitrate within the NOx adsorbent material.[K]

- The other half of the system has its exhaust flow restricted to just a small fraction (~5 percent) of the total flow and operates in a regeneration mode.
  - While the flow is restricted for regeneration, a small quantity of fuel is sprayed into the regenerating exhaust flow at the beginning of the regeneration event.
  - The fuel is oxidized by the oxygen in the exhaust until sufficient oxygen is depleted for the stored NOx to be released. This occurs at exhaust conditions of $\lambda \leq 1$.

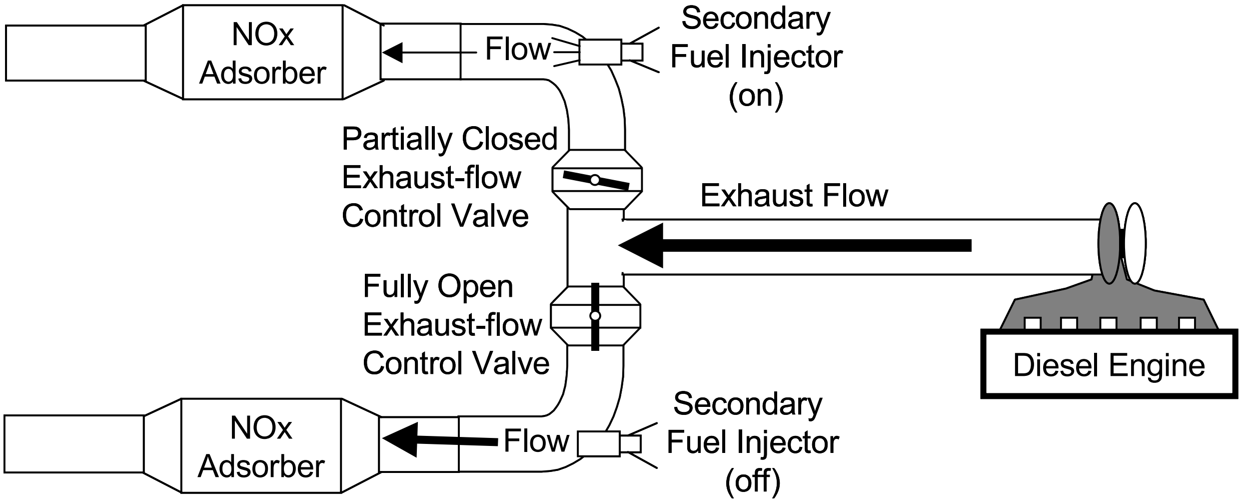
[K] A condition of $\lambda = 1$ means that there are precisely the needed quantity of reactants for complete reaction at equilibrium. $\lambda < 1$ means that there is insufficient oxygen, $\lambda > 1$ means that there is excess oxygen.

- At these conditions, NOx can also be very efficiently reduced to N_2 and O_2 over a precious-metal catalyst.

- At the completion of regeneration, the majority of the flow can then be reintroduced into the regenerated half of the system by opening the flow control valve.

- Simultaneously, flow is restricted to the other half of the system to allow it to regenerate.

Figure 4.1-1
Schematic Representation of the Operation of a Dual-Bed NOx Adsorption Catalyst



Although the schematic shows two separate systems, the diversion of exhaust flow can occur within a single catalyst housing, and with a single catalyst monolith. There may also be advantages to using more than one partition for the NOx adsorber system such as the use of multiple beds allows desulfation of one bed while normal NOx adsorption and regeneration events occur in other beds.

The NOx adsorber performance can be enhanced by incorporating a catalyzed diesel particulate filter (CDPF) into the system. A number of synergies exist between NOx adsorber systems and CDPFs. Both systems rely on conversion of NO to NO_2 over a Pt catalyst for part of their functioning. Partial oxidation reforming of diesel fuel to hydrogen and CO over a Pt-catalyst has been demonstrated for fuel-cell applications. A similar reaction to reform the fuel upstream of the NOx adsorber during regeneration provides a more reactive reductant for desorption and reduction of NOx. Heavier fuel hydrocarbons are known to inhibit NOx reduction on the NOx adsorption catalyst since competitive adsorption by hydrocarbons on the precious-metal sites inhibits NOx reduction during adsorber regeneration.[55] Partial oxidation of the secondary fuel injected into the exhaust during regeneration could lead to sooting of the fuel. Using a CDPF upstream of the NOx adsorber, but downstream of the secondary fuel injection, allows partial oxidation of the fuel hydrocarbons to occur over the Pt catalyst on the surface of the CDPF. The wall-flow design of the CDPF efficiently captures any soot formed during partial oxidation of the fuel injected into the exhaust, preventing any increase in soot emissions. The partial oxidation reaction over the CDPF is exothermic, which can be used increase the rate of temperature rise for the NOx adsorber catalyst after cold starts, similar to the use of light-off catalysts with cascade three-way catalyst systems.[56]

4.1.2.3.3 How Efficient are Diesel NOx Adsorbers?

Research into applying the NOx adsorber catalyst to diesel exhaust is only a few years old but benefits from the larger body of experience with stationary power sources and with lean-burn gasoline systems. In simplest terms the question is how well does the NOx adsorber store NOx under normal lean-burn diesel engine operation, and then how well does the control system perform the NOx regeneration function. Both of these functions are affected by the temperature of the exhaust and of the catalyst surface. For this reason efficiency is often discussed as a function of exhaust temperature under steady-state conditions. This is the approach used in this section and is extended in Section 4.1.3.1.2 below to predict the effectiveness of the NOx adsorber technology when engines operate over the new transient duty cycles. The potential for both NOx storage and reduction to operate at very high efficiencies can be realized through careful emission-control system design, as described below.

The NOx storage function consists of oxidation of NO to NO_2 and then storage of the NOx as a metallic nitrate on the catalyst surface. The effectiveness of the catalyst at accomplishing these tasks is dependent upon exhaust temperature, catalyst temperature, precious-metal dispersion, NO storage volume, and transport time (mass flow rates through the catalyst). Taken as a whole, these factors determine how effectively a NOx adsorber-based control system can store NOx under lean-burn diesel engine operation.

Catalyst and exhaust temperature are important because the rate at which the desirable chemical reactions occur is a function of the local temperature where the reaction occurs. The reaction rate for NO to NO_2 oxidation and for NOx storage increases with increasing temperature. Beginning at temperatures as low as 100°C NO oxidation to NO_2 can be promoted across a platinum catalyst at a rate high enough to allow for NOx storage to occur. Below 100°C the reaction can still occur (as it does in the atmosphere); however, the reaction rate is so slow as to make NOx storage ineffective below this temperature in a mobile source application. At higher exhaust temperatures, above 400°C, two additional mechanisms affect the ability of the NOx adsorber to store NOx. First the NO to NO_2 reaction products are determined by an equilibrium reaction that favors NO rather than NO_2. That is across the oxidation catalyst, NO is oxidizing to form NO_2 and NO_2 is decaying to form NO at a rate that favors a larger fraction of the gas being NO rather than NO_2. As this is an equilibrium reaction when the NO_2 is removed from the gas stream by storage on the catalyst surface, the NOx gases quickly "re-equilibrate" forming more NO_2. This removal of NO_2 from the gas stream and the rapid oxidation of NO to NO_2 means that in spite of the NO_2 fraction of the NOx gases in the catalyst being low at elevated conditions (30 percent at 400°C) the storage of NOx can continue to occur with high efficiencies, near 100 percent.

Unfortunately, the other limitation of high-temperature operation is not so easily overcome. The metallic nitrates that are formed on the catalyst surface and that serve to store the NOx emissions under fuel-lean operating conditions can become unstable at elevated temperatures. That is, the metallic nitrates thermally decompose releasing the stored NOx under lean operating conditions allowing the NOx to exit the exhaust system "untreated." The temperature at which the storage metals begin to thermally release the stored NOx emissions varies dependent upon the storage metal or metals used, the relative ratio of the storage metals, and the washcoat design. Changes to catalyst formulations can change the upper temperature threshold for thermal NOx desorption by as much as 100˚C.[57] Thermal stability is the primary factor determining the NOx control efficiency of the NOx adsorber at temperatures higher than 400-500˚C. NOx adsorber catalyst developers are continuing to work to improve this aspect of NOx adsorber performance, and as documented in EPA's 2002 Highway Progress Review improving temperature performance is being realized.

The NOx adsorber catalyst releases stored NOx emissions under fuel-rich operating conditions and then reduces the NOx over a three-way catalyst function. While the NOx storage function determines the NOx control efficiency during lean operation, it is the NOx release and reduction function that determines the NOx control efficiency during NOx regeneration. Since NOx storage can approach near 100 percent effectiveness for much of the temperature range of the diesel engine, the NOx reduction function often determines the overall NOx control efficiency.

NOx release can occur under relatively cool exhaust temperatures even below 200˚C for current NOx adsorber formulations. Unfortunately, the three-way NOx reduction function is not operative at such cool exhaust temperatures. The lowest temperature at which a chemical reaction is promoted at a defined efficiency (often 50 percent) is referred to as the "light-off" temperature. The 80 percent light-off temperature for the three-way catalytic NOx reduction function of current NOx adsorbers is between 200˚C and 250˚C. Even though NOx storage and release can occur at cooler temperatures, NOx control is therefore limited under steady-state conditions to temperatures greater than this light-off temperature.

Under transient operation, however, NOx control can be accomplished at temperatures below this NOx reduction light-off temperature provided that the period of operation at the lower temperature is preceded by operation at higher temperatures and provided that the low-temperature operation does not continue for an extended period. This NOx control is possible due to two characteristics of the system specific to transient operation. First, NOx control can be continued below the light-off temperature because storage can continue below that temperature. If the exhaust temperature again rises above the NOx reduction light-off temperature before the NOx adsorber storage function is full, the NOx reduction can then precede at high efficiency. Said another way, if the excursions to very low temperatures are brief enough, NOx storage can proceed under this mode of operation, followed by NOx reduction when the exhaust temperatures are above the light-off temperature. Although this sounds like a limited benefit because NOx storage volume is limited, in fact it can be significant, because the NOx emission rate from the engine is low at low temperatures. While the NOx storage rate may be limited such that at high-load conditions the lean-NOx storage period is as short as 30 seconds, at the very low NOx rates typical of low-temperature operation (operation below the NOx reduction light-off temperature) this storage period can increase dramatically. This is due to the NOx mass flow rate from the engine changing dramatically between idle conditions and full load conditions. The period of lean-NOx storage is expected to increase in inverse proportion to the NOx emission rate from the engine. The period of NOx storage under light load conditions therefore can likewise be expected to increase dramatically.

Transient operation can further allow for NOx control below the NOx reduction light-off temperature due to the thermal inertia of the emission-control system itself. The thermal inertia of the emission-control system can work to warm the exhaust gases to a local temperature high enough to promote the NOx reduction reaction even though the inlet exhaust temperatures are below the light-off temperature for the catalyst.

The combination of these two effects was observed during testing of NOx adsorbers at the National Vehicle and Fuel Emissions Laboratory (NVFEL), especially regarding NOx control under idle conditions. It was observed that when idle conditions followed loaded operation, for example when cooling the engine down after a completing an emission test, that the NOx emissions were effectively zero (below background levels) for extended periods of idle operation (for more than 10 minutes). It was also discovered that the stored NOx can be released and reduced in this operating mode, even though the exhaust temperatures were well below 250˚C, provided that the regeneration event was triggered within the first 10 minutes of idle operation (before the catalyst temperature decreased significantly). However, if the idle mode was continued for extended periods (longer than 15 minutes) NOx control eventually diminished. The loss of NOx control at extended idle conditions appeared to be due to the inability to reduce the stored NOx leading to high NOx emissions during NOx regeneration cycles.

NOx control efficiency with the NOx adsorber technology under steady-state operating conditions can be seen to be limited by the light-off temperature threshold of the three-way catalyst NOx reduction function. Further, a mechanism for extending control below this temperature is described for transient operation and is observed in testing of NOx adsorber-based catalyst systems. In addition, as described later in this section, new combustion strategies such as Toyota's low-temperature combustion technology can raise exhaust temperatures at low loads to promote improved NOx performance with a NOx adsorber catalyst.

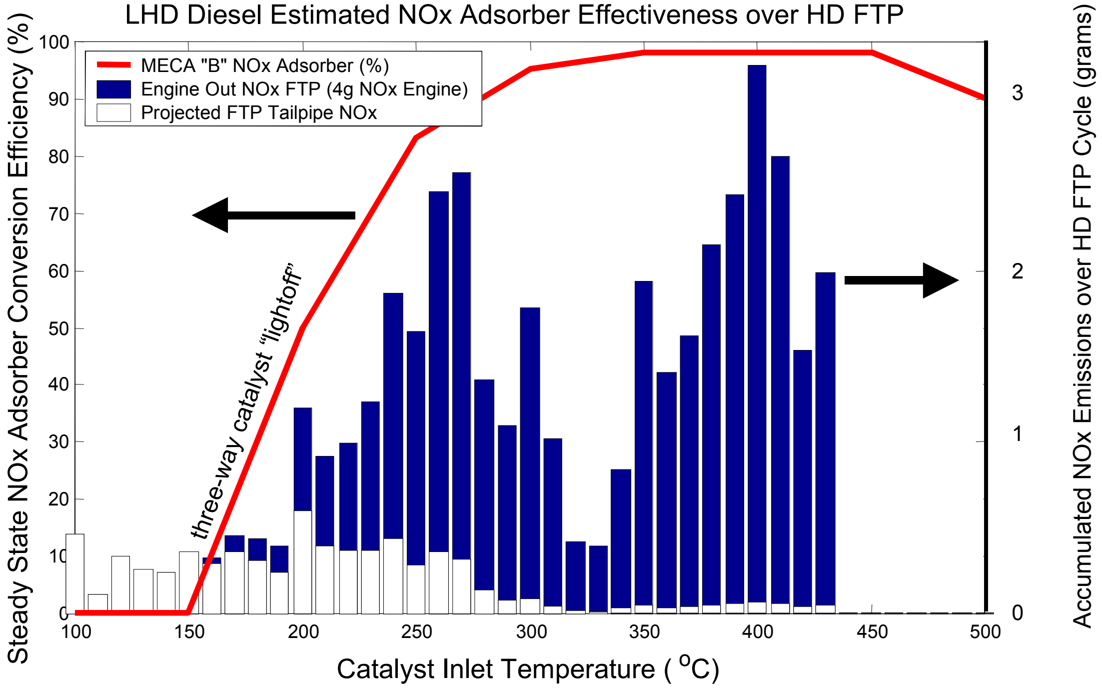
Overall, NOx adsorber efficiency reflects the composite effectiveness of the NOx adsorber in storing, releasing and reducing NOx over repeated lean/rich cycles. As detailed above, exhaust temperatures play a critical role in determining the relative effectiveness of each of these catalyst functions. These limits on the individual catalyst functions can explain the observed overall NOx control efficiency of the NOx adsorber, and can be used to guide future research to improve overall NOx adsorber efficiency and the design of an integrated NOx emission-control system.

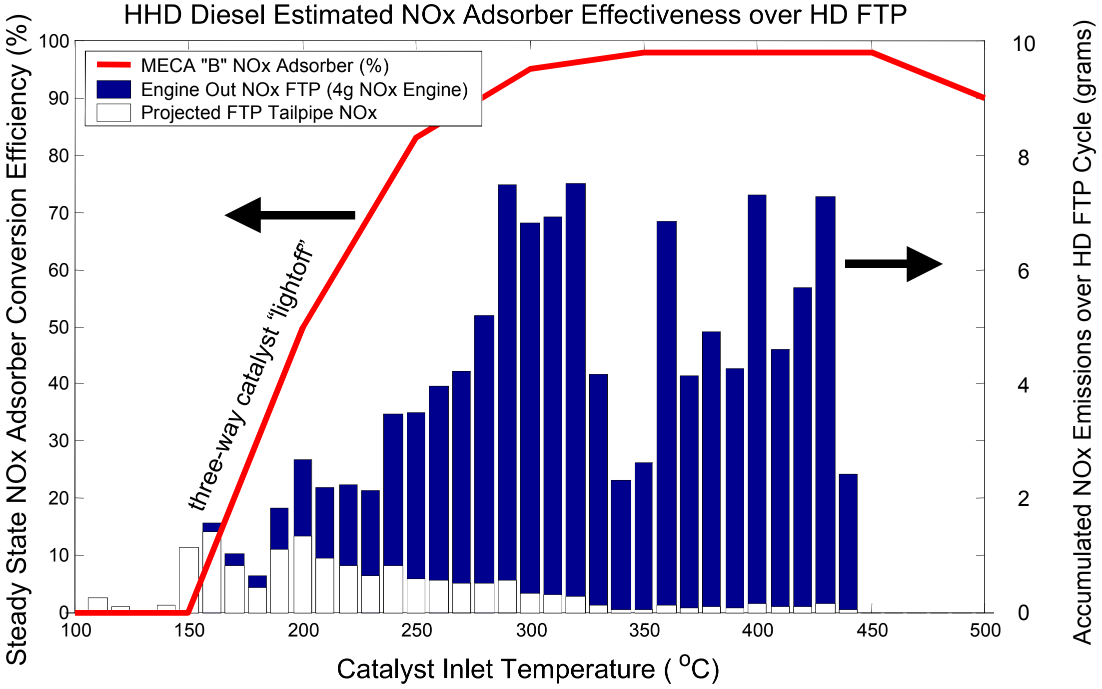
At low exhaust temperatures overall NOx control is limited by the light-off temperature threshold of the three-way NOx reduction function in the range from 200˚C to 250˚C. At high temperatures (above 400˚ to 500˚C) overall NOx control is limited by the thermal stability of the

NOx storage function. For exhaust temperatures between these two extremes NOx control can occur at virtually 100 percent effectiveness.

The ability of the complete system, including the engine and the emission-control system, to control NOx emissions consistently (well in excess of 90 percent) is therefore dependent upon the careful management of temperatures within the system. Figure 4.1-2 provides a pictoral representation of these constraints and indicates how well a diesel engine can match the capabilities of a NOx adsorber-based NOx control system. The figure shows accumulated NOx emissions (grams) over the highway FTP cycle for both a light heavy-duty and a heavy heavy-duty engine. The engine-out NOx emissions are shown as the dark bars on the graphs. The accumulated NOx emissions shown here, divided by the integrated work over the test cycle gives a NOx emission rate of 4 g/hp-hr (the 1998 emission standard for highway heavy-duty diesel engines) for each of these engines. Also shown on the graph as a solid line is the steady-state NOx conversion efficiency for a NOx adsorber, MECA "B", used in testing at NVFEL (see Section 4.1.2.3.5.2 below for more details on testing at NVFEL). The line has been annotated to show the constraint under low-temperature operation (three-way catalyst light-off). The white bars on the graph represent an estimate of the tailpipe NOx emissions that can be realized from the application of the NOx adsorber based upon the steady-state efficiency curve for adsorber MECA "B". These estimated tailpipe emissions are highest in the temperature range below 250˚C even though the engine-out NOx emissions are the lowest in this region. This is due to the light-off temperature threshold for the NOx three-way reduction function.

Figure 4.1-2
NOx Adsorber Efficiency Characteristics versus Exhaust Temperature





Since the conversion efficiencies are based upon steady-state operation, it is likely that the low-temperature performance can be better than estimated here due to a catalyst's ability to store the NOx emissions at these low temperatures and then to reduce them when transient operation raises the exhaust temperatures above the three-way light-off temperature. This assertion provides one explanation for differences noted between this approximation of the NOx efficiency over the highway FTP cycle for the light heavy-duty engine shown in Figure 4.1-2 and actual NOx adsorber efficiency demonstrated with this engine in the NVFEL test program. Based upon the figure above (using the steady-state conversion estimate) the NOx adsorber catalyst should have provided less than an 84 percent reduction in NOx emissions over the highway FTP cycle. However, testing at NVFEL (detailed in Section 4.1.2.3.5) has demonstrated a greater than 90 percent reduction in NOx emissions with this same engine and catalyst pair without significant optimization of the system. Clearly then, steady-state NOx adsorber performance estimates can underestimate the real NOx reductions realized in transient vehicle operation. Nevertheless, we have used this approach as a screening analysis to predict performance for nonroad engines equipped with NOx adsorber catalysts in Section 4.1.3.1.2 below.

The tailpipe NOx emissions are the lowest in the range from 250˚C to 450˚C, even though this is where the majority of the engine-out NOx emissions are created, because of the high overall NOx reduction efficiency of the NOx adsorber system under these conditions. At temperatures above 500˚C the NOx conversion efficiency of the NOx adsorber can be seen to decrease.

Figure 4.1-2 shows that the temperature window of a current technology NOx adsorber catalyst is well matched to the exhaust temperature profiles of a light heavy-duty and a heavy heavy-duty diesel engine operated over the highway FTP cycle. The discussion in Section 4.1.3.1.2 below shows similarly that the nonroad transient cycle (NRTC) is also well matched to the performance of the NOx adsorber catalyst. Testing at NVFEL on the same engine operated over a wide range of steady-state points, shows that even for extended high-load operation, as typified by the 100 percent load test points in the test, NOx conversion efficiencies remained near or above 90 percent (see discussion of the NVFEL test program in Section 4.1.2.3.5 below).

The discussion above makes it clear that when the engine and NOx adsorber-based emission-control system are well matched, NOx reductions can be far in excess of 90 percent. Conversely, it can be inferred that if exhaust temperatures are well in excess of 500˚C or well below 200˚C for significant periods of engine operation then NOx control efficiency may be reduced. Researchers are developing and testing new NOx adsorber formulations designed to increase the high temperature stability of the NOx adsorber and to therefore widen this window of operation.[58]

How effective are NOx adsorbers for cold-start emissions?

In addition to broadening the catalyst temperature window, the exhaust temperature from the diesel engine can be managed to align with the temperature window of the catalyst.

The steady-state analysis discussed above is based on steady-state emission results (i.e., after exhaust temperatures have stabilized), but the NRTC also includes a cold-start test where the catalyst initial temperature will be at ambient conditions (see Section 4.2). The NRTC emission level for the engine is determined by weighting the cold-start emissions by 1/20 (5 percent), and weighting the hot-start emission results by 19/20 (95 percent). Historically, for highway heavy-duty diesel engines that are similar to current technology nonroad diesel engines not equipped with an exhaust emission-control device, the cold-start and hot-start emissions have been nearly identical. However, with the application of emission-control devices which have optimal temperature operating windows, such as a NOx adsorber, the cold-start test will become a design challenge for highway diesel engine manufacturers and for nonroad diesel engine manufacturers, just as it has been a design challenge for light-duty gasoline vehicle manufacturers for more than 20 years.

Manufacturers have several available tools to overcome this challenge:

- The volume, shape, and substrate material have a significant effect on the warm-up time of a NOx adsorber (just as they do for light-duty three-way catalysts). Manufactures will optimize the make-up of the adsorber for best light-off characteristics, such as the thin-walled ceramic monolith catalysts typical of modern low-emission light-duty gasoline applications.

- The packaging of the exhaust emission-control devices, including the use of insulating material and air-gap exhaust systems, will also decrease light-off time, and we expect manufacturers to explore those opportunities.

- The location of the adsorber, with respect to it’s proximity to the exhaust manifold, will have a significant impact on the light-off characteristics.

- As discussed above, NOx adsorbers have the ability to store NOx at temperatures much less than the three-way catalyst function temperature operating window, on the order of 100˚C. This is unlike the performance of catalysts for light-duty gasoline engines, and it allows the NOx adsorber to store NOx for some period of time before the light-off time of the three-way function of its catalyst, resulting in an overall lower effective temperature for the device.

These first four tools available to manufacturers all deal with system design opportunities to improve the cold-start performance of the NOx adsorber system. In addition, manufacturers have several active tools that can be used to enhance the cold-start performance of the system, all based on technologies that may be used to comply with the Tier 3 emission standards (i.e., technologies that will form the baseline for most engines meeting the Tier 4 standards). These include the use of engine start-up routines that have a primary purpose of adding heat to the exhaust to enhance NOx adsorber light-off. For example:

- retarded injection timing;

- intake air throttling;

- post-injection addition of fuel; or

- or increasing back-pressure with an exhaust brake or a VGT system.

We anticipate manufacturers will explore all these tools to choose the best combination necessary to minimize light-off time and improve the cold-start NRTC performance. Highway manufacturers must overcome this same challenge to comply with the HD2007 emission standards some number of years before these nonroad emission standards go into effect. Additionally, highway manufacturers must do this with a higher cold-start weighting of 1/7, rather than 1/20 we are adopting for nonroad diesel engines. This means that highway engine manufacturers must have lower cold-start emissions relative to their hot-start emissions than will nonroad engine manufacturers meeting the Tier 4 standards. We therefore believe that manufacturers of nonroad diesel engines will be able to use the technologies described above to comply with the Tier 4 standards over the NRTC, including the cold-start test.

One light-duty passenger car manufacturer, Toyota, has already demonstrated such an approach to comply with light-duty cold-start requirements. Toyota has shown with its low-temperature combustion technology one mechanism for raising exhaust temperatures even at extremely low-load conditions. The approach, called Low Temperature Combustion (LTC), increases exhaust temperatures at low-load conditions by more than 50˚C while decreasing engine-out NOx emissions.[59] As a result, exhaust temperature are increased into the region for effective NOx adsorber operation even at light loads. The technologies that Toyota uses to accomplish LTC, cooled EGR and advanced common rail fuel systems, are similar to the systems that we expect many nonroad engine manufacturers will use to comply with the Tier 3 standards.

Another example of system integration approaches for diesel engines designed to allow compliance with transient emission control standards including hot and cold emissions can be seen in recent work by the Department of Energy and contractors under the Advanced Petroleum Based Fuels Program - Diesel Emission Control (APBF-DEC). This work documented in a recent SAE paper and in EPA's Highway Diesel Progress Review Report 2, shows that NOx emission can be reduced adequately on a combined hot and cold start FTP test procedure to demonstrate emissions below 0.3 g/bhp-hr.[60,61] The work illustrates both the ability to control NOx emissions under cold-start conditions using rapid warm-up procedures and the ability to reduce NOx emissions below the regulated standards under hot-start conditions to compensate for the slightly elevated emissions levels experienced under cold-start conditions.

How effective are NOx adsorbers over the NTE zone?

We are adopting an NTE standard for nonroad Tier 4 engines that replicates the provisions for highway diesel trucks. A complete discussion of the NTE provisions can be found in Section III.J of the preamble to the final rule. In short, we are setting an NTE emission limit, over a broad range of engine operating conditions, that is 1.5 times the limit that applies for testing over the NRTC and over the steady-state tests. As discussed below, a 90 percent NOx reduction is technologically feasible across the range of engine operating conditions and ambient conditions subject to the NTE standards. Also, as discussed below, some modifications to the NTE provisions to address technical issues that result from the application of advanced NOx catalyst systems were included in the HD2007 standards and are carried over into this final rule.

Section 4.1.2.3.5.2 contains a description of the ongoing NOx adsorber evaluation test program run by our EPA laboratory. Included in that section are test data on four different NOx adsorbers for which extensive steady-state mapping was performed to calculate various steady-state emission levels (See Figures 4.1-10 through 4.1-13). Several of the test modes presented in these figure are not within the NTE zone for NOx, and so would not be subject to the NTE standard. The following modes listed in these four figures are within the NTE zone for NOx: EPA modes 6 - 13, 15, 17, 19, 20. For all of the adsorbers, efficiencies of 90 percent or greater were achieved across the majority of the NTE zone. The region of the NTE zone for which efficiencies less than 90 percent were achieved were concentrated on or near the torque curve (EPA modes 8, 9, 15 and 17), with the exception of Adsorber D, for which EPA modes 6 and 7 achieved 87 percent and 89 percent NOx reduction, respectively. However, Adsorber D was able to achieve NOx reductions greater than 90 percent along the torque curve. The test modes along the torque curve represent the highest exhaust gas temperature conditions for this test engine, on the order of 500˚C. Exhaust temperatures of 500˚C are near the current upper temperature limit of the peak NOx reduction efficiency range for NOx adsorbers. It is therefore not unexpected that the NOx reductions along the torque curve for the test engine are not as high as in other regions of the NTE zone. We expect manufacturers to choose a NOx adsorber formulation that matches the operating range of exhaust gas temperatures for the engine. In addition, the steady-state mode data in Figures 4.1-10 through 4.1-13 were collected under stabilized conditions. In reality, actual in-use operation of a heavy-duty diesel vehicle likely does not experience periods of sustained operation along the torque curve, which diminishes the likelihood that the NOx adsorber bed itself will achieve temperatures in excess of 500˚C. Regardless, as observed in our ongoing diesel progress review and documented in the 2002 diesel progress report, catalyst developers are realizing incremental improvements in the high-temperature NOx reduction capabilities of NOx adsorbers through improvements in NOx adsorber formulations.[62,63,64] As discussed above, only small improvements in the current characteristics are necessary to achieve 90 percent NOx reductions or greater across the NTE zone.

As discussed above, the use of advanced NOx adsorber-based catalyst systems will present cold-start challenges for highway heavy-duty diesel engines, and for nonroad diesel engines, under our Tier 4 program, similar to what light-duty gasoline manufacturers have faced in the past, due to the light-off characteristics of the NOx adsorber. We have previously discussed the tools available to engine manufacturers to overcome these challenges to achieve the NOx standard. The majority of engine operation within the NTE zone will occur at exhaust gas temperatures well above the light-off requirement of the NOx adsorbers. Figures 4.1-10 through 4.1-13 below show that all test modes within the NTE zone have exhaust gas temperatures greater than 300˚C, which is well within the peak NOx reduction efficiency range of current generation NOx adsorbers. However, although NTE testing does not include engine start-up conditions, a diesel engine that has not been warmed up could conceivably be started and very quickly be operated under conditions that are subject to NTE testing; for example, within a minute or less of vehicle operation after the vehicle has left an idle state. The final rule specifies a minimum emission sampling period of 30 seconds for NTE testing. Conceivably, vehicle emissions could be measured against the NTE standards during that first minute of operation, and in all likelihood it would not meet the NTE NOx standard. Given that the NRTC standards will require control of cold-start emissions, manufacturers will be required to pay close attention to cold start to comply with the NRTC. As discussed above, engine operation during NTE testing will be at exhaust gas temperatures within the optimum NOx reduction operating window of the NOx adsorbers. In addition, the NOx adsorber is capable of adsorbing NOx at temperatures on the order of 100˚C. Figures 4.1-10 through 4.1-13 all show NOx emission reductions on the order of 70 - 80 percent are achieved at temperatures as low as 250˚C. We are therefore setting a threshold for exhaust gas temperatures of 250˚C, below which the specified NTE requirements do not apply; we also adopted this provision for the same reason for highway engines in our HD2007 program.

The NTE requirements apply not only during laboratory conditions applicable to the transient test, but also under the wider range of ambient conditions for altitude, temperature and humidity specified in the regulations. These expanded conditions will have minimal impact on the emission-control systems expected to be used to meet the NTE NOx standard. In general, it can be said that the performance of the NOx adsorbers are only affected by the exhaust gas stream to which the adsorbers are exposed. The impact of ambient humidity, temperature, and altitude will therefore affect the performance of the adsorber only to the extent these ambient conditions change the exhaust gas conditions (i.e., exhaust gas temperature and gas constituents). The ambient humidity conditions subject to the NTE requirement will have minimal, if any, impact on the performance of the NOx adsorbers. The exhaust gas itself, independent of the ambient humidity, contains a very high concentration of water vapor, and the impact of the ambient humidity on top of the products of dry air and fuel combustion are minimal. The effect of altitude on NOx adsorber performance should also be minimal or negligible. NTE testing is limited to altitudes below 5,500 feet above sea level. The decrease in atmospheric pressure at 5,500 feet should have minimal impact on the NOx adsorber performance. Increasing altitude can decrease the air-fuel ratio for diesel engines, which can in turn increase exhaust gas temperatures. However, as discussed in the final rule for the highway 2004 standards (Phase 1), highway engines with Phase 1 technology (and thus the similar Tier 3 nonroad diesel engines) can be designed to target air-fuel ratios at altitude that will maintain appropriate exhaust gas temperatures within the ambient conditions specified by the highway NTE test procedure and thus the similar NTE procedure for Tier 4 engines. This approach also allows manufacturers to maintain engine-out PM emission levels near the 0.1 g/hp-hr level. Finally, the NTE regulations specify ambient temperatures that are broader than the NRTC temperature range of 68-86˚F. The NTE test procedure specifies no lower ambient temperature bounds. However, as discussed above, we limit NTE requirements on NOx (and NMHC) for engines equipped with NOx (and/or NMHC) catalysts to include only engine operation with exhaust gas temperatures greater than 250˚C. Low ambient temperatures will therefore not present any difficulties for NTE NOx compliance. NTE standards also apply under ambient temperatures that are higher than the laboratory conditions. The NTE standards apply up to a temperature of 100˚F at sea level, and up to 86˚F at 5,500 feet above sea level. At altitudes in between, the upper NTE ambient temperature requirement is a linear fit between these two conditions. At 5,500 feet, the NTE ambient temperature requirement is the same as the upper end of the temperature range (86˚F) for testing with prescribed duty cycles, and will therefore have no impact on the performance of the NOx adsorbers, considering that majority of the test data described throughout this chapter were collected under laboratory conditions. The NTE upper temperature limits at sea level is 100˚F, which is 14˚F (7.7˚C) greater than the NRTC range. This increase is relatively minor, and while it will increase the exhaust gas temperature; in practice the increase should be passed through the engine to the exhaust gas, and the exhaust gas would be on the order of 8˚C higher. Within the exhaust gas temperature range for a diesel engine during NTE operation, an 8˚C increase is very small. As discussed above, we expect manufacturers to choose an adsorber formulation matched to a particular engine design and we expect the small increase in exhaust gas temperature that can occur from the expanded ambient temperature requirements for the NTE to be taken into account by manufacturers when designing the complete emission-control system.

To summarize, based on the information presented in this chapter, and the analysis and discussion presented in this section, we conclude the NTE NOx requirement (1.5 × NRTC/C1 standard) contained in this final rule will be feasible.

Further discussion of feasibility of the NOx requirement under transient testing conditions can be found in Section 4.1.3.1.2.

4.1.2.3.4 Are Diesel NOx Adsorbers Durable?

The considerable success in demonstrating NOx adsorbers makes us confident that the technology is capable of providing the level of conversion efficiency needed to meet the Tier 4 NOx standard. However, there are several engineering challenges that will need to be addressed in going from this level of demonstration to implementation of durable and effective emission-control systems on nonroad equipment. In addition to the generic need to optimize engine operation to match the NOx adsorber performance, engine and catalyst manufacturers will further need to address issues of system and catalyst durability. The nature of these issues are well understood. The hurdles that must be overcome have direct analogues in technology issues that have been addressed previously in automotive applications and are expected to be overcome with many of the same solutions. With the transfer of highway technologies to nonroad engines anticipated in this rulemaking, we believe we have already addressed the issues highlighted in this section for highway engines well before the start of this nonroad program.

In this section, we will describe the major technical hurdles that must be addressed to ensure that the significant emission reductions from NOx adsorbers occur throughout the life of nonroad diesel engines. This section is organized into separate durability discussions for the system components (hardware) and various near-term and long-term durability issues for the NOx adsorber catalyst itself.

4.1.2.3.4.1 NOx Adsorber Regeneration Hardware Durability

The system we have described in Figure 4.1-1 represents but one possible approach for generating the necessary exhaust conditions to allow for NOx adsorber regeneration and desulfation. The system consists of three catalyst substrates (for a CDPF/Low Temperature NOx Adsorber, a High Temperature NOx Adsorber and an Oxidation Catalyst), a support can that partitions the exhaust flow through the first two catalyst elements, three fuel injectors, and a means to divert exhaust flow through one or more of the catalyst partitions. Though not shown in the figure, a NOx /O_2 sensor is also likely to be needed for control feedback and on-board diagnostics (OBD). All of these elements have already been applied in one form or another to either diesel or gasoline engines in high volume long life applications.

The NOx adsorber system we described earlier borrows several components from the gasoline three-way catalyst systems and benefits from the years of development on three way catalysts. The catalyst substrates (the ceramic support elements on which a catalyst coating is applied) have developed through the years to address concerns with cracking due to thermal cycling and abrasive damage from vehicle vibration. The substrates applied for diesel NOx adsorbers will be virtually identical to the ones used for today's passenger cars in every way but size. They are expected to be equally durable when applied to diesel applications as has already been shown in the successful application of diesel oxidation catalysts (DOCs) on some diesel engines over the last 15 years. Retrofit catalyst-based systems have similarly been applied to nonroad diesel engines with good durability, as described in Section 4.1.3.2 below.

The NOx/O_2 sensor needed for regeneration control and OBD is another component originally designed and developed for gasoline powered vehicles (in this case lean-burn gasoline vehicles) that are already well developed and can be applied with confidence in long life for NOx adsorber-based diesel emission control. The NOx/O_2 sensor is an evolutionary technology based largely on the current Oxygen (O_2) sensor technology developed for gasoline three-way catalyst-based systems. Oxygen sensors have proven to be extremely reliable and long lived in passenger car applications, which see significantly higher temperatures than are normally encountered on a diesel engine.[65,66] Diesel engines do have one characteristic that makes the application of NOx/O_2 sensors more difficult. Soot in diesel exhaust can cause fouling of the NOx/O_2 sensor damaging its performance. However this issue can be addressed through the application of a catalyzed diesel particulate filter (CDPF) in front of the sensor. (See Section 4.1.2.3.2 above, noting synergies that can result from use in tandem of NOx adsorbers and CDPFs.) The CDPF then provides a protection for the sensor from PM while not hindering its operation. Since the NOx adsorber will likely be located downstream of a CDPF in each of the potential technology scenarios we have considered this solution to the issue of PM sooting is readily addressed.

Fuel is metered into a modern gasoline engine with relatively low pressure pulse-width-modulated fuel-injection valves. These valves are designed to cycle well over a million times over the life of a vehicle while continuing to accurately meter fuel. Applying this technology to provide diesel fuel as a reductant for a NOx adsorber system is a relatively straightforward extension of the technology. A NOx adsorber system cycles far fewer times over its life when compared with the current long life of gasoline injectors. However, these gasoline fuel injectors designed to meter fuel into the relatively cool intake of a car cannot be directly applied to the exhaust of a diesel engine. In the testing done at NVFEL, a similar valve design was used that had been modified in material properties to allow application in the exhaust of an engine. While benefitting from the extensive experience with gasoline-based injectors a designer can therefore, in a relatively straightforward manner, improve the characteristics of the injector to allow application for exhaust reductant regeneration. Toyota has shown with its Avensis DPNR diesel passenger car how to use a gasoline direct injection (GDI)-based fuel injector to inject diesel fuel in the exhaust manifold of a diesel engine to allow for NOx adsorber regeneration and desulfation.[67]

The NOx adsorber system we describe in Figure 4.1-1 requires a means to partition the exhaust during regeneration and to control the relative amounts of exhaust flow between two or more regions of the exhaust system. Modern diesel engines already employ a valve designed to carry out this very task. Most modern turbochargers employ a wastegate valve that allows some amount of the exhaust flow to bypass the exhaust turbine to control maximum engine boost and limit turbocharger speed. These valves can be designed to be proportional, bypassing a specific fraction of the exhaust flow to track a specified boost pressure for the system. Turbocharger wastegate valves applied to heavy-duty diesel engines typically last the life of the engine in spite of the extremely harsh environment within the turbocharger. This same valve approach can be applied to accomplish the flow diversion required for diesel NOx adsorber regeneration and desulfation. Since temperatures will typically be cooler at the NOx adsorber compared with the inlet to the exhaust turbine on a turbocharger, the control valve should be equally reliable in this application.

4.1.2.3.4.2 NOx Adsorber Catalyst Durability

In many ways a NOx adsorber, like other engine catalysts, acts like a small chemical process plant. It has specific chemical processes that it promotes under specific conditions with different elements of the catalyst materials. There is often an important sequence to the needed reactions and a need to match process rates to keep this sequence of reactions going. Because of this need to promote specific reactions under the right conditions early catalysts were often easily damaged. This damage prevents or slows one or more the reactions causing a loss in emission control. For example, contaminants from engine oil, like phosphorous or zinc, can attach to catalysts sites partially blocking the site from the exhaust constituents and slowing reactions. Similarly, lead added to gasoline to increase octane levels bonds to the catalyst sites, causing poisoning as well. Likewise, sulfur, which occurs naturally in petroleum products like gasoline and diesel fuel, can poison many catalyst functions preventing or slowing the desired reactions. High exhaust temperatures experienced under some conditions can cause the catalyst materials to sinter (thermally degrade) decreasing the surface area available for reactions to decrease.

All of these problems have been addressed over time for the gasoline three-way catalysts, resulting in the high efficiency and long life durability now typical of modern vehicles. To accomplish this, changes were made to fuels and oils used in vehicles (e.g., lead additives banned from gasoline, sulfur levels reduced in gasoline distillates, specific oil formulations for aftertreatment equipped cars), and advances in catalysts designs were needed to promote sintering-resistant catalyst formulations with high precious-metal dispersion.

The wealth of experience gained and technological advancements made over the last 30 years of gasoline catalyst development can now be applied to the development of the NOx adsorber catalyst. The NOx adsorber is itself an incremental advancement from current three-way catalyst technology. It adds one important additional component not currently used on three-way catalysts, NOx storage catalyst sites. The NOx storage sites (normally alkali or alkaline earth metals) allow the catalyst to store NOx emissions with extremely high efficiency under the lean-burn conditions typical of the diesel exhaust. It also adds a new durability concern due to sulfur storage on the catalyst.

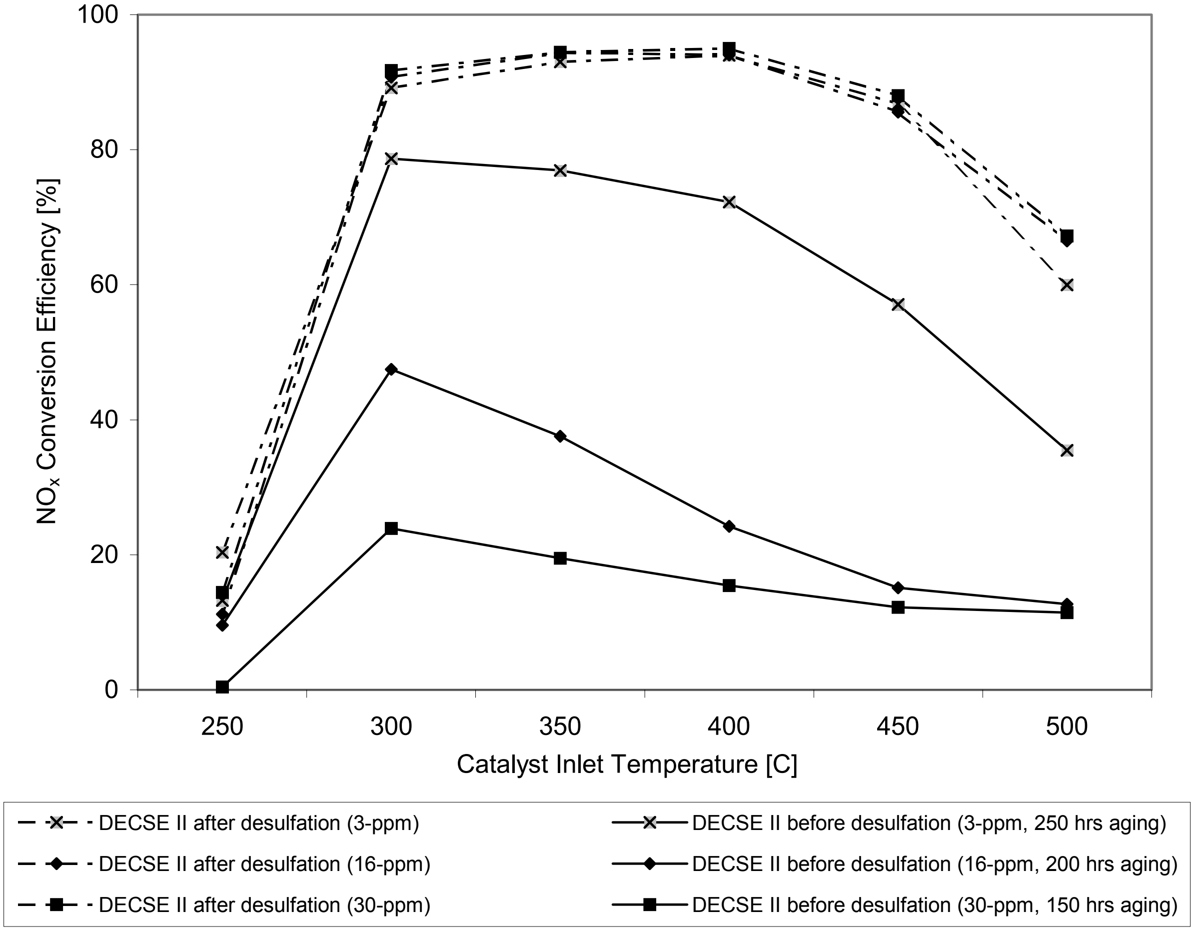
This section will explore the durability issues of the NOx adsorber catalyst applied to diesel engines. It describes the effect of sulfur in diesel fuel on catalyst performance, the methods to remove the sulfur from the catalyst through active control processes, and the implications for durability of these methods. It then discusses these durability issues relative to similar issues for existing gasoline three-way catalysts and the engineering paths to solve these issues. This discussion shows that the NOx adsorber is an incremental improvement upon the existing three-way catalyst, with many of the same solutions for the expected durability issues.

Sulfur Poisoning of the NOx Storage Sites

The NOx adsorber technology is extremely efficient at storing NOx as a nitrate on the surface of the catalyst, or adsorber (storage) bed, during lean operation. Because of the similarities in chemical properties of SOx and NOx, the SO_2 present in the exhaust is also stored on the catalyst surface as a sulfate. The sulfate compound that is formed is significantly more stable than the nitrate compound and is typically not released during the NOx release and reduction step (NOx regeneration step) (i.e., it is stored preferentially to NOx). Since the NOx adsorber is virtually 100 percent effective at capturing SO_2 in the adsorber bed, sulfate compounds quickly occupy the NOx storage sites on the catalyst thereby reducing and eventually rendering the catalyst ineffective for NOx reduction (poisoning the catalyst).

Figure 4.1-3 shows the effect of sulfur poisoning of a NOx adsorber catalyst as reported by the DOE DECSE program. The graph shows the NOx adsorber efficiency versus exhaust inlet temperature under steady-state conditions for a diesel engine-based system. The three dashed lines that overlap each other show the NOx conversion efficiency of the catalyst when sulfur has been removed from the catalyst. The three solid lines show the effect of sulfur poisoning on the catalyst at three different fuel sulfur levels over different periods of extended aging (up to 250 hours). From the figure, it can be seen that even with three ppm sulfur fuel a significant loss in NOx efficiency can occur in as little as 250 hours. Further, it can be seen that quite severe sulfur poisoning can occur with elevated fuel sulfur levels. Catalyst performance was degraded by more than 70 percent over only 150 hours of operation when 30 ppm sulfur fuel was used.[68]

Figure 4.1-3
Comparison of NOx Conversion Efficiency before and after Desulfation



The DECSE researchers drew three important conclusions from Figure 4.1-3:

- Fuel sulfur, even at very low levels like three ppm, can limit the performance of the NOx adsorber catalyst significantly.
- Higher fuel sulfur levels, like 30 ppm, dramatically increase the poisoning rate, further limiting NOx adsorber performance.
- Most importantly though, the figure shows that if the sulfur can be removed from the catalyst through a desulfation (or desulfurization) event, the NOx adsorber can provide high NOx control even after exposure to sulfur in diesel fuel. This is evidenced by the sequence of the data presented in the figure. The three high conversion efficiency lines show the NOx conversion efficiencies after a desulfation event that was preceded by the sulfur poisoning and degradation shown in the solid lines.

It is clear from this data that higher fuel sulfur levels dramatically reduce the efficiency of NOx adsorber catalysts. Sulfur accumulates in the NOx storage sites preventing their use for NOx storage. In other words, they decrease the storage volume of the catalyst. The rate at which sulfur fills NOx storage sites is expected to be directly proportional to the amount of sulfur that enters the catalyst. A doubling in fuel-sulfur levels should therefore correspond to a doubling in the SOx poisoning rate.

The design of a NOx adsorber will need to address accommodating an expected volume of sulfur before experiencing unacceptable penalties in either lost NOx control efficiency or increased fuel consumption due to more frequent NOx regenerations. The amount of operation allowed before that limit is realized for a specific adsorber design will be inversely proportional to fuel sulfur quantity. In the theoretical case of zero sulfur, the period of time before the sulfur poisoning degraded performance excessively would be infinite. For a more practical fuel sulfur level like the 10 ppm average expected with a 15 ppm fuel sulfur cap, the period of operation before unacceptable poisoning levels have been reached is expected to be less than 40 hours (with today's NOx adsorber formulations).[69]

Future improvements in the NOx adsorber technology are expected due to its relatively early state of development. Some of these improvements are likely to include improvements in the kinds of materials used in NOx adsorbers to increase the means and ease of removing stored sulfur from the catalyst bed. However, because the stored sulfate species are inherently more stable than the stored nitrate compounds (from stored NOx emissions), we expect that future NOx adsorbers will continue to be poisoned by sulfur in the exhaust. A separate sulfur release and reduction cycle (desulfation cycle) will therefore always be needed to remove the stored sulfur.

