

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

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4.1 Feasibility of Emission Standards

This section of Chapter 4 documents the technical feasibility analysis we conducted in developing the proposed Tier 4 emissions standards for nonroad diesel engine. The proposed standards and a summary of this analysis can be found in Section III of the preamble. This analysis incorporates recent Agency analyses of diesel emission control technologies for on-highway vehicles and expands those analyses with more recent data and additional analysis specific to the application of technology to nonroad diesel engines.^{1,2}

The 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 horsepower categories (<25 hp, 25 - 75 hp, and >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 nonroad and on-highway diesels has concentrated on improvements to the engine itself to limit the emissions leaving the combustion chamber.

However, during the past 15 years, 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 NO_x exhaust emission control devices, make the widespread commercial use of diesel exhaust emission controls feasible. EPA has recently set new emission standards for on-highway diesel vehicles based on the emission reduction potential of these devices. Through use of these devices, we believe emissions control similar to that attained by gasoline three-way-catalyst applications will be possible for diesel powered on-highway vehicles and nonroad equipment. However, without low sulfur diesel fuel, these technologies cannot be implemented.

4.1.1 PM Control Technologies

Particulate matter from diesel engines is made of three components;

- solid carbon soot,
- volatile and semi-volatile organic matter, 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 pyrolyze, 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 which passes through the engine with no or only partial oxidation and which 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 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.³ 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 of the need for low sulfur fuel below.

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. A number of technologies exist that 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 on-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 in order to meet the new emission standards proposed here offers an opportunity for significant reductions in engine-out PM emissions and possibly for reductions in fuel consumption.

Another means to reduce the soot portion of diesel PM engine-out is to operate the diesel (compression-ignited) engine with a homogenous method of operation rather than the typical heterogenous 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 pyrolyzed 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.^{4,5} Fundamental among these issues is the ability to control the start of combustion.⁶ 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 pressures which 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.^{7,8} 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 possible, while still providing the full range of engine operation. Other approaches that are similarly limited to low load engine operation have been proposed in order to produce a dual combustion mode engine.^{9,10,11}

4.1.1.2 Diesel Oxidation Catalysts (DOCs)

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 on-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.¹² Today, highly active DOC formulations cannot be used for NMHC and CO control because of sulfur in current diesel fuel which will lead to unacceptable sulfate PM emissions as discussed later in this section.

DOCs are also very effective at reducing the air toxic emissions from diesel engines. Test data shows that emissions of toxics such as polycyclic aromatic hydrocarbons (PAHs) can be reduced by more than 80 percent with a DOC.¹³

DOCs are ineffective at controlling the solid carbon soot portion of PM. The solid (soot) typically constitutes 60 to 90 percent of the total diesel PM. Therefore, even with 15 ppm sulfur fuel DOCs would not be able to achieve the level of PM control needed to meet the standard proposed today.

4.1.1.3 Catalyzed Diesel Particulate Filters (CDPFs)

4.1.1.3.1 CDPF PM and HC Control Effectiveness

Emission levels from CDPFs are determined by a number of factors. Filtering efficiencies for solid particle emissions like soot are determined by the characteristics of the PM filter, including wall thickness and pore size. Filtering efficiencies for diesel soot can be as high as 99 percent with the appropriate filter design.¹⁴ 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/bhp-hr). This level of soot emission control is not 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. The SOF portion of diesel PM consists of primarily gas phase hydrocarbons in engine exhaust due to the high temperatures and only forms particulate in the environment when it condenses. Catalytic materials applied to CDPFs can oxidize a substantial fraction of the SOF in diesel PM just as the SOF portion would be 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/bhp-hr), compliance with the 0.01 g/bhp-hr emission standard proposed today may require additional technology beyond the application of a CDPF system alone.^A

Modern on-highway diesel engines have controlled SOF emission rates in order to comply with the existing 0.1 g/bhp-hr emission standards. Typically the SOF portion of PM from a modern on-highway diesel engine contributes less than 0.02 g/bhp-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.).¹⁵ Nonroad diesel engines may similarly need to control engine-out SOF emissions in order to comply with the standard proposed today. 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 engine-out SOF control (i.e., engine-out SOF < 0.02 g/bhp-hr) and the application of catalytic material to the DPF,

^A 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/bhp-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/bhp-hr standard once the other constituents of diesel PM (soot and sulfate) are added. In this case, SOF emissions will need to be reduced engine-out or SOF control greater than 90 percent will need to be realized by the CDPF.

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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/bhp-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.¹⁶ 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.¹⁷

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
Naphthalene	295	50	0	83%	100%
2-Methylnaphthalene	635	108	68	83%	89%
Acenaphthalene	40	0.8	1	98%	98%
Acenaphthene	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 have proposed today to limit nonroad diesel fuel sulfur levels to be 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/bhp-hr over some representative operating cycles using conventional diesel engine oils. This level of emissions will allow for compliance with our proposed PM emissions standard of 0.01 g/bhp-hr, and we further believe that there is room for reductions from this level in order to provide engine manufacturers with additional compliance margin. During our 2002 Highway Progress Review, we learned that a number of engine lubricating oil companies are working to reduce the sulfur content in engine lubricating oils. 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 in order to reduce SOF emissions and secondarily to reduce sulfate PM emissions. While we believe that sulfate PM

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emissions will be the single largest source of the total PM from diesel engines, we believe with the combination of technology, and the appropriate control of engine out PM, that sulfate and total PM emissions will be low enough to allow compliance with a 0.01 g/bhp-hr standard, except in the case of small engines with higher fuel consumption rates as described later in this section.

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.¹⁸ 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 proposed NTE zone, as well as to the test modes which comprise the steady-state test procedures such as the ISO C1. However, engine operation will affect the CDPF regeneration and oxidation of SO₂ 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 proposed 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 SO₂ to SO₃ (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 PM emissions performance with the application of a CDPF over a number of transient and steady-state test cycles.¹⁹ 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 below. 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 would expect engine-out PM emissions to be lower for production Tier 3 compliant diesel engines that will form the technology baseline for Tier 4 engines meeting today’s proposed standard. The engine demonstrated PM emissions of 0.009 g/bhp-hr on the proposed Nonroad Transient Cycle (NRTC) from an engine-out level of 0.256 g/bhp-hr, a reduction of 0.247 g/bhp-hr. The engine also demonstrated excellent PM performance on the existing steady-state ISO C1 cycle with PM emissions of 0.010 g/bhp-hr from an engine-out level of 0.127, a reduction of 0.107 g/bhp-hr. Thus, this engine would be compliant with the emission standard proposed today for ≥ 75 hp variable speed nonroad engines.

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When tested on the proposed optional constant speed variable load cycle (CSVL) (to which this engine would not be subject, under this proposal), the engine-out PM emission levels were 0.407 g/bhp-hr and were reduced to 0.016 g/bhp-hr (a reduction of 0.391 g/bhp-hr) with the addition of the PM filter. As tested, this engine would not be compliant with the proposed optional CSVL standard, but this is not surprising given that this Tier 1 engine was designed for variable speed engine operation and not for single speed operation. We have great confidence given the substantial PM reduction realized in this testing over the proposed CSVL cycle with a CDPF that a properly designed nonroad diesel engine will be able to meet the standard of 0.01 g/bhp-hr.

Table 4.1-2 Transient PM Emissions for a Tier 1 NR Diesel Engine with a CDPF
1999 (Tier 1) Caterpillar 3408 (480hp, 18l)

Test Cycle	PM [g/bhp-hr]		Reduction
	Engine Out	w/ CDPF	%
Proposed Nonroad Transient Cycle (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 Chapter 4.2 of this draft RIA 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/bhp-hr is demonstrated on the AW2 cycle).

The results summarized in the two tables are indicative of the feasibility of the proposed NTE provisions of 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 proposed NTE. 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/bh-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 proposed NTE standard. There are two other test points in Table 4.1-3 which are above the proposed NTE emission level, both at 10 percent engine load. However, both are outside the proposed NTE zone which excludes emissions for engine loads below 30 percent. It is important to note that

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although the engine would not be constrained to meet the proposed NTE under these conditions, the resulting reductions at both points are still substantial in excess of 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.²⁰ 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 cycle would be compliant with the proposed PM standard of 0.01 g/bhp-hr once the appropriate rounding convention is applied.^B It is also interesting to note that the on-highway FTP transient emissions are higher than for either of the proposed nonroad transient tests. This suggests that developing PM compliant engines on the proposed nonroad transient cycles may not be substantially different from developing compliant technologies for on-highway engines.

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

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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]		Reduction
	Engine Out	w/ CDPF	%
Proposed Nonroad Transient Cycle (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 emissions points (see table 4.1-5) have some of the highest brake specific emission rates. These rates are not high enough however to preclude compliance with the steady-state emission cycle, are not within the proposed NTE zone, and still show substantial PM reduction levels.

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]		Reduction
		Engine Out	w/ CDPF	%
%	%			
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 proposed NTE requirement, unlike the proposed nonroad transient cycle (NRTC) or the existing ISO C1 cycle, is not a composite test. In fact, a number of the individual modes within the C1 cycle test fall within the proposed NTE engine control 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 proposed NRTC or C1 standard of 0.01 g/bhp-hr, which is part of the reason the proposed PM NTE standard is greater than the NRTC and C1 PM standards.

The proposed 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 proposed 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 proposed NTE requirements apply up to ambient temperatures which are only 14°F greater than standard test cell conditions (100°F under the proposed NTE, versus 86°F for C1 laboratory conditions). At an altitude of 5,500 feet above sea-level, the proposed NTE applies 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 comply with the PM NTE 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 proposed NTE, we conclude that the proposed PM NTE standard for engines of 75 hp or higher is technologically feasible, provided low sulfur diesel fuel (15 ppm or lower) is available. A discussion of the technical feasibility for engines with rated power lower than 75 hp is given later in this chapter.

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).^C 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 than 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 which is infrequently realized in normal diesel engine operation (for many engines' exhaust temperatures may 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.²¹

However, the catalytic materials that most effectively promote soot and SOF oxidation 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

^C 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).

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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 temperatures compared to 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: are the exhaust temperatures high enough on aggregate to oxidize the engine out PM rate?^D 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 on-highway vehicles.^{22,23,24} However, it is possible that for some nonroad applications the engine out PM 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 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 rates will decrease. Similarly, techniques to raise exhaust temperatures periodically in order to initiate soot oxidation in a PM filter have been developed for on-highway diesel vehicles as typified by the PSA system used on more than 400,000 vehicles in Europe.²⁵

During our 2002 Highway Diesel Progress Review, we investigated the plans of on-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.²⁶ 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 on-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).²⁷ 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 in order to comply with the standards we are proposing today. We have estimated costs for such systems in our cost analysis.

^D 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 rate?” the answer would be no, for all but a very few nonroad or on-highway diesel engines.

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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.²⁸ 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 US Heavy-Duty Federal Test Procedure (HD FTP), 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.^E 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 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.²⁹ 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 to 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).³⁰

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 assured. 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 soot oxidation effectiveness will also provide additional assurance that excessive soot loading which could lead to PM filter failure will not occur.

At a recent conference of the Society of Automotive Engineers (SAE) a paper was presented that documented improvements in catalyzed diesel particulate filter system design in order to improve 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.³¹ 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.

Although 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

^E 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.

applications, there remains the possibility that for some conditions active regeneration systems (backup systems) may be desirable. This is perhaps most likely for vehicles which are operated primarily as passenger vehicles (light duty cars and trucks, and some light heavy-duty trucks). For this reason a number of vehicle manufacturers have 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 a number of 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.³² 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 NO_x adsorbers was highlighted by EPA in the HD2007 RIA but at that time little was known as to the extent of these synergistic benefits.³³ Toyota has developed a combined diesel particulate filter and NO_x adsorber technology dubbed DPNR (Diesel Particulate NO_x Reduction). The mechanism for synergistic PM soot regeneration with programmed NO_x 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 NO_x storage function and under rich conditions created by the NO_x regeneration function were effective at promoting soot oxidation at low temperatures.³⁴ This suggests that the combination of a NO_x 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 CO₂ 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 in order 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. 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

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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 \geq 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 a number of 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. One simple approach to address ash is to increase PM filter size in order to tolerate higher levels of ash accumulation. This approach, although effective, is undesirable due to the added cost and size of the resulting PM filter. A number of companies are investigating means to develop PM filter mechanisms which are more ash tolerant. These approaches include concepts to increase storage area within the filter itself and concepts which promote self-cleaning of the filter perhaps driven by engine and vehicle vibrations during normal vehicle operation. It was not clear during our review that these technologies would be able to fully address ash accumulation, but they were indicative of the potential to increase the interval between necessary ash removal maintenance activities.