NOx Adsorber Desulfation

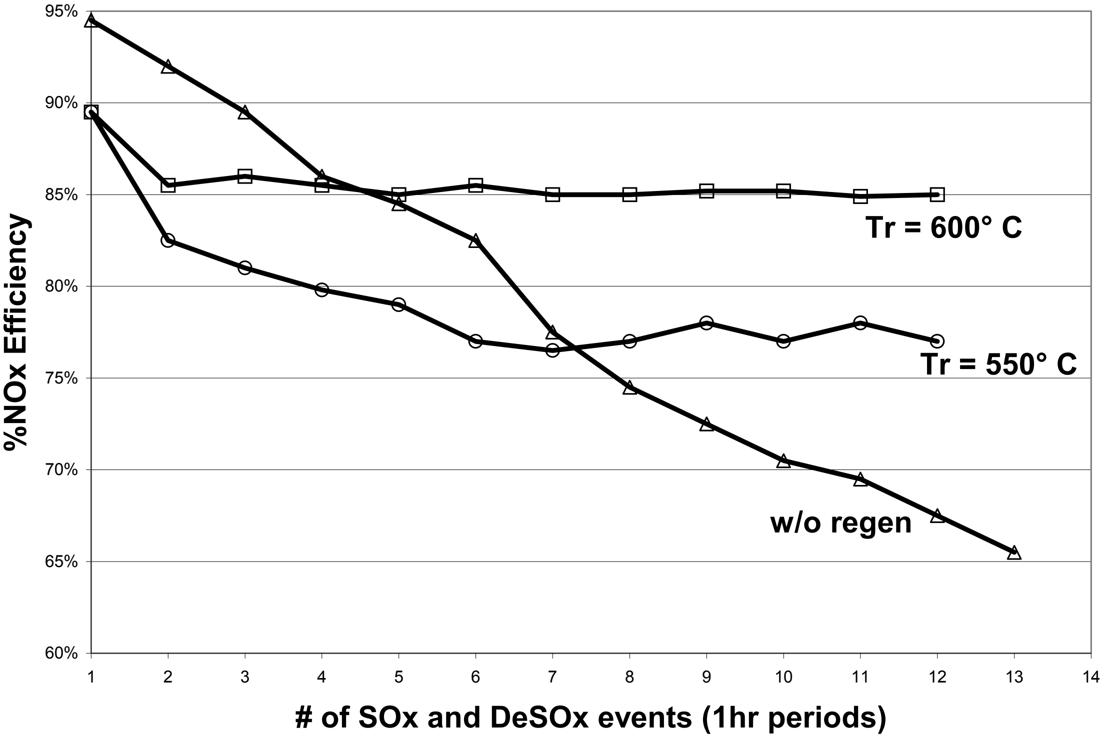
Numerous test programs have shown that sulfur can be removed from the catalyst surface through a sulfur regeneration step (desulfation step) not dissimilar from the NOx regeneration function.[70,71,72,73,74,75] The stored sulfur compounds are removed by exposing the catalyst to hot and rich (air-fuel ratio below the stoichiometric ratio of 14.5 to 1) conditions for a brief period. Under these conditions, the stored sulfate is released and reduced in the catalyst. This sulfur removal process, called desulfation or desulfurization in this document, can restore the performance of the NOx adsorber to near new operation.

Most of the information in the public domain on NOx adsorber desulfation is based upon research done either in controlled bench reactors using synthetic gas compositions or on advanced lean-burn gasoline engine vehicles. As outlined above, these programs have shown that desulfation of NOx adsorber catalysts can be accomplished under certain conditions but the work does not directly answer whether NOx adsorber desulfation is practical for diesel engine exhaust conditions. The DECSE Phase II program answers that question.

Phase II of the DECSE program developed and demonstrated a desulfurization (desulfation) process to restore NOx conversion efficiency lost to sulfur contamination. The engine used in the testing was a high-speed direct-injection diesel selected to provide a representative source of diesel exhaust and various exhaust temperature profiles to challenge the emission-control devices. The desulfation process developed in the DECSE Phase II program controlled the air-fuel ratio and catalyst inlet temperatures to achieve the high temperatures required to release the sulfur from the device. Air-fuel ratio control was accomplished in the program with exhaust gas recirculation (EGR) and a post-injection of fuel to provide additional reductants. Using this approach the researchers showed that a desulfation procedure can be developed for a diesel engine with the potential to meet in-service engine operating conditions and acceptable levels of torque fluctuation. The NOx efficiency recovery accomplished in DECSE Phase II using this approach is shown in Figure 4.1-3, above.

The effectiveness of NOx adsorber desulfation appears to be closely related to the temperature of the exhaust gases during desulfation, the exhaust chemistry (relative air-fuel ratio), and to the NOx adsorber catalyst formulation.[76, 77] Lower air-fuel ratios (more available reductant) works to promote the release of sulfur from the surface, promoting faster and more effective desulfation. Figure 4.1-4 shows results from Ford testing on NOx adsorber conversion efficiency with periodic aging and desulfation events in a control flow reactor test.[78] The control flow reactor test uses controlled gas constituents that are meant to represent the potential exhaust gas constituents from a lean-burn engine. The solid line with the open triangles labeled “w/o regen” shows the loss of NOx control over thirteen hours of testing without a desulfation event and with eight ppm sulfur in the test gas (this is roughly equivalent to 240 ppm fuel sulfur, assuming an air-fuel ratio for diesel engines of 30:1).[79] From the figure it can be seen that without a desulfation event, sulfur rapidly degrades the performance of the NOx adsorber catalyst. The remaining two lines show the NOx adsorber performance with periodic sulfur regeneration events timed at one-hour intervals and lasting for 10 minutes (a one-hour increment on 240 ppm fuel sulfur is approximately equivalent to 34 hours of operation on 7 ppm fuel). The desulfation events were identical to the NOx regeneration events, except that the desulfation events occurred at elevated temperatures. The base NOx regeneration temperature for the testing was 350˚C. The sulfur regeneration, or desulfation, event was conducted at two different gas temperatures of 550˚C and 600˚C to show the effect of exhaust gas temperature on desulfation effectiveness, and thus NOx adsorber efficiency. From Figure 4.1-4 it can be seen that, for this NOx adsorber formulation, the NOx recovery after desulfation is higher for the desulfation event at 600˚C than at 550˚C.

Figure 4.1-4
Flow Reactor Testing of a NOx Adsorber with Periodic Desulfations



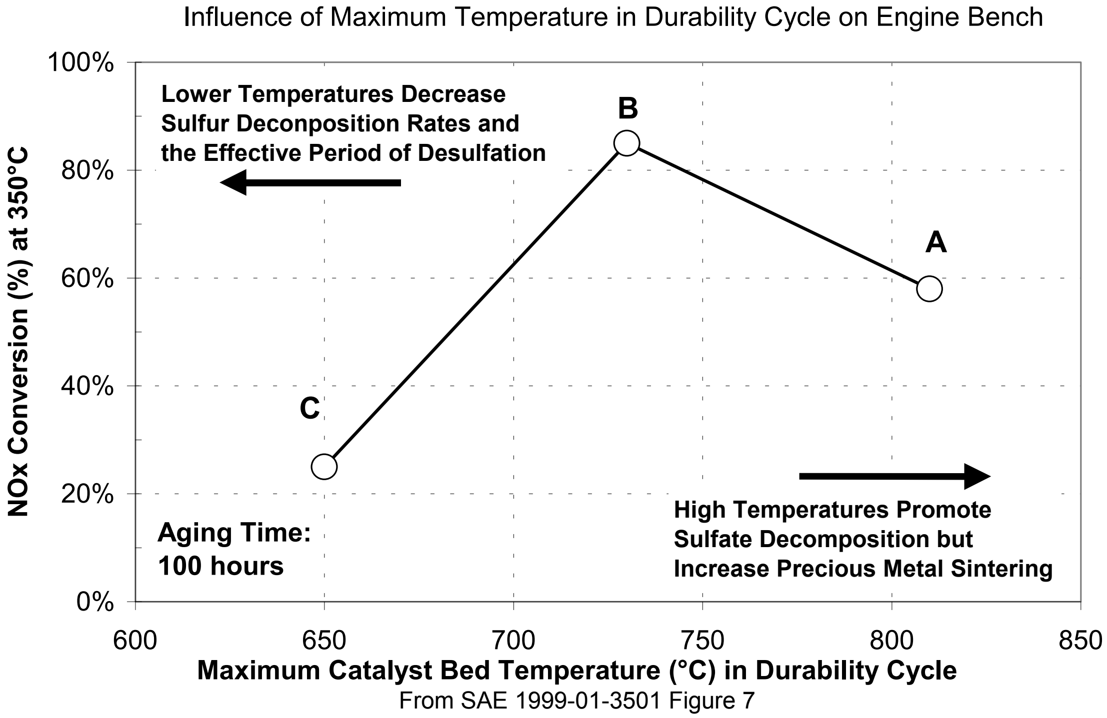
As suggested by Figure 4.1-4, it is well known that the rate of sulfur release (also called sulfur decomposition) in a NOx adsorber increases with temperature.[80,81] However, while elevated temperatures directionally promote more rapid sulfur release, they also can directionally promote sintering of the precious metals in the NOx adsorber washcoat. The loss of conversion efficiency due to exposure of the catalyst to elevated temperatures is referred to as thermal degradation in this document.

Thermal Degradation

The catalytic metals that make up most exhaust emission-control technologies, including NOx adsorbers, are designed to be dispersed throughout the catalyst into as many small catalyst "sites" as possible. By spreading the catalytic metals into many small catalyst sites, rather than into a fewer number large sites, catalyst efficiency is improved. This is because smaller catalyst sites have more surface area per mass, or volume, of catalyst when compared with larger catalyst sites. Since most of the reactions being promoted by the catalyst occur on the surface, increasing surface area increases catalyst availability and thus conversion efficiency. While high dispersion (many small catalyst sites) is in general good for most catalysts, it is even more beneficial to the NOx adsorber catalyst because of the need for the catalytic metal sites to perform multiple tasks. NOx adsorber catalysts typically rely on platinum to oxidize NO to NO_2 prior to adsorption of the NO_2 on an adjacent NOx storage site. Under rich operating conditions, the NOx is released from the adsorption site, and the adjacent platinum (or platinum + rhodium) catalyst site can serve to reduce the NOx emissions into N_2 and O_2. High dispersion, combined with NO oxidation, NOx storage and NOx reduction catalyst sites being located in close proximity, provide the ideal catalyst design for a NOx adsorber catalyst. But high temperatures, especially under oxidizing conditions, can promote sintering of the platinum and other PGM catalyst sites, permanently decreasing NOx adsorber performance.

Catalyst sintering is a process by which adjacent catalyst sites can "melt" and regrow into a single larger catalyst site (crystal growth). The single larger catalyst site has less surface area available to promote catalytic activity than the original two or more catalyst sites that were sintered to form it. This loss in surface area decreases the efficiency of the catalyst.[82] High temperatures, promote sintering of platinum catalysts especially under oxidizing conditions.[83] It is therefore important to limit the exposure of platinum-based catalysts to high exhaust temperatures especially during periods of lean operation. Consequently, the desire to promote rapid desulfation of the NOx adsorber catalyst technology by maximizing the desulfation temperature and the need to limit the exposure of the catalyst to the high temperatures that promote catalyst sintering must be carefully balanced. An example of this tradeoff can be seen in Figure 4.1-5, which shows the NOx conversion efficiency of three NOx adsorber catalysts evaluated after extended periods of sulfur poisoning followed by sulfur regeneration periods.[84] The three catalysts (labeled A, B, and C) are identical in formulation and size but were located at three different positions in the exhaust system of the gasoline direct injection engine used for this testing. Catalyst A was located 1.2 meters from the exhaust manifold, catalyst B 1.8 meters from the exhaust manifold and catalyst C was located 2.5 meters from the exhaust manifold. Locating the catalysts further from the engine lowered the maximum exhaust temperature and thus catalyst bed temperature experienced during the programmed sulfur regeneration cycle. Catalyst A experienced the highest catalyst bed temperature of 800˚C, while catalyst C experienced the lowest catalyst bed temperature of 650˚C. Catalyst B experienced a maximum catalyst bed temperature of 730˚C. Figure 4.1-5 shows that there is an optimum desulfation temperature that balances the tradeoffs between rapid sulfur regeneration and thermal degradation (thermal sintering) at high temperatures.

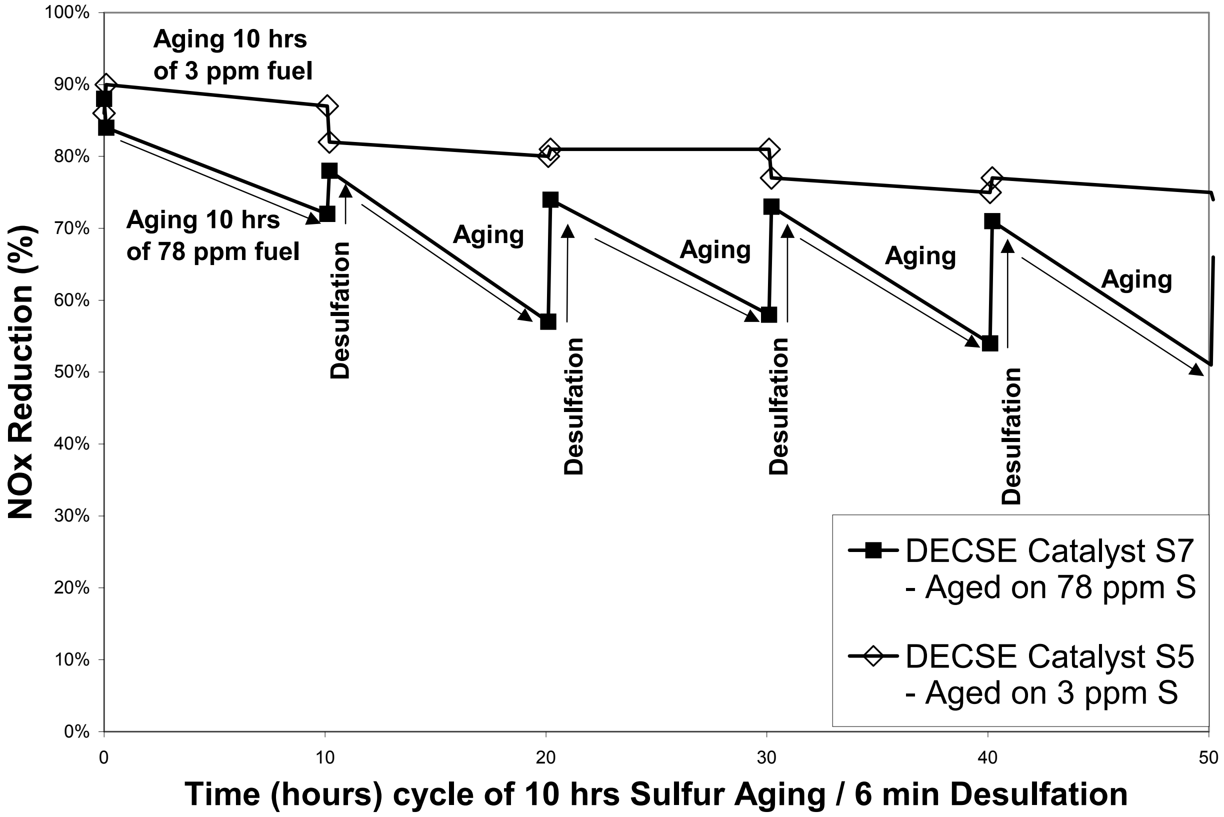
Figure 4.1-5
Influence of Maximum Catalyst Bed Temperature During Desulfation



From SAE 1999-01-3501 Figure 7

The DECSE Phase II program, in addition to investigating the ability of a diesel engine / NOx adsorber-based emission-control system to desulfate, provides a preliminary assessment of catalyst durability when exposed to repeated aging and desulfurization cycles. Two sets of tests were completed using two different fuel sulfur levels (three ppm and 78 ppm) to investigate these durability aspects. The first involved a series of aging, performance mapping, desulfurization and performance mapping cycles. An example of this testing is shown in Figure 4.1-6. The graph shows a characteristic “sawtooth” pattern of gradual sulfur poisoning followed by an abrupt improvement in performance after desulfation. The results shown in Figure 4.1-6 are for two identical catalysts one operated on 3 ppm sulfur fuel (catalyst S5) and the other operated on 78 ppm sulfur fuel (catalyst S7). For the catalyst operated on 3 ppm sulfur fuel the loss in performance over the ten hours of poisoning is noted to be very gradual. There appears to be little need to desulfate that catalyst at the ten-hour interval set in the experiment. In fact it can be seen that in several cases the performance after desulfation is worse than prior to desulfation. This suggests, as discussed above, that the desulfation cycle can itself be damaging to the catalyst. In actual use, we would expect an engine operating on 3 ppm sulfur fuel not to desulfate until well beyond a ten-hour interval and be engineered to better withstand the damage caused by desulfation, as discussed later in this section. For the catalyst operated on 78 ppm sulfur fuel the loss in performance over the ten-hour poisoning period is dramatic. To ensure continued high performance when operating on 78 ppm sulfur fuel, the catalyst requires frequent desulfations. From the figure it can be inferred that the desulfation events need to be spaced at intervals as short as one to two hours to maintain acceptable performance.

Figure 4.1-6
Integrated NOx Conversion Efficiency following Aging and Desulfation



As a follow on to the work shown in Figure 4.1-6, the desulfation events were repeated an additional 60 times without sulfur aging between desulfation events. This was done to investigate the possibility of deleterious affects from the desulfation event itself even without additional sulfur poisoning. As can be seen in Figure 4.1-7, the investigation did reveal that repeated desulfation events even without additional sulfur aging can cause catalyst deterioration. As described previously, high temperatures can lead to a loss in catalyst efficiency due to thermal degradation (sintering of the catalytic metals). This appears to be the most likely explanation for the loss in catalyst efficiency shown here. For this testing, the catalyst inlet temperature was controlled to approximately 700˚C; however, the catalyst bed temperatures may have been higher.[85]

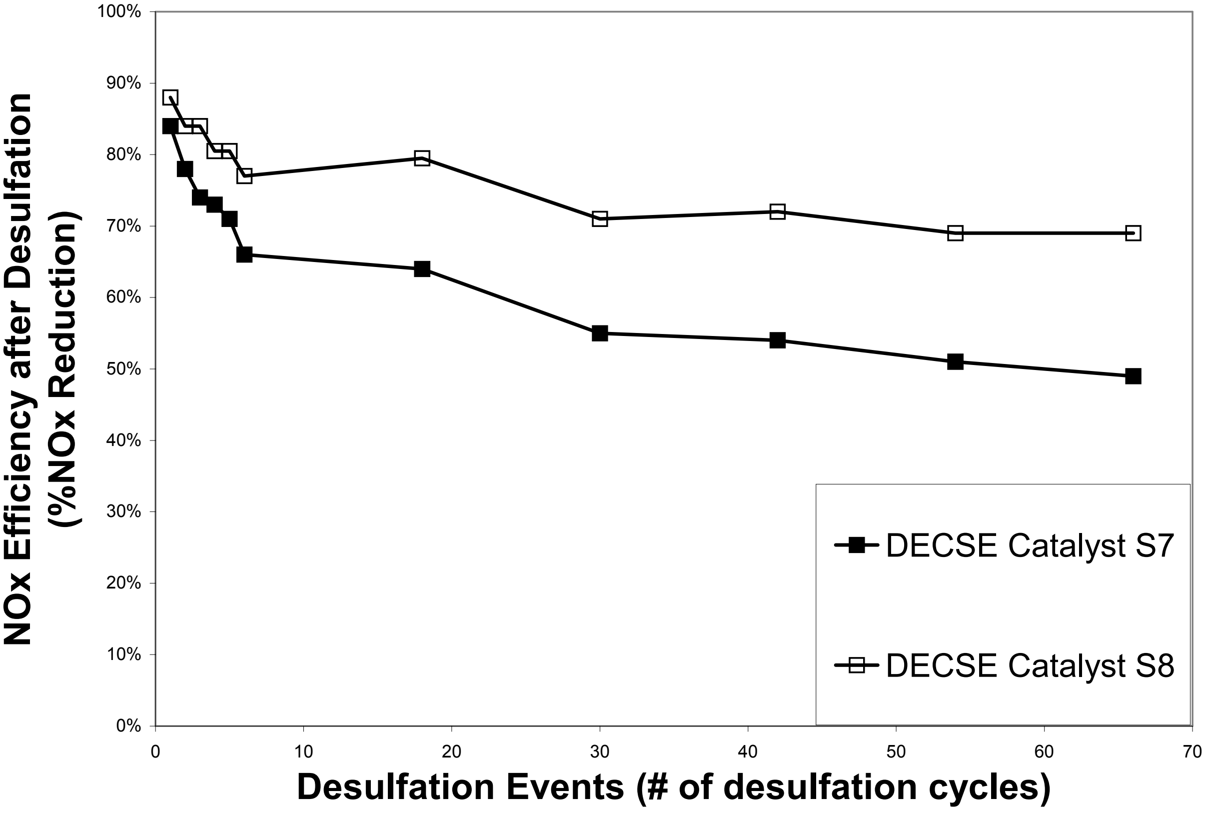
Based on the work in DECSE Phase II, the researchers concluded that:

- The desulfurization procedure developed has the potential to meet in-service engine operating conditions and to provide acceptable driveability conditions.

- Although aging with 78 ppm sulfur fuel reduced NOx conversion efficiency more than aging with three ppm sulfur fuel as a result of sulfur contamination, the desulfurization events restored the conversion efficiency to nearly the same level of performance. However, repeatedly exposing the catalyst to the desulfurization procedure developed in the program caused a continued decline in the catalyst's desulfated performance.

- The rate of sulfur contamination during aging with 78 ppm sulfur fuel increased with repeated aging / desulfurization cycles (from 10 percent per ten hours to 18 percent per ten hours). This was not observed with the three ppm sulfur fuel, where the rate of decline during aging was fairly constant at approximately two percent per ten hours.

Figure 4.1-7
Integrated NOx Conversion Efficiency after Repeated Desulfation



Currently available data on NOx adsorber formulations show clearly that sulfur can be removed from the surface of the NOx adsorber catalyst. The initial high performance after a desulfation event is then degraded over time by the presence of sulfur until the next desulfation event. The resulting characteristic NOx adsorber performance level over time exhibits a saw-tooth pattern with declining performance followed by rapid recovery of performance following desulfation. The rate of this decline increases substantially with higher fuel sulfur levels. Tto ensure a gradual and controllable decline in performance, fuel sulfur levels must be minimized.

However, even given very low fuel sulfur levels, gradual decline in performance must be periodically overcome. The development experience so far shows that diesel engines can accomplish the required desulfation event. The circumstances that effectively promote rapid desulfation also promote thermal degradation. It will therefore be important to limit thermal degradation.

Limiting Thermal Degradation

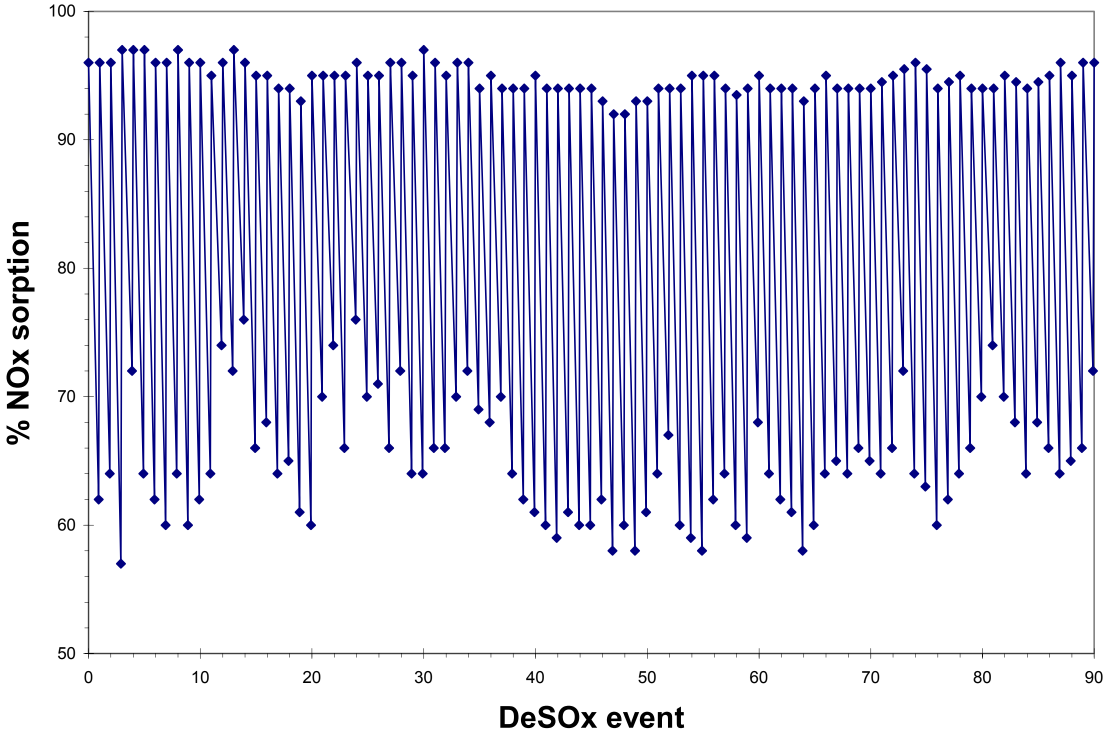
The issue of thermal degradation of NOx adsorber catalyst components is similar to the thermal sintering issues faced by light-duty three-way catalysts for vehicles developed to meet current California LEV and future Federal Tier 2 standards using platinum+rhodium (Pt+Rh) catalysts. Initial designs were marked by unacceptable levels of platinum sintering that limited the effectiveness of Pt+Rh catalysts. This problem has been overcome through modifications to the catalyst supports and surface structures that stabilize the precious metals at high temperatures (>900 ˚C). Stabilization of ceria components using Zirconium (Zr) has pushed the upper temperature limits of ceria migration to well over 1000 ˚C.[86, 87] Stabilization components can function in different ways. Some are used to "fill" structural vacancies, for example "open" locations within a crystalline lattice, thus strengthening the lattice structure. Such strengthening of crystalline lattice structures is particularly important at high temperatures. Other types of stabilizing components can act as obstructions within a matrix to prevent migration of components, or can enhance the mobility of other molecules or atoms, such as oxygen. An approach stabilizing NOx adsorber catalyst components similar to the approaches taken with LEV three-way catalyst designs should help to minimize thermal sintering of components during desulfation.

In many ways, limiting the thermal degradation of the NOx adsorber catalyst should be easier than for the gasoline three-way catalyst. Typical exhaust gas temperatures for a heavy light-duty gasoline truck (e.g., a Ford Expedition) commonly range from 450˚C to more than 800˚C during normal operation.[88] A heavy-duty diesel engine in contrast rarely has exhaust gas temperatures in excess of 500˚C. Further, even during the desulfation event, exhaust temperatures are expected to be controlled below 700˚C. The NOx adsorber applied to diesel engines is therefore expected to see both lower average temperatures and lower peak temperatures when compared with an equivalent gasoline engine. Once thermal degradation improvements are made to NOx adsorber catalysts, thermal degradation will reasonably be expected to be less than the level predicted for future Tier 2 gasoline applications.

In addition to the means to improve the thermal stability of the NOx adsorber by applying many of the same techniques being perfected for the Tier 2 gasoline three-way catalyst applications, an additional possibility exists that the desulfation process itself can be improved to give both high sulfur removal and to limit thermal degradation. The means to do this might include careful control of the maximum temperature during desulfation to limit the exposure to high temperatures. Also, improvements in how the regeneration process occurs may provide avenues for improvement. Low air-fuel ratios (high levels of reductant) are known to improve the desulfation process. The high level of reductant may also help to suppress oxygen content in the exhaust to further limit thermal degradation.

Researchers at Ford Scientific Research Labs have investigated NOx adsorber catalyst desulfation (called DeSOx in their work) to answer the question: "if a regeneration process (sulfur regeneration) is required periodically, will the high temperatures required for the regeneration have deleterious, irreversible effects on NOx efficiency?" To explore the issue of NOx adsorber durability after repeated desulfation events, Ford conducted repeated sequential sulfur poisoning and desulfation cycles with a NOx adsorber catalyst. The results of their experiment are shown in Figure 4.1-8.[89] As shown in Figure 4.1-8, the NOx adsorber sample underwent more than 90 poisoning and desulfation cycles with 12 hours occurring between the end of one desulfation to the end of the next desulfation without a measurable loss in post-desulfation performance. This testing was done using a laboratory tool called a pulsator, used to study ceramic monolith catalyst samples. The ceramic test samples were heated to between 700˚C and 750˚C. These results indicate that for some combinations of temperatures and reductant chemistries the NOx adsorber can be repeatedly desulfated without a significant loss in NOx reduction efficiency. This work indicates that it is possible to optimize the desulfation process to allow for adequate sulfur removal without a significant decrease in NOx reduction efficiency.

Figure 4.1-8
Repeated Sulfur Poisoning and Desulfation on a Bench Pulsator



These results indicate that, with further improvements to the NOx adsorber catalyst design incorporating the experience gained on gasoline three-way catalysts and continuing improvements in the control of the desulfation, degradation of the NOx adsorber catalyst with each desulfation event can be limited. However, the expectation remains that there will be some level of deterioration with desulfation that must be managed to ensure long-term high efficiency of the NOx adsorber. This means that the number and frequency of desulfation events must be kept to a minimum. The key to this is to limit the amount of sulfur to which the catalyst is exposed over its life. In this way, the deterioration in performance between desulfation events is controlled at a gradual rate and the period between desulfations can be maximized to limit thermal degradation.

Overall System Durability

NOx emission control with a NOx adsorber catalyst-based systems is an extension of the very successful three-way catalyst technology. NOx adsorber technology is most accurately described as incremental and evolutionary with system components that are straightforward extensions of existing technologies. The technology therefore benefits substantially from the considerable experience gained over the past 30 years with the today's highly reliable and durable three-way catalyst systems.

The following observations can be made from the data provided in the preceding sections on NOx adsorber durability:

- NOx adsorber catalysts are poisoned by sulfur in diesel fuel, even at fuel sulfur levels as low as three ppm.

- A sulfur regeneration event (desulfation) can restore NOx adsorber performance.

- A diesel engine can produce exhaust conditions that are conducive to desulfation.

- Desulfation events, which require high catalyst temperatures, can cause sintering of the catalytic metals in the NOx adsorber, thereby reducing NOx-control efficiency.

- The means exist from the development of gasoline three-way catalysts to improve the NOx adsorber's thermal durability.

- In carefully controlled experiments, NOx adsorbers can be desulfated repeatedly without an unacceptable loss in performance.

- The number and frequency of desulfation events must be limited to ensure any gradual thermal degradation over time does not excessively deteriorate the catalyst.

Based on these observations, we are confident that NOx adsorber technology for HD2007 and later engines will be durable over the life of heavy-duty diesel vehicles, provided that the engines use fuel with a 15 ppm sulfur cap and that the technology will prove to be similarly durable when applied some years later to nonroad diesel engines to comply with the Tier 4 emission standards. Without the use of this low-sulfur fuel, we can no longer be confident that the increased number of desulfation cycles that will be required to address the impact of sulfur on efficiency can be accomplished without unrecoverable thermal degradation and thus loss of

NOx adsorber efficiency. Limiting the number and frequency of these deleterious desulfation events through the use of diesel fuel with sulfur content less than 15 ppm allows us to conclude with confidence that NOx adsorber catalysts will be developed that are durable throughout the life of a nonroad diesel engine.

4.1.2.3.5 Current Status of NOx Adsorber Development

NOx adsorber catalysts were first introduced in the power generation market less than five years ago. Since then, NOx adsorber systems in stationary source applications have enjoyed considerable success. In 1997, the South Coast Air Quality Management District of California determined that a NOx adsorber system provided the "Best Available Control Technology" NOx limit for gas turbine power systems.[90] Average NOx control for these power generation facilities is in excess of 92 percent.[91] A NOx adsorber catalyst applied to a natural gas fired powerplant has demonstrated better than 99 percent reliability for more than 21,000 hours of operation while controlling NOx by more than 90 percent.[92] The experience with NOx adsorbers in these stationary power applications shows that NOx adsorbers can be highly effective for controlling NOx emissions for extended periods of operation with high reliability.

4.1.2.3.5.1 Lean-Burn Gasoline Engines

The NOx adsorber's ability to control NOx under oxygen-rich (fuel-lean) operating conditions has led industry to begin applying NOx adsorber technology to lean-burn engines in mobile source applications. NOx adsorber catalysts have been developed and are now in production for lean-burn gasoline vehicles in Japan, including several vehicle models sold by Toyota Motor Corporation.[L] The 2000 model year saw the first application of this technology in the United States with the introduction of the Honda Insight, certified to the California LEV-I ULEV category standard. Table 4.1-6 lists some of the 2002 European lean-burn direct-injection gasoline vehicles that use NOx adsorber catalyst technology.[93] These lean-burn gasoline applications are of particular interest because they are similar to diesel vehicle applications in terms of lean-NOx storage and the need for periodic NOx regeneration under transient driving conditions. The fact that they have been successfully applied to these mobile source applications shows clearly that NOx adsorbers can work under transient conditions provided that engineering solutions can be found to periodically cause normally lean-burn exhaust conditions to operate in a rich regeneration mode.

[L] Toyota requires that their lean-burn gasoline engines equipped with NOx adsorbers are fueled on premium gasoline in Japan, which has an average sulfur content of six ppm.

Table 4.1-6 2002 European Lean-Burn Gasoline Direct-Injection Engines

Model	Displacement(liter)	Power(KW/PS)
Audi A2 FSI	1.6	81/110
Audi A4 FSI	2	110/150
BMW 760 iL	6	ca. 300/408
Citroen C5 HPI	2	103/140
Mercedes CLK 200 CGI	1.8	125/170
Mercedes C 200 CGI	1.8	125/170
Mitsubishi Carisma GDI	1.8	90/122
Mitsubishi Space Star GDI	1.8	90/122
Mitsubishi Space Wagon 2.4 GDI	2.4	108/147
Mitsubishi Space Runner 2.4 GDI	2.4	110/150
Mitsubishi Galant 2.4 GDI	2.4	106/144
Mitsubishi Pajero Pinin 2.0 GDI	2	90/122
Mitsubishi Pajero 3.2 V6 GDI	3.5	149/202
Peugeot 406 HPI	2	103/140
VW Lupo FSI	1.4	77/105
VW Polo FSI	1.4	63/85
VW Golf FSI	1.6	81/110
VW Bora FSI	1.6	81/110
Volvo S40 1.8	1.6	90/122

4.1.2.3.5.2 EPA National Vehicle and Fuel Emissions Laboratory

As part of an ongoing effort to evaluate the rapidly developing state of this technology, the Manufacturers of Emission Control Association (MECA) have provided numerous NOx adsorber catalyst formulations to EPA for evaluation. Testing of some of these catalysts at NVFEL revealed that formulations were capable of reducing NOx emissions by more than 90 percent over the broad range of operation in the highway steady-state SET procedure (sometimes called the EURO 4 test). At operating conditions representative of “road-load” operation for a highway trucks, the catalysts showed NOx reductions as high as 99 percent resulting in NOx emissions well below 0.1 g/hp-hr from an engine-out level of nearly 5 g/hp-hr. Figure 4.1-9 shows an engine torque vs. speed map with the various steady-state test modes used in this testing as well as the 8 modes of the ISO-C1 cycle used for nonroad certification. Though not included in the test results shown in Figures 4.1-10 through 4.1-12, the ISO-C1 modes are closely approximated by some other test modes, as can be seen in Figure 4.1-9. We therefore expect similarly good performance on the ISO-C1 test modes. Testing on the highway transient test procedure has shown similarly good results, with hot-start NOx emissions over the highway FTP cycle reduced by more than 90 percent. These results demonstrate that significant NOx reductions are possible over a broad range of operating conditions with current NOx adsorber technology, as typified by the highway FTP cycle and the SET procedure.

The test program at NVFEL can be divided into phases. The first phase began with an adsorber screening process using a single leg of the planned dual-leg system. The goals of this screening process, a description of the test approach, and the results are described below. The next phase of the test program consisted of testing the dual-leg system on a more advanced Tier 3 like diesel engine (i.e., with common rail fuel system and cooled EGR) using a NOx adsorber chosen during the first phase in each of two legs. The current ongoing phase is working on improved systems approaches including a demonstration of an improved package four "leg" system.

Testing Goals—Single-Leg NOx Adsorber System

The goal of the NOx adsorber screening process was to evaluate available NOx adsorber formulations from different manufacturers with the objective of choosing an adsorber with 90 percent or better NOx reduction for continued evaluation. To this end, four different adsorber formulations were provided from three different suppliers. Since this was a screening process and since a large number of each adsorber formulation would be required for a full dual-leg system, it was decided to run half of a dual-leg system (a single-leg system) and mathematically correct the emissions and fuel economy impact to reflect a full dual-leg system. The trade-off was that the single-leg system would be able to run only steady-state modes, as the emissions could not be corrected over a transient cycle. The configuration used for this test was similar to that shown in Figure 4.1-1, but with a catalyst installed only on one side of the system.

Test Approach—Single-Leg NOx Adsorber System

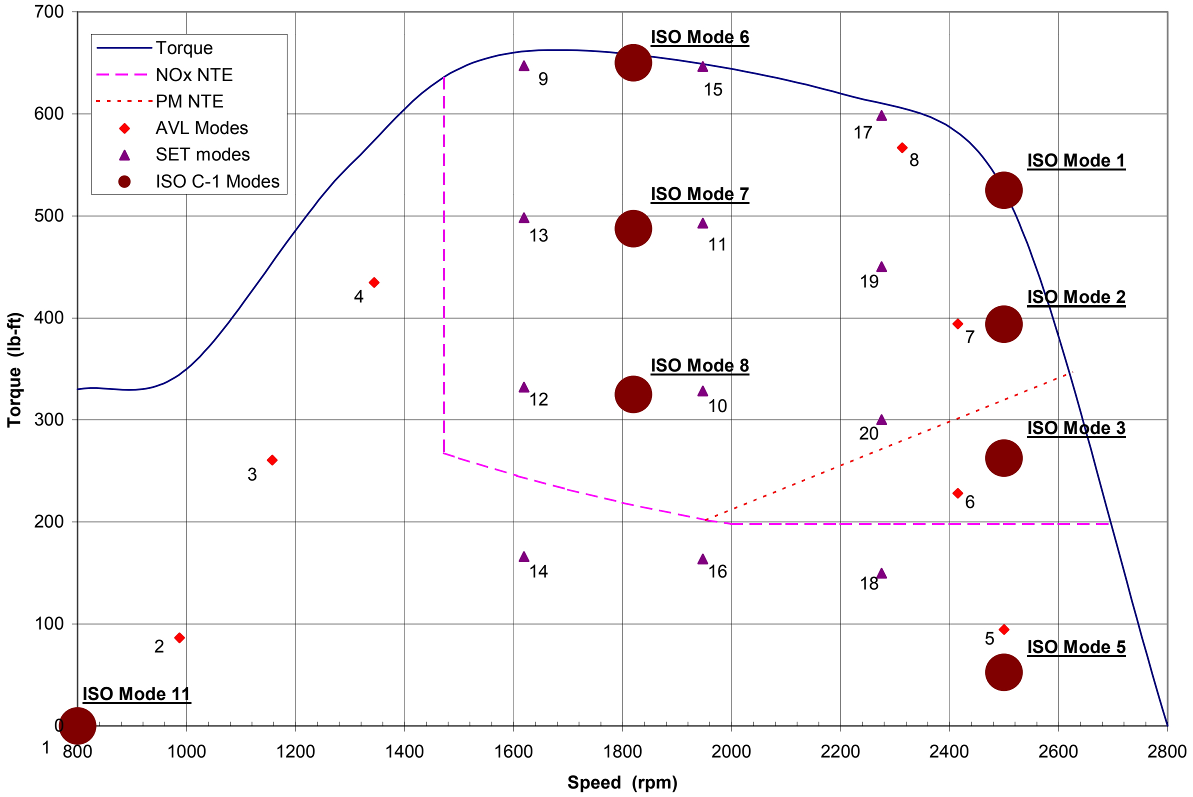
The single-leg system consisted of an exhaust brake, a fuel injector, CDPF, and a NOx adsorber in one test leg. The other leg, the "bypass leg," consisted of an exhaust brake that opened when the test-leg brake was closed; this vented the remainder of the exhaust out of the test cell. Under this setup, the test leg, i.e., the leg with the adsorber, was directed into the dilution tunnel where the emissions were measured and then compensated to account for emissions from the bypass leg. The restriction in the bypass leg was set to duplicate the backpressure of the test leg so that, while bypassing the test leg to conduct a NOx regeneration, the backpressure of the bypass leg simulated the presence of a NOx adsorber system. A clean-up diesel oxidation catalyst (DOC) downstream of the NOx adsorber was not used for this testing.

The measured emissions had to be adjusted to account for the lack of any NOx adsorber in the bypass leg. For this correction, it was assumed that the bypass leg's missing (virtual) adsorber would adsorb only while the actual leg was regenerating. It was also assumed the virtual adsorber would have regeneration fuel requirements in proportion to its adsorbing time. The emission-control performance of the virtual adsorber was assumed to be the same as the performance of the actual adsorber. With these assumptions, the gaseous emissions could be adjusted.[94]

Test Results—Single-Leg NOx Adsorber System

Two sets of steady-state modes were run with each adsorber formulation. These modes consisted of the SET modes and the AVL 8 mode composite FTP prediction.[M] The modes are illustrated in Figure 4.1-9 and are numbered sequentially one through 20 to include both the eight AVL modes and the 13 SET modes (the idle mode is repeated in both tests). The mode numbers shown in the figure are denoted as "EPA" modes in the subsequent tables to differentiate between the AVL and SET modes that have duplicate mode numbers. The highway NTE zone (which is the same as the nonroad NTE zone) is also shown in Figure 4.1-9 to show that these two sets of modes give comprehensive coverage of the NTE zone. The ISO C1 steady-state modes used for nonroad engines are closely represented by the test modes shown here. The only C1 mode not well represented is the 10 percent load point (ISO Mode 5), which is outside of the nonroad NTE zone. The modes were run with varying levels of automation, with the general strategy being to inject sufficient fuel during regeneration to obtain a lambda at or slightly fuel-rich of stoichiometric ($\lambda \leq 1$). The NOx regenerations were then timed to achieve the desired NOx reduction performance. The adsorber formulations were identified as A, B, D, and E. Prior to testing, each set of adsorbers were aged at 2500 rpm, 150 lb-ft for 40 minutes, then 2500 rpm full load for 20 minutes, repeated for a total of 10 hours.

Figure 4.1-9 Steady-State Test Modes from NVFEL Testing and ISO C-1 Modes



[M] The AVL 8 mode test procedure is a steady-state test procedure developed by Anstalt für Verbrennungskraftmaschinen, Prof. Dr. Hans List (or Institute for Internal Combustion Engines) to approximate emission levels that would occur while operating the engine over the transient highway FTP cycle.

The SET and AVL Composite emission results, along with the NOx reduction performance vs. adsorber inlet temperature, are shown in Figures 4.1-10 through 4.1-13 for each of the tested NOx adsorber formulations. The SET composites for all four adsorber formulations had NOx reductions in excess of 90 percent with under a three percent impact on fuel economy. The HC emissions varied most widely, most likely due to differences in regeneration strategies, and to some extent, adsorber formulation. The HC emissions with the exception of adsorber "A" were very good, less than 0.1 g/hp-hr over the SET and less than 0.2 g/hp-hr over the AVL composite. Note that no DOC was used to clean up the HC emissions.

Another point to note is that the EPA mode 1 (ISO-C1 Mode 11) data for each composite is the same. This is because EPA mode 1, low idle, is too cold for effective steady-state regeneration, but efficient NOx adsorption can occur for extended periods of time. (Note that the exhaust temperature at idle is well below the NTE threshold of 250˚C discussed earlier.) For either of these composite tests, a regeneration would not be needed under such conditions. EPA mode 1 has very little impact on either composite in any case because of the low power and emission rate. EPA mode 2 also had very low steady-state temperatures, and the difficulty regenerating at this mode can be seen in the impacts on HC emissions and on fuel economy. But, like EPA mode 1, the engine would adsorb during EPA mode 2 for extended periods without needing regeneration. None of the ISO-C1 modes, other than the idle mode, are similar to EPA mode 2. Further, no attempt was made to apply new combustion approaches such as the Toyota low-temperature combustion technology to raise exhaust temperatures at these operating modes.

The AVL composite showed greater differences between the adsorber formulations than the SET. Three of the adsorbers achieved greater than 90 percent NOx reduction over the AVL composites with the other adsorber at 84 percent NOx reduction. The greater spread in NOx reduction performance was, in part, due to this composite's emphasis on EPA mode 8, which was at the upper end of the NOx reduction efficiency temperature window. Adsorber E had an EPA mode 8 NOx reduction of 66 percent, and the NOx reduction efficiency vs. inlet temperature graph clearly shows that this formulation's performance falls off quickly above 450˚C. In contrast, the other formulations do not show such an early, steep loss in performance. The fuel economy impacts vary more widely also, partly due to the test engineers' regeneration strategies, particularly with the low-temperature modes, and to the general inability to regenerate at very low-temperature modes at steady-state. Note also that none of the regeneration strategies here can be considered fully optimized, as they reflect the product of trial and error experimentation by the test engineers. With further testing and understanding of the technology a more systematic means for optimization should be possible. In spite of the trial and error approach the results shown here are quite promising.

The AVL composite was developed as a steady-state test that would predict engine-out emission levels over the transient highway FTP cycle. As discussed in 4.1.3.1.2 below, NOx adsorber control effectiveness is projected to be more effective over the NRTC than over the highway FTP cycle. The AVL cycle loses some accuracy when testing engines with NOx adsorbers, since regeneration does not occur at the low-temperature modes (EPA modes 1, 2, 5). In real-world conditions, diesel engines do not come to steady-state temperatures at any of these modes, and the adsorber temperatures will be higher at EPA modes 1, 2, and 5 than the stabilized steady-state values used for this modal testing. Consequently, the actual performance over a transient duty cycle should be much better than the composites would suggest (see the discussion of transient testing below).

Based on the composite data and the temperature performance charts, amongst other factors, adsorber formulation B was chosen for further dual-leg performance work. Both composites for this formulation were well above 90 percent. The NOx vs. temperature graph, Figure 4.1-11, also shows that this formulation was a very good match for this engine.

					Base	Adsorber				
EPA Mode	SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC * (g/hp-hr)	FE Impact *
1	1	15%	Idle	0	13.0	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.6	461	0.11	98%	0.92	2.4%
10	3	10%	1947	328	4.7	357	0.07	98%	1.02	2.0%
11	4	10%	1947	493	5.0	411	0.06	99%	1.35	2.6%
12	5	5%	1619	332	5.0	384	0.13	97%	0.11	1.3%
13	6	5%	1619	498	5.0	427	0.24	95%	0.81	1.6%
14	7	5%	1619	166	5.5	287	0.25	95%	1.39	3.3%
15	8	9%	1947	630	4.0	498	0.89	78%	0.36	1.9%
16	9	10%	1947	164	5.0	293	0.14	97%	1.88	4.1%
17	10	8%	2275	599	4.0	515	0.48	88%	1.12	3.8%
18	11	5%	2275	150	4.8	282	0.42	91%	0.68	3.5%
19	12	5%	2275	450	5.0	404	0.08	98%	0.62	3.0%
20	13	5%	2275	300	4.8	357	0.14	97%	0.70	2.8%
Composite Results					4.6		0.31	93%	0.91 *	2.6% *

					Base	Adsorber				
EPA Mode	AVL Mode	AVL Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC * (g/hp-hr)	FE Impact *
1	1	42%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
2	2	8%	987	86	8.80	172	0.83	91%	0.75	7.7%
3	3	3%	1157	261	8.40	346	0.36	96%	1.10	3.1%
4	4	4%	1344	435	5.90	430	0.20	97%	2.16	3.0%
5	5	10%	2500	94	5.50	286	0.37	93%	4.93	3.6%
6	6	12%	2415	228	4.60	325	0.08	98%	2.30	3.6%
7	7	12%	2415	394	4.90	386	0.10	98%	2.38	3.1%
8	8	9%	2313	567	4.10	505	1.06	74%	0.03	1.9%
Composite Results					4.9		0.44	91%	1.69 *	2.9% *

* HC results & FE Impacts do not reflect future potential as they are derived using a 5 g NOx engine which requires more frequent NOx regens than would result using a 2.5 g engine and the tested system was not a fully optimized engine & emission control system.

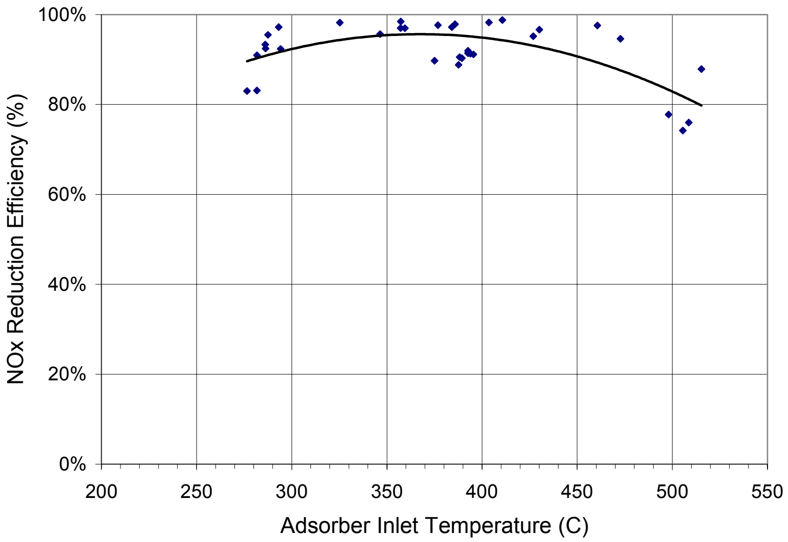


Figure 4.1-10. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber A

					Base	Adsorber				
EPA Mode	SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC * (g/hp-hr)	FE Impact *
1	1	15%	Idle	0	13.0	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.6	498	0.18	96%	0.01	1.2%
10	3	10%	1947	328	4.7	366	0.07	98%	0.04	0.5%
11	4	10%	1947	493	5.0	446	0.14	97%	0.01	1.5%
12	5	5%	1619	332	5.0	375	0.06	99%	0.08	0.7%
13	6	5%	1619	498	5.0	420	0.07	98%	0.10	2.3%
14	7	5%	1619	166	5.5	296	0.18	97%	0.10	0.3%
15	8	9%	1947	630	4.0	524	0.46	89%	0.01	3.2%
16	9	10%	1947	164	5.0	293	0.36	93%	0.05	0.4%
17	10	8%	2275	599	4.0	537	0.56	86%	0.04	4.3%
18	11	5%	2275	150	4.8	280	0.29	94%	0.03	0.4%
19	12	5%	2275	450	5.0	426	0.24	95%	0.04	4.3%
20	13	5%	2275	300	4.8	357	0.11	98%	0.02	0.9%
Composite Results					4.6		0.27	94%	0.03 *	2.2% *

					Base	Adsorber				
EPA Mode	AVL Mode	AVL Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC * (g/hp-hr)	FE Impact *
1	1	42%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
2	2	8%	987	86	8.80	162	0.56	94%	2.11	1.8%
3	3	3%	1157	261	8.40	355	0.30	96%	0.16	0.3%
4	4	4%	1344	435	5.90	446	0.09	98%	0.23	0.9%
5	5	10%	2500	94	5.50	263	0.66	88%	0.25	1.6%
6	6	12%	2415	228	4.60	346	0.11	98%	0.03	0.4%
7	7	12%	2415	394	4.90	403	0.05	99%	0.02	1.4%
8	8	9%	2313	567	4.10	544	0.73	82%	0.35	4.0%
Composite Results					4.9		0.33	93%	0.19 *	2% *

* HC results & FE Impacts do not reflect future potential as they are derived using a 5 g NOx engine which requires more frequent NOx regens than would result using a 2.5 g engine and the tested system was not a fully optimized engine & emission control system.

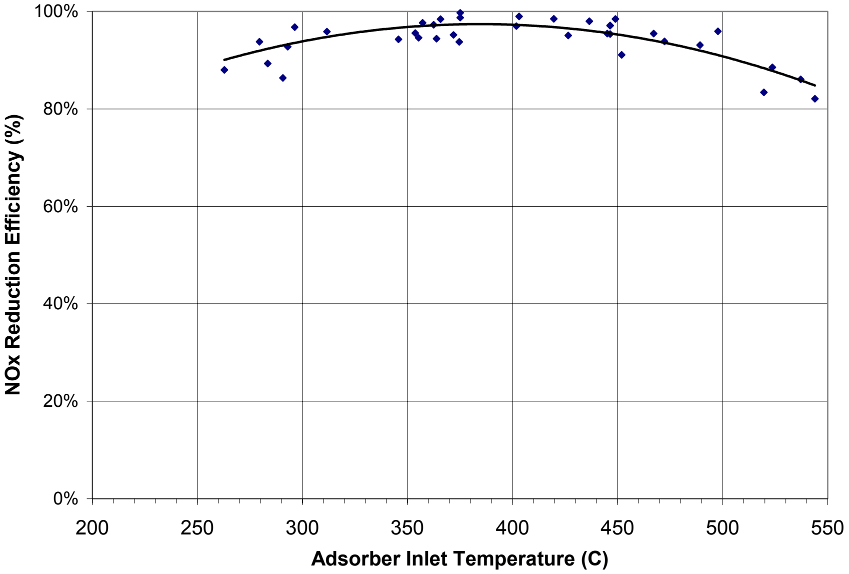


Figure 4.1-11. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber B

					Base	Adsorber				
EPA Mode	SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC * (g/hp-hr)	FE Impact *
1	1	15%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.60	451	0.18	96%	0.07	1.3%
10	3	10%	1947	328	4.70	356	0.14	97%	0.15	1.7%
11	4	10%	1947	493	5.00	400	0.09	98%	0.05	1.6%
12	5	5%	1619	332	5.00	377	0.07	99%	0.01	1.2%
13	6	5%	1619	498	5.00	431	0.11	98%	0.02	1.6%
14	7	5%	1619	166	5.50	305	0.23	96%	0.14	2.3%
15	8	9%	1947	630	4.00	501	0.16	96%	0.04	2.1%
16	9	10%	1947	164	5.00	303	0.15	97%	0.14	3.1%
17	10	8%	2275	599	4.00	489	0.93	93%	0.09	1.7%
18	11	5%	2275	150	4.80	278	0.57	88%	0.18	3.5%
19	12	5%	2275	450	5.00	391	0.12	98%	0.10	1.8%
20	13	5%	2275	300	4.80	330	0.21	96%	0.09	2.9%
Composite Results					4.6		0.28	94%	0.08 *	1.9% *

					Base	Adsorber				
EPA Mode	AVL Mode	AVL Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC * (g/hp-hr)	FE Impact *
1	1	42%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
2	2	8%	987	86	8.80	162	0.56	94%	2.11	1.8%
3	3	3%	1157	261	8.40	359	0.08	99%	0.30	3.1%
4	4	4%	1344	435	5.90	427	0.14	98%	0.19	1.7%
5	5	10%	2500	94	5.50	273	1.25	77%	0.26	6.4%
6	6	12%	2415	228	4.60	301	0.52	89%	0.13	1.9%
7	7	12%	2415	394	4.90	363	0.66	87%	0.04	1.4%
8	8	9%	2313	567	4.10	493	0.31	92%	0.08	1.6%
Composite Results					4.9		0.51	90%	0.14 *	1.9% *

* HC results & FE Impacts do not reflect future potential as they are derived using a 5 g NOx engine which requires more frequent NOx regens than would result using a 2.5 g engine and the tested system was not a fully optimized engine & emission control system.

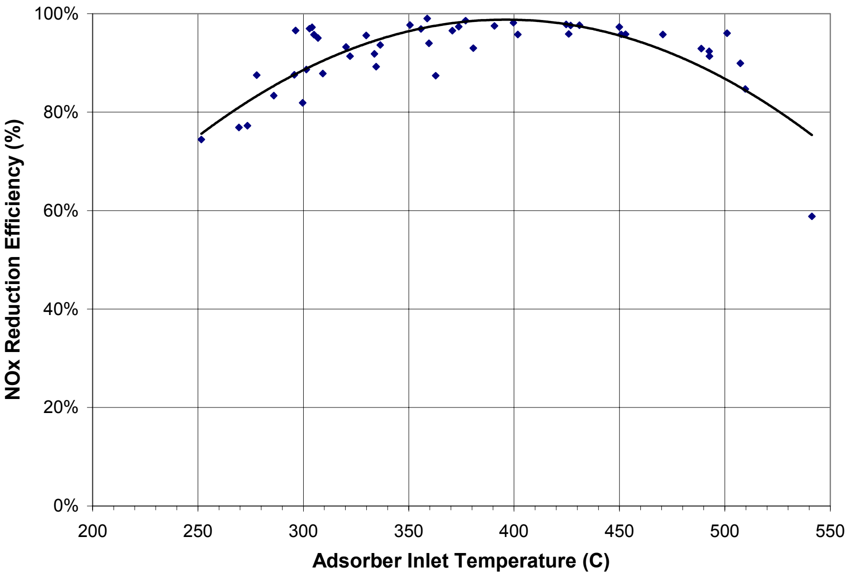


Figure 4.1-12. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber D

					Base	Adsorber				
EPA Mode	SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC * (g/hp-hr)	FE Impact *
1	1	15%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.60	455	0.47	89%	0.02	2.1%
10	3	10%	1947	328	4.70	343	0.07	98%	0.05	0.9%
11	4	10%	1947	493	5.00	442	0.36	93%	0.07	9.0%
12	5	5%	1619	332	5.00	377	0.08	98%	0.01	1.5%
13	6	5%	1619	498	5.00	419	0.29	94%	0.03	1.6%
14	7	5%	1619	166	5.50	412	0.14	98%	0.05	1.7%
15	8	9%	1947	630	4.00	392	0.05	99%	0.02	2.1%
16	9	10%	1947	164	5.00	294	0.09	98%	0.26	4.4%
17	10	8%	2275	599	4.00	492	0.95	76%	0.03	2.0%
18	11	5%	2275	150	4.80	388	0.11	98%	0.03	2.4%
19	12	5%	2275	450	5.00	391	0.12	98%	0.10	1.8%**
20	13	5%	2275	300	4.80	327	0.22	95%	0.02	1.4%
						** Md 19 data from Adsorber D				
		Composite Results			4.6		0.33	93%	0.05 *	2.9% *

					Base	Adsorber				
EPA Mode	AVL Mode	AVL Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC * (g/hp-hr)	FE Impact *
1	1	42%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
2	2	8%	987	86	8.80	166	7.39	16%	1.02	71.9%
3	3	3%	1157	261	8.40	339	0.09	99%	0.05	2.3%
4	4	4%	1344	435	5.90	449	0.65	89%	0.01	2.1%
5	5	10%	2500	94	5.50	256	1.36	75%	0.91	15.8%
6	6	12%	2415	228	4.60	313	0.35	92%	0.21	5.6%
7	7	12%	2415	394	4.90	372	0.12	97%	0.10	2.6%
8	8	9%	2313	567	4.10	508	1.39	66%	0.04	3.3%
		Composite Results			4.9		0.80	84%	0.16 *	5.4% *

* HC results & FE Impacts do not reflect future potential as they are derived using a 5 g NOx engine which requires more frequent NOx regens than would result using a 2.5 g engine and the tested system was not a fully optimized engine & emission control system.

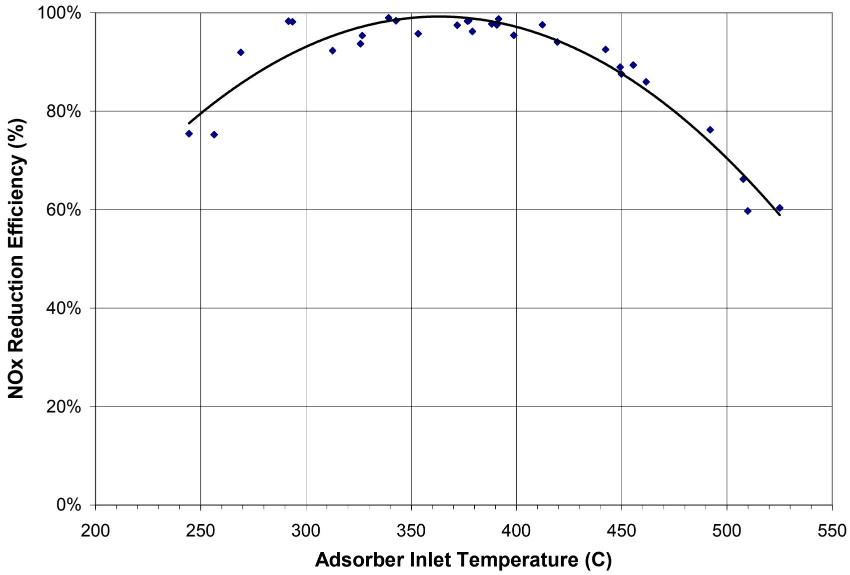


Figure 4.1-13. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber E

Testing Goals—Dual-Leg NOx Adsorber System

After completing the screening process and selecting NOx adsorber "B," the dual-leg system was developed. The dual-leg system was first tested on the same ISB engine as was used for the single-leg testing. The results from that portion of the testing were similar to the single-leg results (i.e., >90 percent NOx reductions for most test modes) and were reported in the HD2007 Regulatory Impact Analysis.[95] Subsequent testing of the NOx adsorber system was made at NVFEL but with a new ISB engine that had been upgraded to include nonroad Tier 3 type technologies, such as common rail fuel injection and cooled EGR. The change in engine technology led to significantly lower engine-out emissions (similar to the levels expected for 2004 highway engines Tier 3 nonroad engines) and to different exhaust gas temperature characteristics. As a result of the engine changes, the overall system performance was improved on both the steady-state test points and on the transient highway FTP cycle.[96] As discussed further in Section 4.1.3.1.2 below, performance over the NRTC is projected to be better than for the highway FTP cycle. Also, as can be seen in Figure 4.1-9 above, the SET steady-state test points are not significantly different from the ISO C1 test points (to which nonroad engines would be subject). Emission reductions are therefore expected to be similar.

Testing Approach—Dual-Leg NOx Adsorber System

The steady-state SET testing was conducted in a manner similar to that used in the screening process described above. The modes were run with varying levels of automation, with the general strategy being to inject sufficient fuel during regeneration to obtain a lambda at or slightly fuel-rich of stoichiometric ($\lambda \leq 1$). The NOx regenerations were then timed to achieve the targeted 90 percent NOx reduction. The regeneration control and optimization strategies are described in more detail in an SAE paper included in the docket for this rule.[97]

Transient regeneration control over the highway FTP cycle was accomplished using a time-based regeneration schedule. This control regenerated on a prescribed schedule of time and fuel quantities, so regenerations occurred at predetermined engine conditions during the transient cycle.

The emission results presented here are only for hot-start portions of the highway FTP cycle. The adsorber system was not optimized for cold-start performance and does not provide a meaningful assessment of adsorber warmup performance. To better simulate the "cold-soak-hot" procedure called for in highway FTP cycle, a preconditioning mode was chosen to provide adsorber temperatures at the start of the "hot" cycle similar to those found following the "cold-soak" portion of the test. The mode chosen was EPA mode 10 (1947 rpm, 328 lb-ft), which resulted in adsorber inlet temperatures (i.e., at the outlet of the CDPF) at the start of the hot cycle of about 280˚C. Another purpose for the preconditioning was to ensure the adsorbers were in the same condition at the start of each test. Given that our regeneration control system did not automatically take into account the starting condition of the NOx adsorbers, this preconditioning was necessary to provide repeatable transient test results.

Test Results—Dual-Leg NOx Adsorber System

The highway SET is made up of the 13 Euro III modes. Several modes were run twice by different engineers, and the best calibration was chosen for the SET composite. Table 4.1-7 shows the SET composite test results. These data show that 90 percent NOx reductions were possible over the SET composite, with a modal NOx reduction range from 89 percent to nearly 100 percent. The adsorber NOx and HC reduction performance varied primarily as a function of exhaust temperature.

Table 4.1-7 SET Results for Dual-Leg System at NVFEL

Modal and composite SET NOx and HC emissions results for the Modified Cummins ISB engine.

Modified Cummins ISB (HPCR, cooled EGR)						**Modified Cummins ISB** (Baseline + CDPF and NOx adsorber catalysts)				
SET Mode	**SET Weighting**	**Speed (rpm)**	**Torque (lb-ft)**	**BSNOx (g/hp-hr)**	**BSHC (g/hp-hr)**	**Outlet T (°C)**	**BSNOx (g/hp-hr)**	**NOx (%-Reduction)**	**BSHC (g/hp-hr)**	**Reductant FE Impact (%)***
1	15%	Idle	0	6.95	6.77	144	0.16	100%	0.00	0.0%
2	8%	1649	633	3.10	0.08	529	0.33	89%	0.03	1.6%
3	10%	1951	324	1.79	0.21	403	0.06	96%	0.01	1.0%
4	10%	1953	490	1.98	0.12	486	0.07	96%	0.02	1.3%
5	5%	1631	328	1.90	0.22	403	0.10	95%	0.01	0.9%
6	5%	1626	496	2.35	0.09	504	0.07	97%	0.02	1.6%
7	5%	1623	161	2.05	0.56	313	0.02	99%	0.03	0.9%
8	9%	1979	609	2.09	0.08	524	0.19	91%	0.03	1.7%
9	10%	1951	159	1.68	0.49	323	0.01	100%	0.02	0.8%
10	8%	2348	560	1.95	0.11	524	0.10	95%	0.04	2.3%
11	5%	2279	145	1.66	0.57	306	0.01	99%	0.02	0.7%
12	5%	2275	447	1.84	0.14	465	0.10	95%	0.01	0.9%
13	5%	2274	296	1.76	0.25	400	0.03	98%	0.01	0.9%
SET Weighted Composite Results:				2.10	0.17		0.12	94%	0.03	1.4%**

Notes:
* Fuel economy impact of fuel-reductant addition for NOx adsorber regeneration.
** Increased exhaust restriction from the wall-flow and flow through monoliths results in a further FE impact of approximately 1-2% over the SET composite.

The fuel economy impact was defined as the percent increase in fuel consumption caused by the adsorber regeneration fuel, or the mass of fuel used for regeneration, divided by the mass of fuel consumed by the engine during one regeneration and adsorption cycle. The fuel economy impact varied from virtually zero to 2.3 percent depending on the mode with a composite fuel economy impact of 1.4 percent. We anticipate significant improvements in regeneration strategies are possible with different system configurations. Also, changes in engine operation designed to increase exhaust temperatures, not attempted in this work, can provide substantial improvements in catalyst performance and potentially a lower fuel economy impact.

Test Results over the Highway FTP Cycle

As with the steady-state test results, the test results over the hot-start portion of the highway FTP cycle showed NOx and PM emission reductions greater than 90 percent. The baseline (without the catalyst system) NOx emissions of 2.7 g/hp-hr were reduced to 0.1 g/hp-hr with the addition of the catalyst system, a better than 95 percent reduction in NOx emissions. Similarly, the PM emissions were reduced to below 0.003 g/hp-hr from a baseline level of approximately 0.1 g/hp-hr, a reduction of more than 95 percent. The fuel economy impact associated with regeneration of the NOx adsorber system was measured as 1.5 percent over the highway FTP cycle. The fuel economy impact associated with increased exhaust restriction from the CDPF was less than the measurement variability for the test cycle (i.e., less than 0.5 percent).[98]

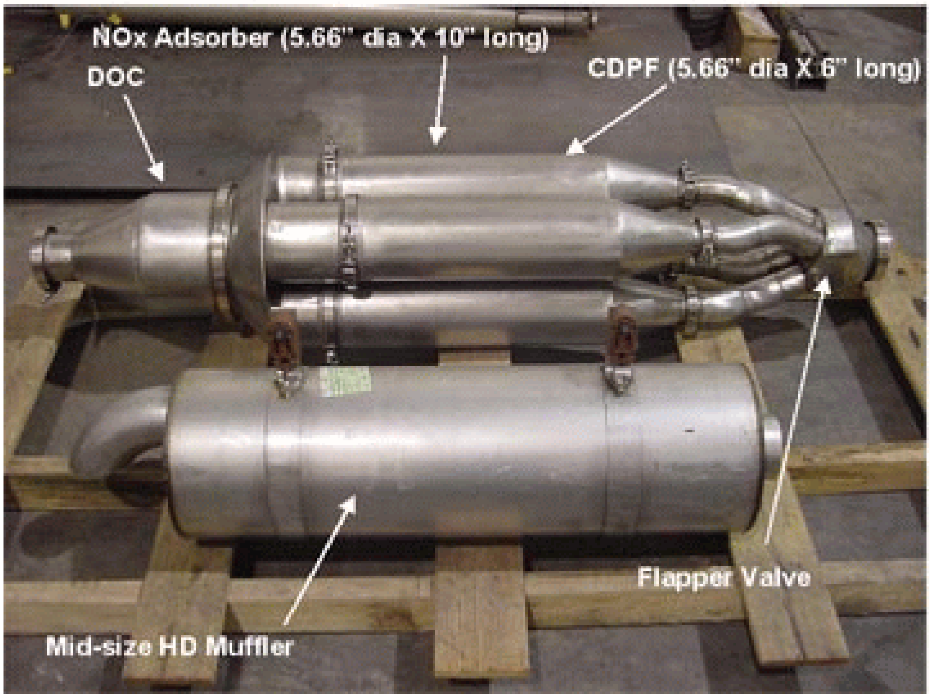
Durability Baseline NOx Adsorber Catalyst Testing

Additional testing was conducted at NVFEL to provide baseline performance data to gauge improvements in NOx adsorber durability performance in support of the HD2007 technology reviews. The data provide a look at the state of adsorber technology in 2001, with a glimpse of improvements that will be made in the future and is documented in a SAE paper.[99] It is clear from the analysis that there were vast differences in the durability performance of the formulations over these short tests. Adsorber suppliers were early on in their development and rapid improvements were being made. Two adsorbers representing one company's progress over two years showed significantly better aging performance (i.e., less degradation over time). This performance was evidenced by its NO_x adsorbing and regeneration performance after 100 hours.[100] In support of the U.S. EPA's continuing effort to monitor NO_x adsorber progress, new formulations are continuing to be evaluated.

Development of a Four "Leg" System Design

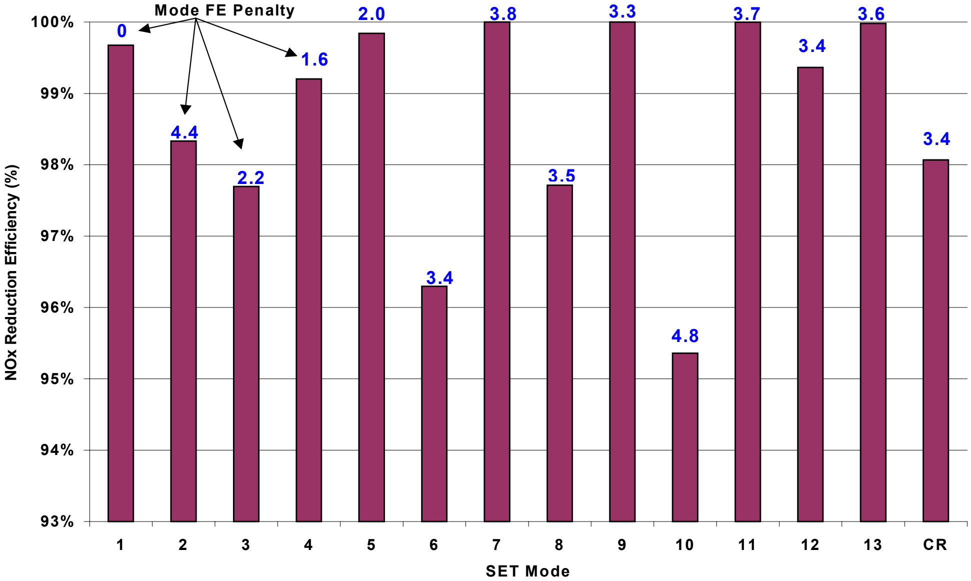
At NVFEL, developments have continued on methods and system designs for NOx adsorber catalyst technologies. A novel four-leg NOx adsorber/PM trap system was developed as an evolution of the proof-of-concept two-leg system that was used for previous testing at NVFEL (the system used in the test results reported here). The four-leg system has a catalyst volume that is less than half of the volume of the two-leg system. This allows the four-leg system to be packaged in a volume not much larger than a muffler for a medium heavy duty truck application as can be seen in Figure 4.1-14. Efforts have also been made to reduce the cost of the system by using simpler injectors and valve actuators.

Figure 4.1 -14 Prototype 4-leg System Compared with a Truck Muffler



Initial testing indicates that the four-leg system at least matches the previous two-leg systems NOx reduction efficiency with similar fuel consumption as can be seen in Figure 4.1-15. Note that the results shown in the figure are based upon the NOx sensor data used in the control system. Work is underway to confirm these steady-state results and to demonstrate the performance over transient cycles.

Figure 4.1-15 Preliminary Results for Prototype Four-Leg System



4.1.2.3.5.3 Department of Energy (DOE) Test Programs

The U.S. Department of Energy (DOE) has funded several test programs at national laboratories and in partnership with industry to investigate the NOx adsorber technology. Most of these test programs are part of the Advanced Petroleum Based Fuel (APBF) program of DOE's Office of Transportation Technology (OTT). The initial phases of the programs are often referred to as the Diesel Emission Control Sulfur Effects (DECSE) program, which are part of the APBF programs. Five reports documenting the DECSE program are available from the DOE OTT website (www.ott.doe.gov/decse) and were used extensively throughout our analysis.[101,102,103 104,105]

In the DECSE program, an advanced diesel engine equipped with common rail fuel injection and exhaust gas recirculation (EGR) was combined with a NOx adsorber catalyst to control NOx emissions. The system used an in-cylinder control approach. Rich regeneration conditions are created for the NOx adsorber catalyst regeneration through increased EGR rates and a secondary injection event designed to occur late enough in the engine cycle so as not to change engine torque output. Using this approach, the DECSE program has shown NOx conversion efficiencies exceeding 90 percent over a catalyst inlet operating temperature window of 300˚C to 450˚C. This performance level was achieved while staying within the four percent fuel economy penalty target defined for regeneration calibration.[106]

Subsequent work organized under the APBF program is commonly referred to as the APBF-Diesel Emission Control program, or APBF-DEC. The ongoing APBF-DEC work includes additional phases to develop prototype CDPF/NOx adsorber systems for a heavy-duty truck, a large sport utility vehicle and a passenger car. The program is looking at all important issues related to the technology including, packaging systems, effective regeneration, emission performance and durability.[107]

4.1.2.3.5.4 Heavy-Duty Engine Manufacturers

Heavy-duty diesel engine manufacturers (highway manufacturers) are currently developing systems to comply with the HD2007 emission standards including the NOx adsorber technology. As noted in EPA's Highway Diesel Progress Review Report 2, which documents in more detail progress by the highway diesel engine industry to develop CDPF and NOx adsorber technology, the progress to develop these emission-control systems is progressing rapidly. Although much of the work being done is protected as confidential business information, a recent public presentation by Daimler Chrysler Powersystems is illustrative some of the work that has been done prior to 2003.[108] The presentation reviews three possible system configurations for a combined CDPF / NOx adsorber system and compares the trade-offs among the approaches. Similar to the results shown in Section 4.1.2.3.5.3 by EPA, a dual-leg system demonstrated 90 percent or higher NOx emission control over a wide range of operation.

Two Japanese truck manufacturers, Toyota and Hino have recently introduced light heavy-duty diesel trucks in Japan using the Toyota developed Diesel Particulate NOx Reduction

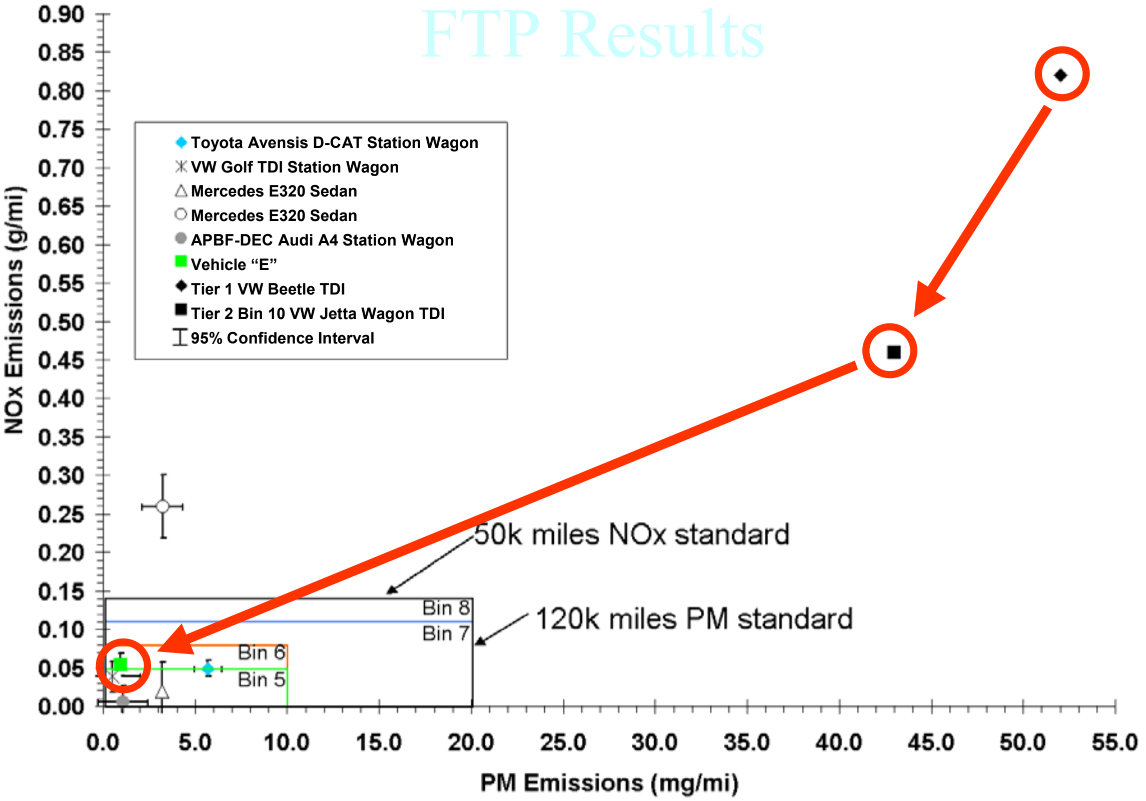
(DPNR) catalyst system. The DPNR system described in a light-duty application in our 2002 Highway Diesel Progress Review, consists of a diesel particulate filter with NOx storage catalyst coated onto the PM filter substrate. In some applications, the system can be further enhanced with the addition of an oxidation catalyst and an additional NOx adsorber catalyst applied to a conventional flow through catalyst substrate. The new trucks introduced in Japan, the Toyota Dyna and the Hino Dutro are commonly used as urban delivery vehicles and as refuse hauling vehicles.

In July 2003, EPA engineers visited Toyota's Higashifuji Technical Center in Japan to participate in testing of the engine and DPNR catalyst system being introduced later in the year as the Toyota Dyna product. EPA participated in several days of testing and reviewed detailed technical information regarding the emission control system and its potential for further development. The information shared with EPA in that test program was designated as confidential business information by Toyota. However, Toyota has published a relatively detailed SAE paper in Japan describing the system and its performance.[109] The paper summarizes the demonstrated emission reduction of the vehicle as aged to an estimated 250,000 kilometers with NOx emissions controlled below 0.5 g/bhp-hr and PM emissions controlled below 0.01 g/bhp-hr.

4.1.2.3.5.5 Light-Duty Diesel Vehicle Manufacturers

Diesel passenger car manufacturers are developing emission-control systems using NOx adsorbers and PM filters in a combined control strategy to meet upcoming Euro IV emission standards for larger passenger cars and sedans in Europe and the light-duty Tier 2 emission standards in the United States. EPA has tested five prototype diesel passenger cars with these technologies over the last year and a half. The results shown in Figure 4.1-16 demonstrate the potential for substantial reductions with NOx adsorber and PM filter technologies when tested with low-sulfur diesel fuel. All five vehicles demonstrated substantial reductions in NOx and PM emissions when compared with a current relatively clean (compared with only a few years ago) diesel passenger cars as represented by the solid black diamond and solid black square in Figure 4.1-16.[110]

Figure 4.1-16 Tier 2 Passenger Car Prototypes Tested at NVFEL on the FTP75 Cycle



One vehicle in the test program, the Mercedes E320, was tested with both new catalyst hardware and aged catalyst hardware. The aged catalyst had experienced the equivalent of the 100,000 km of aging. The aged test results show that the aged catalyst system has lost some amount of NOx storage volume, causing the NOx emissions to breakthrough as the catalyst fills with NOx prior to the periodic NOx regenerations. In this testing, the NOx regeneration period was fixed for the new and aged catalyst at the same interval. It appears from the data that the regeneration interval for the fresh catalyst was too infrequent for the aged catalyst, which had a reduced NOx-storage volume. At the very low NOx emission levels shown in the figure, it takes only a very small breakthrough in NOx emissions to significantly increase the emissions over the lowest control levels. Manufacturers are currently working to keep the number of regeneration episodes to the minimum number to minimize stress on catalyst materials (i.e., limit thermal degradation as discussed in Section 4.2 above). We believe manufacturers are continuing to develop more heat-resistant materials that will reduce overall aging of the catalyst. If such materials had been available at this time, we believe the NOx results for the aged vehicle would have been better. Note however, that the PM emissions show no deterioration for the aged system compared with the new system.

The most recently tested vehicle, vehicle "E" was tested after aging of the catalyst system to the equivalent of 50,000 miles of vehicle operation. The emissions results even after this extended aging where very good demonstrating NOx emission levels below 0.07 g/mile and PM emissions below 0.01 g/mile. Relative to vehicle "D" this demonstrates substantial progress by manufacturers to improve the overall durability of NOx adsorber catalysts.

4.1.2.4 Selective Catalytic Reduction (SCR) Technology

Another NOx catalyst-based emission-control technology is selective catalytic reduction (SCR). SCR catalysts require a reductant, ammonia, to reduce NOx emissions. Because of the significant safety concerns with handling and storing ammonia, most SCR systems make ammonia within the catalyst system from urea. Such systems are commonly called urea SCR systems. Throughout this document, the term SCR and urea SCR may be used interchangeably and should be considered as referring to the same urea-based catalyst system. With the appropriate control system to meter urea in proportion to engine-out NOx emissions, urea SCR catalysts can reduce NOx emissions by over 90 percent for a significant fraction of the diesel engine operating range.[111] Although EPA has not done an extensive analysis to evaluate its effectiveness, we believe it may be possible to reduce NOx emissions with a urea SCR catalyst to levels consistent with compliance with Tier 4 NOx standards.

We have significant concerns regarding a technology that requires extensive user intervention to function properly and the lack of the urea delivery infrastructure necessary to support this technology. Urea SCR systems consume urea in proportion to the engine-out NOx rate. The urea consumption rate can be on the order of five percent of the engine fuel consumption rate. Unless the urea tank is prohibitively large, the urea must therefore be replenished frequently. Most urea systems are designed to be replenished every time fuel is added or at most every few times that fuel is added. There is not a system in place today to deliver or dispense automotive-grade urea to diesel fueling stations. One study conducted for the National Renewable Energy Laboratory (NREL), estimated that if urea were to be distributed to every diesel fuel station in the United States, the cost would be more than $30 per gallon.[112]

We are not aware of a proven mechanism that ensures that the user will replenish the urea supply as necessary to maintain emission-control performance. Further, we believe that, given the additional cost for urea, there will be significant disincentives for the end-user to replenish the urea because the cost of urea can be avoided without equipment performance loss. See *NRDC v. EPA*, 655 F. 2d 318, 332 (D.C. Cir. 1981) (referring to "behavioral barriers to periodic restoration of a filter by a [vehicle] owner" as a valid basis for EPA considering a technology unavailable). Due to the lack of an infrastructure to deliver the needed urea, and the lack of a track record of successful ways to ensure urea use, we have concluded that the urea SCR technology is not likely to be available for general use in the time frame of the Tier 4 standards. We have therefore not based the feasibility or cost analysis of this emission-control program on the use or availability of the urea SCR technology. However, we do not preclude its use for compliance with the emission standards, provided that a manufacturer can demonstrate satisfactorily that the engine will use urea under all conditions. We believe that consistent use of urea can only be ensured only for a few unique installations and therefore believe it is inappropriate to base a national emission-control program on a technology that can effectively serve only in a few niche applications.

This section has described several technologies that can reduce emissions from diesel engines. The following section describes the challenges to applying these diesel engine technologies to engines and equipment designed for nonroad applications.

4.1.3 Can These Technologies Be Applied to Nonroad Engines and Equipment?

The emission standards and the introduction dates for those standards, as described earlier in Section III of the preamble, are premised on the transfer of diesel engine technologies being, or already developed, to meet light-duty and heavy-duty vehicle standards that begin in 2007. The Tier 4 aftertreatment based standards for engines from 75-750 hp will begin to go into effect four years later. This time lag between equivalent highway and nonroad diesel engine standards is necessary to allow time for engine and equipment manufacturers to further develop these highway engine technologies for nonroad engines and to align this program with nonroad Tier 3 emission standards that begin to go into effect in 2006.

The test procedures and regulations for the HD2007 highway engines include a transient test procedure, a broad steady-state procedure and NTE provisions that require compliant engines to emit at or below 1.5 times the regulated emission levels under virtually all conditions. An engine designed to comply with the HD2007 emission standards will meet the Tier 4 standards if it is tested over the transient and steady-state duty cycles specified in the final rule, which cover the same regions and types of engine operation. Said in another way, a highway diesel engine produced in 2007 may be certified in compliance with the transient and steady-state standards in this final rule for nonroad diesel engines several years in advance of the date when these standards are scheduled to go into effect. However, that engine, while compliant with certain of the nonroad emission standards, would not necessarily be designed to address the various durability and performance requirements of many nonroad equipment manufacturers. We expect that the engine manufacturers will need additional time to further develop the necessary emission-control systems to address some of the nonroad issues described below as well as to develop the appropriate calibrations for engine rated speed and torque characteristics required by the diverse range of nonroad equipment. Furthermore, not all nonroad engine manufacturers produce highway diesel engines or produce nonroad engines that are developed from highway products. There is therefore a need for lead time between the Tier 3 emission standards, which go into effect in 2006-2008, and the Tier 4 emission standards. We believe the technologies developed to comply with the Tier 3 emission standards such as improved air handling systems and electronic fuel systems will form an essential technology baseline that manufacturers will need to initiate and control the various regeneration functions required of the catalyst-based technologies for Tier 4. The Agency has given consideration to all these issues in setting the levels and timing of the Tier 4 emission standards.

This section presents some of the challenges of applying advanced emission-control technologies to nonroad engines and equipment and describes why we believe technologies developed for highway diesel engines can be further refined to address these issues in a timely manner for nonroad engines consistent with the Tier 4 emission standards.

4.1.3.1 Nonroad Operating Conditions and Exhaust Temperatures

Nonroad equipment is highly diverse in design, application, and typical operating conditions. This variety of operating conditions affects emission-control systems through the resulting variation in the torque and speed demands (i.e., power demands). This wide range in what constitutes typical nonroad operation makes the design and implementation of advanced emission-control technologies more difficult. The primary concern for catalyst-based emission-control technologies is exhaust temperature. In general, exhaust temperature increases with engine power and can vary dramatically as engine power demands vary.

For most catalytic emission-control technologies there is a minimum temperature below which the chemical reactions necessary for emission control do not occur. The temperature above which substantial catalytic activities is realized is often called the light-off temperature. For gasoline engines, the light-off temperature is typically important only in determining cold-start emissions. Once gasoline vehicle exhaust temperatures exceed the light-off temperature, the catalyst is "lit-off" and remains fully functional under all operating conditions. Diesel exhaust is significantly cooler than gasoline exhaust due to the diesel engine's higher thermal efficiency and its operation under predominantly lean conditions. Absent control action taken by an electronic engine control system, diesel exhaust may fall below the light-off temperature of catalyst technology even when the engine is fully warmed up.

The relationship between the exhaust temperature of a nonroad diesel engine and light-off temperature is an important factor for both CDPF and NOx adsorber technologies. For the CDPF technology, exhaust temperature determines the rate of filter regeneration and if too low causes a need for supplemental means to ensure proper filter regeneration. In the case of the CDPF, it is the aggregate soot regeneration rate that is important, not the regeneration rate at any particular moment in time. A CDPF controls PM emissions under all conditions and can function properly (i.e., not plug) even when exhaust temperatures are low for an extended time and the regeneration rate is lower than the soot accumulation rate, provided that occasionally exhaust temperatures and thus the soot regeneration rate are increased enough to regenerate the CDPF. A CDPF can passively (without supplemental heat addition) regenerate if exhaust temperatures remain above 250˚C for more than 40 percent of engine operation.[113] Similarly (and as discussed in more detail earlier), there is a minimum temperature (e.g., 200˚C) for NOx adsorbers below which NOx regeneration is not readily possible and a maximum temperature (e.g., 500˚C) above which NOx adsorbers are unable to effectively store NOx. These minimum and maximum temperatures define a characteristic temperature window of the NOx adsorber catalyst. When the exhaust temperature is within the temperature window (above the minimum and below the maximum) the catalyst is highly effective. When exhaust temperatures fall outside this window of operation, NOx adsorber effectiveness is diminished. There is therefore a need to match diesel exhaust temperatures to conditions for effective catalyst operation under the various operating conditions of nonroad engines.

Although the range of products for highway vehicles is not as diverse as for nonroad equipment, the need to match exhaust temperatures to catalyst characteristics is still present. This is a significant concern for highway engine manufacturers and has been a focus of our ongoing diesel engine progress review. There we have learned that substantial progress is being made to broaden the operating temperature window of catalyst technologies, while at the same time, engine systems are being designed to better control exhaust temperatures. Highway diesel engine manufacturers are working to address this need through modifications to engine design, modifications to engine control strategies and modifications to exhaust system designs. Engine design changes including the ability for multiple late fuel injections and the ability to control total air flow into the engine give controls engineers additional flexibility to change exhaust temperature characteristics. Modifications to the exhaust system, including the use of insulated exhaust manifolds and exhaust tubing, can help to preserve the temperature of the exhaust gases. New engine control strategies designed to take advantage of engine and exhaust system modifications can then be used to manage exhaust temperatures across a broad range of engine operation. The technology solutions being developed for highway engines to better manage exhaust temperature are built upon the same emission-control technologies (i.e., advanced air handling systems and electronic fuel-injection systems) that we expect nonroad engine manufacturers to use for meeting the Tier 3 emission standards.

4.1.3.1.1 CDPFS and Nonroad Operating Temperatures

EPA has conducted a screening analysis to better understand the effect of engine operating cycles and engine power density on exhaust temperatures, specifically to see if passive CDPF regeneration can be expected under all conditions for nonroad engine applications. Our approach for assessing the likelihood of passive regeneration by a CDPF is based on what we learned from the literature as well as information submitted by various catalyst manufacturers for product verification to our voluntary diesel retrofit program.

For this analysis three representative nonroad engines were tested. The engines are described in Table 4.1-8. In the case of the Cummins engine, the testing was done at three different engine ratings (250hp, 169hp, and 124hp) to evaluate the effect of engine power density on expected exhaust temperatures and therefore the likelihood of passive PM filter regeneration.

Table 4.1-8
Engines Tested to Evaluate PM Filter Regeneration

Engine Model	Model Year	Displacement (L)	Cylinder Number	Rated Power (hp)	Air Induction	Engine Type
Lombardini LDW1003-FOCS	2001	1.0	3	26	naturally aspirated	IDI
Kubota V2203-E	1999	2.2	4	50	naturally aspirated	IDI
Cummins ISB	2000	5.9	6	260	turbocharged intercooled	DI

As described in 4.1.1.3 above, passive filter regeneration occurs when the exhaust temperatures are high enough that on aggregate the PM accumulation rate on the filter is less than the PM oxidation rate on the filter over an extended time period. During that time period there can be periods of low-temperature operation where the PM accumulation rate is higher than the oxidation rates, provided that there are other periods of higher temperature operation where the PM oxidation rate is significantly higher than the accumulation rate. CDPF manufacturers provide guidelines for CDPF applications where passive regeneration is necessary (i.e., no provision for occasional active regeneration is provided). These guidelines are based on the cumulative amount of typical engine operation above and below a particular exhaust temperature. One CDPF manufacturer has stated that passive regeneration will occur if temperatures exceed 250ºC for more than 30 percent of engine operation.[114] Another CDPF manufacturer has stated that catalyzed diesel particulate filters will work properly in the field if the engine exhaust temperature is at least 250-275ºC for about 40-50 percent of the duty cycle.[115]

EPA used the more restrictive of these guidelines to evaluate the likelihood that passive regeneration will during typical nonroad operating cycles. To do this, the exhaust temperatures collected from testing each engine on various nonroad transient duty cycles were sorted in an ascending order. Upon sorting, we identified the 50th and 60th percentile mark of the temperature obtained for a transient cycle run, which lasted anywhere between 8 to 20 minutes for an entire cycle duration. The temperatures associated with the 50th and 60th percentile mark correspond to the minimum temperatures for 50 and 40 percent of the duty cycle, respectively. In addition, we also calculated the average temperature obtained throughout a given cycle.

Tables 4.1-9, 4.1-10, and 4.1-11 show the 50th and 60th percentile temperatures representing the minimum temperatures for 50% and 40% of the duty cycle, respectively. The tables show that the 60th percentile temperature exceeded 250˚C for most of the engine tests on all three engines. The runs that did not result in at least 250˚C for 40% of the duty cycle were from the highway FTP cycle for the two small engines, and from the backhoe cycle for the lowest power rating, i.e., 124 hp, on the Cummins ISB engine.

Table 4.1-9
Engine-out Exhaust Gas Temperature Data - 124, 163, 260 hp Cummins ISB

Cycle		Average T (°C)	50th %tile T (°C)	60th %tile T (°C)	Operation at T m 275°C
Agricultural Tractor	260 hp (test #1454)	418	444	452	92%
	124 hp (test #1518)	319	336	339	89%
Wheel Loader	260 hp (test #1449)	295	323	295	57%
	169 hp (test #1530)	264	277	311	50%
	124 hp (test #1526)	221	222	258	29%
Backhoe	260 hp (test #1455)	261	280	303	52%
	169 hp (test #1528)	236	238	254	24%
	124 hp (test #1523)	185	194	201	0%
JRC Composite	260 hp (test #1660)	311	323	337	75%
	260 hp (test #1661)	317	326	339	78%
	169 hp (test #1529)	289	290	304	61%
	124 hp (test #1525)	252	243	265	37%

Table 4.1-10
Engine-out Exhaust Gas Temperature Data - 50 hp Kubota V2203E

Cycle	Average T (°C)	50th %tile T (°C)	60th %tile T (°C)	Operation at T m 275°C
Agricultural Tractor	518	544	561	96%
Nonroad Composite	289	286	310	56%
Skid Steer Loader	259	257	268	34%
Federal Test Procedure	232	210	238	30%

Table 4.1-11
Engine-out Exhaust Gas Temperature Data - 26 hp Lombardini LDW1003

Cycle	Average T (°C)	50th %tile T (°C)	60th %tile T (°C)	Operation at T m 275°C
Arc Welder	262	257	263	26%
Nonroad Composite	274	271	290	48%
Skid Steer Loader	243	239	252	24%
Federal Test Procedure	177	148	175	15%
Agricultural Tractor	516	548	554	97%

The results shown here lead us to conclude that, for a significant fraction of nonroad diesel engine operation, exhaust temperatures are likely to be high enough to ensure passive regeneration of CDPFs. However, the results also indicate that for some operating conditions it may be that passive filter regeneration is not realized. In the case of those operating conditions, we believe that active backup regeneration systems (systems designed to increase exhaust temperature periodically to initiate filter regeneration) can be used to ensure CDPF regeneration. Additional data regarding in-use temperature operation are contained in a recent report from the Engine Manufacturers Association (EMA) and the European Association of Internal Combustion Engine Manufacturers (Euromot).[116] This report contains data from a range of applications and power categories. Similar to the data presented above, the EMA/Euromot data indicate that, while several nonroad applications generate temperatures high enough to passively regenerate a filter, there are also some applications that require active regeneration.

We have assumed in our cost analysis that all nonroad engines complying with a PM standard of 0.03 g/hp-hr or lower (those engines that we are projecting will use a CDPF) will have an active means to control temperature (i.e., we have costed a backup active regeneration system, though some applications may not need one). We have made this assumption believing that manufacturers will not be able to predict, accurately, in-use conditions for every piece of equipment and will thus choose to provide the technologies on a back-up basis. As explained earlier, the technologies necessary to accomplish this temperature management are enhancements of the Tier 3 emission-control technologies that will form the baseline for Tier 4 engines, and the control strategies being developed for highway diesel engines. We believe there are no nonroad engine applications above 25 hp for which these highway engine approaches will not work. However, given the diversity in nonroad equipment design and application, we believe that additional time will be needed to match the engine performance characteristics to the full range of nonroad equipment.

Matching the operating temperature window of the broad range of nonroad equipment may be somewhat more challenging for nonroad engines than for many highway diesel engines simply because of the diversity in equipment design and equipment use. Nonetheless, the problem has been successfully solved in highway applications facing low-temperature performance situations as difficult to address as any encountered faced by nonroad applications. The most challenging temperature regime for highway engines are encountered at very light-loads as typified by congested urban driving. Under congested urban driving conditions exhaust temperatures may be too low for effective NOx reduction with a NOx adsorber catalyst. Similarly, exhaust temperatures may be too low to ensure passive CDPF regeneration. To address these concerns, light-duty diesel engine manufacturers have developed active temperature management strategies that provide effective emissioncontrol even under these difficult light-load conditions. Toyota has shown with their prototype DPNR vehicles that changes to EGR and fuel-injection strategies can realize an increase in exhaust temperatures of more than 50˚C under even very light-load conditions allowing the NOx adsorber catalyst to function under these normally cold exhaust conditions.[117] Similarly, PSA has demonstrated effective CDPF regeneration under demanding light-load taxi cab conditions with current production technologies.[118] Both of these are examples of technology paths available to nonroad engine manufacturers to increase temperatures under light-load conditions.