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 acid neutralizing additives in engine oil should also decrease. The concept of an engine oil with less ash content is often referred to as "low-ash oil." A number of 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 on-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 on-highway HD2007 emission technology engines would also be appropriate for use on Tier 4 emission technology 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 in order to reduce PM emissions and to reduce operating costs for engine owners. Further improvements in oil consumption may be possible in order 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 fourfold. Current retrofit PM filter ash maintenance intervals can range from 50k miles to more than 200k miles.³⁵

4.1.2 NO_x Control Technologies

Oxides of nitrogen (NO and NO₂, collectively called NO_x) are formed at high temperatures during the diesel combustion process from nitrogen and oxygen present in the intake air. The NO_x formation rate is exponentially related to peak cylinder temperatures and is also strongly related to nitrogen and oxygen content (partial pressures). NO_x 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 NO_x Control Technologies

A number of 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 NO_x emissions, but are limited due to practical and physical constraints of heterogeneous diesel combustion.³⁶

A new form of diesel engine combustion, commonly referred to as homogenous diesel combustion or premixed diesel combustion, can give very low NO_x 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), NO_x emissions can be reduced enough to comply with the 0.3 g/bhp-hr NO_x emission standard that we have proposed today.³⁷ Some engine manufacturers are today producing engines which utilize this technology over a narrow range of engine operation.³⁸ Unfortunately, it is not possible today to apply this technology over the full range of diesel engine operation. We do 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 heterogeneous 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 NO_x Catalyst Technology

Lean NO_x catalysts have been under development for some time, and two methods have been developed for using a lean NO_x catalyst depending on the level of NO_x reduction desired though neither method can produce more than a 30 percent NO_x reduction. The “active” lean NO_x catalyst injects a reductant that serves to reduce NO_x to N₂ and O₂ (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 which allows the NO_x emissions to be reduced by the catalyst.

The lean NO_x 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 NO_x. 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 NO_x 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 NO_x catalysts have been shown to provide up to 30 percent NO_x reduction under limited steady-state conditions. However, this NO_x control is achieved with a fuel economy penalty upwards of 7 percent due to the need to inject fuel into the exhaust stream.³⁹ NO_x reductions over the HD transient FTP are only on the order of 12 percent due to excursions outside the optimum NO_x reduction efficiency temperature range for these devices.⁴⁰ Consequently, the active lean NO_x catalyst does not appear to be capable of enabling the significantly lower NO_x emissions required by the proposed NO_x standard.

The “passive” lean NO_x catalyst uses no reductant injection. Therefore, the passive lean NO_x catalyst is even more limited in its ability to reduce NO_x because the exhaust gases normally contain very few hydrocarbons. For that reason, today’s passive lean NO_x catalyst is capable of best steady state NO_x reductions of less than 10 percent. Neither approach to lean NO_x catalysis listed here can provide the significant NO_x reductions necessary for compliance with the proposed Tier 4 standards.

4.1.2.3 NO_x Adsorber Technology

NO_x 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 stoichiometric conditions found in the exhaust of properly controlled gasoline-powered vehicles. Today, an advancement upon this well-developed three-way catalyst technology, the NO_x adsorber, has shown that it too can make possible extremely low NO_x emissions from lean-burn engines such as diesel engines.^F The potential of the NO_x 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 NO_x standards for on-highway diesel engines beginning in 2007 predicated upon the use of the NO_x adsorber catalyst enabled by significant reductions in fuel sulfur levels (15 ppm sulfur or less). In today’s action, we are proposing similarly stringent NO_x emission standards for nonroad engines greater than 75 hp, again using technology enabled by a reduction in fuel sulfur levels.

NO_x adsorbers work to control NO_x emissions by storing NO_x 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 NO_x is released and reduced across precious metal catalysts. The NO_x storage period can be as short as 15 seconds and as long as 10 minutes depending upon engine out NO_x emission rates and exhaust temperature. A number of methods have been developed to accomplish the necessary brief rich exhaust conditions necessary to regenerate the NO_x adsorber technology including late-cycle fuel injection, also called post injection, in exhaust fuel injection, and dual bed technologies with off-line regeneration.^{41,42,43} This method for NO_x control has been shown to be highly effective when applied to diesel engines but has a number of technical challenges associated with it. Primary among these is sulfur poisoning of the catalyst as described in Section 4.1.2.3.x below.

^F NO_x adsorber catalysts are also called, NO_x storage catalysts (NSCs), NO_x storage and reduction catalysts (NSRs), and NO_x traps.

4.1.2.3.1 How do NO_x Adsorbers Work?

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

Three-way catalysts reduce NO_x emissions as well as HC and CO emissions (hence the name three-way) by promoting oxidation of HC and CO to water and CO₂ using the oxidation potential of the NO_x pollutant, and, in the process, reducing the NO_x emissions to atomic nitrogen, N₂. 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 (CO₂), water (H₂O) and nitrogen (N₂). The oxidizing potential in the exhaust comes from NO_x emissions and some oxygen (O₂) which is not consumed during combustion. The reducing potential in the exhaust comes from HC and CO emissions, which represent 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 NO_x and O₂ 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 NO_x and O₂ in comparison to the reducing potential of the HC and CO present in the exhaust, the excess NO_x 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 NO_x (and O₂) emissions remain almost unchanged from the high engine out 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 NO_x emissions that are an order of magnitude higher, than for gasoline engines equipped with three-way catalysts.

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

The NO_x storage process can be further broken down into two steps. First the NO in the exhaust is oxidized to NO₂ across an oxidation promoting catalyst, typically platinum. Then the NO₂ 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 . In order for the NO_x storage function to work, the NO_x 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, NO_x 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 NO_x , HCs, and CO under the net oxygen rich operating conditions typical of diesel engines.

The NO_x adsorber releases and reduces NO_x emissions under fuel rich operating conditions through a similar two step process, referred to here as NO_x adsorber regeneration. The metallic nitrate becomes unstable under net fuel rich operating conditions, decomposing and releasing the stored NO_x . Then the NO_x is reduced by reducing agents in the exhaust (CO and HCs) across a three-way catalyst system, typically containing platinum and rhodium. Typically, this NO_x regeneration step occurs at a significantly faster rate than the period of lean NO_x storage such that the fuel rich operation constitutes only a small fraction of the total operating time. Since this release and reduction step, NO_x adsorber regeneration, occurs under net fuel rich operating conditions, NO_x 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 NO_x adsorber technology can be summarized as follows. Stoichiometric three-way catalysts work to reduce NO_x , HCs and CO by maintaining a careful balance between oxidizing (NO_x 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 NO_x 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 in order 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, NO_x adsorbers offer the potential to employ the highly effective three-way catalyst chemistry to lean burn engines.

4.1.2.3.2 NO_x Adsorber Regeneration Mechanisms

NO_x adsorbers work to control NO_x emissions by storing the NO_x pollutants on the catalyst surface during oxygen rich engine operation (lean burn engine operation) and then by periodically releasing and reducing the NO_x emissions under fuel rich exhaust conditions. This approach to controlling NO_x 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 NO_x emissions in this manner is the production basis for lean burn NO_x emission

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control in stationary power systems and for lean burn gasoline engines. As outlined below we believe that 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 NO_x adsorbers. That is the engine itself changes in operation periodically between “normal” lean burn (oxygen rich) combustion and stoichiometric or even fuel rich combustion in order to promote NO_x control with the NO_x 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 which 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 NO_x emissions are stored on the surface of the NO_x adsorber catalyst. The period of fuel lean, oxygen rich, operation is determined by the NO_x emission rate from the engine and the storage capacity of the NO_x adsorber. Once the NO_x adsorber catalyst is full (once an unacceptable amount of NO_x is slipping through the catalyst without storage) the engine must switch to fuel rich operation in order to regenerate the NO_x 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 in order 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 in order 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 in order to achieve a net fuel rich operating condition. That is, the primary plus secondary injection events introduce an excess of fuel when compared to the amount of oxygen in the combustion chamber. The secondary injection event occurs very late in the combustion cycle so that no torque is derived from its introduction. This is necessary so that 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 NO_x adsorber and determine when the NO_x regeneration events are necessary. This could be done in a variety of ways, though they fall into two general categories: predictive and reactive. The predictive method would estimate or measure the NO_x 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, a NO_x regeneration would be performed. This particular step is similar to an on-board diagnostic (OBD) algorithm waiting for proper conditions to perform a functionality check. During the NO_x regeneration, sensors would determine how accurately the predictive algorithm performed, and adjust it accordingly. The reactive method is envisioned to monitor NO_x downstream of the NO_x adsorber and, if NO_x slippage is detected, a regeneration event would be triggered. This method is dependent on good NO_x sensor technology. This method would also depend on the ability to

regenerate under any given engine operating condition, since the algorithm would be reacting to indications that the adsorber had reached its NO_x storage capacity. In either case, we believe these algorithms are not far removed from the systems that will be used by nonroad manufacturers to comply with the Tier 3 emission standards and will be virtually identical to the systems used by on-highway manufacturers to comply with the HD2007 emission regulations. When used in combination with the sophisticated control systems that will be available, we expect that NO_x regeneration events can be seamlessly integrated into engine operation such that the driver or equipment 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 NO_x 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 in order to meet the Tier 3 NO_x 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.

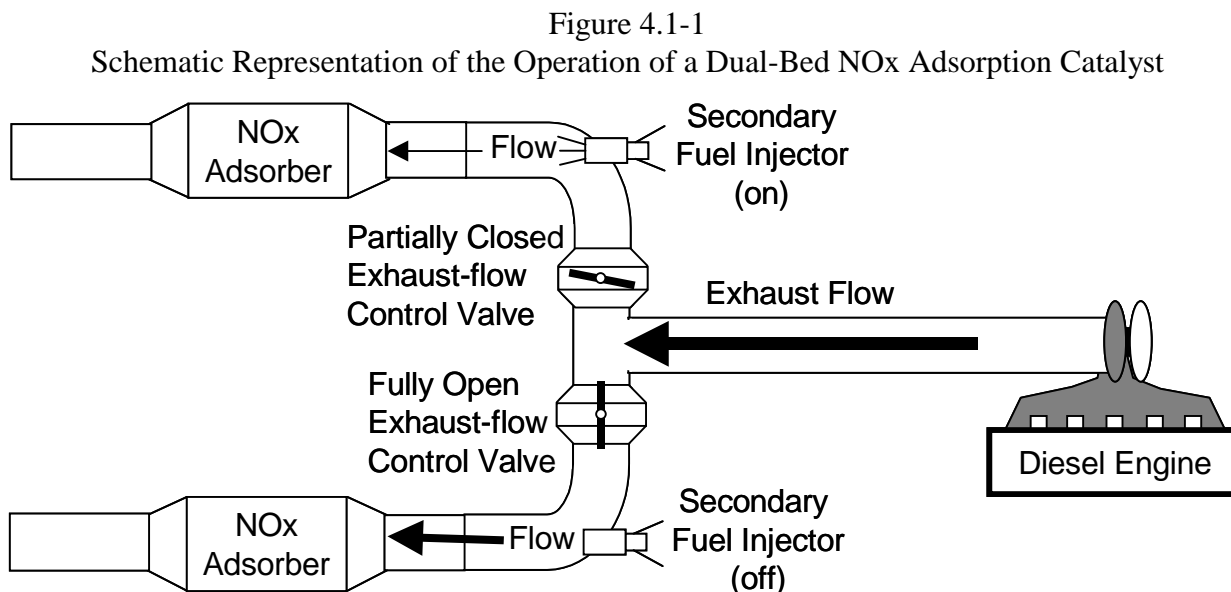
Another approach to accomplish the NO_x adsorber regeneration is through the use of a so called “dual-bed” or “multiple-bed” NO_x adsorber catalyst system. Such a system is designed so that the exhaust flow can be partitioned and routed through two or more catalyst “beds” which operate in parallel. Multiple-bed NO_x 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 in order to generate a rich exhaust stream. One simple example of a multiple bed NO_x 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 would have the following characteristics:

- Half of the system would operate with a major flow in an “adsorption mode”, where most of the exhaust is well lean of stoichiometric ($\lambda > 1$ or $\gg 1$, typical diesel exhaust), NO is converted to NO₂ over a Pt-catalyst, and stored as a metallic nitrate within the NO_x adsorbent material.^G
- The other half of the system would have its exhaust flow restricted to just a small fraction (~5 percent) of the total flow and would operate 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 NO_x to be released. This occurs at exhaust conditions of $\lambda \leq 1$.
 - At these conditions, NO_x can also be very efficiently reduced to N₂ and O₂ over a precious metal catalyst.

^G 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.

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- 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.



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 NO_x adsorber system such as the use of multiple beds allows desulfation of one bed while normal NO_x adsorption and regeneration events occur in other beds.

The NO_x adsorber performance can be enhanced by incorporating a catalyzed diesel particulate filter (CDPF) into the system. A number of synergies exist between NO_x adsorber systems and CDPFs. Both systems rely on conversion of NO to NO₂ 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 NO_x adsorber during regeneration would provide a more reactive reductant for desorption and reduction of NO_x. Heavier fuel hydrocarbons are known to inhibit NO_x reduction on the NO_x adsorption catalyst since competitive adsorption by hydrocarbons on the precious metal sites inhibits NO_x reduction during adsorber regeneration.⁴⁴ 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 NO_x 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 could be used increase the rate of temperature rise for the NO_x adsorber catalyst after cold starts, similar to the use of light-off catalysts with cascade three-way catalyst systems.⁴⁵

4.1.2.3.3 *How Efficient are Diesel NO_x Adsorbers?*

Research into applying the NO_x 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 NO_x adsorber store NO_x under normal lean burn diesel engine operation, and then how well does the control system perform the NO_x 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 4.1.3.1.2 below to predict the effectiveness of the NO_x adsorber technology on the proposed nonroad test cycles. The potential for both NO_x storage and reduction to operate at very high efficiencies can be realized through careful emission control system design as described below.