We are not aware of any in-use operating cycles for nonroad equipment that are more demanding of low-temperature performance than highway urban driving. Both the Toyota and

PSA systems are designed to function even with extended-idle operation typical of a taxi waiting to pick up a fare.[N] By actively managing exhaust temperatures engine manufacturers can ensure highly effective catalyst-based emission-control performance (i.e., compliance with the emission standards) and reliable filter regeneration (failsafe operation) across a wide range of engine operation typical of the broad range of nonroad engine operation in use and the new nonroad transient duty cycle.

The systems described here from Toyota and PSA are examples of highly integrated engine and exhaust emission-control systems based upon active engine management designed to facilitate catalyst function. Because these systems are based upon the same engine control technologies likely to be used to comply with the Tier 3 standards and because they allow great flexibility to trade-off engine control and catalyst control approaches depending on operating mode and need, we believe most nonroad engine manufacturers will use similar approaches to comply with the Tier 4 emission standards. However, there are other technologies available that are designed to be added to existing engines without the need for extensive integration and engine management strategies. One example of such a system is an active DPF system developed by Deutz for use on a wide range on nonroad equipment. The Deutz system has been sold as an OEM retrofit technology that does not require changes to the base engine technology. The system is electronically controlled and uses supplemental in-exhaust fuel injection to raise exhaust temperatures periodically to regenerate the DPF. Deutz has sold over 2,000 of these units and reports that the systems have been reliable and effective. Some manufacturers may choose to use this approach for compliance with the Tier 4 PM standard, especially in the case of engines that may be able to meet the NOx standards with engine-out emission-control technologies (i.e., engines rated between 25 and 75 hp and mobile machines >750 hp).

We believe that, given the timing of the Tier 4 emission standards and the availability and continuing development of technologies to address temperature management for highway engines (whose technologies are transferrable to all nonroad engines with greater than 25 hp power rating), nonroad engines can be designed to meet the emission standards adopted in this final rule in a timely manner.

[N] There is one important distinction between the current PSA system and the kind of system that we project industry will use to comply with the Tier 4 standards: the PSA system incorporates a cerium fuel additive to help promote soot oxidation. The additive serves a similar function to a catalyst to promote soot oxidation at lower temperatures. Even with the use of the fuel additive, passive regeneration is not realized on the PSA system and an active regeneration is conducted periodically involving late cycle fuel injection and oxidation of the fuel on an up-front diesel oxidation catalyst to raise exhaust temperatures. This form of supplemental heating to ensure infrequent but periodic PM filter regeneration has proven to be robust and reliable for more than 500,000 PSA vehicles. Our 2002 progress review found that other manufacturers will be introducing similar systems in the next few years without the use of a fuel additive. One vehicle manufacturer, Renault has recently announced that they will introduce this year a CDPF system on a diesel passenger car that does not rely on an additive to help ensure that regeneration occurs.

4.1.3.1.2 NOx Adsorbers and Nonroad Operating Temperatures

Section 4.1.2.3.3 above describes a method to directionally evaluate the match between the operating temperature characteristics of a diesel engine in typical use and the range of temperatures over which a NOx adsorber catalyst is highly effective, the operating window of the NOx adsorber catalyst technology. The analysis is not effective to accurately predict exact emission results as it does not account for the thermal inertia of the catalyst technologies nor the ability of the NOx adsorber to store NOx at lower temperatures as discussed in more fully in Section 4.1.2.3.3. Nevertheless, this analysis approach can be used to compare predicted performance of an engine with a NOx adsorber catalyst on various test cycles and with various engine configurations.

In this case, we have used this analysis approach to better understand the characteristics of the NRTC and the C1 composite cycle relative to the highway FTP cycle. We have extensive experience testing NOx adsorber catalyst systems on the highway FTP cycle (see discussion above in Section 4.2) showing that NOx reductions in excess of 90% can be expected. Here, we are trying to understand if the NOx performance on the NRTC and the C1 composite cycle should be expected to be better or worse than the highway FTP cycle. To accomplish that, we tested a Cummins ISB (see Table 4.1-8) engine at three different power ratings representative of the range of engine power density currently seen for nonroad diesel engines (250hp, 169hp, and 124hp). Following the technique described in Section 4.1.2.3.3, we estimated a notional NOx adsorber efficiency for the various test cycles and engine power ratings described here. Further, we performed this analysis for several different NOx adsorber mounting locations (i.e., we measured exhaust temperatures at several locations in the exhaust system, a catalyst is not actually installed for this testing). By measuring temperature at several locations, we could further understand the impact of heat loss in the exhaust system on NOx adsorber performance. The results of this testing and analysis are presented in Tables 4.1-12, 4.1-13 and 4.1-14.

Table 4.1-12
Estimated NOx Adsorber Efficiency on Cummins ISB ISO-C1 Composite[a]

Engine Power (hp)	6" from turbo outlet (%)	25" from turbo outlet (%)	4' from turbo outlet (%)	6' 7" from turbo outlet (%)
124	90.5	90.7	90.6	89.8
169	86.2	87.1	88.7	90.8
250	79.5	84.2	85.2	87.9

[a] The estimates are based on the absorber B curve shown in Figure 4.1-11.

Table 4.1-13
Estimated NOx Adsorber Efficiency on Cummins ISB - NRTC Cycle[a]

Engine Power (hp)	6" from turbo outlet (%)	25" from turbo outlet (%)	4' from turbo outlet (%)	6' 7" from turbo outlet (%)
124	85.6	83.9	81.7	77.4
169	93.0	92.2	91.1	88.6
250	91.6	92.9	93.6	93.5

[a] The estimates are based on the absorber B curve shown in Figure 4.1-11.

Table 4.1-14
Estimated NOx Adsorber Efficiency on Cummins ISB - Highway FTP Cycle[a]

Engine Power (hp)	6" from turbo outlet (%)
124	60.3
169	72.4
250	83.0

[a] The estimates are based on the absorber B curve shown in Figure 4.1-11.

Results of the analysis show that for many nonroad engines, the expected exhaust temperatures are well matched for NOx adsorber control giving high NOx conversion efficiencies with today's NOx adsorber technology. The NOx-reduction potential by these devices was higher over nonroad cycles when compared with that achieved from the highway FTP cycle. This higher efficiency obtained from the engine testing results was due to comparatively higher engine-out exhaust temperatures obtained from running on various nonroad transient cycles compared with the highway FTP cycle, thus indicating that the transfer of highway engine technologies developed for the HD2007 emission standards will be able to provide similar or better control for nonroad diesel engines designed to comply with the Tier 4 standards.

4.1.3.1.3 Power Density Trends in Nonroad

An analysis of power density trends in nonroad diesel engines was undertaken to understand what levels of power density to expect in the future for nonroad diesel engines. This analysis included consideration of data from the Power Systems Research 2002 database (PSR). The PSR data includes estimates of nonroad diesel engine model specifications and sales going back at least 20 years. This data set represents the most comprehensive nonroad engine database of this nature available.

This analysis specifically examined trends in power density within various power categories from 1985 to 2000. The PSR database reports both rated power and engine displacement, from which power was calculated.[O] The data were divided into 5 power categories: 70-100 hp; 100 - 175hp; 175 - 300hp, 300 - 600hp, and >600hp. For each power category, a sales-weighted average of power density was calculated for each year. Table 4.1-15 shows the resulting data, as well as the percent change from 1985 to 2000. Figure 4.1-17 is a graphical representation of the data in Table 4.1-15.

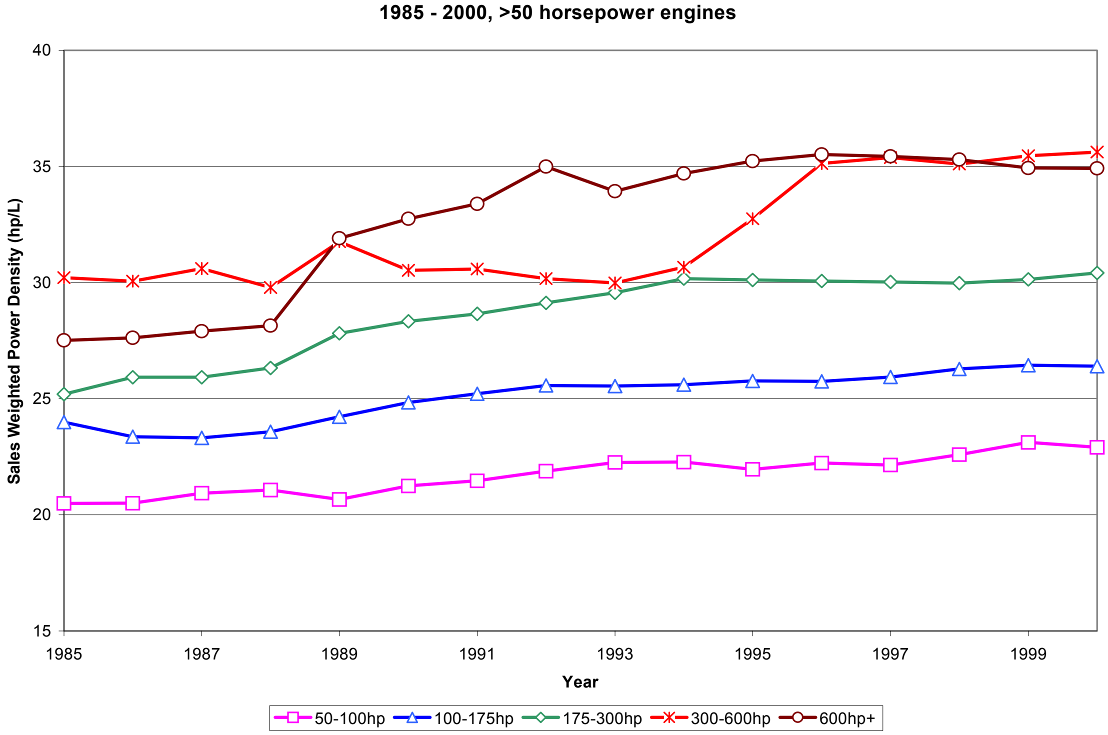
Table 4.1-15
Sales-Weighted Power Density by Power Category (hp/liter), 1985 - 2000

Year	50-100hp	100-175hp	175-300hp	300-600hp	600hp+
1985	20.5	24.0	25.2	30.2	27.5
1986	20.5	23.4	25.9	30.1	27.6
1987	20.9	23.3	25.9	30.6	27.9
1988	21.1	23.6	26.3	29.8	28.1
1989	20.7	24.2	27.8	31.8	31.9
1990	21.2	24.8	28.3	30.5	32.7
1991	21.5	25.2	28.7	30.6	33.4
1992	21.9	25.6	29.1	30.2	35.0
1993	22.3	25.5	29.6	30.0	33.9
1994	22.3	25.6	30.2	30.7	34.7
1995	22.0	25.8	30.1	32.7	35.2
1996	22.2	25.7	30.1	35.1	35.5
1997	22.1	25.9	30.0	35.4	35.4
1998	22.6	26.3	30.0	35.1	35.3
1999	23.1	26.4	30.1	35.5	34.9
2000	22.9	26.4	30.4	35.6	34.9
% Change 1985 - 2000	11%	9%	17%	15%	21%

Figure 4.1-7 shows reasonably steady increase in power density for engines all power categories from 1985 until approximately 1994/1995, though the rate of increase varies between the power categories. From 1994/95 until 2000 most power categories saw either no change or a slight increase in power density, with the exception of the >600hp category, which saw a small decrease. Power density increases by engine rated power, with the 70-100hp category showing the lowest values, with year 2000 being 22.9 hp/liter, and the 300-600hp and 600+hp categories have sales-weighted power densities on the order of 35 hp/liter.

[O] Power density is equal to the engine's rated power divided by the engines total displacement. The data in this memorandum is presented in terms of horsepower per liter.

Figure 4.1-17 Power Density Trends for Nonroad Diesel Engines



4.1.3.2 Durability and Design

Nonroad equipment is designed to be used in a wide range of tasks in some of the harshest operating environments imaginable, from mining equipment to crop cultivation and harvesting to excavation and loading. In the normal course of equipment operation the engine and its associated hardware will experience levels of vibration, impacts, and dust that may exceed conditions typical of highway diesel vehicles. Failing to consider differences in operating conditions in engine and equipment design would be expected to lead to eventual failure of the equipment.

Specific efforts to design for the nonroad operating conditions will be required to ensure that the benefits of these new emission-control technologies are realized for the life of nonroad equipment. Much of the engineering knowledge and experience to address these issues already exists with the nonroad equipment manufacturers. Vibration and impact issues are fundamentally mechanical durability concerns (rather than issues of technical feasibility of achieving emission reductions) for any component mounted on a piece of equipment (e.g., an engine coolant overflow tank). Equipment manufacturers must design mounting hardware such as flanges, brackets, and bolts to support the new component without failure. Further, the catalyst substrate material itself must be able to withstand the conditions encountered on nonroad equipment without itself cracking or failing. There is a large body of real-world testing with retrofit emission-control technologies that demonstrates the durability of the catalyst components themselves even in the harshest of nonroad equipment applications.

Deutz, a nonroad engine manufacturer, sold approximately 2,000 diesel particulate filter systems for nonroad equipment in the period from 1994 through 2000. The very largest of these systems were limited to engine sizes below 850 hp. The majority of these systems were sold into significantly smaller applications. Many of these systems were sold for use in mining equipment. No other applications are likely to be more demanding than this. Mining equipment is exposed to extraordinarily high levels of vibration, experiences impacts with the mine walls and face, and high levels of dust. Yet in meetings with the Agency, Deutz shared their experience that no system had failed due to mechanical failure of the catalyst or catalyst housing.[119] The Deutz system utilized a conventional cordierite PM filter substrate as is commonly used for heavy-duty highway truck CDPF systems. The canning and mounting of the system was a Deutz design. Deutz was able to design the catalyst housing and mounting in such a way as to protect the catalyst from the harsh environment as evidenced by its excellent record of reliable function.

Other nonroad equipment manufacturers have also offered OEM diesel particulate filter systems to comply with requirements of some mining and tunneling worksite standards. Liebherr, a nonroad engine and equipment manufacturer, offers diesel particulater filter systems as an OEM option on 340 different nonroad equipment models.[120] We believe this experience shows that appropriate design considerations, as are necessary with any component on a piece of nonroad equipment, will be adequate to address concerns with the vibration and impact conditions that can occur in some nonroad applications. This experience applies equally well to the NOx adsorber catalyst technologies, as the mechanical properties of DOCs, CDPFs, and NOx adsorbers are all similar. We believe that no new or fundamentally different solutions are needed to address the vibration and impact constraints for nonroad equipment below 750 hp. Engines above 750 hp are fundamentally similar to smaller engines with the most obvious difference being their larger size. Their larger size does create some additional issues regarding the size and physical strength of emission control technologies. While we believe that it may be possible to address these concerns using the same technologies as for engines <750 hp, we recognize that today we have limited evidence to draw that conclusion definitively. As described in Preamble Section II, we have therefore made some revisions to the proposed emission standards for engines >750 hp reflecting technologies (e.g., wire or fiber mesh PM filters) that we can say with confidence will be appropriate and available in the timeframe of this rulemaking.

Certain nonroad applications, including some forms of harvesting equipment and mining equipment, may have specific limits on maximum surface temperature for equipment components to ensure that the components do not serve as ignition sources for flammable dust particles (e.g. coal dust or fine crop dust). Some have suggested that these design constraints might limit the equipment manufacturers ability to install advanced diesel catalyst technologies such as NOx adsorbers and CDPFs. This concern seems to be largely based upon anecdotal experience with gasoline catalyst technologies where, under certain circumstances, catalyst temperatures can exceed 1,000˚C and, without appropriate design considerations, could conceivably serve as an ignition source. We do not believe these concerns are justified in the case of either the NOx adsorber catalyst or the CDPF technology. Catalyst temperatures for NOx adsorbers and CDPFs should not exceed the maximum exhaust manifold temperatures already commonly experienced by diesel engines (i.e., catalyst temperatures are expected to be below 800˚C).[P] CDPF temperatures are not expected to exceed approximately 700˚C in normal use and are expected to reach the 650˚C temperature only during periods of active regeneration. Similarly, NOx adsorber catalyst temperatures are not expected to exceed 700˚C and again only during periods of active sulfur regeneration, as described in Section 4.1.7 below. Under conditions where diesel exhaust temperatures are naturally as high as 650˚C, no supplemental heat addition from the emission-control system will be necessary and therefore exhaust temperatures will not exceed their natural level. When natural exhaust temperatures are too low for effective functioning of the emission-control system, then supplemental heating (as described earlier) may be necessary, but this is not expected to produce temperatures higher than the maximum levels normally encountered in diesel exhaust. Furthermore, even if it were necessary to raise exhaust temperatures to a higher level to promote effective emission control, there are technologies available to isolate the higher exhaust temperatures from flammable materials such as dust. One approach is the use of air-gapped exhaust systems (i.e., an exhaust pipe inside another concentric exhaust pipe separated by an air-gap) that serve to insulate the inner high-temperature surface from the outer surface, which could come into contact with the dust. The use of such a system may be additionally desirable to maintain higher exhaust temperatures inside the catalyst to promote better catalyst function. Another technology to control surface temperature already used by some nonroad equipment manufacturers is water cooled exhaust systems.[121] This approach is similar to the air-gapped system but uses engine coolant water to actively cool the exhaust system. Flammable dust concerns should not prevent the use of either a NOx adsorber or a CDPF, because catalyst temperatures are not expected to be unacceptably high and because remediation technologies exist to address these concerns. In fact, exhaust emission-control technologies (i.e., aftertreatment) have already been applied on both an OEM basis and for retrofit to nonroad equipment for use in potentially explosive environments. Many of these applications must undergo Underwriters Laboratory (UL) approval before they can be used.[122]

We agree that nonroad equipment must be designed to address durable performance for a wide range of operating conditions and applications that are not commonly experienced by highway vehicles. We believe further, as demonstrated by retrofit experiences around the world, that there are technical solutions that allow catalyst-based emission-control technologies to be applied to nonroad equipment.

4.1.4 Are the Standards for Engines >25 hp and <75 hp Feasible?

As discussed in Section II of the preamble, the emission standards for engines between 25 and 75 hp consist of a 2008 transitional standard and long-term 2013 standards. The transitional standard is a 0.22 g/hp-hr PM standard. The 2013 standards consist of a 0.02 g/hp-hr PM

[P] The hottest surface on a diesel engine is typically the exhaust manifold, which connects the engines exhaust ports to the inlet of the turbocharger. The hot exhaust gases leave the engine at a very high temperature (800˚C at high power conditions) and then pass through the turbo where the gases expand driving the turbocharger providing work and are cooled in the process. The exhaust leaving the turbocharger and entering the catalyst and the remaining pieces of the exhaust system is normally at least 100˚C cooler than in the exhaust manifold.

standard and a 3.5 g/hp-hr NMHC+NOx standard. The transitional standard is optional for 50-75 hp engines, as the 2008 implementation date is the same as the effective date of the Tier 3 standards. Manufactures may decide, at their option, not to undertake the 2008 transitional PM standard, in which case their implementation date for the 0.02 g/hp-hr PM standard begins in 2012.

The remainder of this section discusses (1) what makes the 25-75 hp category unique, (2) which engine technology is used currently, (3) which engine technology will be used for applicable Tier 2 and Tier 3 standards, and (4) why the Tier 4 standards are technologically feasible.

4.1.4.1 What makes the 25 - 75 hp category unique?

Many of the nonroad diesel engines ≥75 hp are either a direct derivative of highway heavy-duty diesel engines, or share some common traits with highway diesel engines. These include similarities in displacement, aspiration, fuel systems, and electronic controls. At the time of the proposal, we summarized some of the key engine parameter using data from the 2001 engines certified for sale in the United States. For this final rule, we have also added to this data set by including the 2004 engines certified for sale in the U.S. A comparison of these two data sets show a number of important trends, as discussed below.

Table 4.1-16 contains a summary of some key engine parameters from the 2001 engines certified for sale in the United States, and Table 4.1-17 is a summary of the 2004 engines.[Q]

Table 4.1-16
Summary of Model Year 2001 Key Engine Parameters by Power Category

Engine Parameter	Percent of 2001 U.S. Production[a]			
	0-25 hp	25-75 hp	75-100 hp	>100 hp
IDI Fuel System	83%	47%	4%	<0.1%
DI Fuel System	17%	53%	96%	>99%
Turbocharged	0%	7%	62%	91%
1 or 2 Cylinder Engines	47%	3%	0%	0%
Electronic fuel systems	0%	0%	0%	14%

[a] Based on sales weighting of 2001 engine certification data.

[Q] Data in Table 4.1-16 are derived from a combination of the publically available certification data for model year 2001 engines, as well as the manufacturers reported estimates of 2001 production targets, which is not public information.

Table 4.1-17
Summary of Model Year 2004 Key Engine Parameters by Power Category

Engine Parameter	Percent of 2004 U.S. Production[a]			
	0-25 hp	25-75 hp	75-100 hp	>100 hp
IDI Fuel System	85%	54%	6%	0.0%
DI Fuel System	15%	46%	94%	100.0%
Turbocharged	0%	22%	78%	99.9%
1 or 2 Cylinder Engines	18%	<1%	0%	0%
Electronic fuel systems	0%	0%	18%	61%

[a] Based on sales weighting of 2004 engine certification data.

As can be seen in Table 4.1-16 & 4.1-17, the engines in the 25-75 hp category have some important technology differences from the larger engines. These include a higher percentage of indirect-injection fuel systems, and a lower fraction of turbocharged engines. (The distinction in the <25 hp category is even more different, with no turbocharged engines, a large number of the engines have two cylinders or less, and a significant majority of the engines have indirect-injection fuel systems.)

The distinction is particularly marked with respect to electronically controlled fuel systems. These are commonly available in the ≥ 75 hp power categories (see Table 4.1.17 above showing that the technology is already migrating in significant amounts even into the 75-100 hp power band), but, based on the available certification data as well as our discussions with engine manufacturers, we believe there are very limited, if any in the 25-75 hp category (and no electronic fuel systems in the less than 25 hp category) at this time. The research and development work currently being performed for the heavy-duty highway market is targeted at turbocharged and electronically controlled, direct-injection engines with at least four cylinders and per-cylinder displacements greater than 0.5 liters. As discussed in more detail below (and in the preamble), as well as in Section 4.1.5.1 (regarding the <25 hp category), these engine distinctions are important from a technology perspective and warrant a different set of standards and implementation time-frame for the 25-75 hp category (as well as for the <25 hp category).

At the same time, the data in Tables 4.1-16 and 4.1-17 shows that engine technology is steadily progressing in the nonroad diesel engine market, and the penetration of that technology has increased in the past few years, i.e., from 2001 to 2004. In 2001, only engines in the 300-600hp range were required to comply with Tier 2. Today, in 2004, all engines in the 25-750hp range must comply with the Tier 2 emission standards. As a result of the inherent benefits of electronically controlled fuel systems and turbocharging, and as a response to the Tier 2 emission standards, the penetration of these engine technologies in the past few years has been dramatic. Nearly all engines >100 hp are turbocharged and have direct injection fuel systems. In addition, more than 60 percent of the engines > 100 hp now have electronically controlled fuel systems (up from 14% in 2001). In the 75-100hp range, turbocharging has increased from 62 to

78 percent, and electronically controlled fuel systems have increased from 0 percent in 2001 to 18 percent in 2004. The certification data shows that these electronically controlled fuel systems are available across the full 75-100 hp range, with some engines which use these fuel systems having a rated power of 75 hp and others having a rated power of 99 hp. The data also indicate that the engines in the 75-100 hp range with electronically controlled fuel systems are designed for use in nonroad equipment such as agricultural tractors, mobile cranes, dozers, loaders, fork lifts, and a range of other nonroad equipment. Even in the 25-75 hp range, turbocharging has increased by a factor of 3, from 7 to 21 percent. We expect all of these trends to continue as Tier 2 is fully implemented by 2006, and as the Tier 3 standards are phased-in from 2006 to 2008. Another reason we expect that the trend will continue is because of the inherent benefits for the end-user which result from the use of electronically controlled fuel systems and turbocharging.

4.1.4.2 What engine technology is used currently, and will be used for Tier 2 and Tier 3, in the 25-75hp range?

In the 1998 nonroad diesel rulemaking, we established Tier 1 and Tier 2 standards for engines in the 25-50 hp category. Tier 1 standards were implemented in 1999, and the Tier 2 standards take effect in 2004. The 1998 rule also established Tier 2 and Tier 3 standards for engines between 50 and 75 hp. The Tier 2 standards take effect in 2004, and the Tier 3 standards take effect in 2008. The Tier 1 standards for engines between 50 and 75 hp took effect in 1998. All engines in the 25-75 hp range were first required to meet Tier 2 standards in the 2004 model year, and the MY 2004 data presented in Table 4.1-17 represent Tier 2 technology for this power range.

Engines in the 25-75 hp category use either indirect injection (IDI) or direct injection (DI) fuel systems. The IDI system injects fuel into a pre-chamber rather than directly into the combustion chamber as in the DI system.[123] This difference in fuel systems results in substantially different emission characteristics, as well as several important operating parameters. In general, the IDI engine has lower engine-out PM and NOx emissions, while the DI engine has better fuel efficiency and lower heat rejection.[124]

We expect a significant shift in the engine technology that will be used in this power category as a result of the upcoming Tier 2 and Tier 3 standards, in particular for the 50-75 hp engines. In the 50-75 hp category, the 2008 Tier 3 standards will likely result in the significant use of turbocharging and electronic fuel systems, as well as the introduction of both cooled and uncooled exhaust gas recirculation by some engine manufacturers and possibly the use of charge-air-cooling.[125] To some extent this has already begun to occur as a result of the Tier 2 standards, as discussed above in relation to Tables 4.1-16 and 4.1-17. In addition, we have heard from some engine manufacturers that the engine technology used to meet Tier 3 for engines in the 50-75 hp range will also be made available on those engines in the 25-50 hp range that are built on the same engine platform. For the Tier 2 standards for the 25-50 hp products, a large number of engines already meet these standards; we therefore expect to see more moderate changes in these engines, including an increased penetration of turbocharging.[126]

4.1.4.3 Are the standards for 25 -75 hp engines technologically feasible?

This section discusses the feasibility of both the interim 2008 PM standard and the long-term 2013 standards.

4.1.4.3.1 2008 PM Standards

As just discussed in Section 4.1.4.2, engines in the 25-50 hp category must already meet Tier 1 NMHC+NOx and PM standards. We have examined the model year 2002 engine certification data for engines in the 25-50 hp category.[127] We have also examined the model year 2004 certification data for engines in the 25-50hp category. For the model year 2002 data, there is no Tier 1 PM standard for engines in the 50-75 hp range, and engine manufacturers are therefore not required to report PM emission levels until Tier 2 starts in 2004, so there is no 2002 data to summarize for the 50-75hp range.

Summary of 2002 Model Year Certification Data for 25-50 hp

A summary of the 2002 model year certification data for the 25-50 hp engines is presented in Table 4.1-18, and Figure 4.1-18 is a graph of the HC+NOx and PM results from these same engines. These data indicate that over 10 percent of the engine families already meet the 2008 0.22 g/hp-hr PM standard and 5.6 g/hp-hr NMHC+NOx standard (unchanged from Tier 2 in 2008). These include a variety of engine families using a mix of engine technologies (IDI and DI, turbocharged and naturally aspirated) tested on a variety of certification test cycles.[R] Five engine families are more than 20 percent below the 0.22 g/hp-hr PM standard; an additional 24 engine families that already meet the 2008 NMHC+NOx standards will require no more than a 30 percent PM reduction to meet the 2008 PM standards. Unfortunately, similar data do not exist for engines between 50 and 75 hp for the 2002 model year.

[R] The Tier 1 standards for this power category must be demonstrated on one of a variety of different engine test cycles. The appropriate test cycle is selected by the engine manufacturer based on the intended in-use application of the engine.

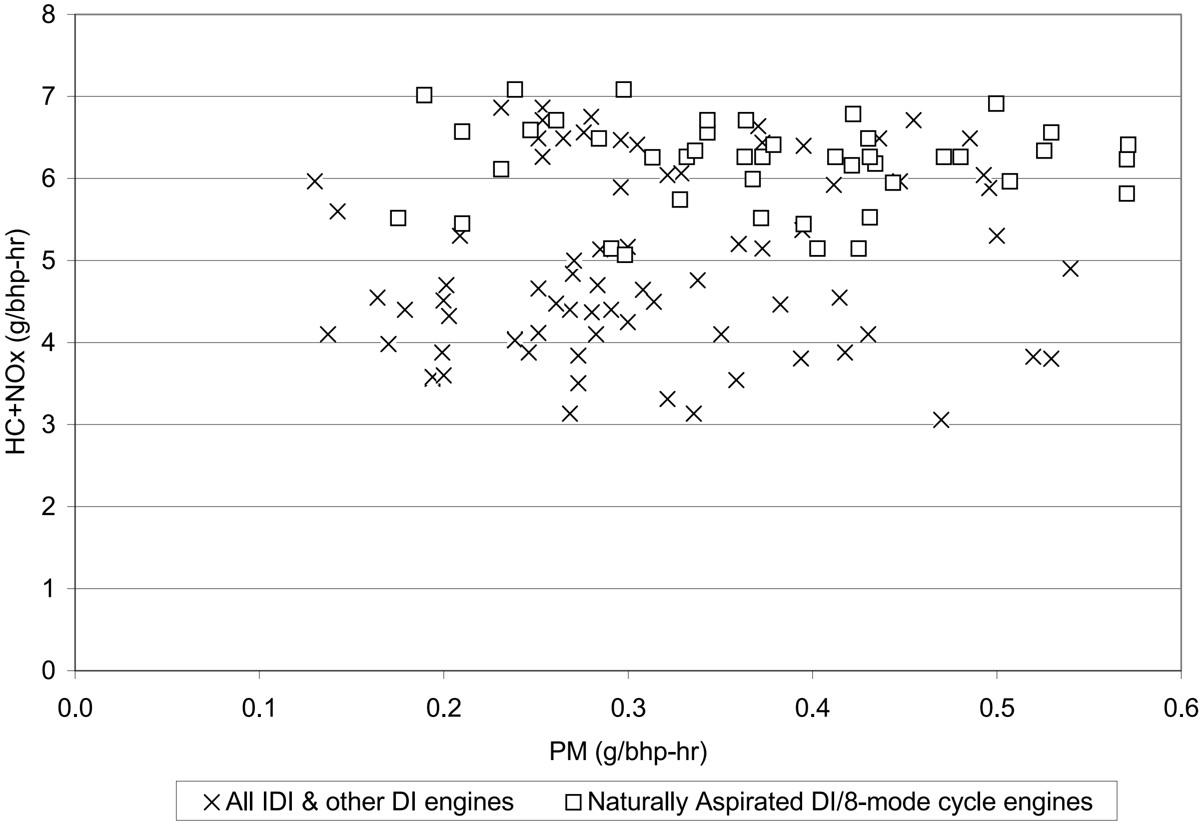
Table 4.1-18
2002 Model Year Certification Data for 25-50 hp Nonroad Diesel Engines

PM Emissions Relative to the 0.22 g/hp-hr Standard	IDI Engines				DI Engines			Totals
	5-mode/ NA	8-mode/ NA	5-mode/ TC	8-mode/ TC	5-mode/ NA	8-mode/ NA	8-mode/ TC	
0 - 5 % below T4[a]	0	0	0	0	0	1	0	1
5 - 20 % below T4[a]	1	5	1	2	0	0	0	9
>20 % below T4[a]	2	1	0	1	0	1	0	5
require ≤30% PM reduction to meet T4[a]	3	15	0	4	0	2	0	24
requires >30%PM reduction and/or	2	17	1	3	8	40	8	79
Total # of Engine Families	8	38	2	10	8	44	8	118

[a] Engine also meets 2008 NMHC+NOx

The model year 2002 engines in this power range use well known engine-out emission-control technologies, such as optimized combustion chamber design and fuel-injection timing control strategies, to comply with the existing standards. These data have a two-fold significance. First, they indicate that some engines in this power range can already achieve the 2008 standard for PM using only engine-out technology, and that other engines should be able to achieve the standard making improvements just to engine-out performance.

Figure 4.1-18 Emission Certification Data for 25-50 HP Model Year 2002 Engines



Summary of 2004 Model Year Certification Data for 25-75 hp

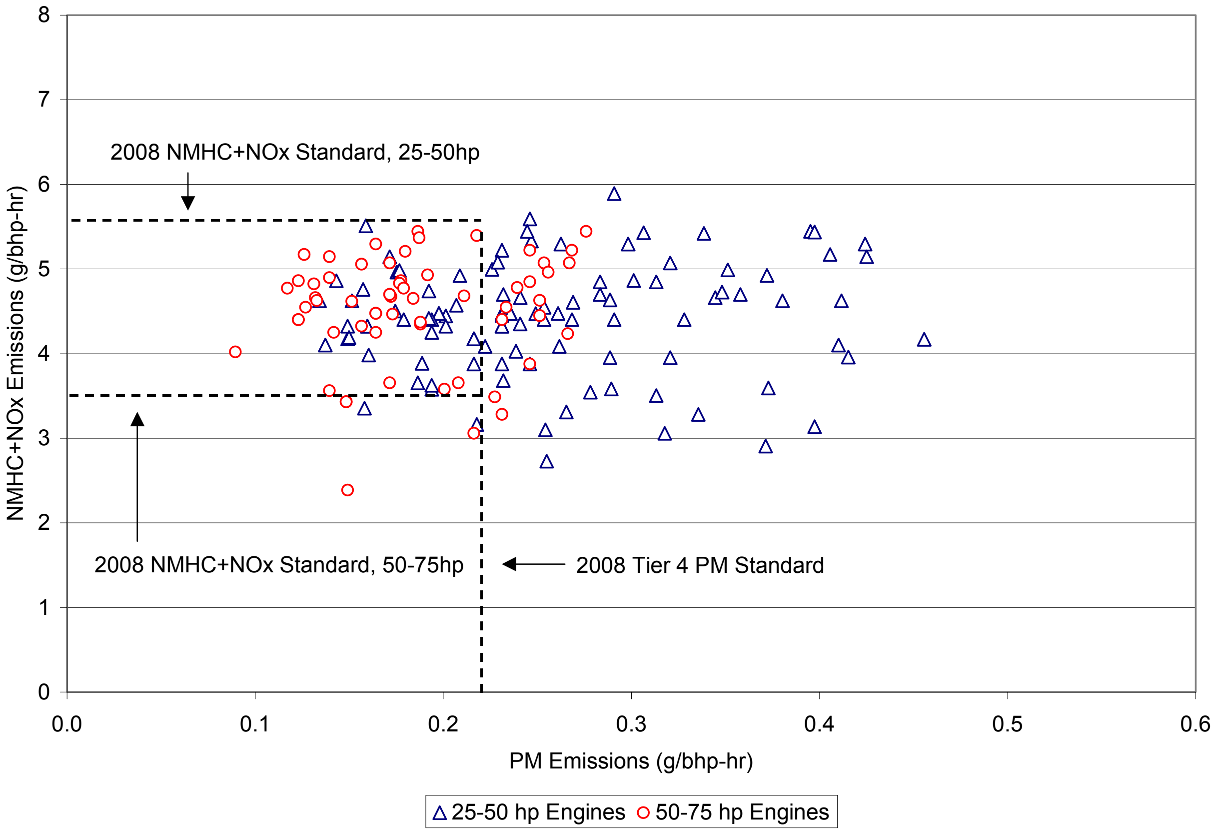
Table 4.1-19 contains a summary of the model year 2004 certification data for PM and NMHC+NOx as it relates to the 2008 Tier 4 emission standards for engines in the 25-75hp range. The data represented in Table 4.1-19 is also shown graphically in Figure 4.1-19. As can be seen, the 2004 data shows 35 percent of the engine families in the 25-50hp range already meet the 2008 0.22 g/hp-hr PM standard and a 5.6 g/hp-hr NMHC+NOx standard (which standard is unchanged from Tier 2 in 2008). In the 50-75 hp range, the data shows 7 percent of the families can meet the 2008 Tier 4 standards (0.22 g/bhp-hr PM and 3.5 g/bhp-hr NMHC+NOx). The relatively low percentage of engines in the 50-75 hp category which meet the Tier 4 standards today is largely a result of the stringency of the Tier 3 NMHC+NOx emission standards, which are required for this power category in 2008. As discussed in our Tier 3 Staff Technical Paper which reviewed the feasibility of the Tier 3 standards, we believe in-cylinder technologies such as cooled EGR will be necessary to comply with the Tier 3 emission standards (and we included the cost of such systems in our assessment of costs for the Tier 3 rule). Technologies such as cooled EGR and advanced fuel systems have been shown to be capable of reducing NOx emissions by 50 percent or more without increasing PM emissions. As can be seen by the data in Figure 4.1-19, more than 70 percent of the engines in the 50-75 hp range are below the 0.22 g/bhp-hr PM level, and a NOx reduction of 50 percent would easily bring these engines into compliance with the Tier 3 NMHC+NOx standards. Finally, when considered as a whole, nearly one-quarter of the model year 2004 engine families in the 25-75 hp range could comply with the Tier 4 2008 PM and NMHC+NOx requirements today.

Table 4.1-19
2004 Model Year Certification Data for 25-75hp Nonroad Diesel Engines

		Naturally Aspirated			Turbocharged			
Power Catergory	PM Emissions < 0.22 g/bhp-hr and 2008 NMHC+NOx standards?	DI	IDI	NA	DI	IDI	TC	Grand Total
25-50 hp, # of Engine Families	No	23	35	58	6	4	10	68
	Yes	12	17	29	2	5	7	36
	Total	35	52	87	8	9	17	104
50-75 hp, # of Engine Families	No	22	11	33	15	9	24	57
	Yes	0	4	4	0	0	0	4
	Total	22	15	37	15	9	24	61

		Naturally Aspirated			Turbocharged			
Power Catergory	PM Emissions < 0.22 g/bhp-hr and 2008 NMHC+NOx standards?	DI	IDI	NA Total	DI	IDI	TC Total	Grand Total
25-50 hp, % of Engine Families	No	66%	67%	67%	75%	44%	59%	65%
	Yes	34%	33%	33%	25%	56%	41%	35%
50-75 hp, % of Engine Families	No	100%	73%	89%	100%	100%	100%	93%
	Yes	0%	27%	11%	0%	0%	0%	72%
25-75hp, % of Engine Families	No	79%	69%	73%	91%	72%	83%	76%
	Yes	21%	31%	27%	9%	28%	17%	24%

Figure 4.1-19 Emissions Certification Data for 25-75 HP Model Year 2004 Engines



Discussion of Certification Data and 2008 Feasibility

Despite the fact that the certification data from recent model years indicates that engine-out techniques are capable of meeting the Tier 4 2008 PM standards for some engines, we are not basing the feasibility of the 2008 PM standard on engine-out techniques alone, as discussed below.

As can be seen from the 2002 model year data in Figure 4.1-18, while the engines are all certified to the same emission standard (Tier 1) with similar engine technology, the emission levels from these engines vary widely. The same can be seen for the 2004 model year data shown in Figure 4.1-19, in particular for the 25-50hp engines. Figure 4.1-18 highlights a specific example of this wide range: engines using naturally aspirated DI technology and tested on the 8-mode test cycle. Even for this subset of DI engines achieving approximately the same HC+NOx level of ~6.5 g/hp-hr, the PM rates vary from approximately 0.2 to more than 0.5 g/hp-hr. There is limited information available to indicate why for these small diesel engines with similar technology operating at approximately the same HC+NOx level the PM emission rates cover such a broad range. We are therefore not predicating the 2008 PM standard on the lowest engine-out emissions being achieved today, because it is uncertain whether or not additional engine-out improvements will lower all engines to the 2008 PM standard. Instead, we believe there are two likely means by which companies can comply with the 2008 PM standard. First, some engine manufacturers can comply with this standard using known engine-out techniques (e.g., optimizing combustion chamber designs, fuel-injection strategies). However, based on the available data as shown in Figure 4.1-18 and 4.1-19, it is unclear whether engine-out techniques will work in all cases. We therefore believe some engine companies will choose to use a combination of engine-out techniques and diesel oxidation catalysts, as discussed below.

Emission Reductions from Engine-out Techniques

For some of the engines not already meeting the 2008 Tier 4 PM standard, engine-out techniques may bring the engines into compliance with the 2008 standards. In our recent Staff Technical Paper on the feasibility of the Tier 2 and Tier 3 standards, we projected that engines greater than 50 hp will rely on some combination of technologies—including electronic fuel systems such as electronic rotary pumps or common-rail fuel systems—to comply with the Tier 3 NMHC+NOx standards.[128] In addition to enabling the Tier 3 NMHC+NOx standards, electronic fuel systems with high injection pressure and the capability to perform pilot-injection and rate-shaping, have the potential to substantially reduce PM emissions.[129] Even for mechanical fuel systems, increased injection pressures can reduce PM emissions substantially.[130] As discussed above, we are projecting that the Tier 3 engine technologies used in engines between 50 and 75 hp, such as turbocharging and electronic fuel systems, will make their way into engines in the 25-50 hp range. However, we do not believe this technology will be required to achieve the Tier 4 2008 PM standard. As demonstrated by the 2002 and 2004 certification data, engine-out techniques such as optimized combustion chamber design, fuel-injection pressure increases and fuel-injection timing can be used to achieve the 2008 Tier 4 standards for many of the engines in the 25-75 hp category without the need to add turbocharging or electronic fuel systems.

Emission Reductions from Diesel Oxidation Catalysts

For those engines not able to achieve the Tier 4 standards with known engine-out techniques, we project that these engines can meet the standards with diesel oxidation catalysts. DOCs are passive flow-through emission-control devices that are typically coated with a precious metal or a base-metal washcoat. DOCs have been proven to be durable in use on both light-duty and heavy-duty diesel applications. In addition, DOCs have already been used to control PM or carbon monoxide on some nonroad applications.[131]

Certain DOC formulations can be sensitive to diesel fuel sulfur levels, and depending on the level of emission reduction necessary, sulfur in diesel fuel can be an impediment to PM reductions. Precious-metal oxidation catalysts can oxidize the sulfur in the fuel and form particulate sulfates. However, even with current high-sulfur nonroad fuel, some manufacturers have demonstrated that a properly formulated DOC can be used in combination with other technologies to achieve the existing Tier 2 PM standards for larger engines (i.e., the 0.15 g/hp-hr standard).[132] However, given the high level of sulfur in current nonroad fuel, the use of DOCs as a PM-reduction technology is severely limited. Data presented by one engine manufacturer regarding the existing Tier 2 PM standard show that, while a DOC can be used to meet the current standard even when tested on 2,000 ppm sulfur fuel, lowering the fuel sulfur level to 380 ppm enabled the DOC to reduce PM by 50 percent from the 2,000 ppm sulfur fuel.[133] Without the availability of 500 ppm sulfur fuel in 2008, DOCs would be of limited use for nonroad engine manufacturers and would not provide the emission-control necessary for most manufacturers to meet the Tier 4 standards. With the availability of 500 ppm sulfur fuel, DOCs can be designed to provide PM reductions on the order of 20 to 50%, while suppressing particulate sulfate reduction.[134] These levels of reductions have been seen on transient duty cycles as well as highway and nonroad steady-state duty cycles. As discussed above, 24 engine families in the 25-50 hp range are within 30 percent of the 2008 PM standard and are at or below the 2008 NMHC+NOx standard for this power range, indicating that use of DOCs should achieve the incremental improvement necessary to meet the 2008 PM standard. However, we also do not believe that an emission level lower than 0.22 g/bhp-hr will be generally feasible in 2008 due to the diesel fuel sulfur level of 500 ppm and consequent potential for sulfate PM formation.

4.1.4.3.2 2013 Standards

For engines in the 25-50 range, we are adopting standards starting in 2013 of 3.5 g/hp-hr for NMHC+NOx and 0.02 g/hp-hr for PM. Additionally, compliance with the existing CO emission standards will need to be demonstrated over new test cycles including the NRTC with cold-start, and NTE. For the 50-75 hp engines, we are adopting a 0.02 g/hp-hr PM standard that will be implemented in 2013, and for those manufacturers who choose to pull-ahead the standard one-year, 2012 (manufacturers who choose to pull-ahead the 2013 standard for engine in the 50-75 range do not need to comply with the transitional 2008 PM standard).

4.1.4.3.2.1 PM Standard

Sections 4.1.1 through 4.1.3 have already discussed catalyzed diesel particulate filters, including explanations of how CDPFs reduce PM emissions, and how to apply CDPFs to nonroad engines. We concluded there that CDPFs can be used to achieve the Tier 4 PM standard for engines ≥75 hp. Specifically we discussed the ability of ceramic based filter technologies to meet the 0.01 g/bhp-hr standard for engines from 75-750 hp and the ability of alternate depth filter technologies to meet a slightly less stringent standard of 0.02 g/bhp-hr standard (0.03 for mobile machines) for engines > 750 hp. As also discussed in Section 4.1.3, PM filters may require active back-up regeneration systems for many nonroad applications. Secondary technologies will likely be needed in addition to enable proper regeneration, possibly including electronic fuel systems such as common rail, which makes possible multiple post-injections for raising exhaust gas temperatures to aid in filter regeneration.

Particulate filter technology, with the requisite trap regeneration technology, can also be applied to engines in the 25 to 75 hp range. The fundamentals of how a filter is able to reduce PM emissions, as described in Section 4.1.1, are not a function of engine power, and CDPFs are just as effective at capturing soot emissions and oxidizing SOF on smaller engines as on larger engines. As discussed in more detail below, particulate sulfate generation rates are slightly higher for the smaller engines; however, we have addressed this issue in the final rule. The PM filter regeneration systems described in Sections 4.1.1 and 4.1.3 are also applicable to engines in this size range and are therefore likewise feasible. Engine manufacturers may prefer some specific trap-regeneration technologies over others in the 25-75 hp category. Specifically, an electronically controlled secondary fuel-injection system (i.e., a system that injects fuel into the exhaust upstream of a PM filter). Such a system has been commercially used successfully by at least one nonroad engine manufacturer, and other systems have been tested by technology companies.[135]

We are, however, adopting a slightly higher PM standard (0.02 g/hp-hr rather than 0.01) for these engines. As discussed in Section 4.1.1, with the use of a CDPF, the PM emissions emitted by the filter are primarily derived from the fuel sulfur. The smaller power category engines tend to have higher fuel consumption than larger engines. This occurs for a number of reasons. First, the lower power categories include a high fraction of IDI engines, which by their nature consume approximately 15 percent more fuel than a DI engine. Second, as engine displacements get smaller, the engine's combustion chamber surface-to-volume ratio increases. This leads to higher heat-transfer losses and therefor lower efficiency and higher fuel consumption. In addition, frictional losses are a higher percentage of total power for the smaller displacement engines, which also contributes to higher fuel consumption. Because of the higher fuel consumption rate, we expect a higher particulate sulfate level, and are therefore adopting a 0.02 g/hp-hr standard.

Test data confirm that this standard, as well as the NTE of 1.5 times the standard, is achievable. In 2001, EPA completed a test program on two small nonroad diesel engines (a 25 hp IDI engine and a 50 hp IDI engine) that demonstrated the 0.02 g/hp-hr standard can be achieved with the use of a CDPF.[136] This test program included testing on the existing 8-mode steady-state duty cycle as well as the new nonroad transient cycle. The 0.02g/hp-hr level was achieved on each engine over both test cycles. In addition, the 0.02 g/hp-hr level was achieved on a variety of nonroad test cycles that are intended to represent several specific applications, such as skid-steer loaders, arc-welders, and agricultural tractors. We believe these data indicate the robust emission-reduction capability of particulate filters and demonstrate that the NTE standard of 1.5 × 0.02 g/hp-hr standard (0.03 g/hp-hr) can be achieved under the NTE test requirements, because the data was generated over a number of test cycles which are intended to represent real in-use operation, such as we would expect the NTE to represent. This test program also demonstrates why we have adopted a slightly higher PM standard for the 25 - 75 hp category (0.02 g/hp-hr vs. 0.01). The data from the test program described above showed fuel consumption rates over the 8-mode test procedure between 0.4 and 0.5 lbs/bhp-hr, while typical values for a modern turbocharged DI engine with 4-valves per cylinder in the ≥75 hp categories are on the order of 0.3 to 0.35 lbs/hp-hr.

The CDPF technology applied to meet the PM standard will also serve to ensure compliance with the existing CO emission standards over the new test procedures. CDPFs can reduce CO emissions by more than 80 percent, a level of control that will more than offset any increase in CO emission due to the new test cycles.

4.1.4.3.2.2 NMHC+NOx Standard

We are adopting a 3.5 g/hp-hr NMHC+NOx standard for engines in the 25 - 50 hp range starting in 2013. This will align the NMHC+NOx standard for engines in this power range with the Tier 3 standard for engines in the 50 - 75 hp range, which starts in 2008. EPA's recent Staff Technical paper, which reviewed the technological feasibility of the Tier 3 standards, contains a detailed discussion of a variety of technologies capable of achieving a 3.5 g/hp-hr standard. These include cooled EGR, uncooled EGR, as well as advanced in-cylinder technologies relying on electronic fuel systems and turbocharging.[137] These technologies are capable of reducing NOx emission by more than 50 percent including when measured over transient test cycles including cold-start.[138] Given the Tier 2 NMHC+NOx standard of 5.6 g/hp-hr, a 50 percent reduction will allow a Tier 2 engine to comply with the 3.5 g/hp-hr NMHC+NOx standard. In addition, because this NMHC+NOx standard is concurrent with the 0.02 g/hp-hr PM standards, which we project will be achievable with particulate filters, engine designers will have significant additional flexibility in reducing NOx because the PM filter will eliminate the traditional concerns with the engine-out NOx vs. PM trade-off. Further, the CDPF technology will substantially reduce NMHC emissions (by more than 80 percent) providing additional control effective to help meet the NOx+NMHC emission standards.

4.1.5 Are the Standards for Engines <25 hp Feasible?

As discussed in Section III of the preamble, there is a new PM standard of 0.30 g/hp-hr for engines less than 25 hp beginning in 2008. As discussed below, the NMHC+NOx and CO levels for this power category is unchanged from Tier 2 levels although compliance will need to be demonstrated over additional test cycles beginning in 2013. This section describes (1) what makes the <25 hp category unique, (2) which engine technologies are currently used in the <25 hp category, and (3) data showing that the new emission standards are technologically feasible.

4.1.5.1 What makes the < 25 hp category unique?

Nonroad engines less than 25 hp are the least sophisticated nonroad diesel engines from a technological perspective. All of the engines currently sold in this power category lack electronic fuel systems and turbochargers (see Table 4.1-17). Nearly 20 percent of the products have two-cylinders or less, and 14 percent of the engines sold in this category are single-cylinder products, several of these have no batteries and are crank-start machines, much like a simple walk-behind lawnmower. In addition, given the available data and taking into account the Tier 2 standards that have not yet been implemented, we are not projecting any significant penetration of advanced engine technology, such as electronically controlled fuel systems, into this category in the next five to ten years.

4.1.5.2 What engine technology is currently used in the <25 hp category?

In the 1998 nonroad diesel rulemaking we established Tier 1 and Tier 2 standards for these products. Tier 1 was implemented in model year 2000, and Tier 2 will be implemented in model year 2005. As discussed in EPA's recent Staff Technical Paper, we project the Tier 2 standards will be met by basic engine-out emission-optimization strategies.[139] We are not predicting that Tier 2 will require electronic fuel systems, EGR, or turbocharging. As discussed in Section 4.1.5.3 of this RIA and in the Staff Technical Paper, a large number of engines in this power category already meet the Tier 2 standards by a wide margin.[140]

Two basic types of engine fuel-injection technologies are currently present in the less than 25 hp category, mechanical indirect injection (IDI) and mechanical direct injection (DI). The IDI system injects fuel into a pre-chamber rather than directly into the combustion chamber as in the DI system. This difference in fuel systems results in substantially different emission characteristics, as well as several important operating parameters. In general, as noted earlier, the IDI engine has lower engine-out PM and NOx emissions, while the DI engine has better fuel efficiency and lower heat rejection.

4.1.5.3 What data support the feasibility of the new standards?

We project that the Tier 4 PM standard can be met by 2008 based on:
—the existence of a large number of engine families already meeting the standards,
—the use of engine-out reduction techniques and
—the use of diesel oxidation catalysts.

We have examined model year 2002 and 2004 engine certification data for nonroad diesel engines less than 25 hp category.[141] Tier 2 does not begin for these engines until model year 2005, and thus all of the data we examined are certified to the Tier 1 emission standards. As described below, there is little difference between these data sets, and it is likely that many of the 2004 model year engine families are carry overs from the model year 2002.

<u>Summary of 2002 Model Year Certification Data for Engines <25 hp</u>

A summary of the model year 2002 certification data for engines <25hp is presented in Table 4.1-20. The data is also shown in graphical form in Figure 4.1-20. These data indicate that some engine families already meet the Tier 4 PM standard (and the 2008 NMHC+NOx standard, unchanged from Tier 2). The current data indicate that approximately 28% of the engine families are already at or below the Tier 4 PM standard, while meeting the 2008 NMHC+NOx standard. These data reflect a range of certification test cycles, and include both IDI and DI engines.[S] Many of the engine families are certified well below the Tier 4 standard while meeting the 2008 NMHC+NOx level. Specifically, 15 percent of the engine families are more than 20 percent below the Tier 4 PM standard. An additional 15 percent of the engine families already meeting 2008 NMHC+NOx standards will require no more than a 30 percent PM reduction to meet the 2008 PM standards. The public certification data indicate that these engines do not use turbocharging, electronic fuel systems, exhaust gas recirculation, or aftertreatment technologies.

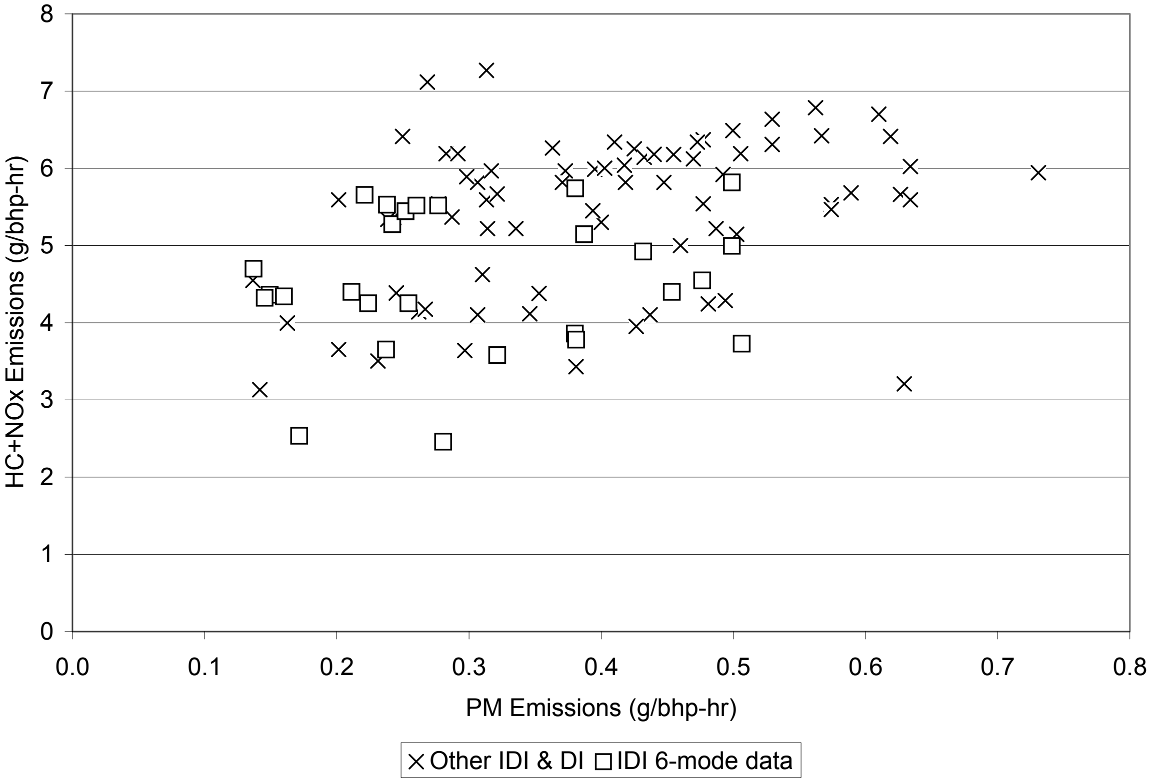
[S] The Tier 1 and Tier 2 standards for this power category must be demonstrated on one of a variety of different engine test cycles. The appropriate test cycle is selected by the engine manufacturer based on the intended in-use applications(s) of the engine.

Table 4.1-20
2002 Model Year Certification Data for <25 hp Nonroad Diesel Engines

PM Emissions Relative to the 0.30 g/hp-hr Standard	IDI Engines			DI Engines			Totals
	5-mode	6-mode	8-mode	5-mode	6-mode	8-mode	
0-5% below T4[a]	1	0	1	0	0	0	2
5-20% below T4[a]	4	6	1	0	0	0	11
>20% below T4[a]	1	9	5	0	1	0	16
require ≤30% PM reduction to meet T4[a]	5	4	4	0	2	0	15
requires >30%PM reduction and/or > 2008 NMHC+NOx std.	7	8	4	18	18	3	58
Total # of Engine Families	18	27	15	18	21	3	102

[a] Engine also meets the 2008 NMHC+NOx standard.

Figure 4.1-20 Emission Certification Data for <25 HP Model Year 2002 Engines



Summary of 2004 Model Year Certification Data for 25-50 hp

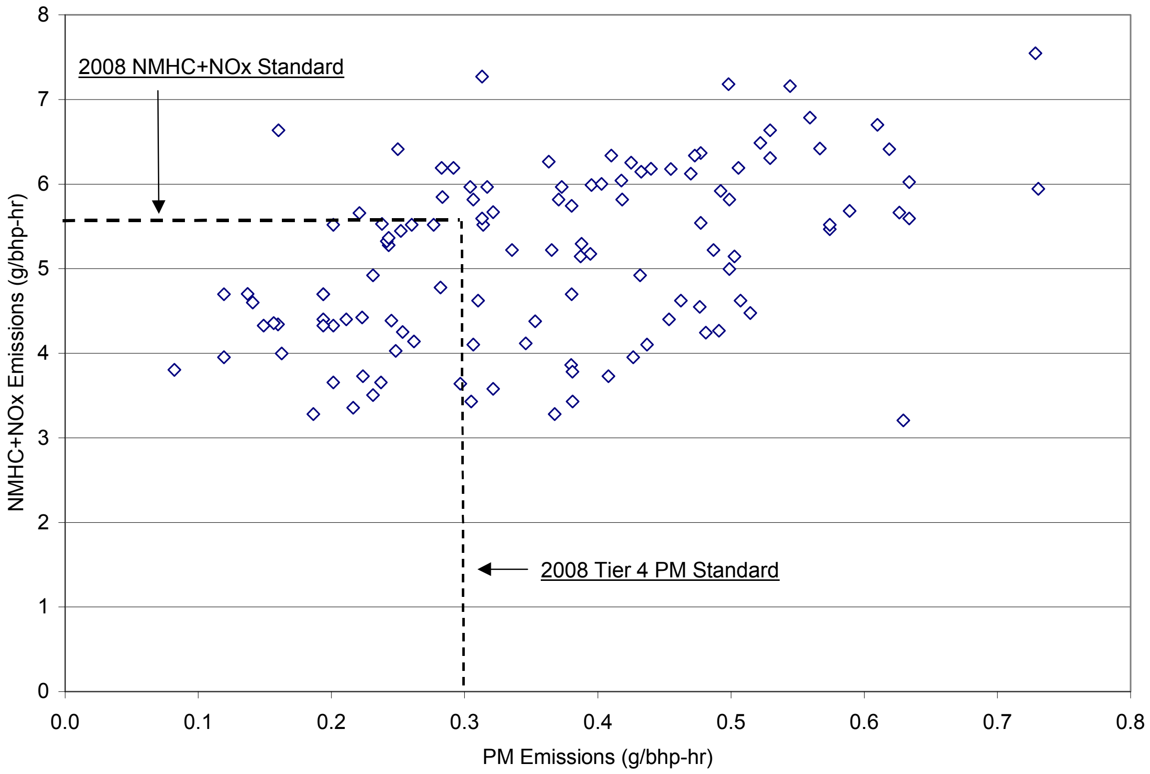
The certification data for model year 2004 engines is summarized in Table 4.1.-21. In general, this data is similar to the 2002 data shown in Table 4.1-20. The data shows that 31% of the certified engines are below the 2008 Tier 4 standards, as compared to 28% in the 2002 data. However, one of the differences is a higher number of 2004 direct-injection engines are below the Tier 4 levels in 2004 (5 out of 48) as compared to 2002 (1 out of 42). This data is also shown in Figure 4.1-21.

Table 4.1-21
2004 Model Year Certification Data for <25hp Nonroad Diesel Engines

	PM Emissions Below 0.30 g/bhp-hr?	Direct Injection Fuel System	Indirect Injection Fuel System	Totals
Engine Family Count	No	43	38	81
	Yes[a]	5	32	37
	Total	48	70	118
% of Engine Families	No	90%	54%	69%
	Yes[a]	10%	46%	31%

[a] Engine also meets the 2008 NMHC+NOx standard.

Figure 4.1-21 Emissions Certification Data for <25 HP Model Year 2004 Engines



Discussion of Certification Data and 2008 Feasibility

These model year 2002 and 2004 engines use well known engine-out emission-control technologies, such as combustion chamber design and fuel-injection timing control strategies, to comply with the existing standards (Tier 1 in both cases). As with 25-75 hp engines, these data have a two-fold significance. First, they indicate that some engines in this power category can already achieve the 2008 PM standard using only engine-out technology, and that other engines should be able to achieve the standard making improvements just to engine-out performance. However, the data does not indicate that all engines could comply with the 2008 PM standard using engine-out techniques alone. Despite being certified to the same emission standards with similar engine technology, the emission levels from these engines vary widely. As can be seen in the Figure 4.1-20, the emission levels cover a wide range. Figure 4.1-20 highlights a specific example of this wide range: engines using naturally aspirated IDI technology and tested on the 6-mode test cycle. Even for this subset of IDI engines achieving approximately the same HC+NOx level of~4.5 g/hp-hr, the PM rates vary from approximately 0.15 to 0.5 g/hp-hr. There is limited information available to indicate why for these small diesel engines with similar technology operating at approximately the same HC+NOx level the PM emission rates cover such a broad range. The model year 2004 data in Figure 4.1-21 shows a similarly large spread in PM emissions. We are therefore not predicating the 2008 PM standard on the combination of diesel oxidation catalysts and the lowest engine-out emissions in the final rule, because it is uncertain whether or not additional engine-out improvements would lower all engines to the 2008 PM standard. Instead, we believe there are two likely means by which companies can comply with the 2008 PM standard. First, some engine manufacturers can comply with this standard using known engine-out techniques (e.g., optimizing combustion chamber designs, fuel-injection strategies). However, based on the available data, it is unclear whether engine-out techniques will work in all cases. We therefore believe some engine companies will choose to use a combination of engine-out techniques and diesel oxidation catalysts, as discussed below.

Emission Reductions from Engine-out Techniques

PM emissions can be reduced through in-cylinder techniques for small nonroad diesel engines using similar techniques as used in larger nonroad and highway engines. As discussed in Section 4.1.1 there several technologies that can influence oxygen content and in-cylinder mixing (and thus lower PM emissions) including improved fuel-injection systems and combustion system designs. For example, increased injection pressure can reduce PM emissions substantially.[142] The wide-range of emission characteristics present in the existing engine certification data likely result from differences in fuel systems and combustion chamber designs. For many of the engines with higher emission levels, further optimization of the fuel system and combustion chamber can provide additional PM reductions.

Emission Reductions from Diesel Oxidation Catalysts

Diesel oxidation catalysts (DOCs) also offer the opportunity to reduce PM emissions from the engines in this power category. As explained earlier, DOCs are passive flow-through emission-control devices that are typically coated with a precious metal or a base-metal wash-coat. DOCs have been proven to be durable in-use on both light-duty and heavy-duty diesel applications. In addition, DOCs have already been used to control either PM or in some cases carbon monoxide on some nonroad applications.[143] However, as discussed in Section 4.1.1, certain DOC formulations can be sensitive to diesel fuel sulfur level. Specifically, precious-metal oxidation catalysts (which have the greatest potential for reducing PM) can oxidize the sulfur in the fuel and form particulate sulfates. Given the high level of sulfur in current nonroad fuel, the use of DOCs as a PM reduction technology is severely limited. Data presented by one engine manufacturer regarding the existing Tier 2 PM standard show that while a DOC can be used to meet the current standard when tested on 2,000 ppm sulfur fuel, lowering the fuel sulfur level to 380 ppm enabled the DOC to reduce PM by 50 percent from the 2,000 ppm sulfur fuel.[144] Without the availability of 500 ppm sulfur fuel in 2008, DOCs would be of limited use for nonroad engine manufacturers and would not provide the emission-control necessary for most engine manufacturers to meet the Tier 4 standards. With the availability of 500 ppm sulfur fuel, DOCs can be designed to provide PM reductions on the order of 20 to 50%, while suppressing particulate sulfate reduction.[145] These levels of reductions have been seen on transient duty cycles as well as on highway and nonroad steady-state duty cycles.

DOCs are also effective to control HC and CO emissions. The application of DOC as a means to comply with the PM standard in 2008 will also provide an effective means to meet the existing standards for NOx+NMHC and CO over the new test cycles in 2013. The increase in NOx emissions over transient test conditions with typical in-cylinder controls are very small as indicated by the transient adjustment factors estimated in the NONROAD model. HC emissions may increase during transient testing conditions, however the ability of a DOC to reduce HC emissions in excess of 80 percent would more than offset any increase in NOx+NMHC emissions observed over the new test cycles. Similarly for CO, the additional CO control allowed by the use of the DOC will more than offset any increase in CO emissions as measured over the new test cycles. For purposes of our cost analysis contained in Chapter 6, we have assumed that all engines certifying to the 2008 interim PM standards will use DOCs for compliance.

4.1.6 Meeting the Crankcase Emission Requirements

The most common way to eliminate crankcase emissions has been to vent the blow-by gases into the engine air intake system, so the gases can be recombusted. Prior to the HD2007 rulemaking, we have required that crankcase emissions be controlled only on naturally aspirated diesel engines. We had made an exception for turbocharged diesel engines (both highway and nonroad) because of concerns in the past about fouling that could occur by routing the diesel particulates (including engine oil) into the turbocharger and aftercooler. However, this is an environmentally significant exception since most nonroad equipment over 75hp use turbocharged engines, and a single engine can emit over 100 pounds of NOx, NMHC, and PM from the crankcase over its lifetime.

Given the available means to control crankcase emissions, we are eliminating this exception for nonroad diesel engines, as we did for highway engines in 2007. We anticipate that the diesel engine manufacturers will be able to control crankcase emissions through the use of closed crankcase filtration systems or by routing unfiltered blow-by gases directly into the exhaust system upstream of the emission-control equipment. However, the crankcase provision has been written such that if adequate control can be had without “closing” the crankcase, then the crankcase vent to the atmosphere. Manufacturers show that they meet this requirement by adding the emissions from the crankcase ventilation system to the emissions from the engine’s exhaust system, either by measuring them separately and adding together mathematically or by routing crankcase emissions into the exhaust stream before sampling for emission measurement.

We expect that manufacturers will have to utilize closed crankcase approaches, as described here to meet the stringent tailpipe emission standards in this final rule. Closed crankcase filtration systems work by separating oil and particulate matter from the blow-by gases through single or dual stage filtration approaches, routing the blow-by gases into the engine’s intake manifold and returning the filtered oil to the oil sump. Oil separation efficiencies in excess of 90 percent have been demonstrated with production ready prototypes of two stage filtration systems.[146] By eliminating 90 percent of the oil that would otherwise be vented to the atmosphere, the system works to reduce oil consumption and to eliminate concerns over fouling of the intake system when the gases are routed through the turbocharger. Hatz, a nonroad engine manufacturer, currently has closed crankcase systems on many of its turbocharged engines.

4.1.7 Why Do We Need 15 ppm Sulfur Diesel Fuel?

As stated earlier, we strongly believe that fuel sulfur control is critical to ensuring the success of NOx and PM aftertreatment technologies. To evaluate the effect of sulfur on diesel exhaust control technologies, we used three key factors for categorizing the impact of sulfur in fuel on emission-control function. These factors were efficiency, reliability, and fuel economy. Taken together, these three factors support the position that the Tier 4 standards are feasible only with diesel fuel sulfur levels of 15 ppm or lower. Brief summaries of these factors are provided below.

The **efficiency** of emission-control technologies to reduce harmful pollutants is directly affected by sulfur in diesel fuel. Initial and long-term conversion efficiencies for NOx, NMHC, CO and diesel PM emissions are significantly reduced by catalyst poisoning and catalyst inhibition due to sulfur. NOx conversion efficiencies with the NOx adsorber technology in particular are dramatically reduced in a very short time due to sulfur poisoning of the NOx storage bed. In addition, total PM control efficiency is negatively impacted by the formation of sulfate PM. As explained in the following sections, the CDPF, NOx adsorber, and urea SCR catalyst technologies described here have the potential to make significant amounts of sulfate PM under operating conditions typical of many nonroad engines. We believe that the formation of sulfate PM will be in excess of the total PM standard, unless diesel fuel sulfur levels are at or below 15 ppm. Based on the strong negative impact of sulfur on emission-control efficiencies for all of the technologies evaluated, we believe that 15 ppm represents an upper threshold of acceptable diesel fuel sulfur levels.

Reliability refers to the expectation that emission-control technologies must continue to function as required under all operating conditions for the life of the engine. As discussed in the following sections, sulfur in diesel fuel can prevent proper operation of both NOx and PM control technologies. This can lead to permanent loss in emission-control effectiveness and even catastrophic failure of the systems. Sulfur in diesel fuel impacts reliability by decreasing catalyst efficiency (poisoning of the catalyst), increasing diesel particulate filter loading, and negatively impacting system regeneration functions. Among the most serious reliability concerns with sulfur levels greater than 15 ppm are those associated with failure to properly regenerate. In the case of the NOx adsorber, failure to regenerate the stored sulfur (desulfate) will lead to rapid loss of NOx emission control as a result of sulfur poisoning of the NOx adsorber bed. In the case of the diesel particulate filter, sulfur in the fuel reduces the reliability of the regeneration function. If regeneration does not occur, catastrophic failure of the filter could occur. It is only by the availability of low-sulfur diesel fuels that these technologies become feasible.

Fuel economy impacts due to sulfur in diesel fuel affect both NOx and PM control technologies. The NOx adsorber sulfur regeneration cycle (desulfation cycle) can consume significant amounts of fuel unless fuel sulfur levels are very low. The larger the amount of sulfur in diesel fuel, the greater the adverse effect on fuel economy. As sulfur levels increase above 15 ppm, the adverse effect on fuel economy becomes more significant, increasing above one percent and doubling with each doubling of fuel sulfur level. Likewise, PM trap regeneration is inhibited by sulfur in diesel fuel. This leads to increased PM loading in the diesel particulate filter and increased work to pump exhaust across this restriction. With low-sulfur diesel fuel, diesel particulate filter regeneration can be optimized to give a lower (on average) exhaust backpressure and thus better fuel economy. As a result, for both NOx and PM technologies, reducing the fuel sulfur level decreases the operating costs of the vehicle.

4.1.7.1 Catalyzed Diesel Particulate Filters and the Need for Low-Sulfur Fuel

CDPFs function to control diesel PM through mechanical filtration of the solid PM (soot) from the diesel exhaust stream and then oxidation of the stored soot (trap regeneration) and oxidation of the SOF. Through oxidation in the catalyzed diesel particulate filter the stored PM is converted to CO_2 and released into the atmosphere. Failure to oxidize the stored PM leads to accumulation in the trap, eventually causing the trap to become so full that it severely restricts exhaust flow through the device, leading to trap or vehicle failure.

Uncatalyzed diesel particulate filters require exhaust temperatures in excess of 650°C in order for the collected PM to be oxidized by the oxygen available in diesel exhaust. That temperature threshold for oxidation of PM by exhaust oxygen can be decreased to 450°C through the use of base metal catalytic technologies. For a broad range of operating conditions typical of in-use diesel engine operation, diesel exhaust can be significantly cooler than 400°C. If oxidation of the trapped PM would occur only at exhaust temperatures lower than 300°C, then diesel particulate filters would be more robust for most applications and operating regimes. Oxidation of PM (regeneration of the trap) at such low exhaust temperatures can occur by using oxidants that are more readily reduced than oxygen. One such oxidant is NO_2.

NO_2 can be produced in diesel exhaust through the oxidation of the nitrogen monoxide (NO), created in the engine combustion process, across a catalyst. The resulting NO_2-rich exhaust is highly oxidizing in nature and can oxidize trapped diesel PM at temperatures as cool as 250°C.[147] Some platinum group metals are known to be good catalysts to promote the oxidation of NO to NO_2. To promote more effective passive regeneration of the diesel particulate filters, significant amounts of platinum group metals (primarily platinum) are therefore being used in the wash-coat formulations of advanced CDPFs. The use of platinum to promote the oxidation of NO to NO_2 introduces several system vulnerabilities affecting both the durability and the effectiveness of the CDPF when sulfur is present in diesel exhaust. (In essence, diesel engine exhaust temperatures are in a range necessitating use of precious-metal catalysts to adequately regenerate the PM filter, but precious-metal catalysts are in turn highly sensitive to sulfur in diesel fuel.) The two primary mechanisms by which sulfur in diesel fuel limits the robustness and effectiveness of CDPFs are inhibition of trap regeneration, through inhibition of the oxidation of NO to NO_2, and a dramatic loss in total PM control effectiveness due to the formation of sulfate PM. Unfortunately, these two mechanisms trade-off against one another in the design of CDPFs. Changes to improve the reliability of regeneration by increasing catalyst loadings lead to increased sulfate emissions and, thus, loss of PM control effectiveness. Conversely, changes to improve PM control by reducing the use of platinum group metals and, therefore, limiting "sulfate make" leads to less reliable regeneration. We believe the best means of achieving good PM emission control and reliable operation is to reduce sulfur in diesel fuel, as shown in the following subsections.

4.1.7.1.1 Inhibition of Trap Regeneration Due to Sulfur

The CDPF technology relies on the generation of a very strong oxidant, NO_2, to ensure that the carbon captured by the PM trap's filtering media is oxidized under the exhaust temperature range of normal operating conditions. This prevents plugging and failure of the PM trap. NO_2 is produced through the oxidation of NO in the exhaust across a platinum catalyst. This oxidation is inhibited by sulfur poisoning of the catalyst surface.[148] This inhibition limits the total amount of NO_2 available for oxidation of the trapped diesel PM, thereby raising the minimum exhaust temperature required to ensure trap regeneration. Without sufficient NO_2, the amount of PM trapped in the diesel particulate filter will continue to increase and can lead to excessive exhaust back pressure and low engine power.

The failure mechanisms experienced by diesel particulate filters due to low NO_2 availability vary significantly in severity and long-term consequences. In the most fundamental sense, the failure is defined as an inability to oxidize the stored particulate at a rate fast enough to prevent net particulate accumulation over time. The excessive accumulation of PM over time blocks the passages through the filtering media, making it more restrictive to exhaust flow. To continue to force the exhaust through the now more restrictive filter, the exhaust pressure upstream of the filter must increase. This increase in exhaust pressure is commonly referred to as increasing "exhaust backpressure" on the engine.

The increase in exhaust backpressure represents increased work being done by the engine to force the exhaust gas through the increasingly restrictive particulate filter. Unless the filter is frequently cleansed of the trapped PM, this increased work can lead to reductions in engine performance and increases in fuel consumption. This loss in performance may be noted by the equipment operator in terms of sluggish engine response.

Full field test evaluations and retrofit applications of these catalytic trap technologies are occurring in parts of the United States and Europe where low-sulfur diesel fuel is already available.[T] The experience gained in these field tests helps to clarify the need for low-sulfur diesel fuel. In Sweden and some European city centers where 10 ppm diesel fuel sulfur is readily available, more than 3,000 catalyzed diesel particulate filters have been introduced into retrofit applications without a single failure. Given the large number of vehicles participating in these test programs, the diversity of the vehicle applications, and the extended time periods of operation, there is a strong indication of the robustness of this technology on 10 ppm low-sulfur diesel fuel.[149] Vehicle applications included intercity trains, airport buses, mail trucks, city buses and garbage trucks. Some vehicles have been operating with traps for more than 5 years and in excess of 300,000 miles. The field experience in areas where sulfur is capped at 50 ppm has been less definitive. In regions without extended periods of cold ambient conditions, such as the United Kingdom, field tests on 50 ppm cap low-sulfur fuel have also been positive, matching the durability at 10 ppm, though sulfate PM emissions are much higher. However, field tests on 50 ppm fuel in Finland, where colder winter conditions are sometimes encountered (similar to many parts of the United States), showed a significant number of failures (~10 percent) due to trap plugging. This 10 percent failure rate has been attributed to insufficient trap regeneration due to fuel sulfur in combination with low ambient temperatures.[150] Other possible reasons for the high failure rate in Finland when contrasted with the Swedish experience appear to be unlikely. The Finnish and Swedish fleets were substantially similar, with both fleets consisting of transit buses powered by Volvo and Scania engines in the 10 to 11 liter range. Further, the buses were operated in city areas and none of the vehicles were operated in northern extremes such as north of the Arctic Circle.[151] Given that the fleets in Sweden and Finland were substantially similar,

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[T] Through tax incentives 50 ppm cap sulfur fuel is widely available in the United Kingdom and 10 ppm sulfur fuel is available in Sweden and in certain European city centers.

and given that ambient conditions in Sweden are expected to be similar to those in Finland, we believe that the increased failure rates noted here are due to the higher fuel sulfur level in a 50 ppm cap fuel versus a 10 ppm cap fuel.[U]

Testing on an even higher fuel sulfur level of 200 ppm was conducted in Denmark on a fleet of 9 vehicles. In less than six months all of the vehicles in the Danish fleet had failed due to trap plugging.[152] The failure of some fraction of the traps to regenerate when operated on fuel with sulfur caps of 50 ppm and 200 ppm is believed to be primarily due to inhibition of the NO to NO_2 conversion, as described here. Similarly the increasing frequency of failure with higher fuel sulfur levels is believed to be due to the further suppression of NO_2 formation when higher sulfur level diesel fuel is used. Since this loss in regeneration effectiveness is due to sulfur poisoning of the catalyst this real-world experience is expected to apply equally well to nonroad engines (i.e., operation on lower-sulfur diesel fuel, 15 ppm versus 50 ppm, will increase regeneration robustness).

As shown above, sulfur in diesel fuel inhibits NO oxidation leading to increased exhaust backpressure and reduced fuel economy. We therefore believe that sulfur levels in nonroad diesel fuel must be at or below 15 ppm to ensure reliable and economical operation over the wide range of expected operating conditions.

4.1.7.1.2 Loss of PM Control Effectiveness

In addition to inhibiting the oxidation of NO to NO_2, the sulfur dioxide (SO_2) in the exhaust stream is itself oxidized to sulfur trioxide (SO_3) at very high conversion efficiencies by the precious metals in the catalyzed particulate filters. The SO_3 serves as a precursor to the formation of hydrated sulfuric acid (H_2SO_4+H_2O), or sulfate PM, as the exhaust leaves the vehicle tailpipe. Virtually all of the SO_3 is converted to sulfate under dilute exhaust conditions in the atmosphere as well in the dilution tunnel used in heavy-duty engine testing. Since virtually all sulfur present in diesel fuel is converted to SO_2, the precursor to SO_3, as part of the combustion process, the total sulfate PM is directly proportional to the amount of sulfur present in diesel fuel. Therefore, even though diesel particulate filters are very effective at trapping the carbon and the SOF portions of the total PM, the overall PM reduction efficiency of catalyzed diesel particulate filters drops off rapidly with increasing sulfur levels due to the formation of sulfate PM downstream of the CDPF.

SO_2 oxidation is promoted across a catalyst in a manner very similar to the oxidation of NO, except it is converted at higher rates, with peak conversion rates in excess of 50 percent. The SO_2 oxidation rate for a platinum-based oxidation catalyst typical of the type that might be used

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[U] The average temperature in Helsinki, Finland, for the month of January is 21°F. The average temperature in Stockholm, Sweden, for the month of January is 26°F. The average temperature at the University of Michigan in Ann Arbor, Michigan, for the month of January is 24°F. The temperatures reported here are from www.worldclimate.com based upon the Global Historical Climatology Network (GHCN) produced jointly by the National Climatic Data Center and Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory (ORNL).

in conjunction with, or as a washcoat on, a CDPF can vary significantly with exhaust temperature. At the low temperatures the oxidation rate is relatively low, perhaps no higher than ten percent. However at the higher temperatures that might be more typical of agricultural tractor use pulling a plow and the highway Supplemental Emission Test (also called the EURO 4 or 13 mode test), the oxidation rate may increase to 50 percent or more. These high levels of sulfate make across the catalyst are in contrast to the very low SO_2 oxidation rate typical of diesel exhaust (typically less than 2 percent). This variation in expected diesel exhaust temperatures means that there will be a corresponding range of sulfate production expected across a CDPF.

The U.S. Department of Energy in cooperation with industry conducted a study entitled DECSE to provide insight into the relationship between advanced emission-control technologies and diesel fuel sulfur levels. Interim report number four of this program gives the total particulate matter emissions from a heavy-duty diesel engine operated with a diesel particulate filter on several different fuel sulfur levels. A straight line fit through this data is presented in Table 4.1-19 showing the expected total direct PM emissions from a diesel engine on the supplemental emission test cycle.[V] The SET test cycle, a 13 mode steady-state cycle that these data were developed on, is similar to the C1 eight mode steady-state nonroad test cycle. Both cycles include operation at full and intermediate load points at approximately rated-speed conditions and torque peak-speed conditions. As a result, the sulfate make rate for the C1 cycle and the SET cycle are expected to be similar. The data can be used to estimate the PM emissions from diesel engines operated on fuels with average fuel sulfur levels in this range.

Table 4.1-19
Estimated PM Emissions from a Diesel Engine at the Indicated Fuel Sulfur Levels

Fuel Sulfur [ppm]	Steady-State Emission-Control Performance[a]	
	Tailpipe PM[b] [g/hp-hr]	PM Increase Relative to 3 ppm Sulfur
3	0.003	--
7[a]	0.006	100%
15[a]	0.009	200%
30	0.017	470%
150	0.071	2300%

[a] The PM emissions at these sulfur levels are based on a straight-line fit to the DECSE data; PM emissions at other sulfur levels are actual DECSE data. (Diesel Emission Control Sulfur Effects (DECSE) Program - Phase II Interim Data Report No. 4, Diesel Particulate Filters-Final Report, January 2000. Table C1.) Although DECSE tested diesel particulate filters at these fuel sulfur levels, they do not conclude that the technology is feasible at all levels, but they do note that testing at 150 ppm is a moot point as the emission levels exceed the engine's baseline emission level.

[b] Total exhaust PM (soot, SOF, sulfate).

[V] Note that direct emissions are those pollutants emitted directly from the engine or from the tailpipe depending on the context in which the term is used, and indirect emissions are those pollutants formed in the atmosphere through chemical reactions between direct emissions and other atmospheric constituents.

Table 4.1-19 makes it clear that there are significant PM emission reductions possible with the application of catalyzed diesel particulate filters and low-sulfur diesel fuel. At the observed sulfate PM conversion rates, the DECSE program results show that the 0.01 g/hp-hr total PM standard is feasible for CDPF equipped engines operated on fuel with a sulfur level at or below 15 ppm. The results also show that diesel particulate filter control effectiveness is rapidly degraded at higher diesel fuel sulfur levels due to the high sulfate PM make observed with this technology. It is clear that PM reduction efficiencies are limited by sulfur in diesel fuel and that, to realize the PM emission benefits sought in this rule, diesel fuel sulfur levels must be at or below 15 ppm.

4.1.7.1.3 Increased Maintenance Cost for Diesel Particulate Filters Due to Sulfur

In addition to the direct performance and durability concerns caused by sulfur in diesel fuel, it is also known that sulfur can lead to increased maintenance costs, shortened maintenance intervals, and poorer fuel economy for CDPFs. CDPFs are highly effective at capturing the inorganic ash produced from metallic additives in engine oil. This ash is accumulated in the filter and is not removed through oxidation, unlike the trapped soot PM. Periodically the ash must be removed by mechanical cleaning of the filter with compressed air or water. This maintenance step is anticipated to occur on intervals of well over 1,500 hours (depending on engine size). However, sulfur in diesel fuel increases this ash accumulation rate through the formation of metallic sulfates in the filter, which increases both the size and mass of the trapped ash. By increasing the ash accumulation rate, the sulfur shortens the time interval between the required maintenance of the filter and negatively impacts fuel economy.

4.1.7.2 Diesel NOx Catalysts and the Need for Low-Sulfur Fuel

NOx adsorbers are damaged by sulfur in diesel fuel because the adsorption function itself is poisoned by the presence of sulfur. The resulting need to remove the stored sulfur (desulfate) leads to a need for extended high temperature operation that can deteriorate the NOx adsorber. These limitations due to sulfur in the fuel affect the overall performance and feasibility of the NOx adsorber technology.

4.1.7.2.1 Sulfur Poisoning (Sulfate Storage) on NOx Adsorbers

The NOx adsorber technology relies on the ability of the catalyst to store NOx as a metallic nitrate (MNO_3) on the surface of the catalyst, or adsorber (storage) bed, during lean operation. Because of the similarities in chemical properties of SOx and NOx, the SO_2 present in the exhaust is also stored by the catalyst surface as a sulfate (MSO_4). The sulfate compound that is formed is significantly more stable than the nitrate compound and is not released and reduced during the NOx release and reduction step (NOx regeneration step). Since the NOx adsorber is essentially 100 percent effective at capturing SO_2 in the adsorber bed, the sulfur build up on the adsorber bed occurs rapidly. As a result, sulfate compounds quickly occupy all of the NOx storage sites on the catalyst thereby rendering the catalyst ineffective for NOx storage and subsequent NOx reduction (poisoning the catalyst).

The stored sulfur compounds can be removed by exposing the catalyst to hot (over 650˚C) and rich (air-fuel ratio below the stoichiometric ratio of 14.5 to 1) conditions for a brief period.[153] Under these conditions, the stored sulfate is released and reduced in the catalyst.[154] While research to date on this procedure has been very favorable regarding sulfur removal from the catalyst, it has revealed a related vulnerability of the NOx adsorber catalyst. Under the high temperatures used for desulfation, the metals that make up the storage bed can change in physical structure. This leads to lower precious-metal dispersion, or "metal sintering," (a less even distribution of the catalyst sites) reducing the effectiveness of the catalyst.[155] This degradation of catalyst efficiency due to high temperatures is often referred to as thermal degradation. Thermal degradation is known to be a cumulative effect. That is, with each excursion to high temperature operation, some additional degradation of the catalyst occurs.

One of the best ways to limit thermal degradation is by limiting the accumulated number of desulfation events over the life of the engine. Since the period of time between desulfation events will likely be determined by the amount of sulfur accumulated on the catalyst (the higher the sulfur accumulation rate, the shorter the period between desulfation events), the desulfation frequency should be proportional to the fuel sulfur level. In other words, for each doubling in the average fuel sulfur level, the frequency and accumulated number of desulfation events are expected to double. We concluded in the HD2007 rulemaking, that this thermal degradation would be unacceptable high for fuel sulfur levels greater than 15 ppm. Some commenters to the HD2007 rule suggested that the NOx adsorber technology can meet the HD2007 NOx standard using diesel fuel with a 30 ppm average sulfur level. This implies that NOx adsorbers can tolerate as much as a four-fold increase in desulfation frequency (when compared with an expected seven to 10 ppm average) without any increase in thermal degradation. That conclusion was inconsistent with our understanding of the technology at the time of the HD2007 rulemaking and remains inconsistent with our understanding of progress made by industry since that time. Diesel fuel sulfur levels must be at or below 15 ppm to limit the number and frequency of desulfation events. Limiting the number and frequency of desulfation events will limit thermal degradation and thus enable the NOx adsorber technology to meet the NOx standard.

This conclusion remains true for the highway NOx adsorber catalyst technology and will be equally true for nonroad engines applying the NOx adsorber technology to comply with the Tier 4 standards.

Nonroad and highway diesel engines are similarly durable, so they consume a similar amount of diesel fuel their lifetimes. This means that both nonroad and highway diesel engines will have the same exposure to sulfur in diesel fuel and will therefore require the same number of desulfation cycles over their lifetimes. This is true independent of the test cycle or in-use operation of the nonroad engine.

Sulfur in diesel fuel for NOx adsorber equipped engines will also have an adverse effect on fuel economy. The desulfation event requires controlled operation under hot and net fuel-rich exhaust conditions. These conditions, which are not part of a normal diesel engine operating cycle, can be created through the addition of excess fuel to the exhaust. This addition of excess fuel causes an increase in fuel consumption.

Future improvements in the NOx adsorber technology, as we have observed in our ongoing diesel progress reviews, are expected and needed to meet the Tier 4 NOx standards. Some of these improvements are likely to include improvements in the means and ease of removing stored sulfur from the catalyst bed. However because the stored sulfate species are inherently more stable than the stored nitrate compounds (from stored NOx emissions) and so will always be stored preferentially to NOx on the adsorber storage sites, we expect that a separate release and reduction cycle (desulfation cycle) will always be needed to remove the stored sulfur. We therefore believe that fuel with a sulfur level at or below 15 ppm sulfur will be necessary to control thermal degradation of the NOx adsorber catalyst and to limit the fuel economy impact of sulfur in diesel fuel.

4.1.7.2.2 Sulfate Particulate Production and Sulfur Impacts on Effectiveness of NOx Control Technologies

The NOx adsorber technology relies on a platinum-based oxidation function to ensure high NOx-control efficiencies. As discussed more fully in Section 4.F.1, platinum-based oxidation catalysts form sulfate PM from sulfur in the exhaust gases significantly increasing PM emissions when sulfur is present in the exhaust stream. The NOx adsorber technology relies on the oxidation function to convert NO to NO_2 over the catalyst bed. For the NOx adsorber this is a fundamental step prior to the storage of NO_2 in the catalyst bed as a nitrate. Without this oxidation function the catalyst will trap only that small portion of NOx emissions from a diesel engine that is NO_2. This would reduce the NOx adsorber effectiveness for NOx reduction from in excess of 90 percent to something well below 20 percent. The NOx adsorber relies on platinum to provide this oxidation function due to the need for high NO oxidation rates under the relatively cool exhaust temperatures typical of diesel engines. Because of this fundamental need for a precious-metal catalytic oxidation function, the NOx adsorber inherently forms sulfate PM when sulfur is present in diesel fuel, since sulfur in fuel invariably leads to sulfur in the exhaust stream.

The Compact-SCR technology, like the NOx adsorber technology, uses an oxidation catalyst to promote the oxidation of NO to NO_2 at the low temperatures typical of much of diesel engine operation. By converting a portion of the NOx emissions to NO_2 upstream of the ammonia SCR reduction catalyst, the overall NOx reductions are improved significantly at low temperatures. Without this oxidation function, low-temperature SCR NOx effectiveness is dramatically reduced, making compliance with the NOx standard impossible. Future Compact-SCR systems therefore need to rely on a platinum oxidation catalyst to provide the required control of NOx emissions. This use of an oxidation catalyst to enable good NOx control means that Compact-SCR systems will produce significant amounts of sulfate PM when operated on anything but the lowest fuel sulfur levels due to the oxidation of SO_2 to sulfate PM promoted by the oxidation catalyst.

Without conversion of NO to NO_2 promoted by oxidation catalysts, neither of these control technologies can meet the Tier 4 NOx standard. Each of these technologies will therefore require low-sulfur diesel fuel to control the sulfate PM emissions inherent in the use of highly active oxidation catalysts. The NOx adsorber technology may be able to limit its impact on sulfate PM emissions by releasing stored sulfur as SO_2 under rich operating conditions. The Compact-SCR technology, on the other hand, has no means to limit sulfate emissions other than through lower catalytic function or lowering sulfur in diesel fuel. The degree to which the NOx emission-control technologies increase the production of sulfate PM through oxidation of SO_2 to SO_3 varies somewhat from technology to technology, but it is expected to be similar in magnitude and environmental impact to that for the PM control technologies discussed previously, since both the NOx and the PM control catalysts rely on precious metals to achieve the required NO to NO_2 oxidation reaction.

At fuel sulfur levels below 15 ppm this sulfate PM concern is greatly diminished. Without this low-sulfur fuel, the NOx control technologies are expected to create PM emissions well in excess of the PM standard regardless of the engine-out PM levels. We therefore believe that diesel fuel sulfur levels will need to be at or below 15 ppm to apply the NOx control technology.

4.2 Transient Emission Testing

4.2.1 Background and Justification

In the 1998 Rulemaking for Nonroad Compression Ignition Engines, we acknowledged that effective in-use control of emissions from nonroad sources would be positively impacted by having a duty cycle that more accurately characterized the transient nature of nonroad activity. While no certification cycle may guarantee complete in-use emission control, a cycle that appropriately characterizes the activity of the subject equipment achieves a greater level of control. The basics of any nonroad transient duty cycle should fulfill the following goals:

- Represent nonroad activity broadly, with a basis in real-world activities through diverse data segments;
- Exercise the engine over its operating range; cycle not limited to a specific speed or load, but traverses the operating range over the engine's full power range;
- Measure particulate matter (PM) on a transient basis;
- Capture the basic characteristics of PM, as currently defined, including:
    - organic and inorganic carbon fractions
    - volatile fraction
    - sulfate fraction
    - ash, etc., and
- Ensure that measures developed to control emissions over the cycle encourage and afford greater assurance of adequate control of emissions in-use.

Since that rulemaking, we have embarked on a strategy for cataloging operational data, generating a duty cycle from those data sets, and compiling a transient composite duty cycle that represents a broad range of activity for nonroad diesel equipment. Working cooperatively with the Engine Manufacturers Association (EMA) and through contract with the Southwest Research Institute (SwRI), we created a set of duty cycles based on the following nonroad applications:

- Agricultural Tractor
- Backhoe Loader
- Crawler Tractor
- Arc Welder
- Skid Steer Loader
- Wheel Loader
- Excavator

These application duty cycles were created from actual speed and load data recorded in-use on each of these pieces of equipment. The strategy for generating the duty cycles and the base data sets differed slightly. However, combining these two strategies has ensured that the strengths of both approaches are integrated into the resultant composite duty cycle. Each of the pieces of equipment represented the top tier of nonroad equipment as defined by their contribution to nonroad diesel inventory as defined by the 1991 Nonroad Engine and Vehicles Emissions Study (NEVES). The pieces of equipment selected have retained their historical significance even today as they appear to match fairly well with EPA modeling data for the impacts of those applications.

The existing steady-state duty cycle affords good coverage of the range of activity seen by nonroad diesel applications; however, it is incomplete. The range of nonroad activity is much broader and much more varied than can be captured by a set of steady-state points (see Figure 4.2-1). No single transient cycle, of reasonable length, could capture the full body of nonroad diesel activity from the various equipment applications. However, it is possible to capture typical operation of nonroad equipment and to extrapolate the applicability of available data to the remainder of nonroad equipment for purposes of certification and modeling. This can’t replace an in-use characterization, but it does drive development of engine design strategies to focus emission-control and performance parameters on a broader set of activity that is much more likely to be seen in use.

A much broader set of data from the nonroad duty cycle generation may be found in Memorandum from Cleophas Jackson to EPA Air Docket A-2001-28. This operational and cycle data demonstrate the amount of nonroad activity that can occur outside the modes of the ISO C1 duty cycle.

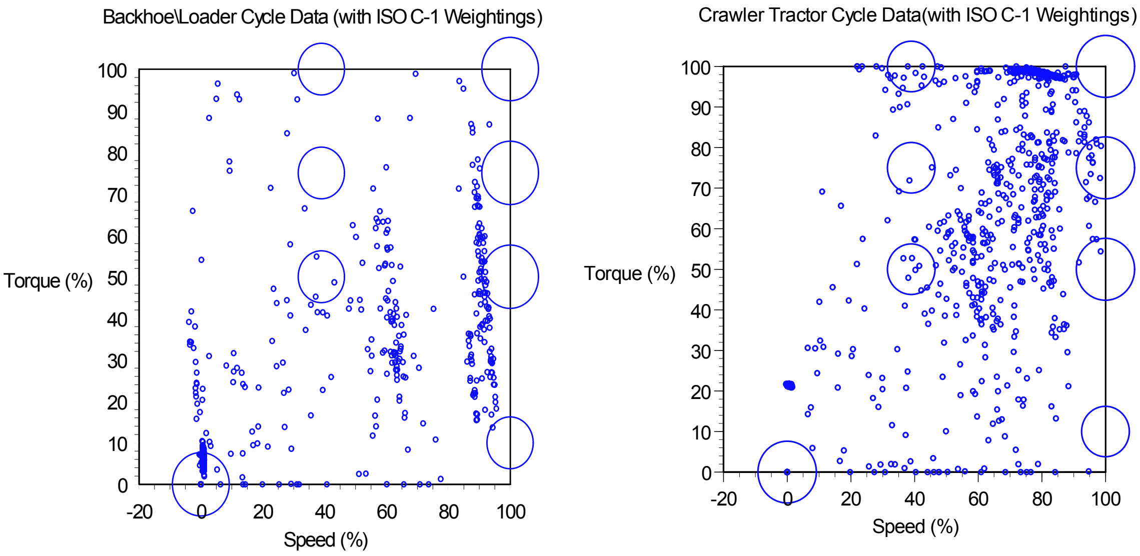
4.2.1.1 Microtrip-Based Duty Cycles

The microtrip-based cycles were created based on a range of activity the equipment is likely to see in use. The weighting of each microtrip impacted the duration of each segment within the resulting duty cycle. Each microtrip was extracted from a full set of data with the equipment being operated within the targeted implement application. The data from the extracted segment were compared with the full body of data for the targeted implement application based on a chi square analysis, with a 95% confidence level, of the nature of the operation. This included a characterization of the speeds, loads, velocities, and accelerations over the full operating map, for the given piece of equipment. Experienced operators conducting actual work operated each unit. The projects ranged from an actual farmer plowing to a backhoe digging a trench for a municipal works project to a wheel loader in a rock quarry loading a truck to a skid steer loader preparing plots in a subdivision under construction. The microtrip-based application duty cycles were the Agricultural Tractor cycle, the Backhoe Loader cycle and the Crawler/Dozer cycle.