The NO_x storage function consists of oxidation of NO to NO₂ and then storage of the NO_x 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 effective a NO_x adsorber based control system can store NO_x 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 NO₂ oxidation and for NO_x storage increases with increasing temperature. Beginning at temperatures as low as 100°C NO oxidation to NO₂ can be promoted across a platinum catalyst at a rate high enough to allow for NO_x 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 NO_x 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 NO_x adsorber to store NO_x. First the NO to NO₂ reaction products are determined by an equilibrium reaction which favors NO rather than NO₂. That is across the oxidation catalyst, NO is oxidizing to form NO₂ and NO₂ is decaying to form NO at a rate which favors a larger fraction of the gas being NO rather than NO₂. As this is an equilibrium reaction when the NO₂ is removed from the gas stream by storage on the catalyst surface, the NO_x gases quickly “re-equilibrate” forming more NO₂. This removal of NO₂ from the gas stream and the rapid oxidation of NO to NO₂ means that in spite of the NO₂ fraction of the NO_x gases in the catalyst being low at elevated conditions (30 percent at 400°C) the storage of NO_x 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 NO_x emissions under fuel lean operating conditions can become unstable at elevated temperatures. That is, the metallic nitrates thermally decompose releasing the stored NO_x under lean operating conditions allowing the NO_x to exit the exhaust system “untreated.” The temperature at which the storage metals begin to thermally release the stored NO_x 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 NO_x desorption by as much as 100°C.⁴⁶ Thermal stability is the primary factor determining the NO_x control efficiency of the NO_x adsorber at temperatures higher than 400-500°C. NO_x adsorber catalyst developers are continuing to

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work to improve this aspect of NO_x adsorber performance, and as documented in EPA's 2002 Highway Progress Review improving temperature performance is being realized.

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

NO_x release can occur under relatively cool exhaust temperatures even below 200°C for current NO_x adsorber formulations. Unfortunately, the three-way NO_x 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 NO_x reduction function of current NO_x adsorbers is between 200°C and 250°C. Therefore, even though NO_x storage and release can occur at cooler temperatures, NO_x control is limited under steady-state conditions to temperatures greater than this light-off temperature.

Under transient operation however, NO_x control can be accomplished at temperatures below this NO_x 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 NO_x control is possible due to two characteristics of the system specific to transient operation. First, NO_x control can be continued below the light-off temperature because storage can continue below that temperature. If the exhaust temperature again rises above the NO_x reduction light-off temperature before the NO_x adsorber storage function is full, the NO_x reduction can then precede at high efficiency. Said another way, if the excursions to very low temperatures are brief enough, NO_x storage can proceed under this mode of operation, followed by NO_x reduction when the exhaust temperatures are above the light-off temperature. Although this sounds like a limited benefit because NO_x storage volume is limited, in fact it can be significant, because the NO_x emission rate from the engine is low at low temperatures. While the NO_x storage rate may be limited such that at high load conditions the lean NO_x storage period would be as short as 30 seconds, at the very low NO_x rates typical of low temperature operation (operation below the NO_x reduction light-off temperature) this storage period can increase dramatically. This is due to the NO_x mass flow rate from the engine changing dramatically between idle conditions and full load conditions. The period of lean NO_x storage would be expected to increase in inverse proportion to the NO_x emission rate from the engine. Therefore, the period of NO_x storage under light load conditions could likewise be expected to increase dramatically as well.

Transient operation can further allow for NO_x control below the NO_x 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 NO_x 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 NO_x adsorbers at NVFEL, especially with regards to NO_x control under idle conditions. It was observed that when idle

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conditions followed loaded operation, for example when cooling the engine down after a completing an emission test, that the NO_x emissions were effectively zero (below background levels) for extended periods of idle operation (for more than 10 minutes). Additionally it was discovered that the stored NO_x could 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) NO_x control eventually diminished. The loss of NO_x control at extended idle conditions appeared to be due to the inability to reduce the stored NO_x leading to high NO_x emissions during NO_x regeneration cycles.

NO_x control efficiency with the NO_x adsorber technology under steady-state operating conditions can be seen to be limited by the light-off temperature threshold of the three-way catalyst NO_x reduction function. Further, a mechanism for extending control below this temperature is described for transient operation and is observed in testing of NO_x adsorber based catalyst systems. Additionally, 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 NO_x performance with a NO_x adsorber catalyst.

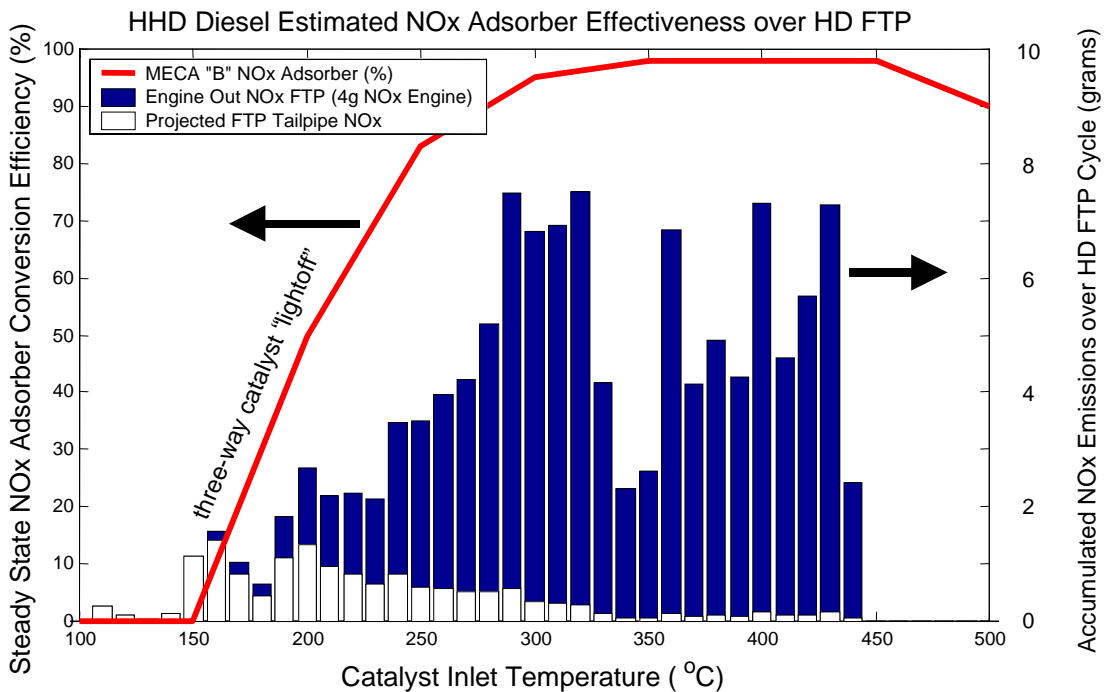
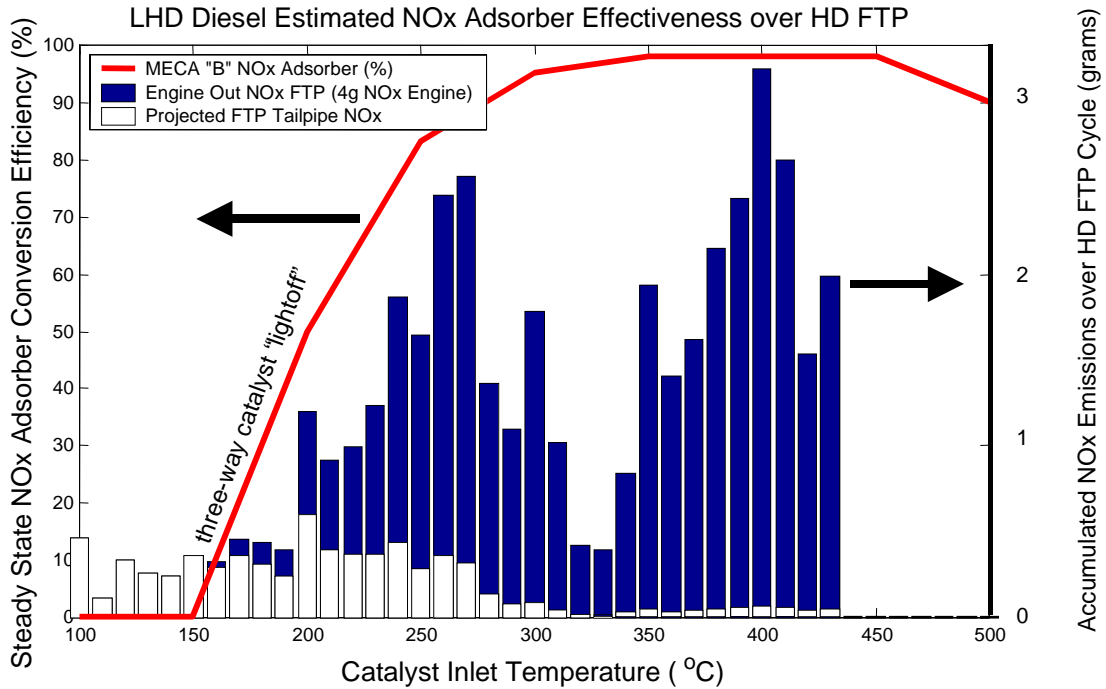
Overall, NO_x adsorber efficiency reflects the composite effectiveness of the NO_x adsorber in storing, releasing and reducing NO_x over repeated lean/rich cycles. As detailed above, exhaust temperatures play a critical role in determining the relative effectiveness of each of these catalyst functions.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

At low exhaust temperatures overall NO_x control is limited by the light-off temperature threshold of the three-way NO_x reduction function in the range from 200°C to 250°C. At high temperatures (above 400° to 500°C) overall NO_x control is limited by the thermal stability of the NO_x storage function. For exhaust temperatures between these two extremes NO_x control can occur at virtually 100 percent effectiveness.

The ability of the complete system including the engine and the emission control system to control NO_x 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 pictorial representation of these constraints and indicates how well a diesel engine can match the capabilities of a NO_x adsorber-based NO_x control system. The figure shows accumulated NO_x emission (grams) over the on-highway heavy-duty FTP test for both a light heavy-duty (LHD) and a heavy heavy-duty (HHD) engine. The engine-out NO_x emissions are shown as the dark bars on the graphs. The accumulated NO_x emissions shown here, divided by the integrated work over the test cycle gives a NO_x emission rate of 4 g/bhp-hr (the 1998 on-highway HD emission standard) for each of these engines. Also shown on the graph as a solid line is the steady-state NO_x conversion efficiency for a NO_x 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 NO_x emissions that could be realized from the application of the NO_x 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 NO_x 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 could be better than estimated here due to catalyst's ability to store the NO_x 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 to the FTP NO_x efficiency for the LHD engine shown in Figure 4.1-2 above and actual NO_x adsorber efficiency demonstrated with this engine in the NVFEL test program. Based upon the figure above (using the steady-state conversion estimate) the NO_x adsorber catalyst should have provided less than an 84 percent reduction in NO_x emissions over the FTP. However, testing at NVFEL (detailed in Section 4.1.2.3.5) has demonstrated a greater than 90 percent reduction in NO_x emissions with this same engine and catalyst pair without significant optimization of the system. Clearly then, steady-state NO_x adsorber performance estimates can underestimate the real NO_x reductions realized in transient vehicle operation. Nevertheless, we have used this approach as a screening analysis to predict performance for nonroad engines equipped with NO_x adsorber catalysts in Section 4.1.3.1.2 below.

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

Figure 4.1-2 shows that the temperature window of a current technology NO_x 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 heavy-duty FTP driving cycle. The discussion in 4.1.3.1.2 below shows similarly that the proposed nonroad transient test cycle (NRTC) is also well matched to the performance of the NO_x 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, NO_x 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 NO_x adsorber-based emission control system are well matched, NO_x 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 NO_x control efficiency may be reduced. Researchers are developing and testing new NO_x adsorber formulations designed to increase the high temperature stability of the NO_x adsorber and to therefore widen this window of operation.⁴⁷

How effective are NO_x 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 proposed NRTC also includes a cold-start test where the catalyst initial temperature will be at ambient conditions. The complete proposed NRTC test sequence will include both a cold start emission test and a hot start emission test as described more fully in 4.2. The NRTC emission level for the engine is determined by weighting the cold-start emissions by 1/10 (10 percent), and weighting the hot-start emission results by 9/10 (90 percent).

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Historically, for on-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 exhaust emission control devices, such as a NO_x adsorber, the cold-start test will become a design challenge for on-highway diesel engine manufacturers and, with this proposal, for nonroad diesel engine manufacturers, just as it has been a design challenge for light-duty gasoline vehicle manufacturers for more than 20 years. As discussed above, NO_x adsorbers do have optimal temperature operating windows, and thus will represent a design challenge.

Manufacturers have a number of tools available to them to overcome this challenge:

- The volume, shape, and substrate material have a significant effect on the warm-up time of a NO_x adsorber (just as they do for a light-duty three-way catalysts). Manufacturers 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 its proximity to the exhaust manifold, will have a significant impact on the light-off characteristics.
- As discussed above, NO_x adsorbers have the ability to store NO_x 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 light-duty gasoline catalysts, and it would allow the NO_x adsorber to store NO_x for some period of time prior to 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 NO_x adsorber system. In addition, manufacturers have a number of active tools which can be used to enhance the cold-start performance of the system all based on technologies which may be used to comply with the Tier 3 emission standards (i.e., technologies which will form the baseline for engines meeting the proposed Tier 4 standards). These include the use of engine start-up routines which have a primary purpose of adding heat to the exhaust to enhance NO_x 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 of these tools in order to choose the best combination necessary to minimize light-off time and improve the cold-start NRTC performance.