4.2.1.2 "Day-in-the-Life"-Based Duty Cycles

In attempting to address real-world activity, another strategy was employed for the second set of nonroad duty cycles. This approach was termed the “day-in-the-life” strategy. It could be said that this approach yielded only a single or perhaps two microtrips per piece of equipment. This approach was employed to capture data for work that would have otherwise have been done regardless of EPA data collection needs. With these pieces, the data recorded was simply data generated as selected pieces of equipment were used by contractors or construction personnel during their normal operation versus being asked to do certain types of operation. The day-in-the-life duty cycles consisted of the Skidsteer Loader cycle, the Arc Welder cycle, the Rubber Tire Loader cycle, and the Excavator cycle. The Excavator Cycle is in fact a composite duty cycle assembled from three equal time segments of operating data from two different excavators.

Figure 4.2-1
Backhoe Loader and Crawler Tractor Cycle Data versus the ISO 8178-4 C1 Cycle



4.2.2 Data Collection and Cycle Generation

4.2.2.1 Test Site Descriptions

Operators were instructed to complete a job commensurate with the functionality of the vehicle and at their customary pace. Experienced operators conducted their normal work with a given piece of nonroad equipment. The work conducted by the equipment during the data collection was actual work and not artificial scenarios, which ensured the accuracy of the data.

4.2.2.1.1 Agricultural Tractor Cycle Operation

The John Deere agricultural tractor was operated by an experienced farmer on his farm. The farmer was asked to conduct the following activities as he normally would on any given work day. This activity formed the basis for the microtrips for the agricultural tractor duty cycle. The microtrip activity segments included: planter, tandem offset discing (35 foot), bedder, cultivator, ripper (10 row), folding chisel plow, and turnaround. The work was conducted during spring planting season in Hamlin, Texas, using an actual in-use field being prepared for cultivation. The tractor was used to make passes with each selected implement. The normal load operation retained for inclusion in the cycle generation was the “normal” operation with each implement. The data from the intentionally, highly loaded pass were not included in the eventual Agricultural Tractor cycle.

4.2.2.1.2 Backhoe Loader Cycle Operation

The Caterpillar backhoe loader was utilized on a site by the City of Houston, Utility Maintenance Division, Fleet Management Department to conduct the following activities: roading, trenching, loading and grade and level. The operation was conducted by a municipal employee experienced in the operation of the backhoe conducting that activity. Engine data were collected during the repair of a collapsed city sewage line in a residential neighborhood. The activity included demolishing the road over the sewage line, trenching to reach the pipe, craning to remove the old pipe and install the new pipe, backfilling, loading, spreading gravel, and finish-grading the site.

4.2.2.1.3 Crawler Tractor Cycle Operation

The Caterpillar D4 Tractor was used to conduct the following activity on the grounds of Southwest Research Institute by an experienced operator. The microtrips included road bed preparation, clearing activity, and pit activity. The operation was examined at three independent sites. Site 1 included clearing trees and brush for a construction site. At Site 2 the equipment dug and prepared a road bed. At Site 3 V-trench and pit operations were examined. This activity was similar to preparing a site for a small building foundation.

4.2.2.1.4 Wheel Loader Operation

The Caterpillar 988F Wheel Loader was operated at Redland Stone Products Company (quarry) in San Antonio, Texas. Data were collected between June 8 and June 10, 1998. The equipment was operated from morning until midnight, working to fill construction and mining trucks, open-topped trailers of Class-8 highway trucks, and rail cars.[156] The material being moved was typical for a quarry application, including aggregate of various densities, such as crushed stone, gravel, and sand. Twenty-six hours of data were gathered at the quarry for the wheel loader.

4.2.2.1.5 Skid Steer Loader Operation

The Daewoo skid steer loader was operated at a construction site for a new complex of townhouses in the San Antonio, Texas, area by a commercial site preparation company. The equipment was used to create drives for individual homes. Specifically, the skid steer loader was used to haul and position aggregate foundation material to prepare the driveway and sidewalk areas prior to laying asphalt. Over twelve hours of data were gathered over three work days for the skid steer loader. The implement used by the skid steer loader during this operation was its bucket.

4.2.2.1.6 Arc Welder Operation

The Lincoln Electric 250-amp arc welder was operated at Redland Stone Products Company (quarry) in San Antonio, Texas. Data were collected over a single work day. The equipment was used to perform repairs on a large, mobile steel crusher tower by a private contract firm, Holt. Eight hours of data were gathered at the quarry for the arc welder.

4.2.2.1.7 Excavator Operations

The Hitachi EX300LC excavator was operated at 3 different sites over 7 days in the greater San Antonio metropolitan area. Data were collected during Winter 1998 and Spring 1999. The equipment was used to level ground at a building site, to load aggregate materials into trucks at a quarry and to dig trenches and transport pipes for a sewer project. Almost thirty-nine hours of data were gathered for this excavator.

The Caterpillar 320BL excavator was operated at 4 different sites over 6 days in the greater San Antonio metropolitan area. Data were collected during Winter 1998 and Spring 1999. The equipment was used to perform digging, trenching, pipe transport and placement and backfilling associated with an on-going sewer project. More than thirty-eight hours of data were gathered for this excavator.

4.2.2.2 Engine and Equipment Description

In generating the microtrip-based and the day-in-the-life duty cycles, the equipment selected were based on the highest sales volume applications and the contribution of those applications to the ambient inventories for NOx and PM. Those cycles were created based on a John Deere 4960 Agricultural Tractor, Caterpillar 446B Backhoe Loader, and a Caterpillar D4H Crawler Tractor. The detailed description of the engines may be seen in Table 4.2-1 through Table 4.2-3.[157]

Table 4.2-1
Agricultural Tractor—John Deere 4960

Engine Characteristic	Value
Rated Speed (rpm)	2200
Peak Torque (Nm)	970
Peak Power (kW)	189.2
Low Idle Speed (rpm)	850
Operating Range (rpm)	850-2400
Other Engine Descriptors	7.6L displacement, electronic controls

Table 4.2-2
Backhoe Loader—Caterpillar 446B

Engine Characteristic	Value
Rated Speed (rpm)	2200
Peak Torque (Nm)	405
Peak Power (kW)	76.8
Low Idle Speed (rpm)	800
Operating Range (rpm)	800-2300
Other Engine Descriptors	CAT 3114-D17 engine

Table 4.2-3
Crawler Tractor—Caterpillar D4H

Engine Characteristic	Value
Rated Speed (rpm)	2200
Peak Torque (Nm)	442
Peak Power (kW)	85
Low Idle Speed (rpm)	800
Other Engine Descriptors	3204-D17 engine

The engines used for data generation for the day-in-the-life approach were from a skid steer loader, an arc welder, and a wheel loader. The engine parameters of the Caterpillar 988F Series II rubber tire loader, the Lincoln arc welder and the Daewoo skidsteer loader are listed in Table 4.2-4 through Table 4.2-6.

Table 4.2-4
Rubber Tired Loader—1997 Caterpillar 988F Series II

Engine Characteristic	Value
Rated Speed (rpm)	2080
Peak Torque (Nm)	2908
Peak Power (kW)	321
Low Idle Speed (rpm)	850
Operating Range (rpm)	850-2250
Other Engine Descriptors	CAT 3408E-TA engine, Caterpillar HEUI Fuel System, electronic

Table 4.2-5
Arc Welder—1997 Lincoln Electric Shield-Arc 250

Engine Characteristic	Value
Rated Speed (rpm)	1,725
Peak Torque (Nm)	162
Peak Power (kW)	28.3
Low Idle Speed (rpm)	1375
Operating Range (rpm)	800-1900
Other Engine Descriptors	Perkins D3.152 engine

Table 4.2-6
Skid Steer Loader—1997 Daewoo DSL-601

Engine Characteristic	Value
Rated Speed (rpm)	2,800
Peak Torque (Nm)	121 Nm
Peak Power (kW)	30.6 kW
Low Idle Speed (rpm)	800
Peak Torque Speed (rpm)	1,700
Other Engine Descriptors	Yanmar 4TNE84 engine, 2.0 L Displacement, in-line 4 cyl, naturally aspirated

Two pieces of equipment were selected for generating the excavator duty cycle based on estimates of equipment population and power distribution among excavators in the nonroad equipment inventory in the United States at that time.[158] With the highest excavator sales volumes being in the 60-130 kW and 130-225 kW ranges, the Agency created its excavator duty cycle based on both a Hitachi EX300LC excavator at 155 kW (208 hp) and a Mitsubishi/CAT 320 BL excavator at 95 kW (128 hp). The detailed description of the engines may be seen in Table 4.2-7 and Table 4.2-8.

Table 4.2-7
Excavator (higher power output)—1997 Hitachi EX300LC

Engine Characteristic	Value
Rated Speed (rpm)	2,200
Peak Torque (Nm)	Nm (636 lbs-ft)
Peak Power (kW)	155 kW
Low Idle Speed (rpm)	680
Peak Torque Speed (rpm)	1,500
Other Engine Descriptors	ISUZU A-6SD1TQA(AC/JI) engine, 9.8 L displacement, mechanical controls

Table 4.2-8
Excavator (lower power output)—1997 Mitsubishi/CAT 320 BL

Engine Characteristic	Value
Rated Speed (rpm)	1,800
Peak Torque (Nm)	Nm (473lbs-ft)
Peak Power (kW)	95 kW
Low Idle Speed (rpm)	800
Peak Torque Speed (rpm)	1,200
Other Engine Descriptors	Mitsubishi/CAT 3066T engine, 6.4 L displacement

4.2.2.3 Data Collection Process

The data collection process for both the microtrip-based and the day-in-the-life duty cycles was based on collecting engine operational data in the field by mechanical and electronic means. Engine speed data were measured by instrumenting the engine of each piece of equipment with a tachometer to measure engine speed in revolutions per minute (rpm). The torque was measured either mechanically by linear transducer or as transmitted across the engine's control area network as a fuel-based torque signal. The mechanical torque measurement utilized rack position to determine the load being demanded of the engine. To calibrate the voltage signal from the linear actuator the engine rack position versus actual fuel rate and engine-out torque were determined based on laboratory evaluation of the same model engine. Once a map of engine speed, load, actual torque, and fuel rate was compiled, the in-field load was determined based on rack position and engine speed, as measured by the tachometer.

Data loggers were used to record field data during operation and the data loggers were equipped with flash memory media. The data loggers recorded engine parameters only during operation, so data gathering did not occur while the engine was stopped. Data collection rates varied from cycle to cycle from a rate of 3.33 Hz to 5 Hz. Using cubic spline interpolation, the data were then reduced to 1 Hz format for the purpose of cycle generation.

4.2.2.4 Cycle Creation Process

The basic methodology of comparing extracted segments to the full body of data were used for both duty cycle types. The major difference is in how the activity was defined for each. The microtrip-based activity specified the type of work performed by various implements for a given piece of nonroad equipment in an effort to effectively incorporate the different types of operation through which the equipment could be exercised over its lifetime. The day-in-the-life approach was meant simply to characterize the nature of the full range of activity seen by the equipment during its typical operation over the period of evaluation. The body of data for neither approach was meant to be all encompassing to the extent that no other activity would be expected from that piece of equipment over its lifetime. The microtrip approach represents the broadest sweep in the compilation of nonroad operation. The resulting duty cycles in each case do represent the most representative set of data from the full body of data collected.

4.2.2.4.1 Microtrip Cycle Creation

The contractor that conducted the in field testing and data reduction was Southwest Research Institute (SwRI) with significant input from the Engine Manufacturers Association (EMA) and direction from the United States Environmental Protection Agency (EPA). The methodology used for creating the microtrip-based cycles involved extracting the actual data by comparing the running window of actual data to the full body of data that was collected for each type of activity. This involved a chi-square[W] analysis comparing observed to expected data. The observed data set was the data being evaluated for inclusion in the cycle for the specific active window. The expected data set was represented by the full body of data from the given activity. The chi-square comparison involved assessing the following for each window of operation:

- Rate of change in speed (dSpeed)
- Rate of change in torque (dTorque)

[W] $\sum(O_i - E_i)^2 / E_i$ where O_i is the Observed frequency in the ith interal and E_i is the Expected frequency in the ith interval based on the frequency distribution of the entire population for the given quantity.

- Power
- Rate of change in power (dPower)
- Speed and torque
- Torque and dSpeed
- Speed and dTorque
- Duration and magnitude of change in power

The specific steps involved in cycle generation were the following:

1. Separate the raw vehicle data into data files by vehicle activity.
2. Load first activity file.
3. Calculate power. Add to raw data file.
4. Normalize speed using the FTP process and manufacturer's specified rated speed. Normalize torque, and power using measured peak values and create a scalar-normalized data file.
5. Calculate the time derivative of normalized speed, torque, and power.
6. Calculate the duration and magnitude of all increases, decreases, and steady-state periods from the normalized power data.[X] Count occurrences of duration and magnitude of changes in power for selected ranges.
7. Count occurrences of power and rates of change of speed, torque, and power for selected ranges. Count occurrences of speed and torque, change in speed at selected torque levels, change in torque at selected speed levels, and duration and magnitude of changes in power for selected ranges. The relative frequencies of occurrence (RFO) were collected within the specified ranges of activity (e.g. normalized range of speed of 20 units).
8. Characteristic graphs of each activity was created for each piece of equipment. Several formats were used to characterize the various analysis of the equipment operation:
   - Scatter plots of normalized speed and load data
   - RFO data for delta[Y] speed versus normalized torque
   - RFO data for normalized speed versus delta normalized torque
   - RFO plots of magnitudes and duration of delta power
9. The analysis of steps 1-8 was conducted by SwRI for each activity for each duty cycle.
10. The scalar normalized speed data (based on manufacturer specified rated speed) and normalized torque (or load - based on the peak torque available at the given speed) was used to generate the final set of activity comparisons for extracting the "actual" data for the microtrip from the full body of activity data collected for the specific application.

Microtrip Weightings

The microtrips of the agricultural tractor cycle, backhoe loader cycle, and crawler cycle were weighted based on feedback from the engine manufacturers on the amount of time each

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[X] Steady-state is defined as any instantaneous change in normalized speed or normalized torque with a magnitude less than 2%.

[Y] Delta is used to describe the instantaneous rate of change of the specified quantity.

application was expected to operate using a given implement performing a set function over the lifetime of that piece of equipment. The microtrip weighting for the Agricultural Tractor cycle may be seen in Figure 4.2-2 to Figure 4.2-4. The cycle creation was based on linking the microtrips with transition points between each activity segment.

Figure 4.2-2

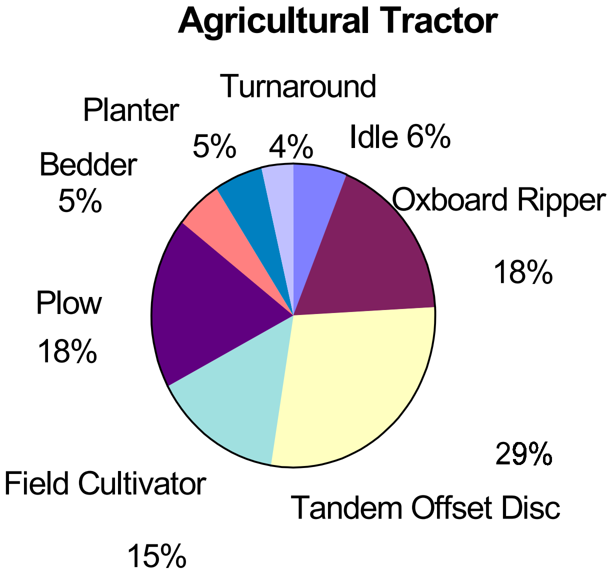


Figure 4.2-3

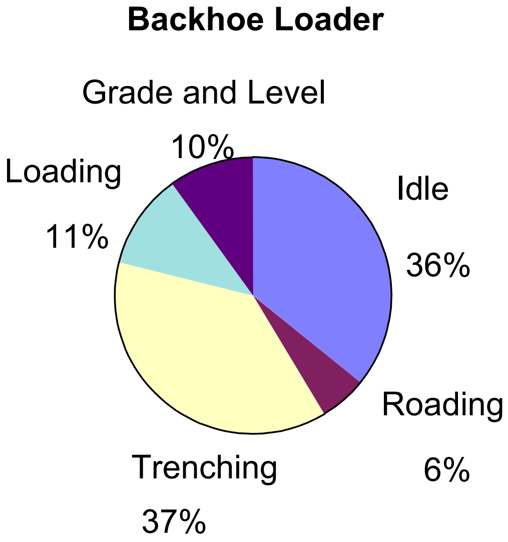
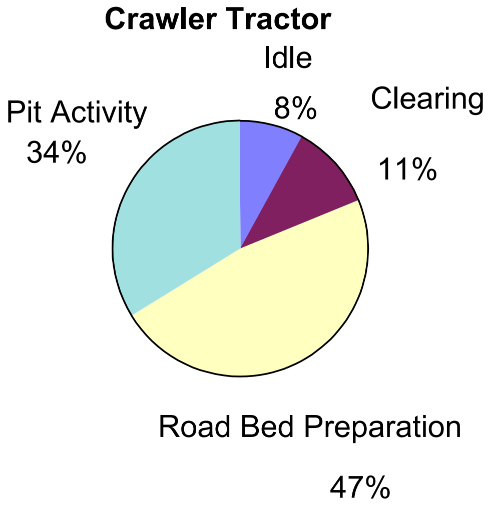


Figure 4.2-4



In generating the duty cycles and conducting the analyses, relative frequency of occurrence of various parameters as reported by the contractor were compared with the full set of real-world data. Figure 4.2-5 shows the difference in the full set of real-world data collected versus the microtrip, for one activity type. As can be seen in this figure, the difference in the total data set and the identified microtrip was relatively small, based on the relative frequency of occurrence.

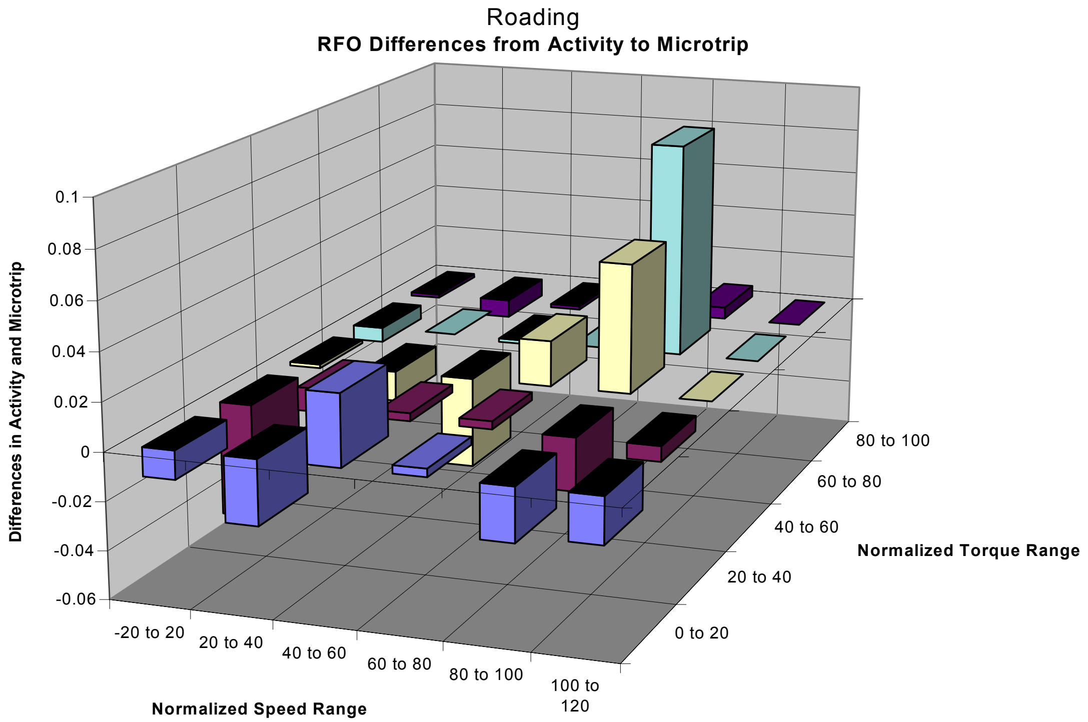


Figure 4.2-.5
Example of Microtrip vs. Data Set for Tractor Activity

Cycle Creation

Each of the microtrip-based duty cycles were created based on the statistical analysis previously described. The linked component microtrips were then reduced to 1 Hz data from the original 3.33 Hz signal using a cubic spline interpolation. The duty cycle was then speed and torque normalized, based on the maximum available power/torque mapping. These duty cycles were the first set of cycles that were used for creating the composite nonroad transient duty cycle.

4.2.2.4.2 Day-in-the-Life Duty Cycle Generation

In generating the day-in-the-life data, a similar chi-square analysis was used to compare RFO data from the running window of data with the full body of data. The distinction lies in that this was not done for multiple activity types for each piece of equipment. The analysis was conducted using a nineteen-minute window incremented at one-minute intervals. The approach used for data reduction, while similar, also varied in that the bin increments used for the day-in-the-life duty cycles was 100 rpm and 200 lb-ft for torque versus the normalized 20 percent windows from the microtrip approach. The steps taken by SwRI are as follows.

1. Define "bins" sized at 100 rpm for speed by 200 ft-lb for torque.
2. Sort entire data file (e.g. 376,768 observations ~ 26 hours) into bins.
3. Compute a frequency table to indicate the number of observations contained in each bin. Similar to the RFO bins from the microtrip analysis.
4. Increment within data file by 1 minute, and sort the next 19 minutes
5. Compute the chi-square statistic for comparison with frequency distribution of the population data file.
6. The approach to analyzing each nineteen-minute "window" of activity was repeated at one-minute increments for the entire body of data.
7. The window of activity that best represented the full body of data for that piece of equipment was selected as the most typical duty cycle.
8. Four iterations on the analysis was conducted to develop a typical 1 duty cycle, a typical 2 duty cycle, a high transient speed[Z] duty cycle, and a high transient torque duty cycle for each application.
9. For each window of activity, the data used were the actual, contiguous data from the body of data for that piece of equipment.

Given the nature of this data-generation process, the detailed analysis needed for weighting the microtrips and determining the time basis for inclusion into a composite cycle was not needed. The resulting duty cycles were simply the result of the extraction of data from the complete raw data set, which were subsequently normalized.

4.2.2.4.3 Excavator Cycle Generation

Data files for each piece of equipment were appended together in chronological order to form a data population for that excavator. Each data population contained columns for time of data acquisition (incremented at 5 Hz), engine speed, and rack position. Data for engine speed and rack position were used to compute a column for torque in units of pound-feet (lb-ft), based on the rack-to-torque algorithm using correlation information compiled earlier for the corresponding excavator engine. Tasks of choosing the representative segments to form a composite excavator cycle were then initiated based on these two different data populations.

The in-use data population of each excavator was sorted into two-dimensional intervals or "bins," and a histogram was compiled based on the frequency of occurrences for speed and torque pairs within the designated bins. The percent or relative frequency of occurrence (RFO) is considered a histogram that describes the data population. By choosing a segment that closely matched the characteristic RFO compilation, it is therefore rationalized that the chosen segment is indeed representative of the given data population. Using the same bin intervals as were applied to create a histogram (RFO) for each data population, a similar histogram was created for each 380-second candidate segment of data. Each candidate segment overlapped the previous segment by 320 seconds, as the process for excerpting candidate segments incremented through

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[Z] High transient duty cycles (speed or torque) represent the single most transient speed or torque window of data (highest number and magnitude of instantaneous changes in speed or torque) from the full body of data.

the data population using a 60-second step size. Chi-square analyses tested each candidate segment to rank each segment by comparing its RFO histogram to the RFO histogram created for its associated data population. The following is the approach used for computing a chi-square statistic, relative frequency of occurrence distributions to that of the corresponding population for engine speed and torque values, for each candidate segment:

1. Define “bins” for speed expressed in rpm, and torque as lb-ft
2. Sort each data population (approximately 38 hours, at 5 Hz) into bins
3. Compute a relative frequency of occurrence table to indicate the percentage of observations contained in each bin
4. Increment through the data population by 60 seconds, sort the next 380-second segment into similar bins, and compute a relative frequency of occurrence table
5. Compute a chi-squarea statistic for comparing the frequency distribution of the segment to that of the population
6. Repeat Steps 4 and 5 for all such 380-second candidate segments, for an entire data population
7. Sort segments by increasing chi-square rank (low statistic means good correlation)

Note: The chi-square statistic is the summation of:

$$(O_i - E_i)^2 / E_i$$

where O_i is the observed frequency in the ith interval of the 380-second sample window, and E_i is the expected frequency of the ith interval based on the frequency distribution of the entire population.

The sliding 380-second "window" was used to determine the distribution of speed-torque combinations experienced by each type of equipment over the entire range of operating data collected on each unit. The "window" was advanced by one-minute increments through the data to determine a most typical segment for each excavator and a second most typical segment for the lower-powered unit.

Based on initial torque map information obtained with each engine on the steady-state test bench, a normalizing process was applied to each of the 5 Hz data segments (part of “data smoothing”). FTP normalizing methods outlined in the 40 CFR part 86, subpart N, were used for expressing observed engine speed and torque values for the three selected segments of 5 Hz data in terms of the percentage of an engine’s full load performance and idle speed. The 5 Hz data for segments chosen to represent the first- and second-most typical segments in the data population generated with the Caterpillar 320BL excavator were normalized using the rated speed and torque map information obtained with the Caterpillar 3066T engine mounted on the steady-state test bench. Similarly, the 5 Hz data for the segment best representing the typical operation of the higher powered Hitachi excavator were normalized using torque map information obtained for the Isuzu A-6SD1T engine on the steady-state test bench.

An averaging method was applied to the three selected segments to convert each segment from the original 5 Hz to 1 Hz data files. Each 5 Hz data pair was first normalized and then the percentage values were averaged. In general, the smoothing technique produced a value for speed and a value for torque for each one-second interval (1 Hz) by averaging the five values in the interval of interest.

After establishing in-use operating engine speed and torque data populations for excavators rated in both the low and high power ranges, three representative segments were appended together to form a 20-minute composite excavator cycle. The first two segments were the most representative data from the lower and higher powered excavators, respectively. The third segment represented the second-most typical data from the lower-powered excavator (i.e., ranked number two in chi-square analyses for that population). This resulted in a composite cycle that was apportioned with two-thirds data gathered from the Caterpillar 320BL excavator rated in the 100 to 175 hp range, and one-third from data gathered from the Hitachi EX300LC excavator rated in the 176 to 300 hp range. The three segments were then joined into a composite 20-minute excavator duty cycle by the addition of appropriate transition segments leading into and linking each segment of transient operation. A three-second transition joined Segment 1 and Segment 2, and similarly another three-second transition joined Segments 2 and 3. A no-load idle condition was appended for 27 seconds at the beginning and end of the cycle.

4.2.3 Composite Cycle Construction

Having all seven application cycles in hand, including the four cycle variations apiece for the arc welder, skidsteer loader and rubber-tire loader, we began construction of a transient composite nonroad duty cycle. The approach for addressing the weighting of contributions from each equipment type to the composite cycle was left at equally weighting each contribution. While consideration was given to population-weighted or inventory-based weighting factors for the composite cycle, in the interest of ensuring a universally applicable cycle, no unique weighting factors were assigned. The decision of which data segments to extract from the component duty cycles was based on uniqueness of operation (avoidance of replicate data in the composite cycle) and level of transient operation (steady-state operation was not included in the transient cycle).[AA] Extracted cycle segments were linked using three second transition periods, when needed, to ensure smooth transitions within the cycle and to avoid spurious data generation based on changes in speed and load that were unrealistic between segments. Transition periods were deemed necessary when the change in the magnitude of the torque or speed value was greater than twenty using the normalized data. The cycle was constructed using the denormalized segments for each component cycle based on the original engine map for the engines used to generate the component cycles. Once the raw data were available, the normalization based on the max speed map was conducted. This was necessary because each cycle was originally normalized using different procedures (e.g., FTP speed and torque

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[AA] Steady State Operation is defined as an instantaneous speed or torque change less than 2% of the maximum magnitude.

normalization or GCS[BB] speed with FTP torque normalization). The MAP used for normalizing the raw data remained FTP-based (percent of maximum torque at the given speed) for torque. The Maximum Speed Determination was used for the speed normalization. Figure 4.2-6 identifies the location of the cycle segments as extracted from the component application duty cycles, the segment duration, and segment position in the composite duty cycle.

Figure 4.2-6

Supplemental NRTC (Nonroad Transient Composite) Cycle

Application Number	Nonroad Application	Application Duration (seconds)	Application in Cycle Position (#seconds)	Segments from Application Cycle (#seconds)	Segment Name	Segment Duration (seconds)	Cumulative Cycle Time (seconds)	Segment in Cycle Position (#seconds)
					Start/Transition	28	28	0-28
1	Backhoe Loader	206	29-234	52-86	Roading	35	63	29-63
				108-141	Trenching	34	97	64-97
				174-218	Loading	45	142	98-142
				351-442	Grade/Level	92	234	143-234
2	Rubber-Tire Loader	184	235-418	746-822	Typical Operation	77	311	235-311
				531-637	Hi-Spd Transient	107	418	312-418
3	Crawler-Dozer	209	419-627	85-206	Road Bed Prep	122	540	419-540
				376-462	Clearing	87	627	540-627
4	Agricultural Tractor	150	628-777	265-414	AgTractor	150	777	628-777
5	Excavator	35	778-812	319-338	LowerHp (128Hp)	20	797	778-797
				431-445	HigherHp (208Hp)	15	812	798-812
					Transition	3	815	813-815
6	Arc Welder	204	816-1019	1007-1103	Typical Operation	97	912	816-912
				544-650	Hi-Spd Transient	107	1019	913-1019
7	Skid Steer Loader	185	1020-1204	264-365	Typical Operation	102	1121	1020-1121
				150-232	Hi-Trq Transient	83	1204	1122-1204
					Idle/Transition/End	34	1238	1215-1238

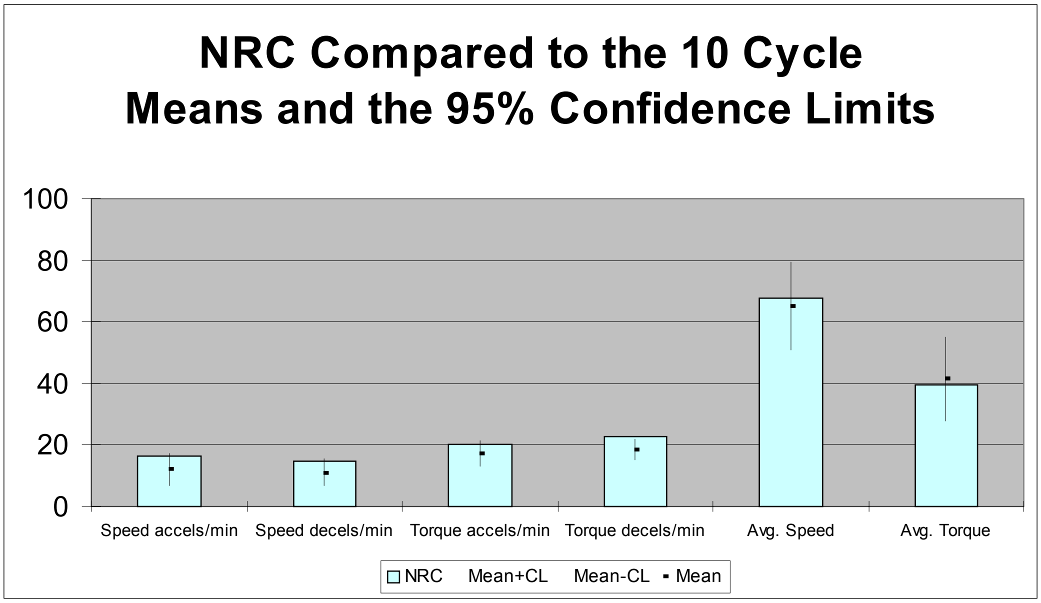
[BB] GCS Speed or Governed Central Speed is defined as the speed corresponding to the point along the engine's MAP (maximum allowable power) curve at which power is 50% of maximum measured rated power once the maximum measured power has been surpassed.

4.2.4 Cycle Characterization Statistics

The characterization of the operational data were also subsequently revisited for purposes of comparison in addressing composite cycle construction. The nature of the transient activity is characterized in a report to EPA by Dyntel.[159] The goal of the analysis was to provide an assessment of the transient nature of nonroad activity between different applications. These analyses (small bin, large bin, and general cycle) were used to address the comparability of the resulting composite nonroad diesel transient duty cycle to the component data set that was collected for each of the component cycles. The size of the bin was simply a reference to the scale used for the analysis (either coarse or fine). As may be seen in Figure 4.2-7, the composite nonroad transient duty cycle fit well within the average of all of the original nonroad duty cycles based on the operational data. The figure is a plot of the nonroad composite cycle characteristics with the statistics of the remainder of the nonroad diesel cycles plotted as a mean with the standard deviation between those statistics from the other cycles shown. The ten cycles represented include:

- Ag Tractor
- Crawler
- Skid Steer Typical 1
- Wheel Loader High Torque Transient
- Arc Welder High Torque Transient
- Backhoe
- Arc Welder Typical 2
- Wheel Loader Typical 1
- Excavator
- Skid Steer Loader High Torque Transient

Figure 4.2-7
Summary of Nonroad Cycles Comparison to NR Composite



4.2.5 Cycle Normalization/Denormalization Procedure

The actual values for speed and load in rpm and lbs-ft for each of the application cycles needed to be converted into normalized values before any application cycle could be used on an engine, other than the engine originally used to create the application cycle itself. This process of normalization entailed converting the actual in-use operating speed and load values of the "raw" duty cycle, as recorded from the engine used to create the cycle originally, into a percentage of that engine's maximum achievable speed and load values. This yields a schedule of percentage-based speed and load values that can be converted to absolute values for speed (rpm) and load (lbs-ft). This conversion depends on applying the normalized percentage values for speed and load to the maximum achievable power (MAP) for the new test engine. Multiplying the percentage values of the normalized cycle by the measured speed and load maximums of the new engine's MAP curve, in fact, denormalizes the cycle. This means that the denormalized speed and load values may be used as commanded values on a test cell dynamometer to exercise the new engine in exactly the same manner as the original engine was run for a particular application cycle. The load values in lbs-ft for each of the seven types of application cycles and all their cycle permutations, i,e., Typical, High Transient Speed , etc., were all converted to normalized values (and conversely, into denormalized values, at later times) using the FTP normalization procedure detailed in 40 CFR Part 86. The speed values in rpm for each type of application cycle were normalized initially in one of three different ways.

The speed values in each of the original microtrip cycles, the agricultural tractor, backhoe loader, and crawler-dozer, were all normalized using the FTP procedure. The speed values in each of the original day-in-the-life cycles, rubber tire loader, skidsteer loader and arc welder were all normalized using the governed central speed procedure (GCS).[CC] The speed values in the excavator cycle were normalized, and later denormalized, using the FTP normalization procedure detailed in 40 CFR Part 86. However, in time and for the construction of EPA's composite nonroad cycle, all the application cycles were normalized using the Agency's Maximum Speed determination procedure.

The Maximum Speed Determination procedure uses the measured speed and load values from an engine's power curve to determine what is the maximum power that the engine can attain and at what speed that engine will achieve its maximum power. This value for speed at maximum power can then be used in lieu of a manufacturer's rated speed number for a particular engine to conduct a normalization or denormalization of engine or cycle for purposes of running a duty cycle on a particular engine. The procedure is based on a spreadsheet calculation and is discussed in our analysis of comments associated with the final rule for marine diesel engines (64 FR 73300, December 29, 1999).[160, 161] As detailed in Figure 4.2-8, the maximum speed can be found below the point on the engine power curve that is the farthest distance from the point of

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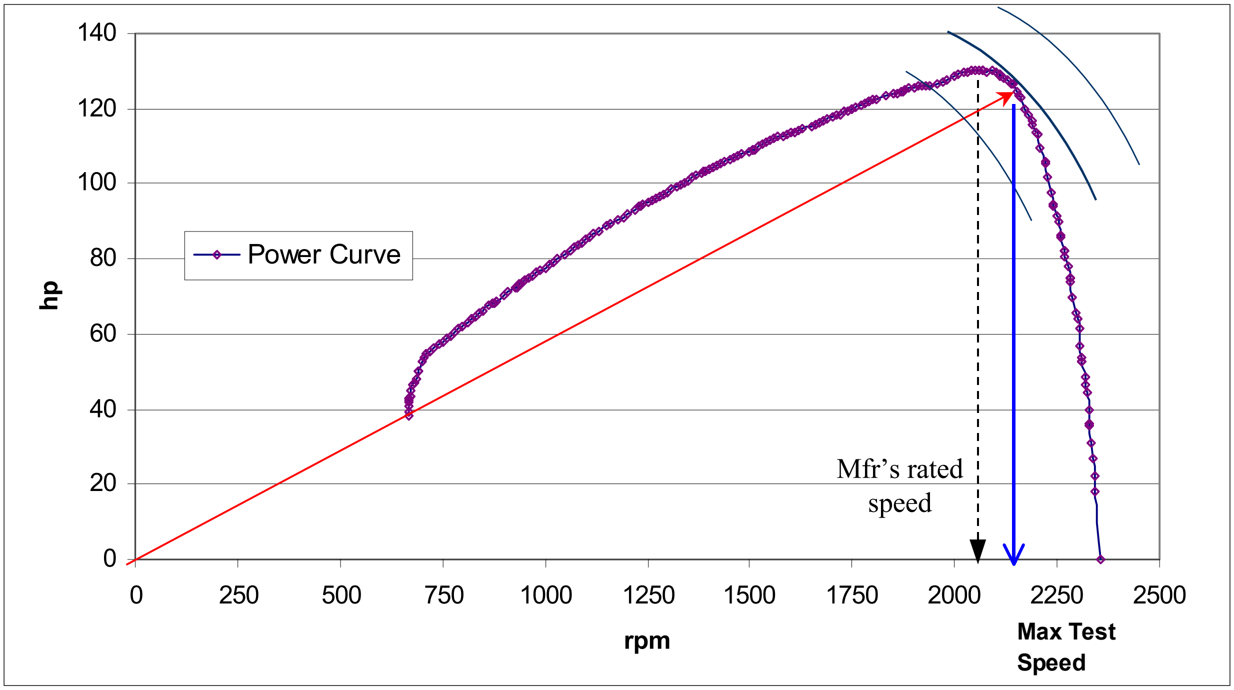
[CC] GCS is the speed value on the Maximum Achievable Power (MAP) curve of an engine at which the engine's speed is 50% of the measured rated power for that engine, after measured rated power has been passed on the MAP curve.

origin of the graph of engine's measured speed and power values. That farthest point on the curve is described as the point of maximum power achievable by the engine under study.

Figure 4.2-8
Maximum Test Speed Determination



4.2.6 Cycle Performance Regression Statistics

In assessing the nonroad transient duty cycles, ten nonroad diesel engines were exercised over the nonregulatory[162] nonroad duty cycles to assess emission impacts of each duty cycle, as well as to determine the ability of typical nonroad diesel engines to pass the existing highway cycle performance regression statistics. That data may be seen in a report from SwRI with an accompanying EPA summary of the results in the Memorandum to EPA Air Docket 2001-28 from Cleophas Jackson entitled "Nonroad Duty Cycle Regression Statistics." Subsequent analysis on the composite nonroad transient cycle was based on test cell data collected from testing at the National Vehicle and Fuel Emissions Laboratory and Southwest Research Institute, as well as through the European Commission's Joint Research Center (EC-JRC), and various engine manufacturers from the United States, Europe, and Japan.

4.2.7 Constant-Speed, Variable-Load Equipment Considerations

Some nonroad diesel engines operate in equipment that calls for constant engine speeds. Some examples of engines in this category of nonroad diesel equipment include pumps, electrical power generator sets (gen sets), pavement saws and cement mixers. While the operating speed in many cases is not truly constant, it is generally true that the unit's speed will vary little during operation. These types of equipment are more tolerant of changes in operating load than other more closely governed constant-speed nonroad applications. Some pieces of constant-speed equipment will be governed to a nominal “zero” variation in rpm during operation for critical operations such as maintenance of electrical power and refrigeration loads. For those engines designed to operate under less restrictive, more “transient” conditions, the Agency had proposed an alternative constant-speed, variable-load (CSVL) transient duty test cycle over which an engine manufacturer might operate their engines. The CSVL duty cycle was meant to capture emissions from these infrequent modes of operation. However, after a review of comments and a broader look at the wide range of applications embraced by the constant-speed, variable-load segment of the nonroad diesel equipment population, the Agency has chosen not to adopt a CSVL transient test cycle at this time. Instead, EPA, with all of its stakeholders in this regard, will map out a process of engine testing and analysis to better characterize constant-speed equipment in-use to design the most appropriate test cycle for the largest number of constant-speed engines. Consideration will also be given to addressing the operation of gen set applications as a potentially unique subset of this category. EPA undertakes this process with an eye to initiating a rulemaking which would lead to promulgation of a transient cycle for constant-speed engines before the Agency's 2007 Nonroad Technical Review.

4.2.7.1. Background on Cycle Considered

The CSVL transient test cycle was derived from EPA's Arc Welder Highly-Transient Torque nonroad application duty cycle. That cycle was developed on a direct-injection, naturally-aspirated, 30kW (40 hp) diesel arc welder engine, a constant-speed application running at variable load. The Highly-Transient Torque cycle, one of four arc welder cycles, is comprised of a single twenty-minute segment of all the real-time operating data collected on that engine.

While designed to control nonroad engines in a broad range of constant-speed applications, commenters noted that EPA’s proposed CSVL test cycle had an average speed which was lower than the speed which many manufacturers considered optimal for their constant-speed engines in-use. Further, EPA had received comments that many constant speed engines operated near or at their rated engine rpm during much of that engine's useful life, as with electrical generating sets in particular. EPA had proposed that these constant-speed engines, when tested in the laboratory with installed speed governors, be required to meet cycle statistics for engine load but not for engine speed. This relief was aimed at addressing the twin concerns that many engines operated at a significantly high percent of their rated speed much of the time in-use and had different degrees of engine speed variation during that operation.

Engine manufacturers raised additional design concerns for constant-speed engines required to meet emission standards over EPA’s proposed cycle. Their concerns generally focused on the fact that the cycle had relatively light engine loads and was derived from an arc welder powered by a naturally-aspirated engine. Commenters questioned the representativeness of the CSVL cycle for generators, which they claimed was a more common application within the constant-speed engine population than was an arc welder. A second issue involved the average load that would be experienced by an engine running on the CSVL test cycle. The average load factor of the normalized application cycle was approximately 25% of engine capacity. Manufacturers of constant-speed engines with significantly higher load factors on their engines during operation, upwards of 90% of normalized engine load at constant speed, argued that their engines would not be able to pass cycle-regression statistics for certification without significant re-tuning of the engines to operate over the CSVL cycle. Several commenters noted that some nonroad constant-speed engines with high brake-mean effective pressures (BMEP), or high rated-power constant-speed engines, were narrowly focused on providing higher power capability at a single speed while meeting emission requirements. These engines used larger, less-responsive turbochargers to achieve their requisite higher BMEP. Manufacturers pointed out that the smaller BMEP engine on which the arc welder cycles were developed was more responsive to torque changes than their high BMEP engines were designed to encounter. As such, these manufacturers felt that their engines would be penalized by the number and magnitude of torque changes in the CSVL cycle.

At the same time, however, the Agency shared engine manufacturers' concerns for creating a duty cycle that achieved emission reductions while appropriately modeling in-use operation of their engines. EPA would have find it unproductive to require an approach that lead merely to improvements in the operation and emissions of the engine under laboratory conditions which, were in turn unrelated to the engine's in-use operation. Based on the comments the Agency has received regarding the constant-speed, variable-load duty cycle, we intend to continue to work with all interested parties to develop a new constant-speed, variable-load duty cycle. The Agency envisions that any new test cycle would result in comparable stringency for ensuring effective in-use control, as does the current duty cycle developed for fully transient test characterization - EPA's NRTC test cycle.

4.2.7.2. Follow-on Constant-Speed Engine Testing and Analysis

In consultation with the Engine Manufacturers Association (EMA) and other stakeholders, the Agency will embark on a process with the nonroad engine and equipment manufacturers that will result in collection of additional engine operation data that will appropriately characterize the operation of nonroad diesel engines used in equipment in constant-speed applications. To ensure that the data collected is robust and applicable to most, if not all, segments of the nonroad equipment market, and to facilitate global technical regulations and eventual cycle harmonization, the Agency, manufacturers and other interested parties, in consultation with non-domestic governmental entities will work together to develop a plan that incorporates the following elements:

Define operation of a non-generator, non-transient equipment class:

– Target Equipment/Application Types[DD]

[DD]- When the arc welder application was originally considered for inclusion in the cycle generation effort, EMA endorsed EPA's choice of the arc welder as a constant speed application.

    - •air/gas compressors, pressure washers, water/irrigation pumps, oil field equipment, hydro power units, leaf blower/vacuums, shredders, bore/drill rigs, mixing equipment, pavement saws, arc welding sets, chippers/shredders/grinders, light plants/sign boards, tampers, rammers, and plate compactors, concrete/industrial saws, crushers/material handling equipment and refrigeration/AC equipment;
- – Engine Speed Range - anticipate EMA feedback
- – Power range
    - • 25 to 175 hp, 175-350 hp[EE], and 350 to 750 hp
- – Market Sectors
    - • construction, agriculture, maintenance/handling, pumps/welders

Define sample sizes, duration of "cycle" for application intercomparisons :

- – Number of pieces of equipment in each category
    - • Sufficient to discern significant differences in speed and load characteristics
- – Number of hours of operation per application per site
    - • Forty or more hours of operating data

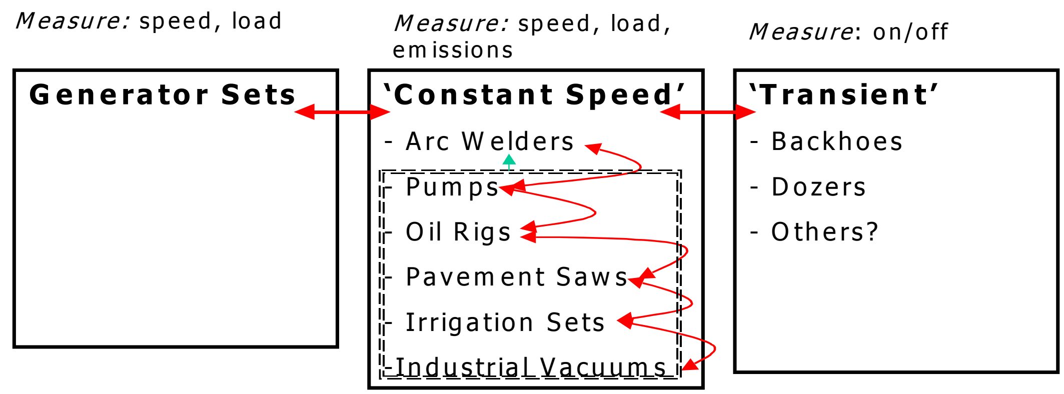
Define data collection parameters:

- – Speed
- – Load
- – Exhaust Temperature
- – Engine Oil Temperature (1st 20 minutes of engine on after 4 hours of engine off)
- – Engine Coolant Temperature (1st 20 minutes of engine on after 4 hours of engine off)

In addition to ensuring that the sampling plan addresses the issues outlined above, EPA will seek agreement among the stakeholders on the level of involvement of all parties in the data collection and generation, data reduction and analysis, and final cycle construction and assessment efforts. Initially, the logistical questions concerning program timing and duration of all parts of the data collection and eventual cycle development efforts would have to be charted and agreed upon by program participants. EPA expects that broad groupings of nonroad engines from various applications would then be compared between and among each other to determine whether particular applications differed in terms of speed and load operating characteristics (see Figure 4.2-9 below). One question which is particularly important is whether “constant speed” applications are similar to one another, but different than either transient or generator-type applications. As we move forward with the process of data collection and subsequent cycle generation, other interested parties, including the state of California, will also be invited to participate in these efforts. Future engine emission control technologies would need to be anticipated and considered for their impacts on nonroad equipment emissions.

[EE] The Agency's current data base for cold start operation includes construction equipment in the power range of 150 to 350 hp.

Figure 4.2-9



Engine Categories
with respect to Certification Cycles

Arrows represent examples of comparisons between applications and engine groups, to determine whether applications differ in terms of speed/load characteristics. An important question is whether the 'constant speed 'applications are similar to each other, but different from generators and 'Transient applications.'