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On-highway manufacturers must overcome this same challenge in order to comply with the HD2007 emissions standards some number of years before these proposed nonroad emission standards go into effect. Additionally, on-highway manufacturers must do this with a higher cold start weighting of 1/7 rather than 1/10 as proposed today for nonroad engines. This means that on-highway engine manufacturers must have lower cold start emissions relative to their hot start emissions than will nonroad engine manufacturers having to meet our proposed Tier 4 standards. Therefore, we believe that the technologies we expect on-highway engine manufacturers to use for compliance (i.e., the technologies delineated above) for the 2007 standards will be more than capable of being applied to nonroad diesel engines in order to comply with the proposed Tier 4 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 NO_x emissions engine out.⁴⁸ As a result, exhaust temperature are increased into the region for effective NO_x 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.

How effective are NO_x adsorbers over the proposed NTE?

We are proposing an NTE standard for nonroad Tier 4 engines that replicates the provisions for on-highway diesel trucks. A complete discussion of that proposal can be found in chapter 4.3. In short, the proposal would set an NTE emissions limit that is 1.5 times the NRTC emissions limit over a broad range of engine operating conditions. As discussed below, a 90 percent NO_x reduction is technologically feasible across the range of engine operating conditions and ambient conditions subject to the proposed NTE standards. Also, as discussed below, some modifications to the proposed NTE provisions to address technical issues which arise from the application of advanced NO_x catalyst systems were included in the HD2007 standards and are carried over into this proposal.

Section 4.1.2.3.5.2 contains a description of the ongoing NO_x adsorber evaluation test program run by our EPA laboratory. Included in that section is test data on four different NO_x adsorbers for which extensive steady-state mapping was performed in order 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 proposed NTE NO_x control zone, and would not be subject to the proposed NTE standard. The following modes listed in these four figures are within the proposed NTE NO_x control zone, 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 proposed NTE zone. The region of the proposed 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 NO_x reduction respectively. However, Adsorber D was able to achieve NO_x 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 NO_x reduction efficiency range for NO_x adsorbers, therefore it is not unexpected that the NO_x

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reductions along the torque curve for the test engine are not as high as in other regions of the proposed NTE zone. We would expect manufacturers to choose a NOx adsorber formulation which matches the exhaust gas temperature operating range of 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 would likely not see periods of sustained operation along the torque curve, and therefore the likelihood the NOx adsorber bed itself would achieve temperatures in excess of 500°C would be diminished. 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.^{49,50,51} As discussed above, only small improvements in the current characteristics are necessary in order to achieve 90 percent NOx reductions or greater across the proposed NTE control zone.

As discussed above, the use of advanced NOx adsorber based catalyst systems will present cold-start challenges for on-highway heavy-duty diesel engines, and for nonroad diesel engines, under our proposed 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 in order to achieve the NOx standard. The majority of engine operation which occurs within the proposed NTE control 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 which are within the proposed NTE control 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, though the proposed NTE does not include engine start-up conditions, it is conceivable that a diesel which has not been warmed up could be started and very quickly be operated under conditions which are subject to the proposed NTE standard; for example, within a minute or less of vehicle operation after the vehicle has left an idle state. The proposed NTE regulations specify a minimum emissions sampling period of 30 seconds. Conceivably the vehicle emissions could be measured against the proposed NTE provisions during that first minute of operation, and in all likelihood it would not meet the proposed 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, operation with the proposed NTE 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. Therefore, we have proposed to set a low temperature exhaust gas threshold of 250°C, below which the specified NTE requirements do not apply, a provision we also adopted (for the same reason) for on-highway engines in our HD2007 program, and we are proposing a similar provision for Tier 4.

The proposed 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 proposed NTE NOx standard. In general, it can be said that the performance of the NOx adsorbers are only effected by the exhaust gas stream to which the adsorbers are exposed. Therefore, the impact of ambient humidity, temperature, and altitude will only effect the performance of the adsorber 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 proposed NTE requirement will have minimal, if any, impact on the performance of the NO_x 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 NO_x adsorber performance should also be minimal, if any. The proposed NTE test procedure regulations specify an upper bound on NTE testing for altitude at 5,500 feet above sea-level. The decrease in atmospheric pressure at 5,500 feet should have minimal impact on the NO_x 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 on-highway Phase 1 (2004) final rule, Phase 1 technology HDDEs (and thus similar Tier 3 nonroad diesel engines) can be designed to target air-fuel ratios at altitude which will maintain appropriate exhaust gas temperatures, as well as maintain engine-out PM levels near the 0.1 g/bhp-hr level, within the ambient conditions specified by the on-highway NTE test procedure and thus the similar NTE procedure proposed today for Tier 4 nonroad engines. Finally, the proposed NTE regulations specify ambient temperatures which are broader than the NRTC temperature range of 68-86°F. The proposed NTE test procedure specifies no lower ambient temperature bounds. However, as discussed above, we have proposed to limit NTE requirements on NO_x (and NMHC) for engines equipped with NO_x (and/or NMHC) catalysts to include only engine operation with exhaust gas temperatures greater than 250°C. Therefore, low ambient temperatures will not present any difficulties for NTE NO_x compliance. The proposed NTE also applies under ambient temperatures which are higher than the laboratory conditions. The proposed NTE applies 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 proposed NTE ambient temperature requirement is a linear fit between these two conditions. At 5,500 feet, the proposed NTE ambient temperature requirement is the same as the upper end of the FTP temperature range (86°F), and therefore will have no impact on the performance of the NO_x adsorbers, considering that majority of the test data described throughout this chapter was collected under laboratory conditions. The proposed 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 manufacturer to choose an adsorber formulation which is matched to a particular engine design, and we would expect the small increase in exhaust gas temperature which can occur from the expanded ambient temperature requirements for the proposed NTE will be taken into account by the manufacturer 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 proposed NTE NO_x requirement (1.5 x NRTC/C1 standard) contained in this final rule will be feasible.

Further discussion of feasibility of the NO_x requirement under transient testing conditions can be found in section 4.1.3 below (NRTC cycle) and in section 4.2 (CSV cycle).

4.1.2.3.4 Are Diesel NO_x Adsorbers Durable?

The considerable success in demonstrating NO_x adsorbers makes us confident that the technology is capable of providing the level of conversion efficiency needed to meet the proposed NO_x 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 NO_x adsorber performance, engine and catalyst manufacturers will further need to address issues of system and catalyst durability. The nature of these issues are understood well today. 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 on-highway technologies to nonroad engines as anticipated in this rulemaking, all of the issues highlighted in this section while not addressed today, are expected to have already been addressed for on-highway engines well before the start of this nonroad program.

In this section we will describe the major technical hurdles to address in order to ensure that the significant emission reductions enabled through the application of NO_x adsorbers is realized throughout the life of nonroad diesel engines. The section is organized into separate durability discussions for the system components (hardware) and various near and long term durability issues for the NO_x adsorber catalyst itself.

4.1.2.3.4.1 NO_x 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 NO_x adsorber regeneration and desulfation. The system consists of three catalyst substrates (for a CDPF/Low Temperature NO_x Adsorber, a High Temperature NO_x 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. Although not shown in the figure, a NO_x /O₂ 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 NO_x 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 NO_x 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 4.1.3.2 below.

The NO_x/O₂ 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 NO_x adsorber based diesel emission control. The NO_x/O₂ sensor is an evolutionary technology based largely on the current Oxygen (O₂) 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 would normally be encountered on a diesel

engine.^{52,53} Diesel engines do have one characteristic that makes the application of NO_x/O₂ sensors more difficult. Soot in diesel exhaust can cause fouling of the NO_x/O₂ 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 NO_x adsorbers and CDPFs.) The CDPF then provides a protection for the sensor from PM while not hindering its operation. Since the NO_x adsorber is expected to 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 NO_x adsorber system is a relatively straightforward extension of the technology. A NO_x adsorber system would expect to cycle far fewer times over its life when compared to 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. Thus, while benefitting from the extensive experience with gasoline-based injectors a designer can, 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 in order to allow for NO_x adsorber regeneration and desulfation.⁵⁴

The NO_x 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 in order 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 in order 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 could be applied in order to accomplish the flow diversion required for diesel NO_x adsorber regeneration and desulfation. Since temperatures will be typically cooler at the NO_x adsorber compared to the inlet to the exhaust turbine on a turbocharger, the control valve would be expected to be equally reliable when applied in this application.

4.1.2.3.4.2 NO_x Adsorber Catalyst Durability

In many ways a NO_x 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 in order 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.

Technologies and Test Procedures for Low-Emission Engines

For example, contaminants from engine oil, like phosphorous or zinc, could attach to catalyst sites partially blocking the site from the exhaust constituents and slowing reactions. Similarly, lead added to gasoline in order 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. In order 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 NO_x adsorber catalyst. The NO_x 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, NO_x storage catalyst sites. The NO_x storage sites (normally alkali or alkaline earth metals) allow the catalyst to store NO_x 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 NO_x 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 NO_x adsorber is an incremental improvement upon the existing three-way catalyst, with many of the same solutions for the expected durability issues.

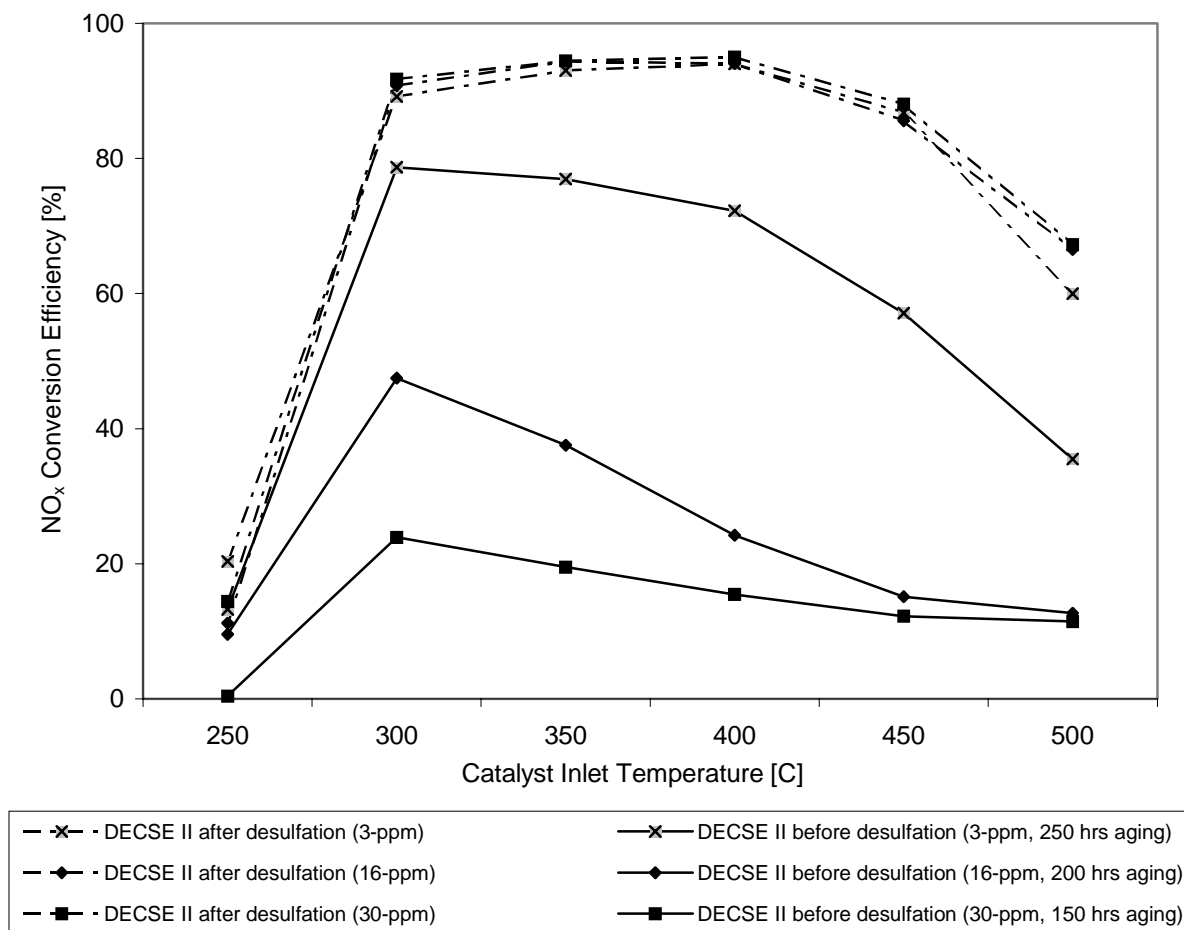
Sulfur Poisoning of the NO_x Storage Sites

The NO_x adsorber technology is extremely efficient at storing NO_x as a nitrate on the surface of the catalyst, or adsorber (storage) bed, during lean operation. Because of the similarities in chemical properties of SO_x and NO_x, the SO₂ 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 NO_x release and reduction step (NO_x regeneration step) (i.e. it is stored preferentially to NO_x). Since the NO_x adsorber is virtually 100 percent effective at capturing SO₂ in the adsorber bed, sulfate compounds quickly occupy the NO_x storage sites on the catalyst thereby reducing and eventually rendering the catalyst ineffective for NO_x reduction (poisoning the catalyst).

Figure 4.1-3 shows the effect of sulfur poisoning of a NO_x adsorber catalyst as reported by the DOE DECSE program. The graph shows the NO_x 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 NO_x 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 NO_x 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.⁵⁵

Figure 4.1-3
Comparison of NO_x 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 NO_x adsorber catalyst significantly.
- Higher fuel sulfur levels, like 30 ppm, dramatically increase the poisoning rate, further limiting NO_x 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 NO_x adsorber can provide high NO_x

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 NO_x conversion efficiencies after a desulfation event which was preceded by the sulfur poisoning and degradation shown in the solid lines.

The increase in sulfur poisoning rate is important to understand in order to look at the means to overcome the dramatic sulfur poisoning shown here. Sulfur accumulates in the NO_x storage sites preventing their use for NO_x storage. In other words, they decrease the storage volume of the catalyst. The rate at which sulfur fills NO_x storage sites is expected to be directly proportional to the amount of sulfur that enters the catalyst. Therefore, for a doubling in fuel sulfur levels a corresponding doubling in the SO_x poisoning rate would be predicted.

The design of a NO_x adsorber will need to address accommodating an expected volume of sulfur before experiencing unacceptable penalties in either lost NO_x control efficiency or increased fuel consumption due to more frequent NO_x 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 NO_x adsorber formulations).⁵⁶

Future improvements in the NO_x 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 NO_x 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 NO_x emissions), we expect that future NO_x adsorbers will continue to be poisoned by sulfur in the exhaust. Therefore a separate sulfur release and reduction cycle (desulfation cycle) will always be needed in order to remove the stored sulfur.

NO_x Adsorber Desulfation

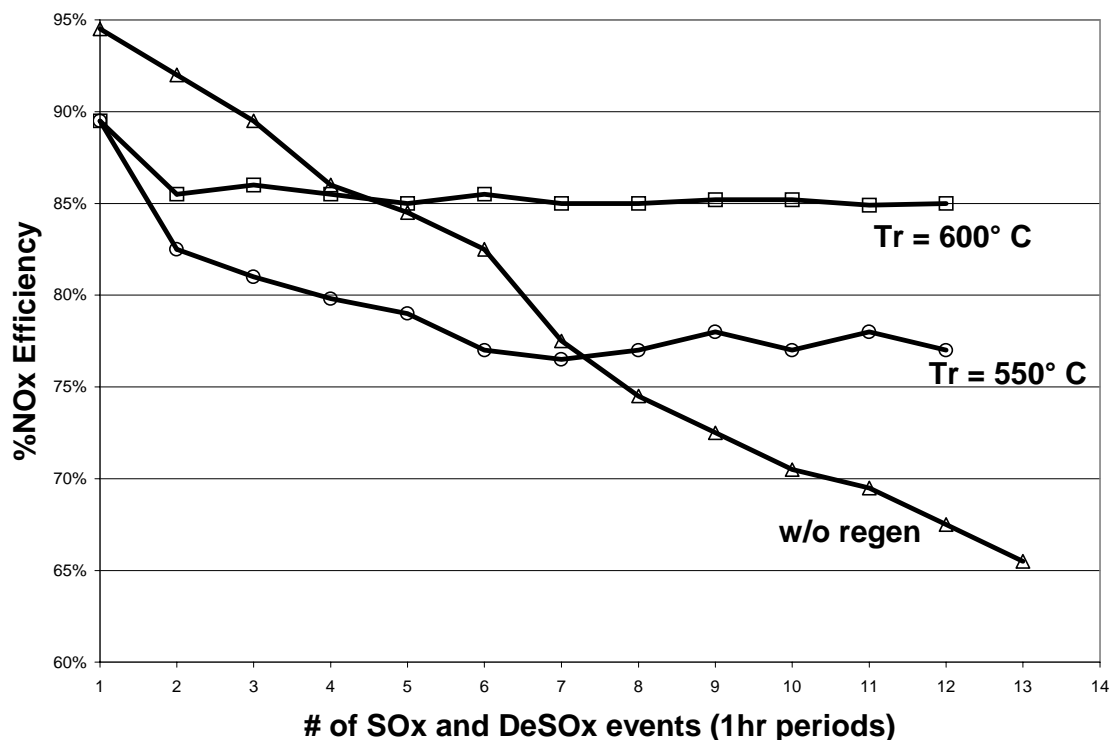
Numerous test programs have shown that sulfur can be removed from the catalyst surface through a sulfur regeneration step (desulfation step) not dissimilar from the NO_x regeneration function.^{57,58,59,60,61,62} The stored sulfur compounds are removed by exposing the catalyst to hot and rich (air-fuel 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 NO_x adsorber to near new operation.

Most of the information in the public domain on NO_x 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 NO_x adsorber catalysts can be accomplished under certain conditions but the work does not directly answer whether NO_x 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 NO_x 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 to fuel ratio and catalyst inlet temperatures to achieve the high temperatures required to release the sulfur from the device. Air to 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 could be developed for a diesel engine with the potential to meet in-service engine operating conditions and acceptable levels of torque fluctuation. The NO_x efficiency recovery accomplished in DECSE Phase II using this approach is shown in Figure 4.1-3, above.

The effectiveness of NO_x adsorber desulfation appears to be closely related to the temperature of the exhaust gases during desulfation, the exhaust chemistry (relative air to fuel ratio), and to the NO_x adsorber catalyst formulation.^{63, 64} Lower air to 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 NO_x adsorber conversion efficiency with periodic aging and desulfation events in a control flow reactor test.⁶⁵ 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 NO_x 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 to fuel ratio for diesels of 30:1).⁶⁶ From the figure it can be seen that without a desulfation event, sulfur rapidly degrades the performance of the NO_x adsorber catalyst. The remaining two lines show the NO_x 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 would be approximately equivalent to 34 hours of operation on seven ppm fuel). The desulfation events were identical to the NO_x regeneration events, except that the desulfation events occurred at elevated temperatures. The base NO_x 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 NO_x adsorber efficiency. From Figure 4.1-4 it can be seen that, for this NO_x adsorber formulation, the NO_x 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 NO_x 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 NO_x adsorber increases with temperature.^{67,68} However, while elevated temperatures directionally promote more rapid sulfur release, they also can directionally promote sintering of the precious metals in the NO_x 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.

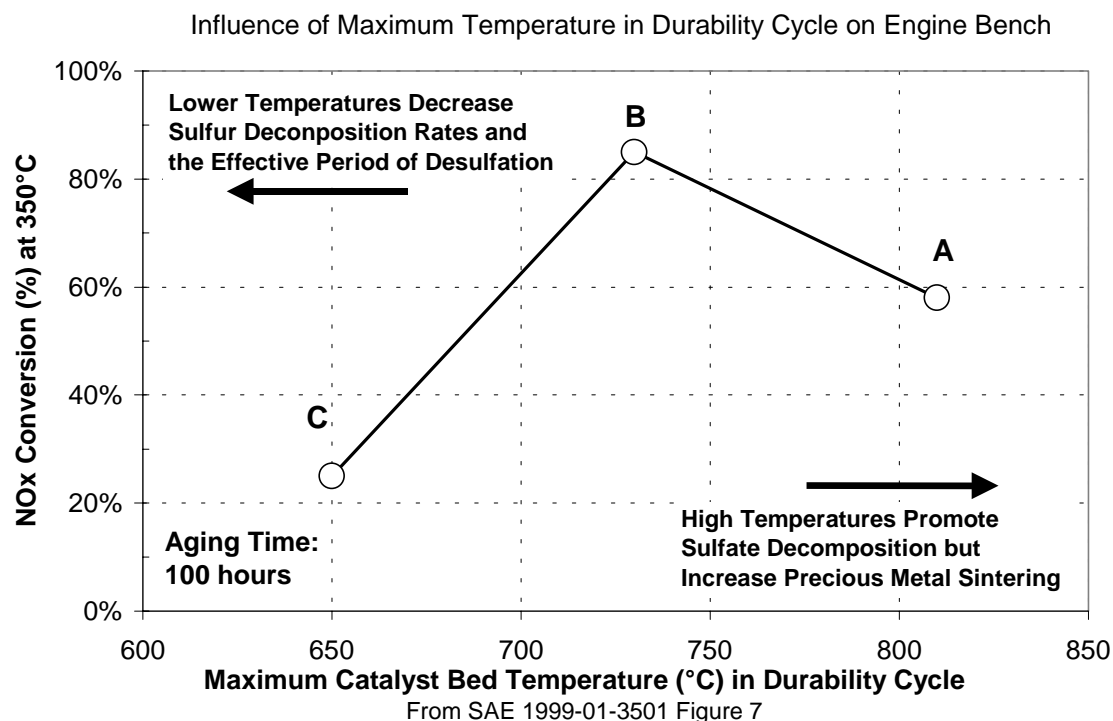
Thermal Degradation

The catalytic metals that make up most exhaust emission control technologies, including NO_x 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 to 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 NO_x adsorber catalyst because of the need for the catalytic metal sites to perform multiple tasks. NO_x adsorber catalysts typically rely on platinum to oxidize NO to NO₂ prior to adsorption of the NO₂ on an adjacent NO_x storage site. Under rich operating conditions, the NO_x is released from the adsorption site, and the adjacent platinum (or platinum + rhodium) catalyst site can serve to reduce the NO_x emissions into N₂ and O₂. High dispersion, combined with NO oxidation, NO_x storage and NO_x reduction catalyst sites being

located in close proximity, provide the ideal catalyst design for a NO_x adsorber catalyst. But high temperatures, especially under oxidizing conditions, can promote sintering of the platinum and other PGM catalyst sites, permanently decreasing NO_x adsorber performance.

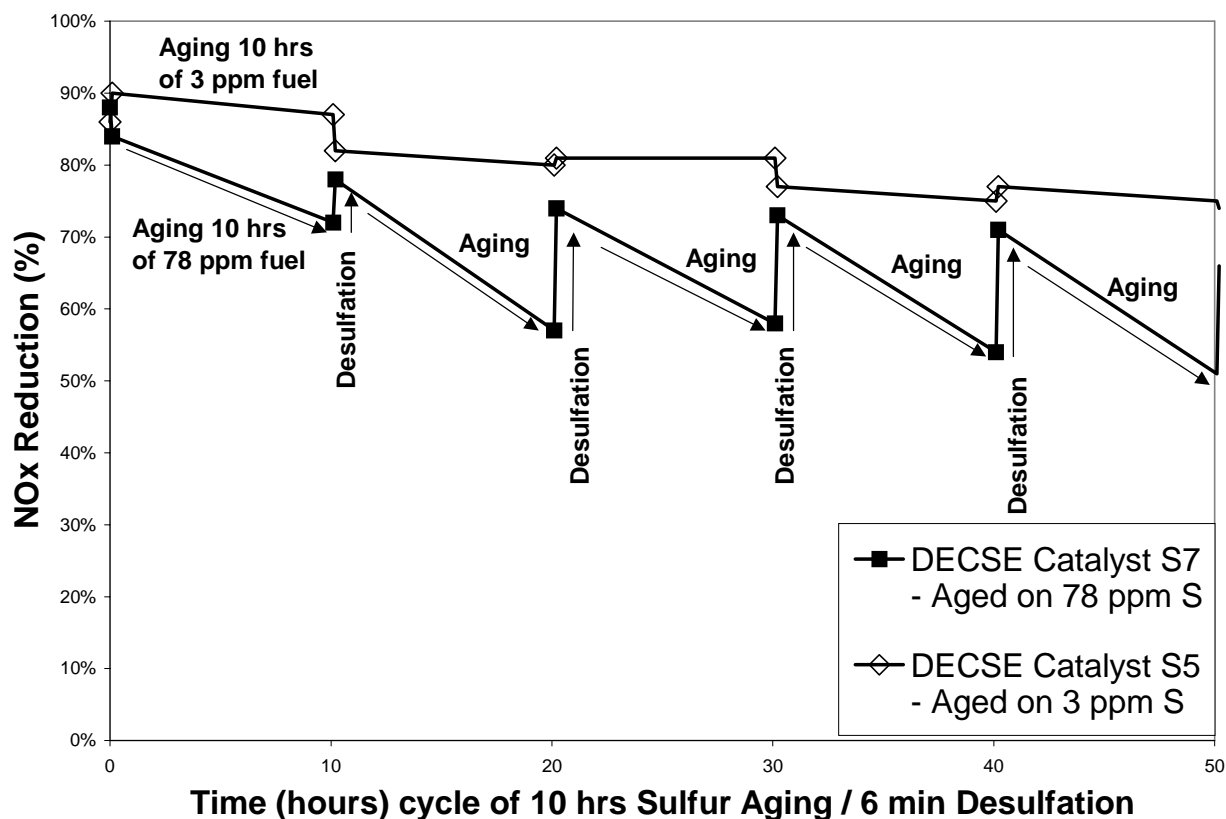
Catalyst sintering is a process by which adjacent catalyst sites can “melt” and regrow into a single larger catalyst site (crystal growth). The single larger catalyst site has less surface area available to promote catalytic activity than the original two or more catalyst sites that were sintered to form it. This loss in surface area decreases the efficiency of the catalyst.⁶⁹ High temperatures, promote sintering of platinum catalysts especially under oxidizing conditions.⁷⁰ Therefore, it is 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 NO_x 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 below, which shows the NO_x conversion efficiency of three NO_x adsorber catalysts evaluated after extended periods of sulfur poisoning followed by sulfur regeneration periods.⁷¹ 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 an optimum desulfation temperature exists which 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



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 below 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 would suggest as discussed above, that the desulfation cycle can itself be damaging to the catalyst. In actual use we would expect that an engine operating on 3 ppm sulfur fuel would not desulfate until well beyond a ten hour interval and would 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. In order to ensure continued high performance when operating on 78 ppm sulfur fuel the catalyst would require frequent desulfations. From the figure it can be inferred that the desulfation events would need to be spaced at intervals as short as one to two hours in order to maintain acceptable performance.