4.2.8 Cycle Harmonization

4.2.8.1 Technical Review

One concern raised by the engine manufacturers was that the mapping method used to generate the real-world torque data introduced an error by no appropriately accounting for the impact of transient activity of the actual torque signal from the engine. The basis of the issue was primarily a torque signal in the field, based on the rack position, that may not have actually occurred had an in-line torque meter been employed. Two aspects of this warrant review. The first aspect of actual torque versus inferred torque. The second aspect of this issue is whether or not rack position or the demanded load is an appropriate metric for developing duty cycles representing real-world operation. To address the second issue in the context of responsiveness of a nonroad engine, it should be clear that, although feedback torque from the engine provides a clear signal of what was accomplished by the engine, it is not a fair metric of the demanded load. Given the fact that a typical operator or driver tends to demand a desired torque the engine's response to that demand, though not distinct, is a separate issue. It is this reasoning through which command cycles are generated. The command cycle represents the speed and load demanded of the engine. The engine's responsiveness can be addressed through performance statistics.

Engine manufacturers sought to address the first concern through a playback analysis that addressed the Iα correction as an offset to the commanded load signal. The playback approach would involve rerunning one of the engines (identical engine model) in the test cell over the defined duty cycle with the calculated Iα offset to measure torque using an in-line torque meter. Manufacturers provided the inertia data for their engines either used for cycle development or anticipated to be included in the testing program. The data provided by members of the Engine Manufacturers Association (EMA) may be seen in Table 4.2-9 and Table 4.2-10.

Table 4.2-9
Nonroad Diesel Engines Used for Cycle Generation

No.	Engine Mfg	Engine Model	Machine Mfg	Machine Model	Application	Rated Power (Kw)	Peak Torque (N m)	Rated Speed (RPM)	Low Idle (RPM)
1	Caterpillar	3204-D17	Caterpillar	Cat D4H	Crawler Tractor	85 peak	442	2200	800
2	Caterpillar	3114-D17	Caterpillar	Cat 446B	Backhoe Loader	76.8 peak; 70.8 rated	405	2200	800
3	Caterpillar	3408E - TA	Caterpillar	988F-II	Wheel Loader (2)	321		2100	850
4	Isuzu	A-6SD1 TQA	Hitachi	EX-300LC	Excavator High Power	161	834	2000	850
5	John Deere	6081	John Deere	JD 4960	Ag Tractor	186	970	2200	850
6	Mitsubishi	3066T	Caterpillar	Cat 320 Excavator	Excavator Low Power	95	641	1800	860
7	Perkins	'97 D3.152	Lincoln	97 'Shield-Arc' 250, K1283	Arc Welder	28		1725	800 (1)
8	Yanmar	'97 4TNE84	Daewoo	DSL-601	Skid Steer Loader	31	121	2800	800

Table 4.2-10
Engine Inertia Data Used for Iα Correction Calculation

No.	Engine Mfg	Engine Model	Total Inertia (Kg-m2)	Total Inertia (N-m-s2)	Engine Inertia (N-m-s2 = kg-m2)	Flywheel Inertia (N-m/s2 = kg-m2)
1	Caterpillar	3204-D17	1.7899	1.7899	0.2249	1.5650
2	Caterpillar	3114-D17	0.9770	0.9770	0.5550	0.4220
3	Caterpillar	3408E - TA	2.8637	2.8637	1.3147	1.5490
4	Isuzu	A-6SD1 TQA	7.5303	7.5303	2.8263	4.7040
5	John Deere	6081	2.4400	2.4400	0.5000	1.9400
6	Mitsubishi	3066T	0.9160	0.9160	0.2160	0.7000
7	Perkins	'97 D3.152	0.1083	0.1083	0.1083	
8	Yanmar	'97 4TNE84	0.2317	2.3629		

The correction that was undertaken by EPA and Southwest Research Institute (SwRI) used the following methodology. The original 3 Hz data set was used to correct the torque data rather than interpolated 1 Hz data to ensure the raw data were corrected to avoid error propagation within the 1 Hz scalar data.

1. Apply the Iα correction to calculate the new torque command.
2. Apply original technique to create 1 Hz raw command cycles using the cubic spline interpolation for the those cycles that were originally collected at 3.33 Hz.
3. Each resultant correct raw data duty cycle was then normalized using the Maximum Speed determination method (See Section 4.2.3).

4. Cycle segments for the Composite Nonroad Transient duty cycle were then reassemble from the component duty cycles.

The result of the correction, as conducted by SwRI, was that there were very small modifications to the most severe torque excursions. The peaks and valleys were trimmed slightly. The overall change in the cycle resulted in less than 0.5% correction, typically.

4.2.8.2 Global Harmonization Strategy

4.2.8.2.1 The Need for Harmonization

Given the increasingly global marketplace in which nonroad engines are sold, alignment of standards and procedures helps facilitate introduction of cleaner technology at lower across in multiple markets. Given the nature of the nonroad diesel market with a large number of very diverse product offerings and in some cases, small niche market volumes, the ability to design once for different markets helps reduce the costs, especially of the lower volume equipment models. While alignment of limit values may be a key component of harmonized regulations, alignment of test procedures, measurement protocols, and other aspects of certification and testing procedures help reduce the testing burden manufacturers will face when selling and distributing their products in multiple markets. Much of the development of new procedures and test methods has originated in the United States, Europe, and Japan. While other markets tend to adopt emission limits and procedures as a part of a more global process on a different time frame. Given the nature of regulatory and technological development, allowing the leading markets for which new technology will need to be introduced to have comparable protocols simply reduces the costs those markets will be forced to absorb. In any effort to utilize procedures in multiple regulatory arenas, care should be taken to include an assessment of equivalence and appropriateness. In so doing, both Europe and the United States conducted an assessment of real-world operation of nonroad diesel equipment. The data-collection effort in the United States started in 1995. The subsequent data-collection effort in Europe confirmed that, as expected, nonroad diesel activity in Europe was comparable.

In moving forward with a single test cycle for both Europe and the United States, and potentially a global nonroad diesel cycle, the basic framework for the cycle was agreed upon. In addition to the work initiated by the Agency in compiling a nonroad transient duty cycle, it was important to ensure that concerns about global suitability be addressed. The context used for this assessment in Europe was the existing European Transient Cycle (ETC). While this duty cycle was developed for highway diesel applications, it was seen as an adequate basis for which European industry and government staff could assess EPA's proposed Nonroad Transient Duty Cycle. Representatives from Japan's government and industry have periodically participated in this process as well; however, no such framework for comparison was requested for the evaluation process from any representative from Japan. Throughout the development of the duty cycle, industry representatives from the United States, Europe, and Japan have provided detailed technical input. In Table 4.2-11 shows early results presented by Deutz exercising a nonroad diesel engine over the EPA-generated Nonroad Transient Duty Cycle indicating an ability to pass cycle performance criteria with only a slight problem with the Torque Intercept statistic.

Table 4.2-11
Initial Deutz Data Submission for
EPA Nonroad Diesel Transient Duty Cycle (Nov. 13, 2000)

			Speed	Torque	Power
Standard error of estimate (SE)	measured	NRTC	56,48 rpm	7,58%	7,15%
		ETC	24,29 rpm	6,59%	5,67%
	tolerance		max 100 rpm	max 13%	max 8 %
Slope of the regression line (m)	measured	NRTC	1,010	0,925	0,968
		ETC	0,990	0,963	0,976
	tolerance		0,95 to 1,03	0,83 to 1,03	0,89 to 1,03
Regression coefficient (r^2)	measured	NRTC	0,996	0,958	0,973
		ETC	0,993	0,980	0,981
	tolerance		min 0,9700	min 0,88	min 0,91
Y intercept of the regression line (b)	measured	NRTC	18,01 rpm	30,10 Nm	3,62 kW
		ETC	17,67 rpm	5,80 Nm	0,62 kW
	tolerance		+/- 50 rpm	+/- 20 Nm	+/- 4 kW

red:	out of tolerance
green:	near to tolerance limit

4.2.8.2.2 Harmonization Methodology

The composite Nonroad Transient (NRTC) duty cycle developed by the Agency was used as the reference cycle for conducting subsequent development and testing work. It was originally introduced to the global regulatory community and engine industry in Geneva in June 2000. After an on-going dialogue with industry in the United States and Europe, additional modifications were suggested by the European Commission based on manufacturer concerns with their ability to meet test cell performance statistics with this duty cycle. In September 2001, it was decided by a joint European, American, and Japanese government and industry workgroup that the Joint Research would use the then "candidate" cycle to conduct additional changes commensurate with the goal of not allowing the instantaneous transient speed and torque changes to be greater than those experienced within the European Transient Cycle (ETC). Using a Bessel filtering algorithm, the cycle was then modified by the EC-JRC to meet the ETC target of 23% of torque events faster than 4 seconds. The two cycles may be seen on a time basis in Figures 4.2-11 and 4.2-10. The average load and average speed of each cycle are shown in Table 4.2-12. The speed characteristics of the original cycle were similar to the speed characteristics of the ETC. This is not an indication that the speed trace was identical, but rather that the maximum instantaneous speed changes of the NRTC were similar to the maximum instantaneous speed changes of the ETC.[FF]

[FF] Memorandum to EPA Air Docket A-2001-28 from Cleophas Jackson, Report from the JRC entitled "Contribution to the NRTC Development Based on Test Data Supplied by Engine Manufacturers," February 26, 2001.

Figure 4.2-10
EPA Nonroad Transient Test Cycle as of March 2001

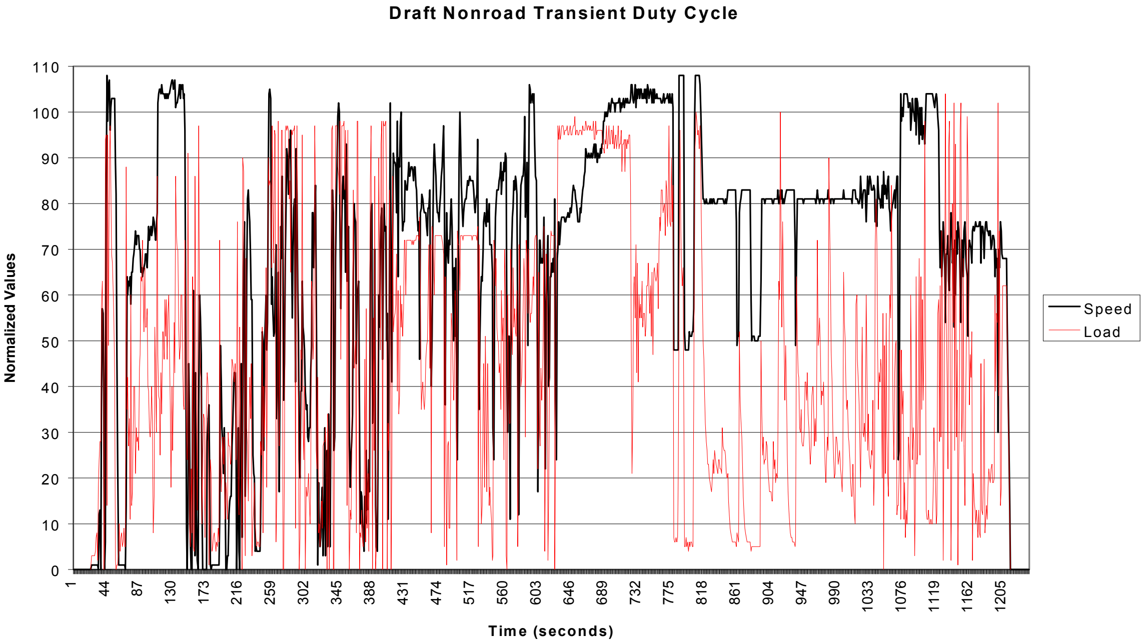


Table 4.2-12
Comparison of Cycle Averages

Duty Cycles	Average Normalized Speed	Average Normalized Torque
EPA NRTC	63%	47%
JRC Modified NRTC	68%	39%

The following figures 4.2-12 through 4.2-16 describe the JRC Modified NRTC with respect to speed and load and the transient nature of the cycle. This will be contrasted with the same characteristics of the EPA- generated NRTC. The JRC modified NRTC was also known as the San Antonio cycle or the JRC.

Figure 4.2-11
JRC Nonroad Transient Test Cycle after Bessel Filtering

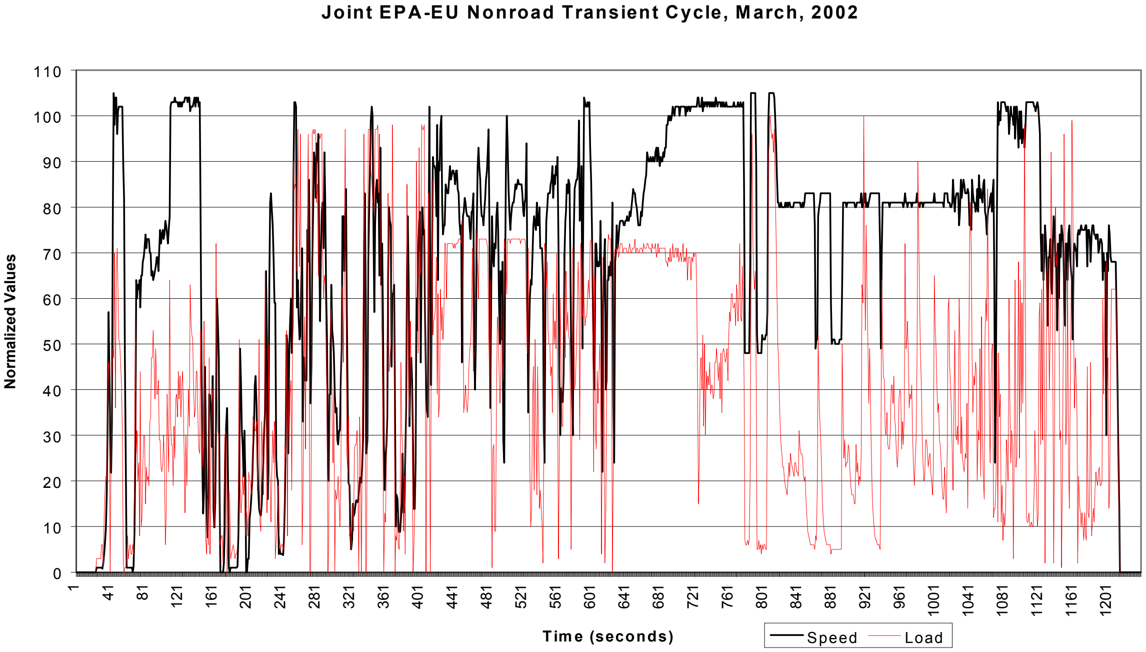


Figure 4.2-12

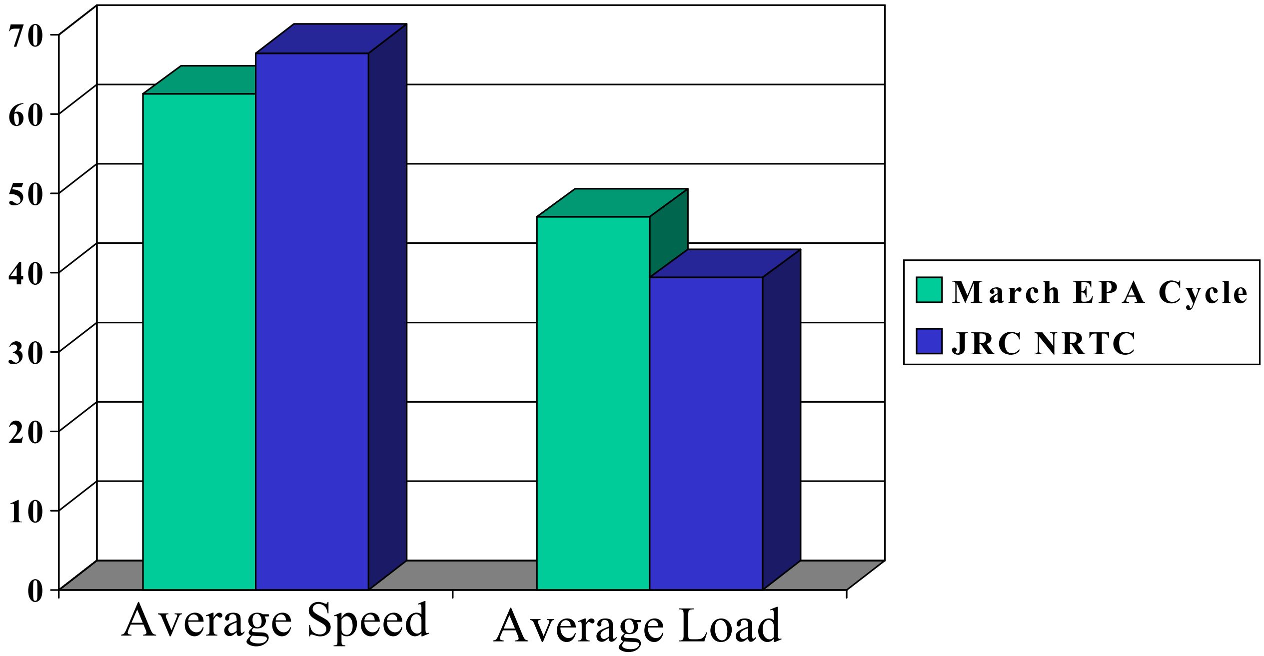


Figure 4.2-13
Average Speed Changes of the EPA NRTC

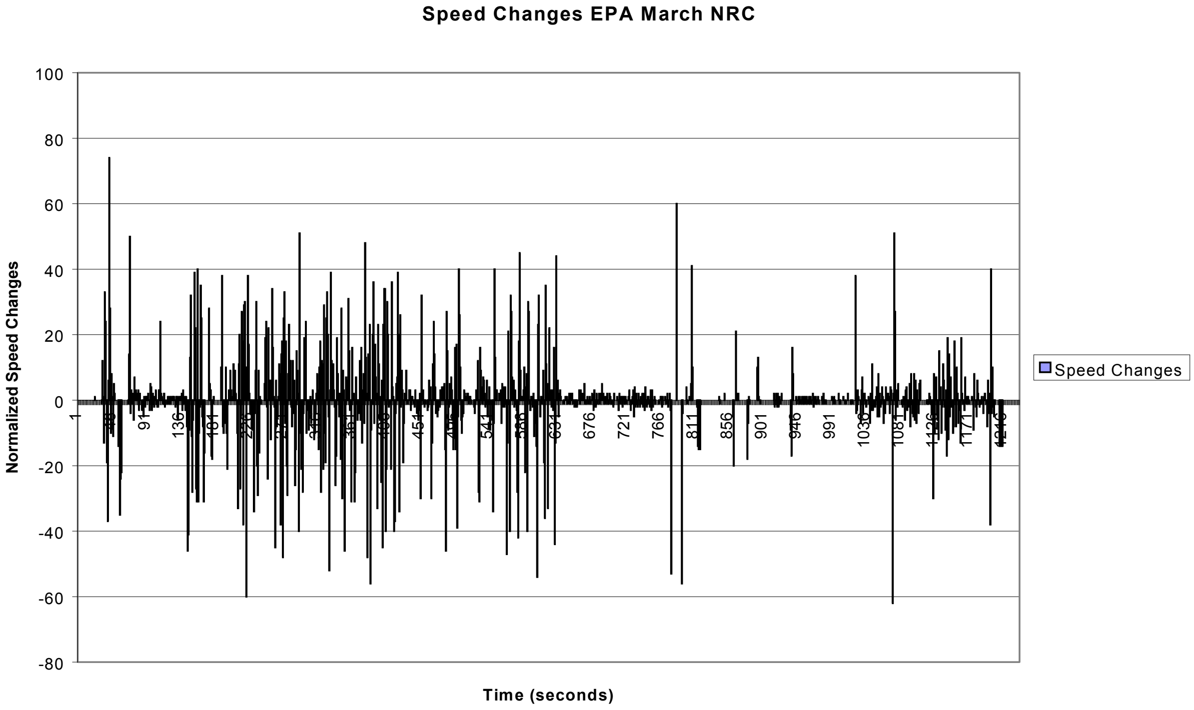


Figure 4.2-14
Average Speed Changes of JRC Modified NRTC

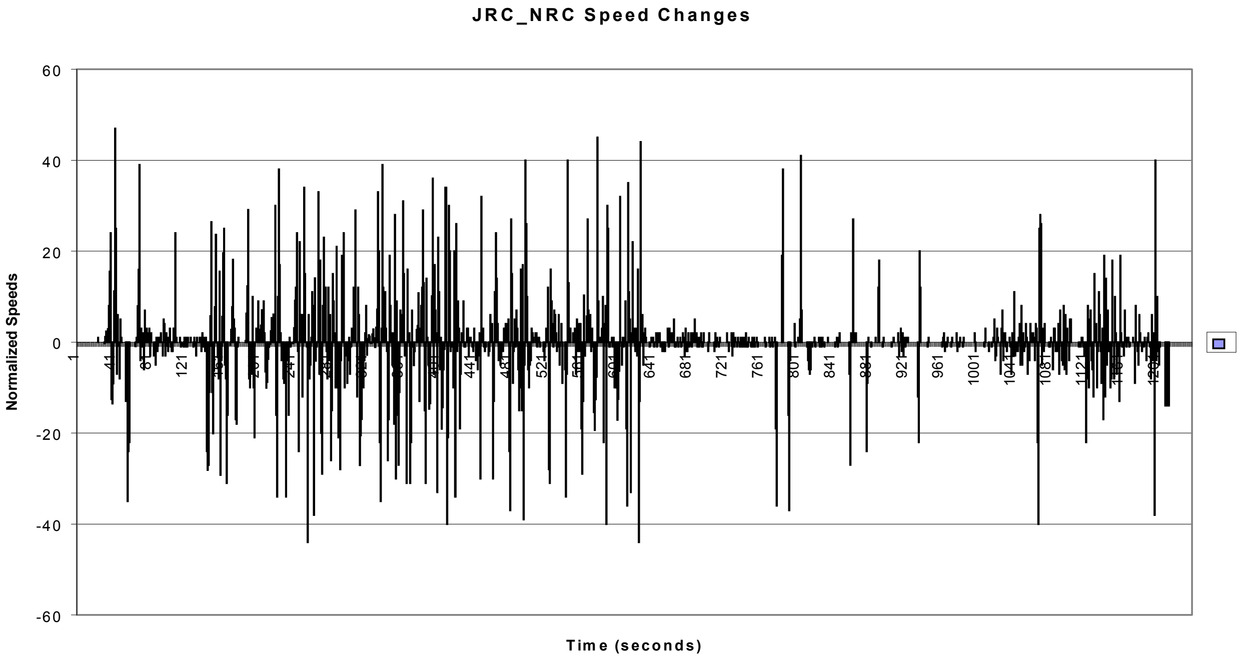


Figure 4.2-13
Average Speed Changes of the EPA NRTC

Figure 4.2-15
Average Load Changes of JRC Modified NRTC

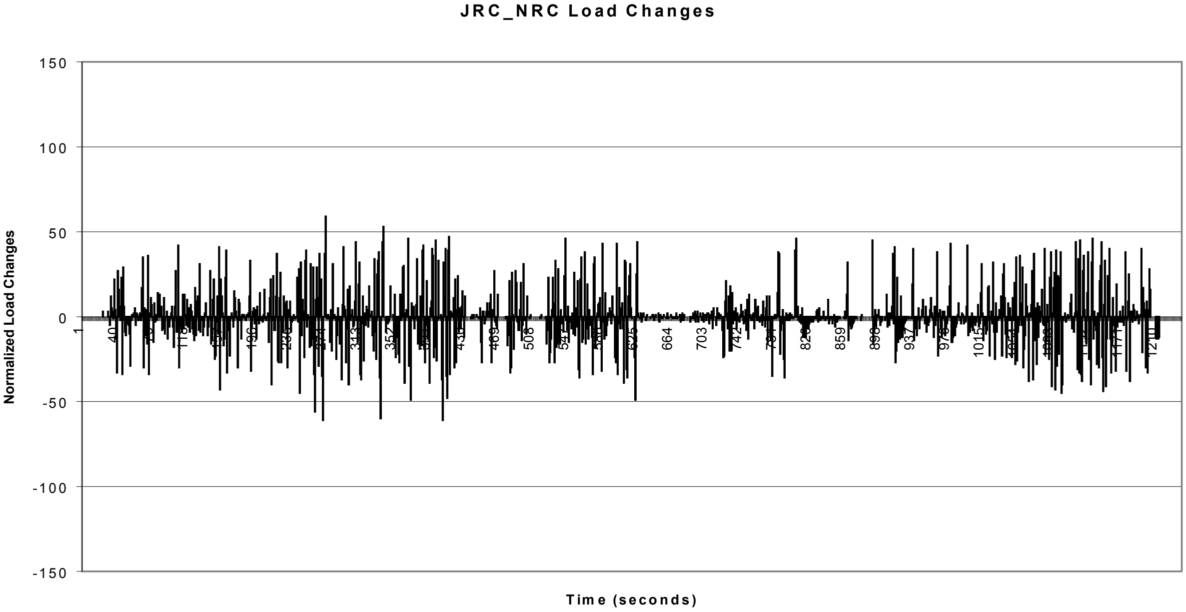
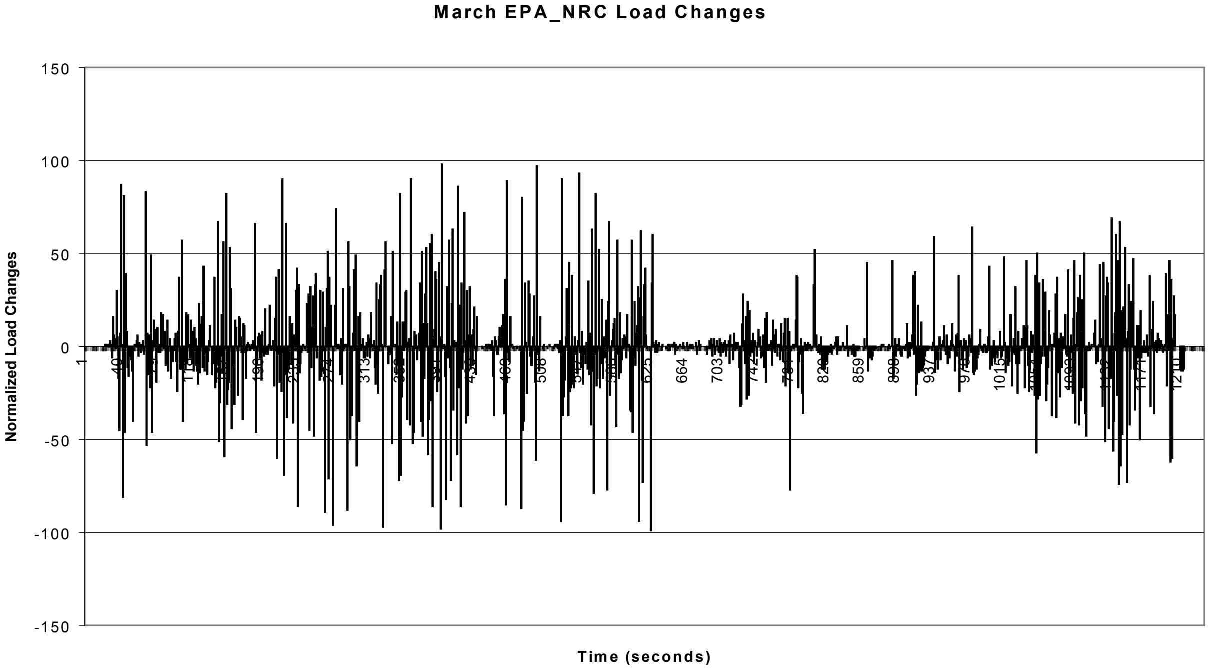


Figure 4.2-16
Average Load Changes of the EPA-Generated NRTC



Given the modifications in the duty cycle, it was critical to assess the impact on the emission signature of the cycle. Table 4.2-13 shows that the emission signature, based on tests at the National Vehicle and Fuel Emissions Laboratory and at Southwest Research Institute as of May 2001, were relatively unchanged.

Table 4.2-13
Emissions and Cycle-Regression Performance Summary as Presented to the Workgroup on June 1, 2001, at the Joint Research Center in Ispera, Italy

Caterpillar 3508	**NOx**		**PM**		**Speed**							
Heavy Duty	**Mean**	**Standard Dev.**	**Mean**	**Standard Dev.**	**SE**		**M**		**R2**		**B**	
850 hp					**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**
Sep-00	10.30	0.02	0.20	0.004	79	1.41	1.03	0	0.949	0.001	-35	2.83
Mar-01	10.14	0.03	0.20	0.002	90	2.12	1.01	0.01	0.939	0.002	-9	3.54
JRC	11.198	0.03	0.20	0.004	68	0.71	1.03	0.00	0.962	0.001	-33	1.41

Torque								**Power**							
SE		**M**		**R2**		**B**		**SE**		**M**		**R2**		**B**	
Mean	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**
15	0	0.8	0	0.734	0.004	184	0	14	0	0.88	0	0.801	0.283	29.6	0.283
15	0	0.83	0.007	0.734	0.001	188.5	3.54	14	0	0.9	0	0.804	0.002	29.5	1.273
12	0	0.91	0.007	0.765	0.001	56	1.41	11	0	0.95	0	0.823	0	6.1	0.141

Cummins ISB	**NOx**		**PM**		**Speed**							
Medium Duty	**Mean**	**Standard Dev.**	**Mean**	**Standard Dev.**	**SE**		**M**		**R2**		**B**	
					Mean	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**
Sep-00	3.76	0.01	0.08	0.001	54.7	24.62	0.987	0.011	0.987	0.010	30.0	3.11
Mar-01	3.79	0.03	0.08	0.003	68	18.67	0.98	0.01	0.982	0.008	32	14.48
JRC-Max Spd	4.06	0.03	0.08	0.002	66	6.22	0.98	0.00	0.978	0.005	34	5.23
JRC-ETC Pk Spd	4.09	0.01	0.08	0.009	50	8.15	0.98	0.00	0.991	0.003	37	6.68

Torque								**Power**							
SE		**M**		**R2**		**B**		**SE**		**M**		**R2**		**B**	
Mean	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**	**Mean**	**Std dev.**
69.7	2.06	0.955	0.011	0.930	0.005	30.0	3.11	14.8	0.35	0.979	0.009	0.943	0.003	4.5	0.361
67.5	3.12	0.96	0.008	0.933	0.007	26.7	2.64	14.9	0.61	0.981	0.007	0.943	0.005	4.2	0.404
43.5	0.14	0.981	0.002	0.960	0.001	12.0	0.354	9.9	0.21	0.994	0.002	0.961	0.002	1.6	0.141
48.4	2.63	0.985	0.00306	0.946	0.005	11.6	1.386	10.0	0.68	0.999	0.002	0.958	0.005	1.6	0.265

As noted earlier, EPA modified the cycle between September 2000 and March 2001 to address concerns related to the Arc Welder duty cycle segment of the NRTC. The modified EPA version was provided to JRC in early 2001, for its subsequent analysis; however, not knowing the impact of the changes, all three cycles were tracked until the September 2000 version was eventually dropped.

In subsequent data submitted by engine manufacturers through December 5, 2001, the validity of the cycle from an emission signature and test cell feasibility perspective was evidenced. Data submitted by Yanmar, Daimler Chrysler, Deere, Caterpillar, and Cummins to the JRC summary and analysis effort gave clear indication that the duty cycle could be run across multiple power ranges with good cycle performance results and consistent emission signature.[GG] The cycle performance regression statistics would be defined based on nonroad engines, rather than adopting the highway performance statistics without review. The concern raised by Daimler Chrysler was that the cycle-regression statistics needed to be sufficiently

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[GG] Memorandum from Cleophas Jackson to EPA Air Docket A-2001-28, # II-A-170 "JRC December 5, 2001, Report on Cycle Performance."

stringent to ensure an accurate and repeatable emission signature was achieved.[HH] With the conclusion of the international workgroup's efforts, EPA considered the cycle to be complete. In an effort to facilitate the use of the cycle as a global nonroad transient duty cycle, it has been introduced into GRPE as a candidate cycle for the global compendium. The ISO procedure 8178-11 is being drafted to address test cell procedures for exercising an engine over the duty cycle. New limit values for the cycle performance regression statistics were developed as a part of this process and may be seen in Table 4.2-14[II].

Table 4.2-14
NRTC Cycle-Regression Statistics[163]

	Speed [rpm]	Torque [N·m]	Power [kW]
Standard Error of Estimate of Y on X	100 rpm	13% of power map maximum engine torque	8% of power map maximum
Slope of the regression line, m	0.95 to 1.03	0.83-1.03 (hot) 0.77-1.03 (cold)*	0.89-1.03 (hot) 0.87 -1.03 (cold)[a]
Coefficient of determination, r^2	min 0.970	min 0.8800 (hot) min 0.8500 (cold)*	min 0.9100 (hot) min 0.8500 (cold)
Y intercept of the regression line, b	± 50 rpm	± 20 N·m or ± 2.0% of max engine torque, whichever is greater	± 4 kW or ± 2.0% of max power, whichever is greater

[a] Under consideration by ISO workgroup.

4.2.9 Cold-Start Transient Test Procedure

Nonroad diesel engines typically operate in the field by starting and warming to a point of stabilized hot operation at least once in a workday. Such "cold-start" conditions may also occur at other times over the course of the workday, such as after a lunch break. We have observed that certain test engines, which generally had emission-control technologies for meeting Tier 2 or Tier 3 standards, had elevated emission levels for about 10 minutes after starting from a cold condition. The extent and duration of increased cold-start emissions will likely be affected by changing technology for meeting Tier 4 standards, but there is no reason to believe that this effect will lessen. In fact, cold-start concerns are especially pronounced for engines with catalytic devices for controlling exhaust emissions, because many require heating to a "light-off"

[HH] Memorandum from Cleophas Jackson to EPA Air Docket A-2001-28, ######*Nonroad Transient Duty Cycle Development Report*, Cornetti, G., Hummel, R., and Jackson, C.

[II] The deletion point criteria for engine manufacturers to use in deriving these cycle performance statistics may be found in regulations at 40 CFR Part 1039, subpart F and Part 1065.530. See also cycle performance criteria discussions in Memorandum from Cleophas Jackson to EPA Air Docket A-2001-28, ###### *Nonroad Transient Duty Cycle Development Report*, Cornetti, G., Hummel, R., and Jackson, C. and Memorandum from Matthew Spears to EPA Air Docket A-2001-28, ##### "Test Point Omission Criteria for Determining Cycle Statistics".

or peak-efficiency temperature to begin working. EPA's highway engine and vehicle programs, which increasingly involve such catalytic devices, address this by specifying a test procedure that first measures emissions with a cold engine, then repeats the test after the engine is warmed up, weighting emission results from the two tests for a composite emission measurement.

In the proposal, we described an analytical approach that led to a weighting of 10 percent for the cold-start test and 90 percent for the hot-start test. Manufacturers pointed out that their analysis of the same data led to a weighting of about 4 percent for cold-start testing and that a high cold-start weighting would affect the feasibility of the proposed emission standards. Manufacturers also expressed a concern that there would be a big test burden associated with cold-start testing.

Unlike steady-state tests, which always start with hot-stabilized engine operation, transient tests come closer to simulating actual in-use operation, in which engines may start operating after only a short cool-down (hot-start) or after an extended soak (cold-start). The new transient test and manufacturers' expected use of catalytic devices to meet Tier 4 emission standards make it imperative to address cold-start emissions in the measurement procedure.[JJ] We are therefore adopting a test procedure that requires measurement of both cold-start and hot-start emissions over the transient duty cycle, much like for highway diesel engines. We acknowledge that limited data are available to establish an appropriate cold-start weighting. For this final rule, we are therefore opting to establish a cold-start weighting of 5 percent. This is based on a typical scenario of engine operation involving an overnight soak and a total of seven hours of operation over the course of a workday. Under this scenario, the 20-minute cold-start portion constitutes 5 percent of total engine operation for the day. Section 4.1.2.3.3 above addresses the feasibility of meeting the emission standards with cold-start testing. Regarding the test burden associated with cold-start testing, we believe that manufacturers will be able to take steps to minimize the burden by taking advantage of the provision that would allow for forced cooling to reduce total testing time.

We believe the 5-percent weighting is based on a reasonable assessment of typical in-use operation and it addresses the need to design engines to control emissions under cold-start operation. We believe cold-start testing with these weighting factors will be sufficient to require manufacturers to take steps to minimize emission increases under cold-start conditions. Once manufacturers apply technologies and strategies to minimize cold-start emissions, they will be achieving the greatest degree of emission reductions achievable for those conditions. A higher weighting factor for cold-start testing will likely not be more effective in achieving in-use emission control.

However, given our interest in controlling emissions under cold-start conditions and the relatively small amount of information available in this area, we intend to revisit the cold-start weighting factor for transient testing in the future as additional data become available.

[JJ] Note that the cold-start discussion applies only to engines that are subject to testing with transient test procedures. For example, this excludes constant-speed engines and all engines over 750 hp.

Additionally, as the composite transient test represents a combination of variable-speed and constant-speed operations, we would consider operating data from both of these types of engines in evaluating the cold-start weighting. We will apply the same cold-start weighting, as well, when we adopt a transient duty cycle specifically for engines certified only for constant-speed operation.

The planned data-collection effort will focus on characterizing cold-start operation for nonroad diesel equipment. The objective will be to reassess, and if necessary, develop a weighting factor that accounts for the degree of cold-start operation so that in-use engines effectively control emissions during these conditions. As we move forward with this investigation, other interested parties, including the State of California, will be invited to participate. We are interested in pursuing a joint effort, in consultation with other national government bodies, to ensure a robust and portable data set that will facilitate common global technical regulations. This effort will require consideration of at least the following factors:

- What types of equipment will we investigate?
- How many units of each equipment type will we instrument?
- How do we select individual models that will together provide an accurate cross-section of the type of equipment they represent?
- When will the program start and how long will it last?
- How should we define a cold-start event from the range of in-use operation?

We expect to complete our further evaluation of the cold-start weighting in the context of the 2007 Technology Review, if not sooner. In case changes to the regulation are necessary, this timing will allow enough time for manufacturers to adjust their designs as needed to meet the Tier 4 standards.

4.2.10 Applicability of Component Cycles to Nonroad Diesel Market

In the 1997-1998 time frame, we started to pursue application-specific operating duty cycles that could be normalized for laboratory testing of nonroad diesel engines. With a standardized set of operating duty cycles, we would have a basis upon which to compare the brake-specific emission rates of nonroad engines, both within and across power categories, or bands. These cycles became the component cycles of the NRTC cycle. The choice of the seven nonroad component application duty cycles was based on the frequency of finding engines of that particular mode of operation in the nonroad population and summing those with engines/equipment doing related work. Agricultural tractors were seen to have operations generally similar to combines and off-highway trucks in addition to tractors. Arc welders represented the broad group of constant-speed applications. The backhoe-loader group included most of the lawn/garden/commercial turf tractors, commercial lifts and sweepers. The crawler/dozer application matched with other dozer, grader and scraper applications. Rubber-tire loaders were found to be similar to industrial and rough terrain forklifts, aircraft support and forestry equipment. Skidsteer loaders were seen, at the time, as a unique application/category. Finally, excavators and cranes were grouped together as similar applications. In time, the seven base nonroad equipment applications, agricultural tractor, arc welder, backhoe loader, crawler-dozer, excavator, rubber-tire loader and skidsteer loader were characterized for their daily operations and engine duty cycles were constructed for each type of work.

4.2.10.1 Market Representation of Component Cycles

The determination of which cycles best represent the nonroad equipment population in the United States was aided by an analysis of the our nonroad equipment population database.[164] Our source of data placed the total 1995 nonroad equipment population figure at 7,100,113 units in the United States. The population broke out into at least 59 different equipment applications, or specific work categories. Agricultural tractors held the largest percentage by far at approximately 34% of units. Constant-speed applications like generating sets, A/C and refrigeration units comprised a further 14%. Of the remaining pieces of the nonroad equipment, another 11% of the total population were constant-speed engines like welders, air compressors and irrigation rigs. Commercial lawn and garden equipment made up an additional 7.5% of all units, with combines, backhoe and skidsteer loaders at 12%, each application adding a further 4% to the total population. In the approximately 20% of units remaining, rubber-tire loaders and crawler-dozers constituted 6% of all nonroad units, each contributing 3% to the nonroad population. Excavators and cranes comprised a little more than 2% of the total equipment population. The seven component application classesalone covered 51% of all nonroad equipment units. When "related" nonroad applications were grouped with the original seven applications, over 95% of the nonroad equipment population was represented by the component applications.

4.2.10.2 Inventory Impact of Equipment Component Cycles

When EPA created an emission distribution from its database according to a list of the seven nonroad applications used to create the NRTC duty cycle, those seven base applications accounted for 59 percent of regulated nonroad engine emissions (see Table 4.2-16).

Table 4.2-16
Emissions Attributable to Base Nonroad Applications

Application	Emission Distribution by Application
Ag tractor	34%
Welder	1%
Backhoe/loader	6%
Crawler	7%
Excavator	3%
R/T Loader	6%
Skid/steer	2%
Total	59%

4.2.10.3 Power and Sales Analysis

The nonroad equipment market is broad and varies in both range of power available and application, or intended use, of each piece of equipment. EPA's database was the source for the distribution of nonroad applications between the various engine power bands. Agricultural tractors, while accounting for fully a third of the nonroad equipment population, are built generally to smaller engine displacement specifications and so constituted only 20% of total nonroad power. With similar equipment applications included, the equipment equipped with engines that have power or displacement similar to that of agricultural tractors approaches 30 percent. Backhoe loaders, crawler dozers and rubber-tire loaders together accounted for 12 percent of the total power in the nonroad population and, with similar applications included, accounted for approximately 35 percent of total nonroad power. The last three cycle component applications—excavators, skidsteer loaders and arc welders, with arc welders and like equipment generally falling under 50 hp—constitute only 8 percent of total nonroad power. However, because small constant-speed engines exist in numerous applications, they also constitute a large number of discrete units in the nonroad population. This helps to explain their relatively large contribution (18%) as a group of similar applications to total nonroad power. Taking the sum of power represented by all applications similar to the seven component equipment applications found in the NRTC cycle, we have represented equipment operations and engine displacements and, by analogy, in-use operations of 91% of nonroad equipment units.

4.2.10.4 Broad Application Control

Aggregating all those equipment classifications whose operating characteristics were similar to the seven NRTC component cycles for their emission contributions, we found that the composite nonroad cycle covered emissions from almost 96% of the documented applications in the nonroad equipment population (see Table 4.2-17).

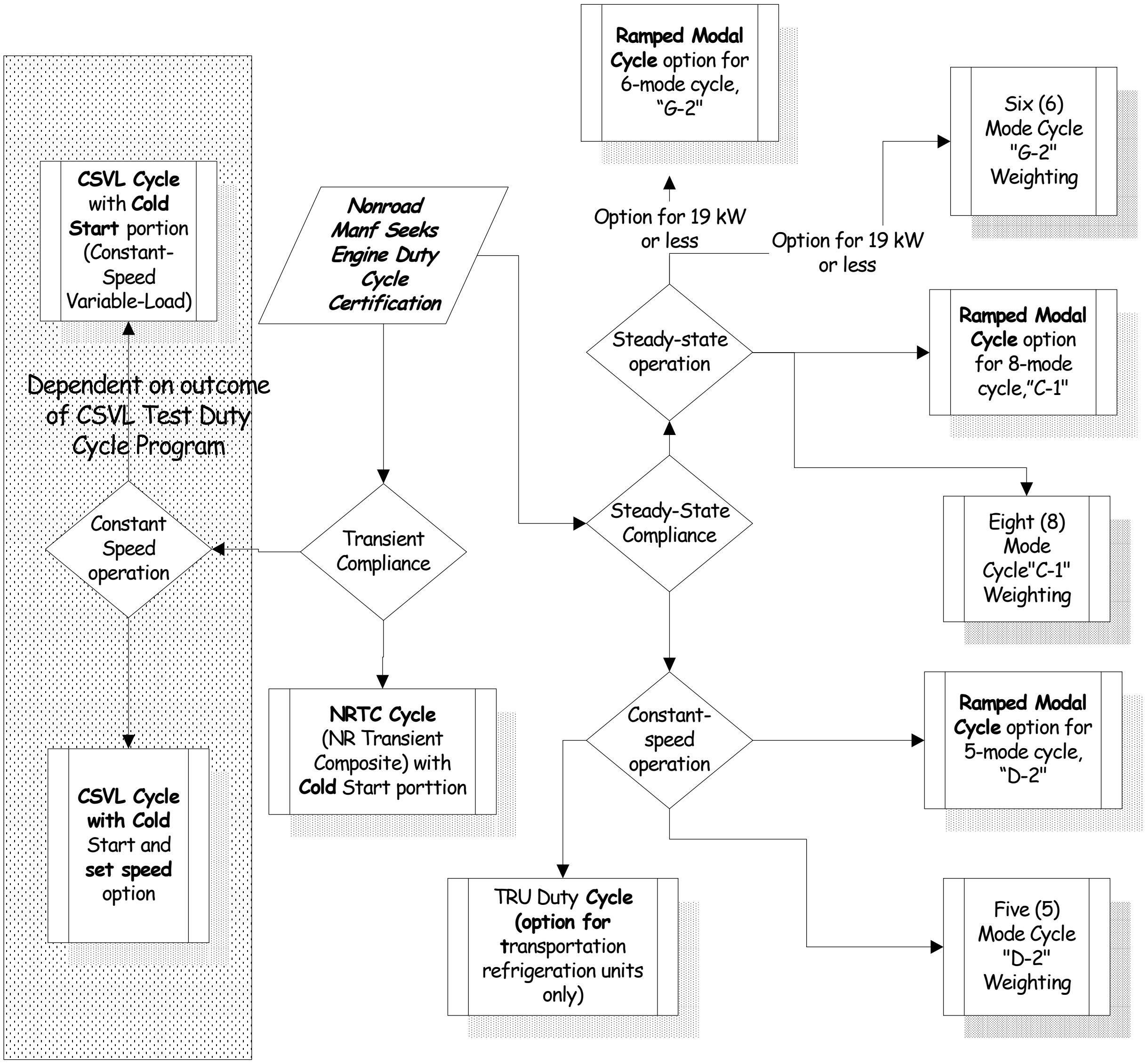
Table 4.2-17
Similarities Among Various Nonroad Equipment Applications

Application	Other Applications with Similar Operating Characteristics	Emission Distribution	Cycle characterization
Ag tractor	Combine Off-Hwy Tractor Off-Hwy Truck	38.4%	Heavy-load operation along governor/lug curve
Welder	Air Compressors Gas Compressors Generators Pumps Bore/Drill Rigs Cement Mixers Chippers/Grinders Concrete/Ind. Saw Crush/Proc. Equip Hydr. Power Unit Irrigation Sets Leaf Blow/Vacs Lt Plants/Signal Board Oil Fld Equip. Plate Compactors Pressure Washers Refrigeration/AC Shredder	25.2%	Transient loads at tightly governed rated speeds
Backhoe/loader	Aerial Lifts Comm. Turf Scrub/Sweeper Front Mowers Lawn/Grdn. Tractor Rear Eng. Rider Specialty carts Terminal Tractor	13.5%	Widely varying loads and speeds, weighted toward lighter operation; most like highway operation
Crawler	Graders R/T Dozer Scrapers Trenchers	5.7%	Widely varying loads and speeds, weighted toward heavier operation
Excavator	Cranes	2.4%	Transient loads at loosely governed rated speed
R/T Loader	Aircraft Support Forest Equip Forklifts Rough Trn Fork.	6.7%	Stop and go driving with widely varying loads.
Skid/steer	—	3.6%	Widely varying loads at different nominally constant-speed points
Total		95.5%	

4.2.11 Final Certification Cycle Selection Process

Figure 4.2-18 outlines the process by which a manufacturer of a particular nonroad diesel engine might approach certification using the nonroad transient and steady-state test requirements (NTE certification requirements have been deliberately omitted from this discussion to simplify the presentation).

Figure 4.2-18
NR Diesel Engine Transient and Steady-State Testing Requirements



4.3 Steady-State Testing

Recognizing the variety of both power classes and work applications to be found within the nonroad vehicle and engine population, EPA will retain current Federal steady-state test procedures for nonroad engines. The steady-state duty cycle applicable in each of the following categories: 1) nonroad engines 25 hp and greater; 2) nonroad engines less than 25 hp; and 3) nonroad engines having constant-speed, variable-load applications, (e.g., generator sets) will remain, respectively, the 8-mode cycle, the 6-mode cycle, and the 5-mode cycle.[KK] Manufacturers are required to meet emission standards under steady-state conditions in addition to meeting any emission standards under transient test cycle requirements. Steady-state test cycles are needed so that testing for certification will reflect the broad range of operating conditions experienced by these engines. A steady-state test cycle represents an important type of modern engine operation, in power and speed ranges that are typical in-use. The mid-to-high speeds and loads represented by present steady-state testing requirements are the speeds and loads at which these engines are designed to operate for extended periods for maximum efficiency and durability. Manufacturers would perform each steady-state test following all applicable test procedures detailed in regulations at 40 CFR Part 1039, subpart F, e.g., procedures for engine warm-up and exhaust emissions measurement. The testing must be conducted with all emission-related engine control variables in the maximum NOx-producing condition which could be encountered for a 30 second or longer averaging period at a given test point. Details concerning the three steady-state procedures for nonroad engines and equipment can be found in regulations at 40 CFR 1039.505 and in Appendices I-III to Section 1039 which follow that section, one for each cycle.

4.3.1 Ramped Modal Cycle

4.3.1.1 Introduction and Background

In response to manufacturers' concerns for the potential of some PM trap-equipped diesel engines to exhibit highly variable emissions under current emission test cycles, EPA has developed ramped modal versions of its steady-state certification duty cycles. These ramped modal cycle emission tests will reliably and consistently report steady-state emissions from PM trap and other emission control hardware-equipped nonroad engines.