Figure 4.1-6
Integrated NO_x 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 could have been higher.⁷²

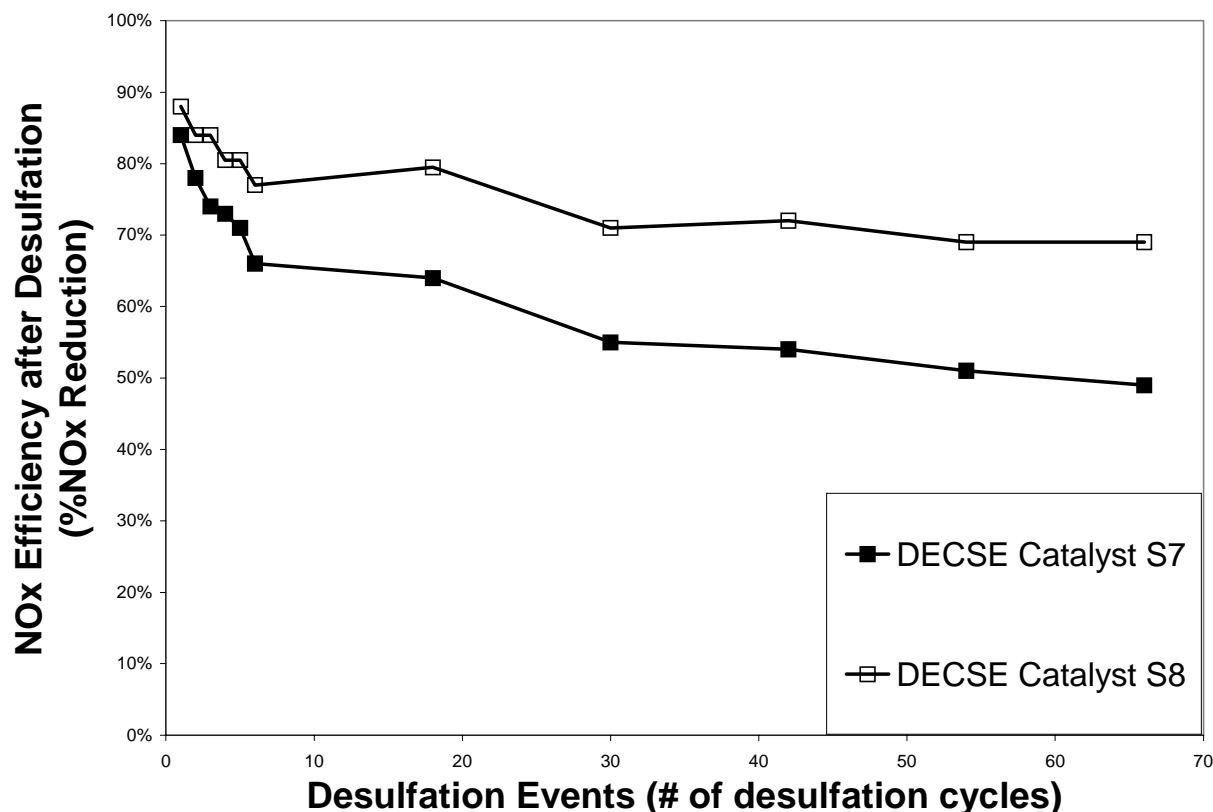
Based on the work in DECSE Phase II, the researchers concluded that:

- 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 NO_x 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 NO_x Conversion Efficiency after Repeated Desulfation



The data available today on current NO_x adsorber formulations shows clearly that sulfur can be removed from the surface of the NO_x 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 NO_x 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. In order to 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 NO_x 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 which 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.^{73, 74} Stabilization components can function in a number of 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 to the stabilization of NO_x adsorber catalyst components that is similar to the approaches taken with LEV three-way catalyst designs should help to minimize thermal sintering of components during desulfation.

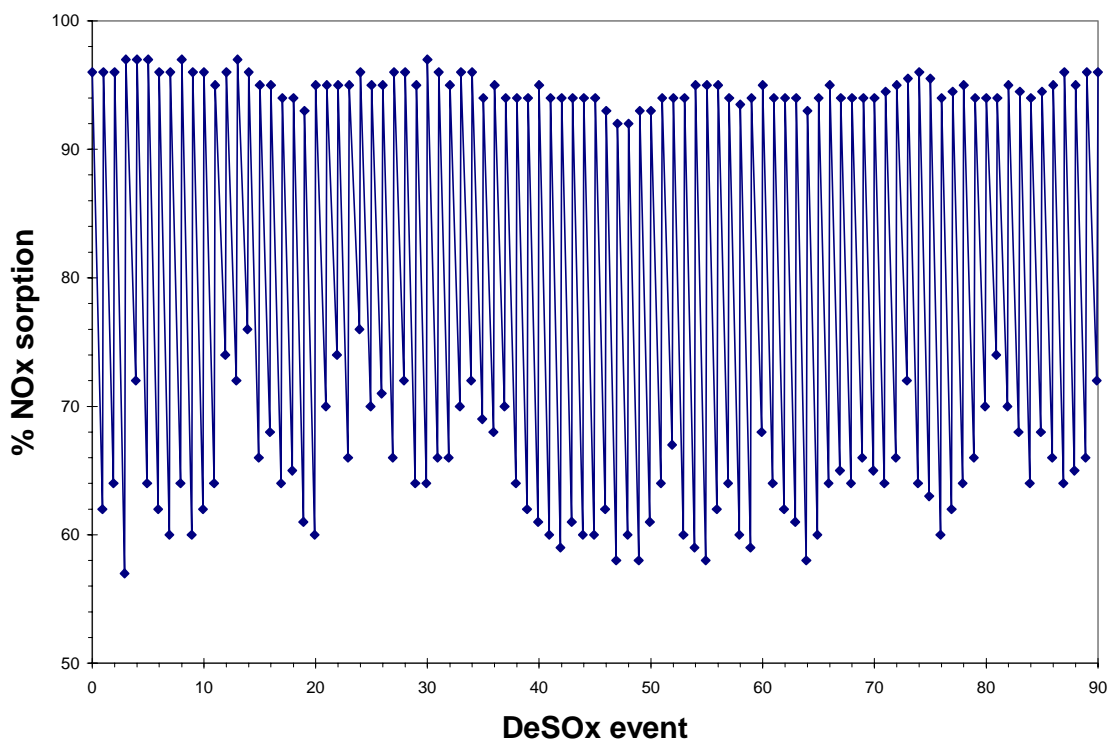
In many ways, limiting the thermal degradation of the NO_x adsorber catalyst should be easier than for the gasoline three-way catalyst. Typical exhaust gas temperatures for a heavy light-duty gasoline truck (e.g., a Ford Expedition) commonly range from 450°C to more than 800°C during normal operation.⁷⁵ 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. Therefore the NO_x adsorber when applied to diesel engines is expected to see both lower average temperatures and lower peak temperatures when compared to an equivalent gasoline engine. Once thermal degradation improvements are made to NO_x 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 NO_x 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 in order to limit the exposure to high temperatures. Also, improvements in how the regeneration process occurs may provide avenues for improvement. Low air to 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 NO_x adsorber catalyst desulfation (called DeSO_x 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 NO_x efficiency?” To explore the issue of NO_x adsorber durability after repeated desulfation events, Ford conducted repeated sequential sulfur poisoning and desulfation cycles with a NO_x adsorber catalyst. The results of their experiment are shown in Figure 4.1-8.⁷⁶ As shown in Figure 4.1-8, the NO_x 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 NO_x adsorber can be repeatedly desulfated without a

significant loss in NO_x 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 NO_x reduction efficiency.

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



These results indicate that, with further improvements to the NO_x adsorber catalyst design incorporating the experience gained on gasoline three-way catalysts and continuing improvements in the control of the desulfation, degradation of the NO_x 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 NO_x 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

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

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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 in order 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 MY2007 and later engines will be durable over the life of heavy-duty diesel vehicles, provided fuel with a 15 ppm sulfur cap is used and that the technology will prove to be similarly durable when applied some years later to nonroad diesel engines to comply with the proposed 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.⁷⁷ Average NOx control for these power generation facilities is in excess of 92 percent.⁷⁸ 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.⁷⁹ 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

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The NO_x adsorber's ability to control NO_x under oxygen rich (fuel lean) operating conditions has led industry to begin applying NO_x adsorber technology to lean burn engines in mobile source applications. NO_x 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.^H The 2000 model year saw the first U.S. application of this technology with the introduction of the Honda Insight, certified to the California LEV-I ULEV category standard. Table 4.1-6 below lists some of the 2002 European lean-burn direct-injection gasoline vehicles which uses NO_x adsorber catalyst technology.⁸⁰ These lean burn gasoline applications are of particular interest because they are similar to diesel vehicle applications in terms of lean NO_x storage and the need for periodic NO_x regeneration under transient driving conditions. The fact that they have been successfully applied to these mobile source applications shows clearly that NO_x 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.

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 (NVFEL)

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 NO_x adsorber catalyst formulations to EPA for evaluation. Testing of some of these catalysts at the National Vehicle and Fuel Emission Laboratory (NVFEL) revealed that formulations were capable of reducing NO_x emissions by more than 90 percent over the broad range of operation in the on-highway steady-

^H Toyota requires that their lean burn gasoline engines equipped with NO_x adsorbers are fueled on premium gasoline in Japan, which has an average sulfur content of six ppm.

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state SET procedure (sometimes called the EURO 4 test). At operating conditions representative of “road-load” operation for a heavy duty on-highway truck, the catalysts showed NO_x reductions as high as 99 percent resulting in NO_x emissions well below 0.1 g/bhp-hr from an engine out level of nearly 5 g/bhp-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. Although not included in the test results shown in figures 4.1-10 through 4.1-12, the ISO-C1 modes are closely approximated by a number of other test modes as can be seen in figure 4.1-9. Therefore, we would expect similarly good performance on the ISO-C1 test modes. Testing on the on-highway transient test procedure has shown similarly good results, with hot start FTP NO_x emissions reduced by more than 90 percent. These results demonstrate that significant NO_x reductions are possible over a broad range of operating conditions with current NO_x adsorber technology, as typified by the FTP 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 NO_x 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 NO_x Adsorber System

The goal of the NO_x adsorber screening process was to evaluate available NO_x adsorber formulations from different manufacturers with the objective of choosing an adsorber with 90 percent or better NO_x 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 only be able to run 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 on only one side of the system.

Test Approach -- Single Leg NO_x Adsorber System

The single leg system consisted of an exhaust brake, a fuel injector, CDPF, and a NO_x 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 set up, 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 NO_x regeneration, the backpressure of the bypass leg simulated the presence of a NO_x adsorber system. A clean-up diesel oxidation catalyst (DOC) downstream of the NO_x adsorber was not used for this testing.

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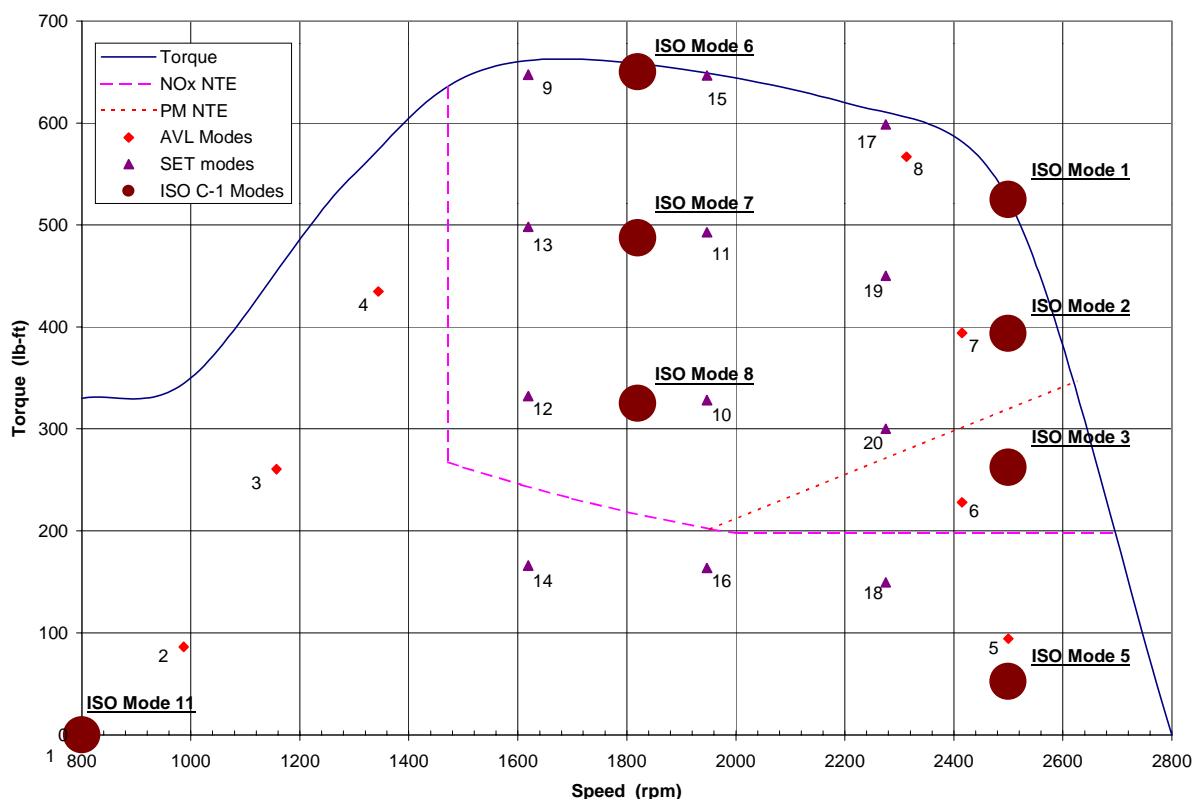
The measured emissions had to be adjusted to account for the lack of any NO_x adsorber in the bypass leg. For this correction, it was assumed that the bypass leg's missing (virtual) adsorber would adsorb only while the actual leg was regenerating. It was also assumed the virtual adsorber would have regeneration fuel requirements in proportion to its adsorbing time. The emissions 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.⁸¹

Test Results -- Single Leg NO_x 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.¹ 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 which have duplicate mode numbers. The on-highway NTE (which, of course, is the same as the proposed nonroad NTE) zone is also shown in Figure 4.1-9 to show that these two sets of modes give comprehensive coverage of the proposed 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 proposed 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 NO_x regenerations were then timed to achieve the desired NO_x 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.

¹ 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 the transient FTP.

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



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 FE impact. 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. It should be noted 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 proposed 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 HC and FE impacts. But, like EPA mode 1, EPA mode 2 would adsorb for extended periods of time without need for 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 in order to raise exhaust temperatures at these operating modes.

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The AVL composite showed greater differences between the adsorber formulations than the SET. Three of the adsorbers achieved greater than 90 percent NO_x reduction over the AVL composites with the other adsorber at 84 percent NO_x reduction. The greater spread in NO_x reduction performance was, in part, due to this composite's emphasis on EPA mode 8, which was at the upper end of the NO_x reduction efficiency temperature window. Adsorber E had an EPA mode 8 NO_x reduction of 66 percent, and the NO_x 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 FE 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. It should be noted 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 engine-out emission prediction of the HDDE transient cycle. As discussed in 4.1.3.1.2 below, NO_x adsorber control effectiveness is projected to be more effective over the NRTC than over the on-highway HDDE transient cycle. With exhaust emission control devices, it loses some of its accuracy because of the inability of the emission control devices to be regenerated at the low temperature modes (EPA modes 1, 2, 5). In real world conditions, the HDDE does 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 HDDE transient cycle performance is expected to be much better than the composites would suggest (See 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 NO_x 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.

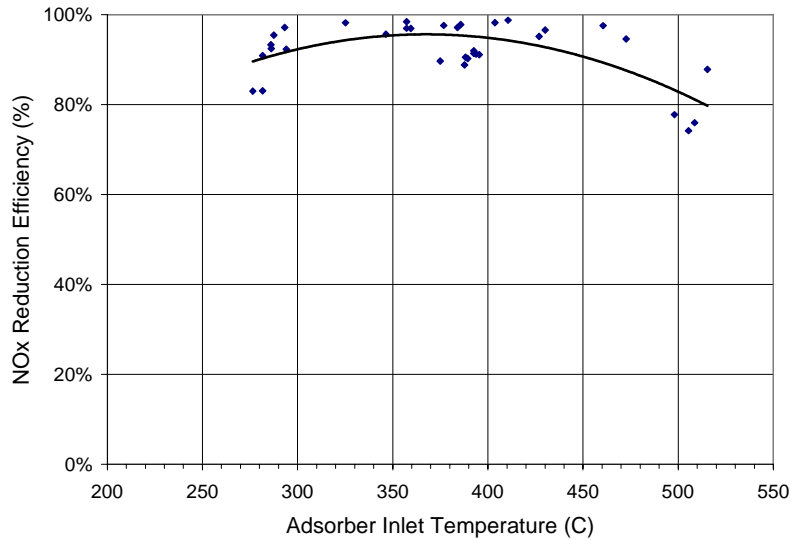


Figure 4.1-10. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber A

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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 *	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 *	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.

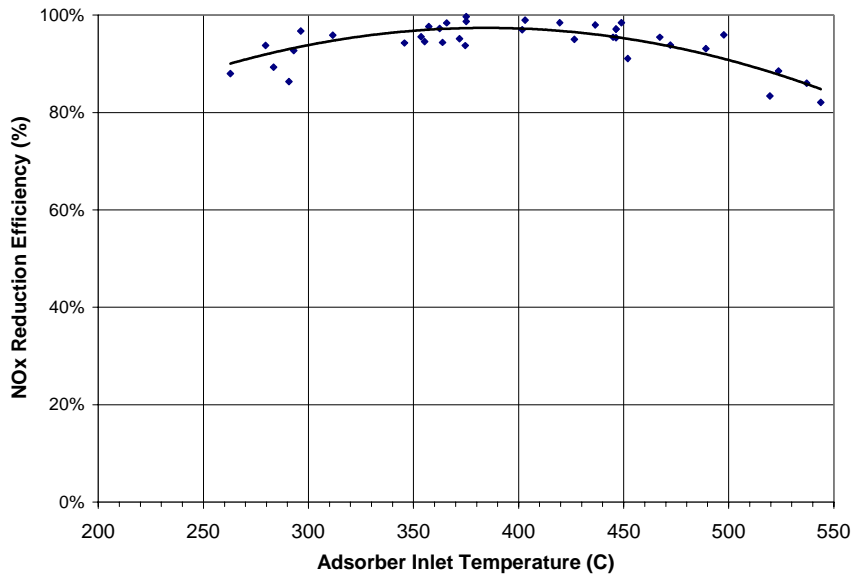


Figure 4.1-11. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber B

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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.

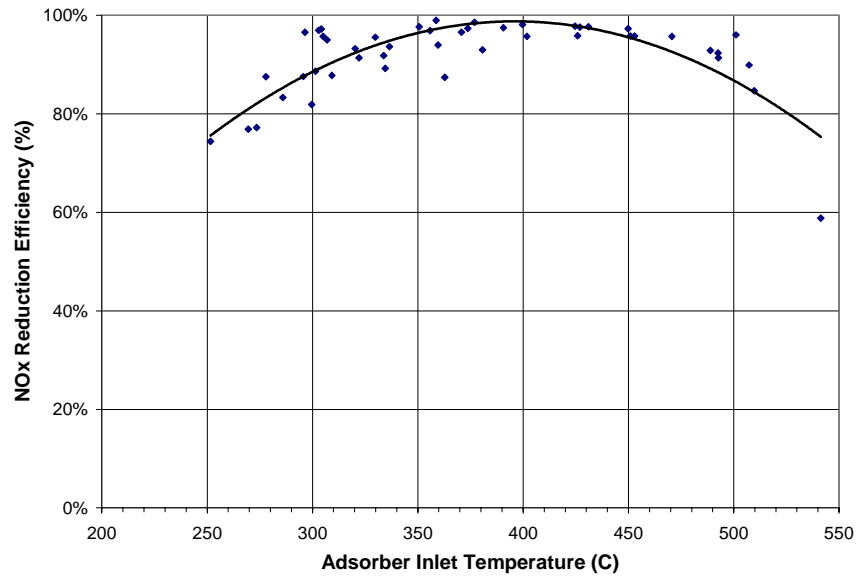


Figure 4.1-12. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber D

Technologies and Test Procedures for Low-Emission Engines

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 *	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%
Composite Results						4.6	** Mid 19 data from Adsorber D			
							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 *	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.

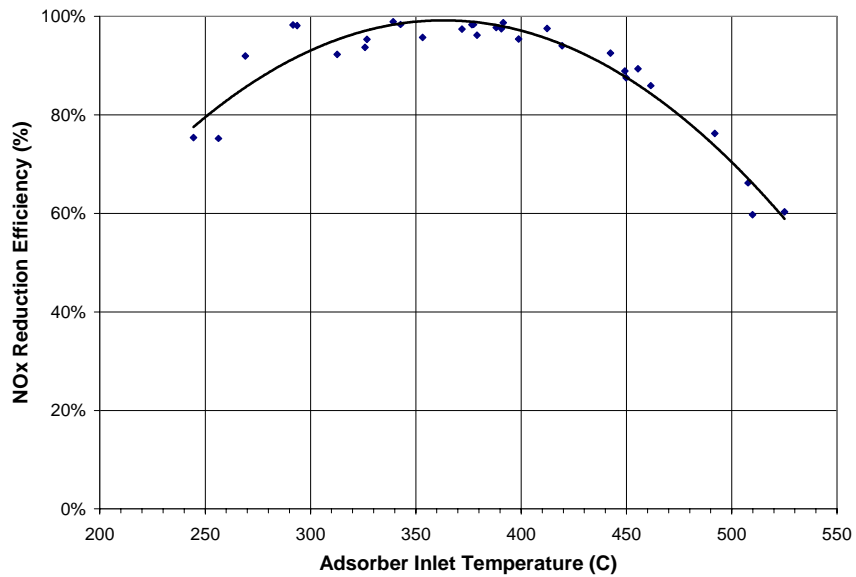


Figure 4.1-13. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber E

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 RIA.⁸² 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 HD2004 levels and the expected Tier 3 levels) 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 HD FTP transient test cycle.⁸³ As discussed further in 4.1.3.1.2 below, performance over the NRTC is projected to be better than for the on-highway HD 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), therefore emissions reductions would be 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.⁸⁴

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

The transient HDDE FTP results presented here are for hot-start cycles only. The adsorber system was not optimized for cold start performance and would not provide a meaningful assessment of adsorber warmup performance. In order to better simulate the “cold-soak-hot” procedure called for in the HDDE FTP, a preconditioning mode was chosen to provide adsorber temperatures at the start of the “hot” cycle that would be 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 on-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

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the SET composite test results. These data show that 90 percent NO_x reductions were possible over the SET composite, with a modal NO_x reduction range from 89 percent to nearly 100 percent. The adsorber NO_x and HC reduction performance varied primarily as a function of exhaust temperature.

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

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

Modified Cummins ISB (HPCR, cooled EGR)						Modified Cummins ISB (Baseline + CDPF and NO _x adsorber catalysts)				
SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	BSNO _x (g/hp-hr)	BSHC (g/hp-hr)	Outlet T (°C)	BSNO _x (g/hp-hr)	NO _x (%-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 NO_x 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 FE 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 FE impact varied from virtually 0 to 2.3 percent depending on the mode with a composite FE 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.

HDDE Transient FTP Test Results

As with the steady-state test results, the hot-start FTP test results showed NO_x and PM emissions in excess of 90 percent. The baseline (without the catalyst system) NO_x emissions of 2.7 g/bhp-hr were reduced to 0.1 g/bhp-hr with the addition of the catalyst system, a better than 95 percent reduction in NO_x emissions. Similarly, the PM emissions were reduced to below 0.003 g/bhp-hr from a baseline level of approximately 0.1 g/bhp-hr, a reduction of more than 95 percent. The fuel economy impact associated with regeneration of the NO_x adsorber system was measured as 1.5 percent over the 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).⁸⁵

Durability Baseline NO_x Adsorber Catalyst Testing

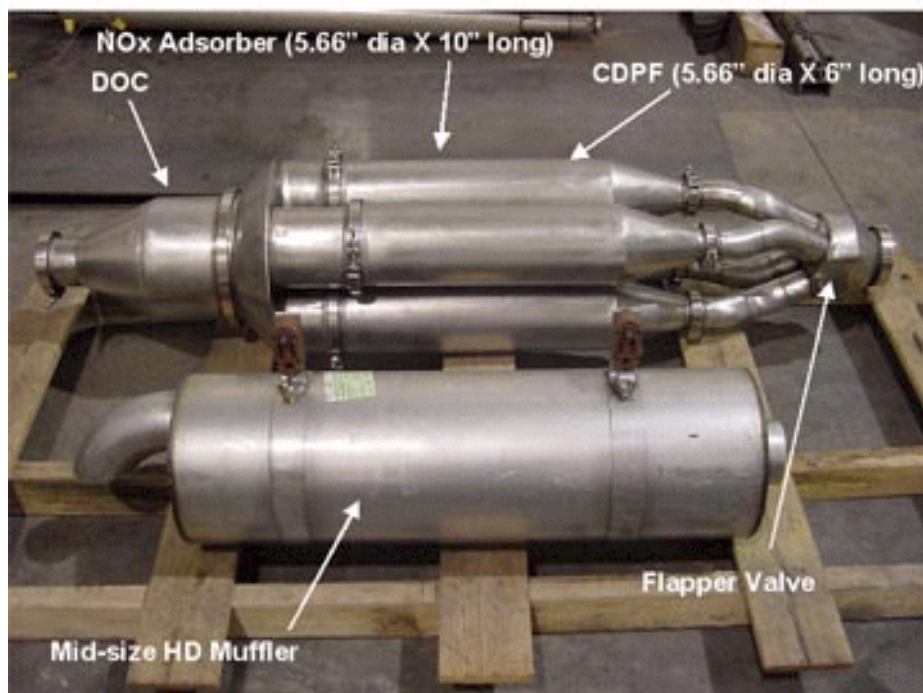
Draft Regulatory Impact Analysis

Additional testing was conducted at NVFEL to provide baseline performance data to gauge improvements in NO_x adsorber durability performance in support of the 2007 Highway technology reviews. The data provides 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.⁸⁶ 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 2 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.⁸⁷ 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