For all the laboratory- based steady-state testing currently specified in 40 CFR Part 89, EPA has determined that any certification steady-state test cycle may be run as a ramped modal cycle (RMC). A RMC consists of the same series of steady-state test modes, but they are connected to one another by gradual ramps in engine speed and/or torque. However, the mode order is rearranged so as to alternate between high- and low-torque modes. In a RMC, the steady-state modes are connected with linear speed and torque transitions. The difference is that these transitions are sampled as part of the test. In other words, emissions sampling would start at the beginning of a RMC and would not stop until the last mode of the cycle is completed.

Instead of using weighting factors for each steady-state mode, a RMC specifies different time durations for each mode. Time durations are proportioned to weight each mode and transition to reflect the exact original ISO steady-state test weighting factors upon which the certification

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[KK] The three certification steady-state test cycles are similar to test cycles found in International Standard ISO 8178-4:1996 (E) and remain consistent with the existing 40 CFR Part 89 steady state duty cycles.

testing is based. The information and test cycle tables needed to run a certification steady-state test cycle as a RMC are given in 40 CFR Section 1039.505(a)(2). Refer to 40 CFR Part 1039, subpart F for the procedures required for transforming and running a particular test cycle on a specific engine.

Because a RMC weights individual modes by the amount of time spent at each mode, we considered the effect of a RMC's total test time on emissions. Based on the RMC data presented in this section, we concluded that if insufficient time was spent in an individual mode, the mode would not adequately represent the steady-state condition that was intended. This effect was exaggerated when engines with aftertreatment systems were tested. By inspecting data from individual modes, we determined that emissions differences between a RMC and its respective certification steady-state test cycle occurred primarily when exhaust temperatures between the two cycles differed greatly.

As mentioned earlier in this section, the modes in the RMC are intentionally arranged to alternate between high- and low-torque modes. This results in more moderate and repeatable aftertreatment temperatures overall. However, in some cases, more time in certain modes would have helped to achieve exhaust temperatures over a RMC that were more representative of exhaust temperatures for typical steady-state cycles.

The appropriate total time for the RMC was in part determined from testing of a diesel engine equipped with both a NO_x adsorption catalyst and PM trap exhaust emission controls, which will be described in this section. Based on the number of modes in a given steady-state cycle, we determined that twenty minutes is an appropriate total time for a RMC that has five or fewer steady-state modes. Twenty minutes is also an appropriate minimum time for collecting an adequate PM sample from an engine certified to a PM standard less than 0.05 g/kW-hr. For which has six to ten modes, thirty minutes is an appropriate total time. Thirty minutes ensures that the lightly weighted modes on the RMC have adequate time to approach the same exhaust temperatures achieved when the test is run as a steady-state test. For a RMC with ten to fourteen modes, forty minutes is an appropriate total test time. A forty-minute length ensures that a sufficient amount of the total test time was spent at steady-state rather than in transition from one mode to the next. For all of the RMCs, these times ensure that less than 10% of the total time is spent in transition from one steady-state mode to the next.

There are a number of advantages to running a steady-state test as a RMC. The current procedure for conducting a steady-state test allows emission sampling periods as short as the last minute of each mode.[165] Discrete aftertreatment regeneration events, NO_x and SO_x regeneration for NO_x adsorption catalysts, forced PM regeneration for PM traps, etc., typically cause short-duration sharp increases in NO_x, HC and PM emissions. Thus, it may be challenging to gather good, repeatable emissions from the current steady-state procedures since a regeneration event may or may not be sampled in a given mode. For sampling low concentrations of PM, this inconsistency is exaggerated because the short sample time per mode may not provide enough PM sample to weigh in a repeatable way. Furthermore, without specific start and stop times for sampling each mode, an anticipated regeneration event may be intentionally or unintentionally included or excluded. With a RMC, this variability is removed by requiring emissions sampling over the entire cycle.

There are other advantages to running a steady-state test as a RMC. The RMC reduces the number of sampling system starts and stops. This is significant at low emission standards when considering that a previous mode's emissions may be incorrectly included in the next mode due to an unavoidable dead volume in a sampling system. The longer sampling period of a RMC also increases the mass of the PM sampled. This is extremely significant because the PM standard already approaches the minimum detection limits for many current PM microbalances.

The RMC also enables the use of batch sampling systems, such as bag samplers. This is an advantage because batch sampling systems are generally capable of quantifying lower levels of pollutants with less uncertainty than continuous sampling systems at low emission concentrations. This may be due to:

1. Gas analyzer zero-drift over time can be a much larger percentage of the measured value for continuous measurements at continuous low average emission concentrations. This is much less of an issue with batch measurements at low concentrations, since they can conduct a zero and span operation immediately preceding the concentration measurement.

2. Zero-drift and transient response of the NO_x analyzer from engines using high-capacity NO_x-adsorption catalysts can be a significant challenge for continuous measurement systems. For some modes of operation, NO_x emissions are truly at, or very close to, zero during adsorption with a rapid spike in NO_x emissions during regeneration. Covering the full dynamic range requires:

    a. automatic range switching to allow measurement on a low-concentration analyzer range when NO_x is near zero during adsorption and switching to a higher range to catch the NO_x spike during regeneration, accepting the uncertainty introduced from loss of data during the short duration needed to accomplish range switching; or

    b. operating on a single higher concentration analyzer range and accepting the uncertainty and increased zero-drift introduced at low concentrations during adsorption; or

    c. operating on a single lower concentration analyzer range and accepting loss of data that is "clipped" when the analyzer signal saturates during regeneration.

    Batch-sampled NO_x can be measured using a single analyzer range appropriate for the measured concentration and the same sample can be measured repeatedly over more than one range using the same analyzer. Thus, repeat measurements may be utilized to ensure an accurate measurement at the lowest possible range.

3. During a continuous measurement, each instantaneous emission concentration measurement has a level of uncertainty associated with it that propagates from each collected data point to the final integrated concentration. By contrast, a batch-sampled emission measurement is

typically a stabilized average of repeated measurements of a near-constant concentration within the bag or other grab-sample container.

During EPA testing of the first pre-production prototype light-duty diesel vehicle (Toyota Avensis D-Cat) with a NO_x adsorption catalyst system, continuous and bag-sampled NO_x agreed to within 4% at very low integrated mass concentrations, but the coefficient of variance for the continuous NO_x measurement was approximately four times the coefficient of variance for the bag-sampled NO_x measurement, which was likely due to a combination of the above effects.

Use of a RMC can also significantly reduce the cost of steady-state testing. Not only is the per-test cost anticipated to be lower with the RMC, but the lower thermal-load on CVS and air-handling systems due to less sustained high-load operation during testing may reduce the cost for construction of test facilities. The RMC can typically be accomplished in much less time, further reducing total cost.

4.3.1.2 Comparison of Steady-State vs. RMC Testing

4.3.1.2.1 Manufacturer's testing

An engine manufacturer provided paired and unpaired emissions data to EPA comparing the 13-mode highway SET (supplemental emissions test) to a RMC developed from the highway SET. The paired data contain 34-39 test replicates representing 29 light-heavy, medium-heavy, and heavy-heavy-duty highway engine families in the range of 250 - 500 hp certified to the 2004 model year heavy-duty on-highway emission standards. The engines were not equipped with exhaust aftertreatment, but were equipped with high-pressure, electronically controlled fuel injection systems and cooled EGR systems. The unpaired data are for 10 engine families built from one basic engine platform for a heavy-heavy-duty engine of approximately 15 liters displacement. The paired data are summarized in Figures 4.3-1 and 4.3-2. The results of a F-test comparison of the unpaired SET data to the RMC data are presented in table 4.3-1. Emissions results did not differ significantly between the SET and the RMC. Further, when comparing the uncertainty of the RMC to the SET, it met the F-test criteria at a 90% confidence level using the test equivalency criteria as per an EPA letter to the Engine Manufacturers Association, dated December 12, 2002 regarding guidance on test procedures for heavy-duty on-highway and non-road engines (page 3, item 1).[166]

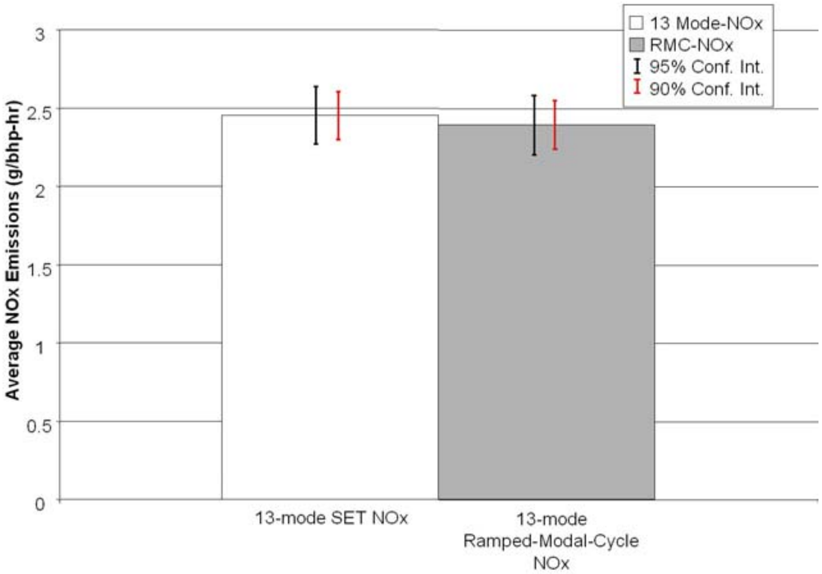

Figure 4.3-1: A comparison of SET and RMC NO_x emissions based on paired data from 29 engine families certified to a 2.5 g/bhp-hr NO_x and 0.1 g/bhp-hr PM standard.

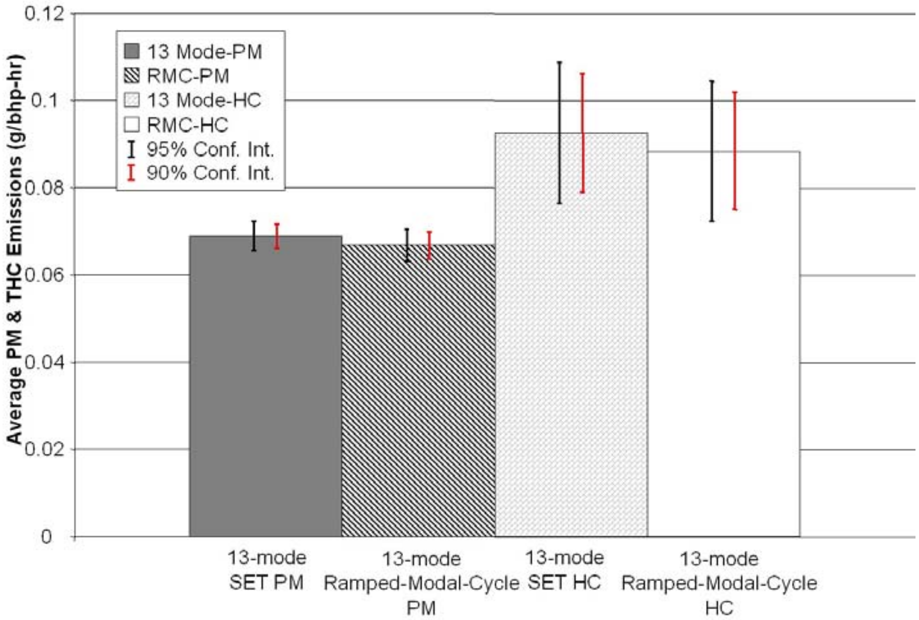

Figure 4.3-2: A comparison of SET and RMC PM and total HC emissions based on paired data from 29 engine families certified to a 2.5 g/bhp-hr NO_x and 0.1 g/bhp-hr PM standard.

Table 4.3-1: F-test comparison of the RMC to the SET steady-state test. NO_x and HC emissions were measured using continuous analyzers. Note that the ability to use batch-sampling for NO_x and HC would further reduce the standard-deviation for the RMC. The PM measurement for the SET also used a single, flow-weighted PM filter sample. Using one filter-sample per mode would likely have further increased the variability in the SET steady-state tests.

	NO_x	**PM**	**HC**	**CO**	**CO_2**
Mean Emissions (SET)	2.029	0.0754	0.072	0.329	507
σ_{SET}	0.056	0.0080	0.014	0.062	13
Mean Emissions (RMC)	1.931	0.078	0.072	0.372	510
σ_{RMC}	0.070	0.0057	0.013	0.091	17
F-test					
$F_{90\%}$:	2.44	2.44	2.44	2.44	2.44
F_{RMC}:	1.56	0.516	0.776	2.18	1.69
Pass at 90% Confidence Interval?	*Pass*	*Pass*	*Pass*	*Pass*	*Pass*

4.3.1.2.2 EPA testing over the 8-mode C-1 cycle and its RMC derivative (with and without exhaust aftertreatment)

EPA has determined that its 8-mode C-1 test cycle (40 CFR Part 89) may be run as a RMC. The RMC version of this cycle consists of the same series of eight steady-state test modes but the modes are connected to one another by linear speed and torque transitions. That is, emissions sampling would start at the beginning of this RMC and would not stop until its last "mode" was completed. As well, the mode order from the 8-mode C-1 cycle is rearranged in this RMC to alternate between high-load and low-load modes. Instead of using weighting factors for each steady-state mode, the RMC specifies different time durations for each mode. Time durations are proportioned to weight each mode exactly as the original C-1 weighting factors. The information needed to run an 8-mode C-1 test cycle as a RMC is given in 40 CFR, §1039.505. The procedures required for transforming and running this test cycle with a specific engine are found on 40 CFR Part 1039 subpart F.

To compare the emission levels between a steady-state 8-mode C-1 test and the corresponding RMC test, four engines ranging from 42 to 400 brake-horsepower (bhp) were tested at Southwest Research Institute (SwRI) and at EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL). Table 4.3-2 below contains a summary of the specifications of these engines. The testing was performed with engines having various exhaust configurations. The Yanmar engine had no exhaust aftertreatment while the Kubota engine was tested both with and without a DOC. The DDC engine was tested with a continuously-regenerating trap (CRT) system that used a platinum-catalyzed DOC located upstream of a non-catalyzed PM trap.

Table 4.3-2: Engine properties

Engine	Model Year	Power (bhp)	Fuel Inj.	Displ. (L)	Air Induction	Configurations tested
Yanmar 4TNE84	2002	48	DI	1.99	Naturally Aspirated	No exhaust aftertreatment
Kubota V1903E	2001	42	IDI	1.9	Naturally Aspirated	With and without DOC
DDC Series 60	1998	400	DI	12.7	Turbocharged	With CRT (passive regeneration)
Cummins ISB	2000	180	DI	5.9	Turbocharged	With CDPF + NO_x adsorption catalyst system

The Cummins ISB engine was tested with a system which combined a catalyzed diesel particulate filter (CDPF) with a NOx adsorption catalyst.[167] The engine was also equipped with a high-pressure common-rail fuel injection system and cooled low-pressure-loop EGR.. The test configuration of the ISB engine was that of a 180 b-hp rated nonroad engine and EPA developed the engine's test calibration values.

Table 4.3-3, below, summarizes the engine operating conditions for the 8-mode C-1 cycle and for the RMC derived from that cycle. The RMC contains a "split idle mode" (the idle condition occurs twice versus once in the 8-mode C-1). Note also that it is possible to run the 8-mode C-1 cycle with different lengths of time-in-mode. A period of five-minutes duration per steady-state mode is allowable under current regulations in 40 CFR Part 89 and there is no limit on maximum time-in-mode. Different exhaust sampling periods are also allowed, having a minimum length of 60 seconds and no maximum length. Thus, for the 8-mode C-1 steady-state cycle, the minimum time-in-mode under current regulations would be a period of four minutes of stabilization with one minute of sampling per mode. The maximum time for stabilization and sampling are left undefined.

All of the engines were tested using a twenty minutes long RMC derived from the 8-mode C-1 cycle. The EPA-modified Cummins ISB was also tested using a thirty minutes long RMC cycle. The length of time spent in each mode for the 8-mode C-1 test cycles varied by engine. The Yanmar and Kubota engines were tested over the 8-mode C-1 test cycle at mode lengths of ten minutes each. Gaseous emissions and PM emissions were sampled for the last five minutes of each ten-minute mode. The DDC and the modified Cummins ISB engines were tested over the 8-mode C-1 cycle at mode lengths totaling ten minutes each. Their gaseous and PM emissions were sampled for the last three minutes of each ten-minute mode. The modified Cummins ISB engine was also tested using a five minutes long mode length over the 8-mode C-1 cycle. For those tests having a five minutes long mode length, the first four minutes were used for stabilization and the last minute was used for emissions sampling to model the minimum time specifications found in 40 CFR Part 89.

Table 4.3-3:
Engine operating conditions for the steady-state 8-Mode C-1 and RMC tests

8-Mode C-1	1	2	3	4	5	6	7	8	
Speed	Rated				Intermediate			Idle	
Torque	100	75	50	10	100	75	50	No load	
RMC	1	2	3	4	5	6	7	8	9
Speed	Idle	Intermediate			Rated				Idle
Torque	No load	100	50	75	100	10	75	50	No load

Figures 4.3-3 and 4.3-4 below summarize the emissions results obtained from emission testing on the DDC Series-60 engine. However, due to the use of a non-standard PM sampling medium and measurement inconsistencies associated with filter handling during emission testing, PM data are not available for these tests (PM mass loss was attributed to physical damage to the sample filters after installation into the sampling cassettes). As shown in these figures, NO_x emissions for both engine-out and CRT-out configurations of this engine over the RMC and 8-mode C-1 test cycles do not differ at the 95% confidence interval. Differences between HC and CO emission levels over the two cycles were either negligible or extremely low during all testing and well under the Tier 4 emission standards.

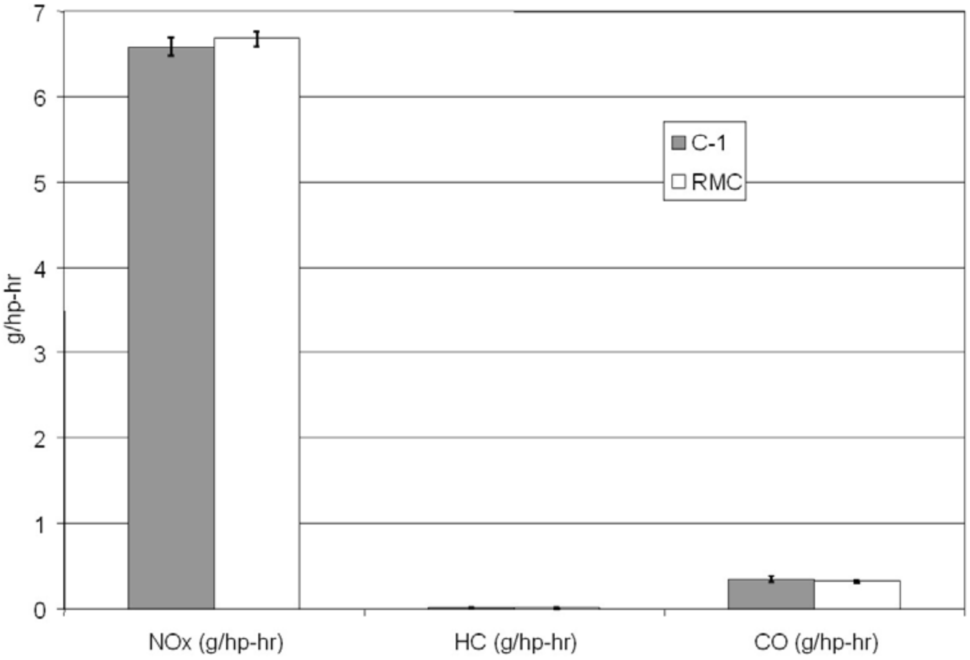

Figure 4.3-3: Emissions from the DDC Series-60 engine over the steady-state 8-mode C-1 test and the 20-minute RMC test with no exhaust aftertreatment.

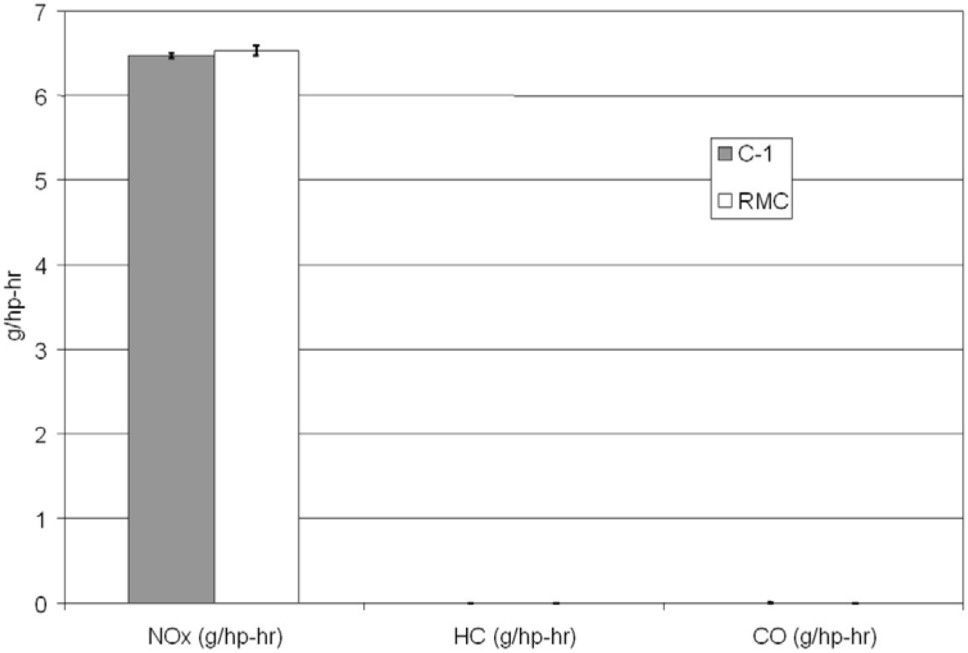

Figure 4.3-4: Emissions from the DDC Series-60 engine over the steady-state 8-mode C-1 test and the 20-minute RMC test with a CRT.

Figures 4.3-5 and 4.3-6 compare exhaust emissions from the Kubota V1903E engine over both the 8-mode C-1 and RMC cycles without and fitted with a DOC, respectively. PM emissions over both test cycles from both of the tested engine configurations did not differ at either the 95% or 90% confidence interval. There was however a general trend toward a reduced coefficient of variance for RMC versus 8-mode C-1 PM emissions and the number of replicates was insufficient for a rigorous F-test comparison of variance. Differences in mean NO_x emissions in the no exhaust aftertreatment configuration were small, and did not differ at a 95% confidence interval, but did differ at a 90% confidence interval. CO emissions were somewhat lower over the RMC, possibly due to increased CO oxidation caused by the somewhat higher exhaust temperatures of that cycle compared to the 8-mode C-1 cycle. In both cases, though, CO emissions were less than 50% of the Tier 4 standard.

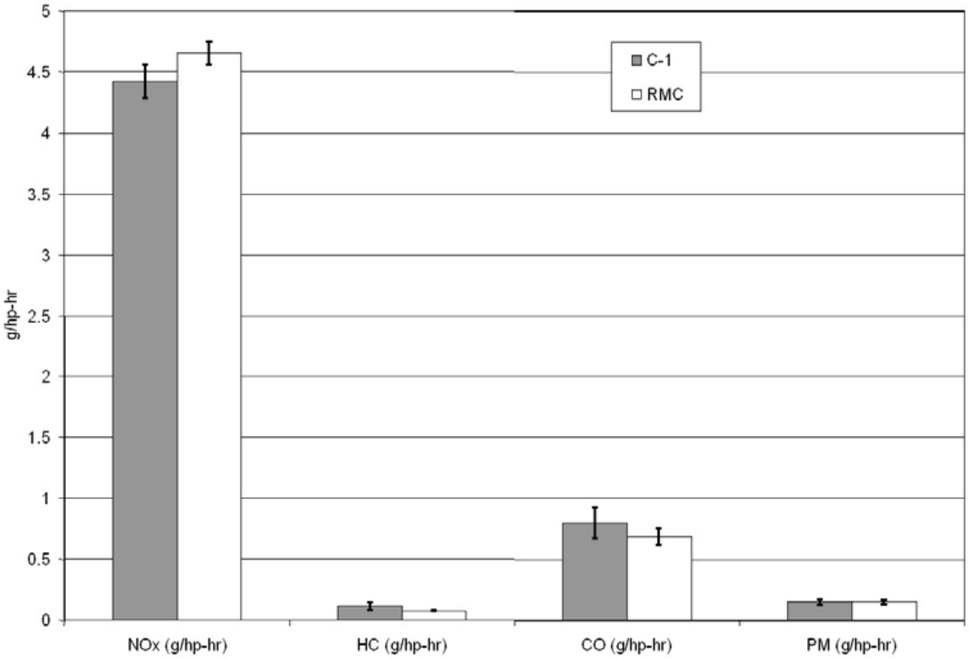

Figure 4.3-5: Emissions for the Kubota V1903E engine with no exhaust aftertreatment over the steady-state 8-mode C-1 test and the 20-minute RMC test.

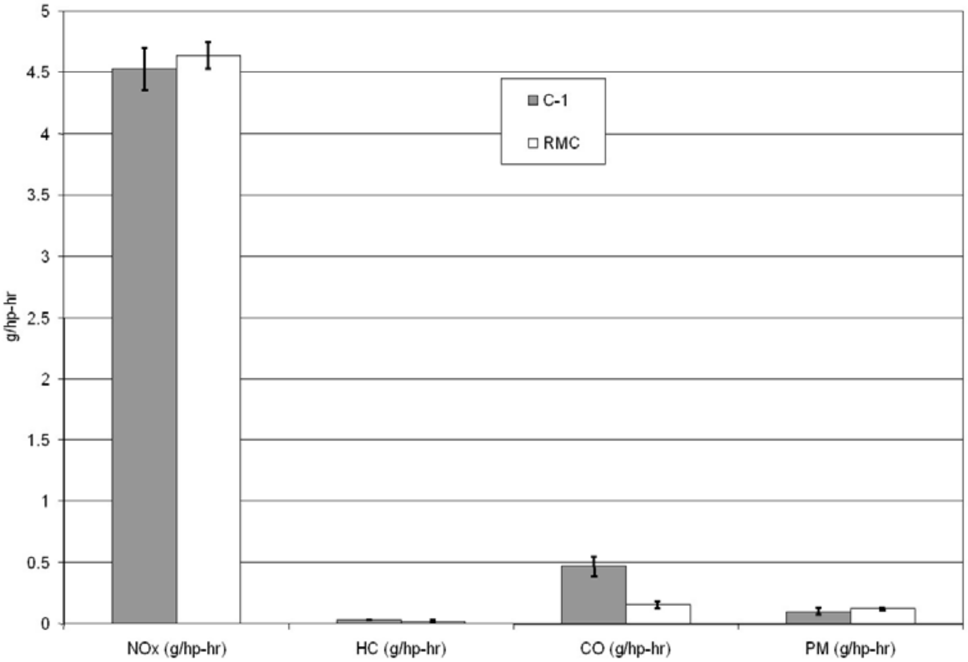

Figure 4.3-6: DOC-out emission levels obtained from the Kubota V1903E engine over the steady-state 8-mode C-1 test and the 20-minute RMC test.

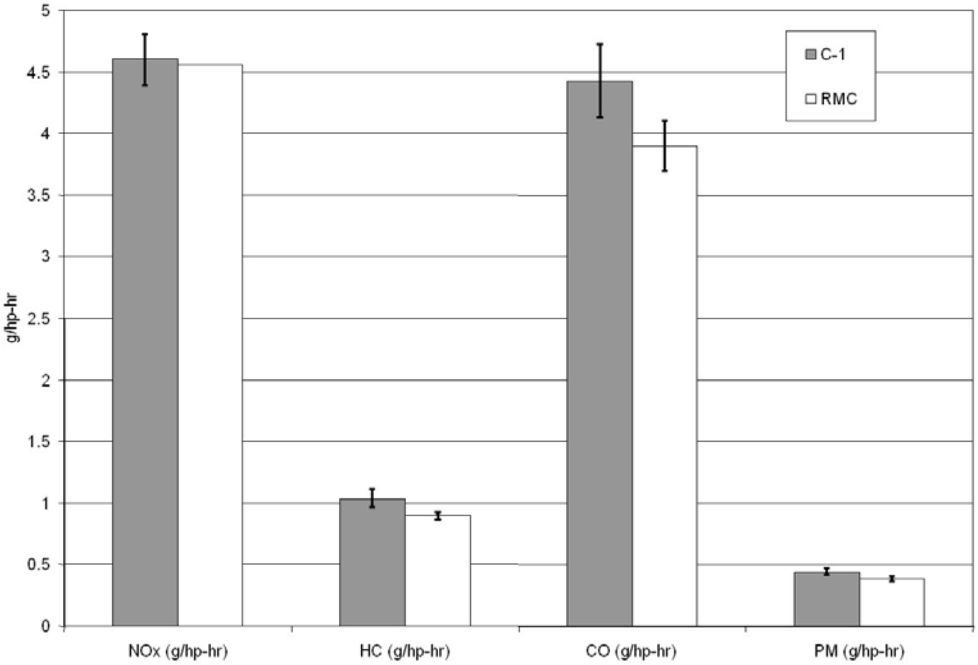

Figure 4.3-7: Engine-out emission levels obtained from the Yanmar 4TNE84 engine over the steady-state 8-mode C-1 test and the 20-minute RMC test.

Emissions from the Yanmar 4TNE84 engine operating without exhaust aftertreatment over both the 8-mode C-1 and 20 minutes long RMC test cycles are summarized above in Figure 4.3-7. As can be seen in this figure, the average engine-out NO_x emission over the RMC is within the 95% confidence interval of the NO_x data gathered over the steady-state 8-mode C-1 test, although the number of test replicates were insufficient to determine a confidence interval for the RMC for this particular data comparison. With regards to the HC and CO emissions, the data showed a slight, statistically significant difference for these emissions of 5% or less between the two cycles. CO emissions exceeded the Tier 1 standards over the 8-mode C-1 cycle and were unusually high for a diesel engine over both of these cycles. This may indicate that a mechanical problem exists with this particular test engine.

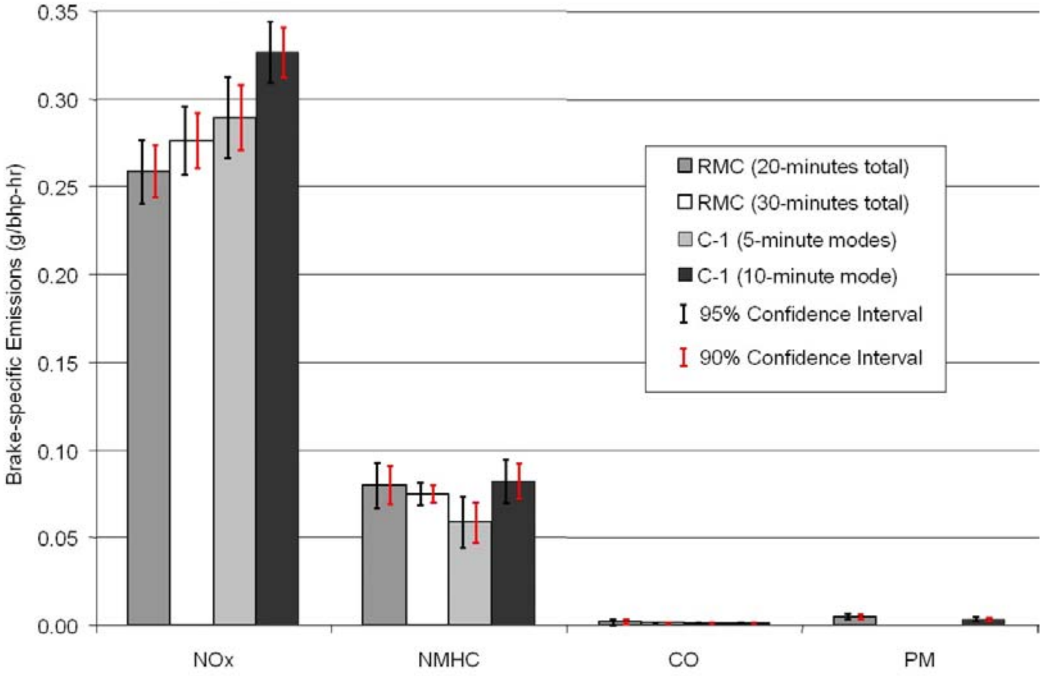

Figure 4.3-8: Emissions from the EPA-modified Cummins ISB engine over the steady-state 8-mode C-1 test cycle and the RMC test cycle. Note that the data represent the 2 different mode lengths specified for the 8-mode C-1 and two different total test times for the RMC. PM emissions were only available for the 10 minutes per mode 8-mode C-1 and the 20 minutes long RMC results. Results are shown for mean-emissions calculated for 7 test replicates. Confidence intervals were calculated using a 2-sided Student t-test.

Figure 4.3-8 above compares the emission levels obtained from testing the Cummins ISB engine on the 8-mode C-1 cycle at both five minutes per mode and ten minutes per mode, as described in 40 CFR Part 89, with the RMC version of that cycle at both twenty minutes and thirty minutes of total cycle time. The five minutes and ten minutes per mode represent mode lengths that are currently used in the 8-mode C-1 test cycle for emissions testing of nonroad diesel engines. PM emissions were measured only for the ten minutes per mode 8-mode C-1 and the twenty minutes total time RMC cycles, which among the cycles investigated represented the largest differences in exhaust temperature and gaseous emissions. PM emissions were extremely low due to the use of the CDPF and were approximately 50% of the Tier 4 standards. Mean PM emissions for these two cycles did not differ at either a 95% or a 90% confidence level. Some statistically significant differences in mean NO_x emissions were found between the various cycles used, including the two different mode length 8-mode C-1 cycles, due to differences in exhaust temperatures achieved over individual cycles. There were statistically significant differences in mean NO_x emissions between the ten minutes per mode and the five minutes per mode 8-mode C-1 cycles. Likewise, there were statistically significant differences in mean NO_x emissions between the ten minutes per mode 8-mode C-1 and both the twenty and thirty minutes total time RMCs. Differences in mean NO_x emissions between the thirty minutes total time RMC and the five minutes per mode 8-mode C-1 were not statistically significant at either a 95% or a 90% confidence level. All other emission levels were extremely low over both the RMC and the 8-mode C-1 tests. Mean HC, CO and PM emissions did not differ significantly at either a 95% or a 90% confidence level for either of these cycles.

4.3.1.2.3 Summary of engine test results

These data confirm that emissions from engines which do not use NO_x adsorption catalysts are relatively insensitive to the choice of the 8-mode C-1 test cycle or its RMC counterpart. Neither are these engine emissions sensitive to the impact of time spent at any steady-state speed-load set-point. However, the effect of test cycle length and time-in-mode on exhaust temperatures did have an impact on NO_x emissions when an engine was equipped with a NO_x adsorption catalyst system, due to the:

1. effect of catalyst temperature on the ability to oxidize NO-to-NO_2 for NO_x storage (kinetically-limited at low temperatures and equilibrium-limited at high temperatures);

2. effect of thermal-desorption of NO_x at high temperatures; and

3. difficulty in effectively vaporizing fuel reductant at very low exhaust temperatures.

Based on NO_x emissions and engine exhaust temperature data from EPA tests of the modified Cummins ISB engine, a thirty minutes total time 8-mode C-1-based RMC was selected as comparable to the five minutes per mode 8-mode C-1 test cycle for NO_x emission and engine exhaust temperature results. Furthermore, based on the results of both EPA and engine manufacturer testing, the Agency has determined that steady-state test procedures should be modified to include changes necessary to allow repeatable NO_x emission results for all steady-state testing conducted on engines having catalytic exhaust emission controls for NO_x emissions. Steady-state testing for certification will be conducted in the following manner:

1. The manufacturer may choose either the appropriate laboratory-based certification steady-state test cycle or its RMC derivative as found in regulations at 40 CFR, Section 1039.505. For RMC tests with five or fewer modes, the length of the RMC test cycle will be

twenty-minutes long. For RMC tests with six to nine modes, the length of that test cycle will be thirty-minutes long. For RMC tests with ten or more modes, the length of that test cycle will be forty-minutes long.

2. When testing an engine having an exhaust aftertreatment system which reduces NOx emissions, a manufacturer will operate that engine for four to six minutes, then sample emissions for one to three minutes in each mode. The sampling time for PM emissions may be extended to improve measurement accuracy, using good engineering judgment. If a longer sampling time is chosen for PM emissions, the manufacturer must calculate and validate cycle performance statistics for the gaseous and PM sampling periods separately.

3. When testing other engines, a manufacturer will operate those engines for at least five minutes, then sample emissions for at least one minute in each mode.

These changes in measurement procedures for nonroad engines have been incorporated into regulations at 40 CFR Section 1039.505.

4.3.2 Transportation Refrigeration Unit Test Cycle

Transportation refrigeration units (TRU), a specific application of steady-state engine operation, are refrigeration systems powered by diesel engines designed to refrigerate perishable products that are transported in various containers, including semi-trailers, truck vans, shipping containers, and rail cars. TRU engines are relatively small with most units ranging from 7 to 38 kW (10 to 50 horsepower)[LL].

Engines that are designated as TRU engines at the time of certification are expected to operate in the field primarily under steady-state conditions. These engines may from time to time be subject to minor setpoint performance perturbations; however those changes are not expected to last for a total duration at any one point of greater than 30 seconds and are not multiple, highly transient, repetitive changes in speed or load such as seen in the nonroad transient duty cycle. These parameters appropriately characterize TRU equipment operation independent of unit application, whether used for fresh product (chilled to 3°C) or for frozen goods at the standard maximum rating (-20°C). So, to that end, EPA has adopted a four-mode steady-state test cycle designed specifically for engines used in TRU applications.

The TRU certification test cycle consists of four steady-state modes of operation. Two modes are to be run at 50% of the manufacturer's declared peak torque value for that engine. The remaining two modes are to be run at 75% of that same declared peak torque value for that same engine. One of the modes at 50% load is to be run at the engine manufacturer's speed at peak, or rated, power, while the other mode at 50% load is to be run at the engine manufacturer's

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[LL] Information on the proposed TRU cycle may be found on and downloaded from the CARB website at http://www.arb.ca.gov/diesel/dieselrrp.htm. In particular, see the Technical Bulletin to the Proposed TRU cycle determination.

"intermediate" test speed. Likewise, one of the modes at 75% load is to be run at the engine manufacturer's speed at rated horsepower and the remaining mode at 75% load is to be run at the manufacturer's "intermediate" test speed. All four modes would be weighted equally in determining a particular mode's contribution to the engine's total test cycle emissions. Early data submissions in response to California-ARB's call for TRU engine operating data showed that the majority of TRU engines operated in-use in at least three, if not all four of the test cycle's modes[168]. It was equally clear from comments to the rule that a TRU test cycle was more representative of refrigeration unit operation than the nonroad cycles currently available to manufacturers since TRUs generally did not operate at low idle, high idle, peak torque or rated power conditions.

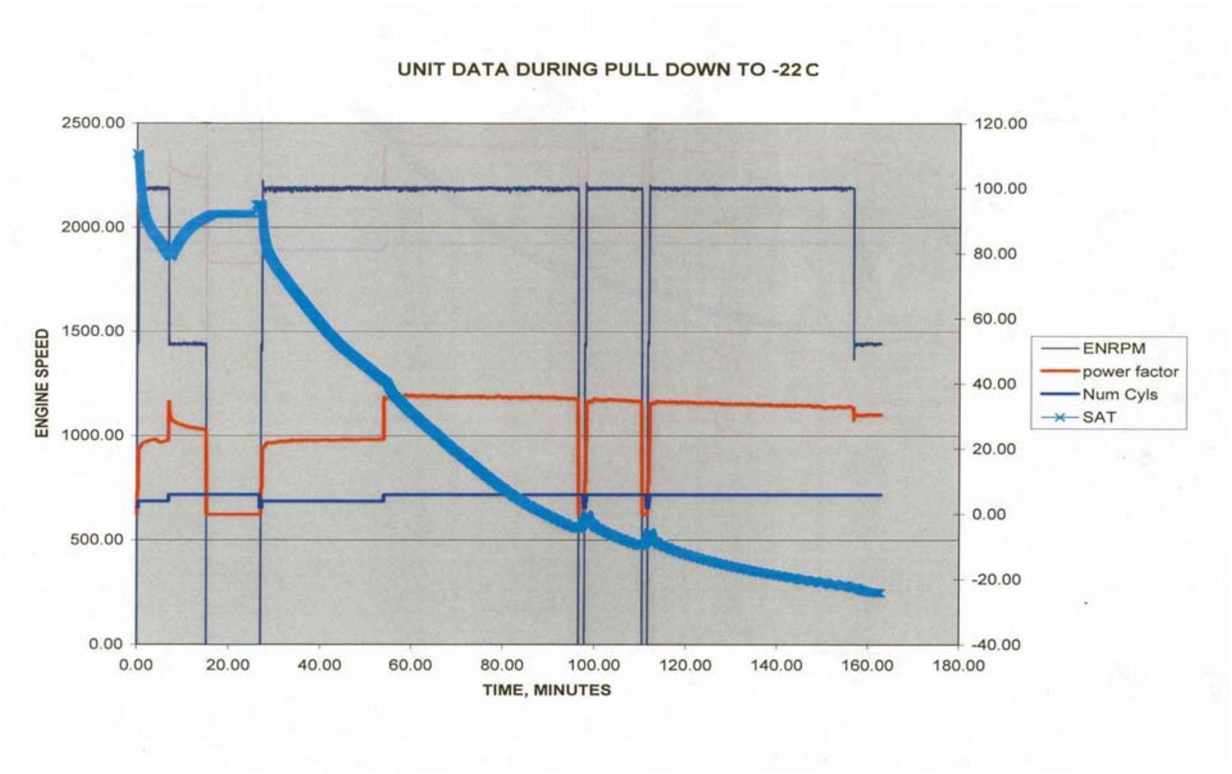
EPA will allow manufacturers to test their engines under a broad definition of intermediate test speed, similar to recommendations found in ISO-8178-4 steady-state test guidelines. The intermediate speed shall be the declared maximum torque speed if it occurs between 60% and 75% of rated speed / maximum test speed. If the declared maximum torque speed is less than 60% of rated speed, then the intermediate speed shall be 60% of the rated speed. If the declared maximum torque speed is greater than 75% of the rated speed then the intermediate speed shall be 75% of rated speed. This will enable an engine manufacturer to more closely match the TRU cycle at engine certification to the operation of their engines in-use.

The set point value for speed in a TRU engine is expected to remain consistent without repetitive transient changes on a 1 hertz basis. The magnitude of any changes in actual speed from the engine are expected to be under 2% which is consistent with the Agency's treatment of operation as steady state in the creation of the transient duty cycle. Additionally, the set point value demanded by the application remains within this 2% steady state definition. Should application demands differ from the steady state condition for speed, the engine shall not be considered an actual steady state TRU engine. The TRU engine is likewise not allowed to drop, or drift[MM], from a load set point by more than 15% of torque at the speed for a particular operating mode before changing its load setpoint.

As seen below in Figure 4.3-9[169], the operation of the typical piece of TRU equipment tested is relatively consistent, as evidenced by the power factor curve, a surrogate for engine response to load demand on the unit. Many factors may affect unit "drift" from a set point, but that set point of operation does not deteriorate significantly over longer periods of time, in minutes. TRU equipment is responsive to feedback from a broad number of engine operating parameters and user input options. Operating temperature, intake air temperature, i.e., ambient, and exhaust air temperature are some engine operating parameters to which the engine must be responsive. User or owner inputs include tolerances around set point temperatures, minimum time-on, and minimum time-off for the unit. Likewise the condition and age of the engine and container, especially the insulation, may influence ability to hold a desired temperature, or load[170],[171].

[MM] Drift is restricted to load deterioration not to exceed 15% over a sixty minute duration.

Figure 4.3-9
TRU Equipment Operation at Pull-Down



The expectation is that the engine is governed in such a way that this demand is not possible. If that engine is deemed a steady-state TRU engine at the time of certification, the application within which the engine is sold, must meet these standards of operation.

As an additional way of ensuring that TRU certification is limited to those engines for which it is warranted, we are adding a requirement that any TRU-certified engine must meet appropriate NTE standards for any in-use operation. Practically, this means that TRU engines are subject to NTE standards based on the normal operation that these engines would experience in the field. This is limited neither to later model years nor to any particular range of engine speeds and loads. If TRU engine operation is limited as much as manufacturers have described, the resulting “NTE zone” should be practically limited to a narrow range of speeds and loads very close to those points represented by the specified duty cycle.

4.4 Not-to-Exceed Testing

The Agency's examination of emissions data from heavy duty highway diesel engines , and the confidential discussions with several heavy duty diesel engine manufacturers, led EPA to the conclusion that the 1.25 emission cap associated with the not-to-exceed zone requirement is technologically feasible. This conclusion has not changed since the initiation of the not-to-exceed concept. The Agency believes the 1.25 factor proposed for the not-to-exceed standard provides sufficient room to allow for the uneven nature of the emission maps. For these reasons, EPA believes the primary technologies discussed earlier in this chapter will provide the necessary NMHC+NOx and PM control on the existing steady state, as well as on the transient cycle testing and not-to-exceed zone testing.

The goal of the Not-To-Exceed (NTE) limits on nonroad diesel engines remains consistent with the reasoning for highway heavy duty diesel engines . The NTE helps ensure that emission benefits are achieved in-use and provides a practical approach for a post-promulgation in-use testing program. The NTE established for the highway heavy duty diesel engines has been demonstrated to be not only feasible, but practical. The NTE approach provides an area under the maximum allowable torque curve of an engine for which an engine may not exceed a specified value for the regulated pollutants. The NTE zones, limits, and ambient conditions are described in detail below.

The advantages to adopting an NTE strategy originally adopted for highway diesel engines are numerous. These include:

- Proven design strategy can be utilized by manufacturers
- Development costs can be minimized as new test protocols will not need to be refined
- Assurance of comparable control effectiveness analogous to existing programs
- Demonstrated effectiveness in the heavy duty highway diesel market can be carried forward to the nonroad diesel market
- Allows for direct comparison of control effectiveness in-use

The Not-To-Exceed (NTE) provision was initially finalized for HDDEs certified to the 2004 FTP emission standards with implementation beginning in model year 2007. (See 65 FR 59896, October 6, 2000.) The NTE approach establishes an area (the "NTE control area") under the torque curve of an engine where emissions must not exceed a specified value for any of the regulated pollutants.[NN] The NTE requirements apply under engine operating conditions that could reasonably be expected to be seen in normal vehicle operation and use which occur during the conditions specified in the NTE test procedure. (See 40 CFR 86.1370.) This test procedure covers a specific range of engine operation and ambient operating conditions (i.e., temperature, altitude, and

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[NN] Torque is a measure of rotational force. The torque curve for an engine is determined by an engine "mapping" procedure specified in the Code of Federal Regulations. The intent of the mapping procedure is to determine the maximum available torque at all engine speeds. The torque curve is merely a graphical representation of the maximum torque across all engine speeds.

humidity). The NTE control area, emissions standards, ambient conditions and test procedures for nonroad diesel engines are described in the 40 CFR 1039.515.

The NTE provisions for nonroad diesel engines mirror the highway diesel program and so a manufacturer will need to undertake the engine mapping procedure as defined in 40 CFR 1065; however, speed definitions will need to be determined based on 40 CFR 86.1360(c). Valid NTE compliance evaluation will be based on the following factors:

- Operating speeds greater than the speed determined by: $n_{lo} + 0.15 \times (n_{hi} - n_{lo})$
- Engine load points greater than or equal to 30% of the maximum torque value produced by the engine
- Brake Specific Fuel Consumption (BSFC) requirements as specified in 40 CFR 86.1370-2007 (b)(3)
- Exclusion areas for which the NTE requirement does not apply may be found in 40 CFR 86.1370-2007 (e.g. PM carve-out zones for engines certifying to a PM standard above 0.07 g / kW-hr)
- Control area limits as defined in 40 CFR86.1370-2007 (d) for averaging times that may or may not include discrete regeneration events
- Corrections for ambient conditions as defined in 40 CFR 86.1370-2007 (e)
- Cold temperature exclusions as adopted in 40 CFR 86.1370-2007 (f)
- Engines equipped with NOx and NMHC aftertreatment systems (both single and multi-bed systems) with warm-up provisions as defined in 40 CFR 86.1370-2007 (g)

The NTE requirements will not apply during engine start-up conditions 40 CFR 86.1370-2007 (g). In addition, with the application of advanced exhaust emission control devices, an exhaust emission control device warm-up provision is a necessary criterion for the NTE to address the impact of thermal inertia on aftertreatment efficiency for the catalytic reduction strategies. Until the exhaust gas temperature on the outlet side of the exhaust emission control device(s) achieves 250 degrees Celsius, the engine is not subject to the NTE as discussed in 40 CFR 86.1370-2007 (g). Control of cold-start emissions is expected to happen through the nonroad transient cycle cold-start provisions.

For a more detailed technical description of the application of the NTE Zone to diesel engines, please see the Regulatory Impact Analysis: Heavy -Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements EPA420-R-00-026.

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