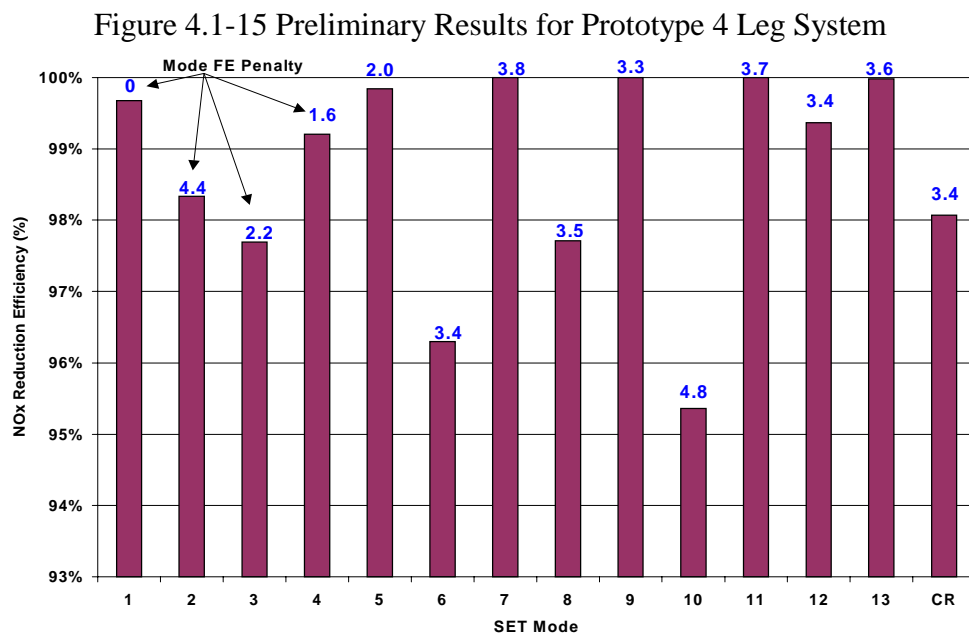
At NVFEL, developments have continued on methods and system designs for NO_x adsorber catalyst technologies. A novel four leg NO_x adsorber/PM trap system was developed as an evolution of the proof-of-concept two leg system that was used for previous testing at NVFEL (the system used in the test results 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 below. 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 to a Truck Muffler



Initial testing indicates that the four leg system at least matches the previous two leg systems NO_x 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 NO_x sensor data used in the control system. Work is

underway to confirm these steady-state results and to demonstrate the performance over transient cycles.



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 NO_x 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 is itself one 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.^{88,89,90 91,92}

In the DECSE program, an advanced diesel engine equipped with common rail fuel injection and exhaust gas recirculation (EGR) was combined with a NO_x adsorber catalyst to control NO_x emissions. The system used an in-cylinder control approach. Rich regeneration conditions are created for the NO_x 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 NO_x 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.⁹³

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/NO_x 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, emissions performance and durability.⁹⁴

Draft Regulatory Impact Analysis

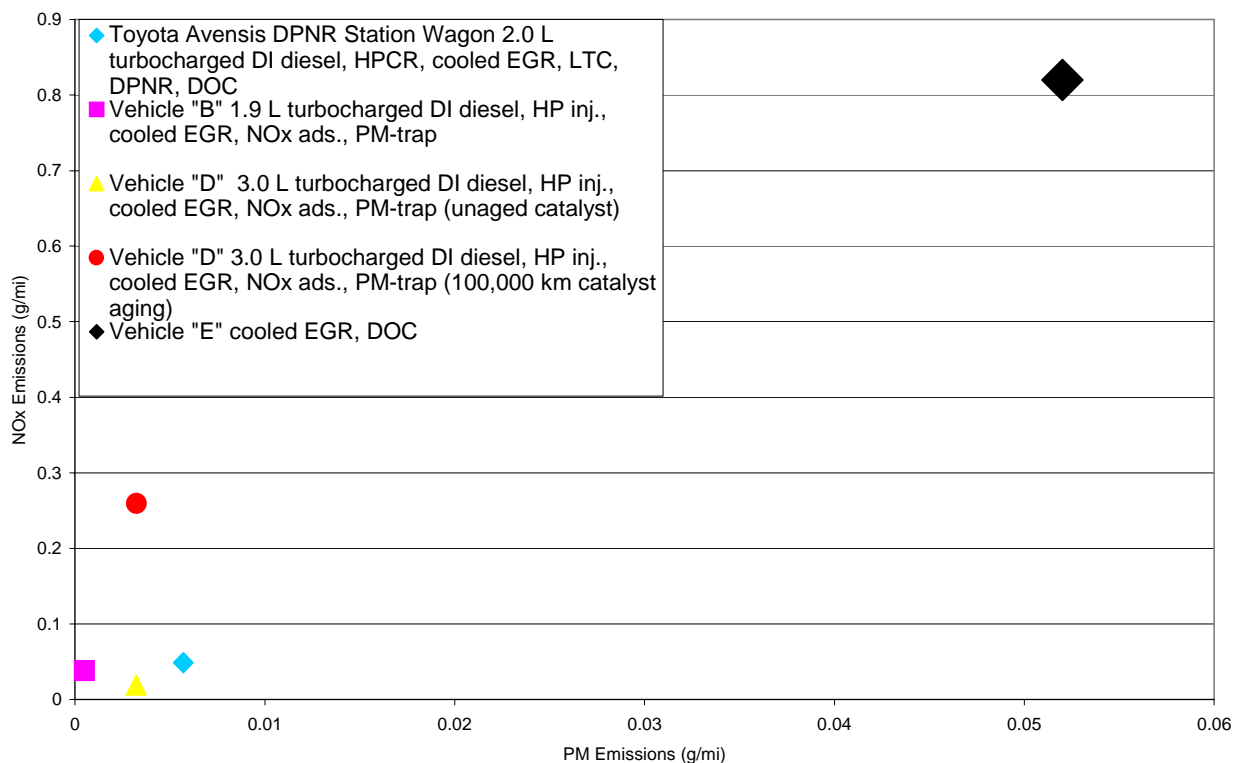
4.1.2.3.5.4 Heavy-Duty Engine Manufacturers

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 the 2002 Highway Diesel Progress Review, which documents in more detail progress by the on-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 2003.⁹⁵ 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 4.1.2.3.5.3 by EPA, a dual leg system demonstrated 90 percent or higher NOx emissions control over a wide range of operation.

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 three prototype diesel passenger cars with these technologies over the last year. The results shown in figure 4.1-16 below demonstrate the potential for substantial reductions with NOx adsorber and PM filter technologies when tested with low sulfur diesel fuel. All three vehicles demonstrated substantial reductions in NOx and PM emissions when compared to a current day relatively clean (compared to only a few years ago) diesel passenger car as represented by the large black diamond on figure 4.1-16.

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



One vehicle in the test program, vehicle “D,” 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 would appear 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 emissions levels shown in the figure, it only takes a very small breakthrough in NOx emissions to significantly increase the emissions over the lowest control levels. At the current time manufacturers are working to keep the number of regeneration episodes to the minimum number in order to minimize stress on catalyst materials (i.e., limit thermal degradation as discussed in section 4.2 above). We believe that 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 that 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 to the new system.

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 NO_x emissions, urea SCR catalysts can reduce NO_x emissions by over 90 percent for a significant fraction of the diesel engine operating range.⁹⁶ Although EPA has not done an extensive analysis to evaluate its effectiveness, we believe it may be possible to reduce NO_x emissions with a urea SCR catalyst to levels consistent with compliance with today's proposed NO_x standards.

We have significant concerns regarding a technology that requires extensive user intervention in order 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 NO_x rate. The urea consumption rate can be on the order of five percent of the engine fuel consumption rate. Therefore, unless the urea tank is prohibitively large, the urea must 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. Today, there is not a system in place 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.⁹⁷

We are not aware of a proven mechanism that ensures that the user will replenish the urea supply as necessary to maintain emissions performance. Further, we believe given the additional cost for urea, that there will be significant disincentives for the end-user to replenish the urea because the cost of urea could 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 proposed standards. Therefore, we have not based the feasibility or cost analysis of this emission control program on the use or availability of the urea SCR technology. However, we would not preclude its use for compliance with the emission standards provided that a manufacturer could demonstrate satisfactorily to the Agency that urea would be used under all conditions. We believe that only a few unique applications will be able to be controlled in a manner such that urea use can be assured, and therefore believe it is inappropriate to base a national emission control program on a technology which can serve effectively only in a few niche applications.

This section has described a number of 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 standards that we are proposing today for engines of 75 hp, or greater, will begin to go into effect four years later. This time lag between equivalent on-highway and nonroad diesel engine standards is necessary in order to allow time for engine and equipment manufacturers to further develop these on-highway technologies for nonroad engines and to align this program with nonroad Tier 3 emission standards that begin to go into effect in 2006.

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The test procedures and regulations for the HD2007 on-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 2007 highway emission standards would comply with the equivalent nonroad emission standards proposed today if it were to be tested over the transient and steady-state nonroad emission test procedures proposed today, which cover the same regions and types engine operation. Said in another way, an on-highway diesel engine produced in 2007 could be certified in compliance with the transient and steady-state standards proposed today for nonroad diesel engines several years in advance of the date when these standards would go into effect. However, that engine, while compliant with certain of the nonroad emission standards proposed today, 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 on-highway diesel engines or produce nonroad engines that are developed from on-highway products. Therefore, there is 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 which 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 of these issues in setting the emission standards and the timing of those standards as proposed today.

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

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 only important 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 NO_x 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.⁹⁸ Similarly (and as discussed in more detail earlier), there is a minimum temperature (e.g., 200°C) for NO_x adsorbers below which NO_x regeneration is not readily possible and a maximum temperature (e.g., 500°C) above which NO_x adsorbers are unable to effectively store NO_x. These minimum and maximum temperatures define a characteristic temperature window of the NO_x 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, NO_x adsorber effectiveness is diminished. Therefore, there is 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 on-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 on-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. On-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 on-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 in order to comply with 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

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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 below. In the case of the Cummins engine, the testing was done at three different engine ratings (250hp, 169hp, and 124hp) in order 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 earlier in this chapter, 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 250°C for more than 30 percent of engine operation.⁹⁹ Another CDPF manufacturer has stated that catalyzed diesel particulate filters will work properly in the field if the engine exhaust temperature is at least 250-275°C for about 40-50 percent of the duty cycle.¹⁰⁰

EPA used the more restrictive of these guidelines to evaluate the likelihood that passive regeneration would be realized on a number of 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

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60th percentile temperature exceeded 250°C for most of the engine tests on all three engines. The runs which did not result in at least 250°C for 40% of the duty cycle were from the on-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)	50 th %tile T (°C)	60 th %tile T (°C)	Operation at T ≥ 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)	50 th %tile T (°C)	60 th %tile T (°C)	Operation at T ≥ 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)	50 th %tile T (°C)	60 th %tile T (°C)	Operation at T ≥ 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%

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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 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 is contained in a recent report from the Engine Manufacturers Association (EMA) and the European Association of Internal Combustion Engine Manufacturers (Euromot).¹⁰¹ This report contains data from a range of applications and power categories. The similar to the data presented above, the EMA/Euromot indicates that while a number of nonroad applications do generate temperatures high enough to passively regenerate a filter, there are also a number of applications which would require active regeneration.

We have assumed in our cost analysis that all nonroad engines complying with a PM standard of 0.02 g/bhp-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 regeneration system, although 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 on-highway diesel engines. We do not believe that there are any nonroad engine applications above 25 horsepower 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 in order to match the engine performance characteristics to the full range of nonroad equipment.

We believe that given the timing of the emissions standards proposed today, and the availability and continuing development of technologies to address temperature management for on-highway engines which technologies are transferrable to all nonroad engines with greater than 25 hp power rating, that nonroad engines can be designed to meet the proposed standards in a timely manner.

Matching the operating temperature window of the broad range of nonroad equipment may be somewhat more challenging for nonroad engines than for many on-highway diesel engines simply because of the diversity in equipment design and equipment use. Nonetheless, the problem has been successfully solved in on-highway applications facing low temperature performance situations as difficult to address as any encountered faced by nonroad applications. The most challenging temperature regime for on-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 NO_x reduction with a NO_x 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 emissions control 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 NO_x adsorber catalyst to function under these normally cold exhaust conditions.¹⁰² Similarly, PSA has demonstrated effective CDPF regeneration under demanding light-load taxi cab conditions with

current production technologies.¹⁰³ 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 nonroad equipment in-use operating cycles which would be considered to be more demanding of low temperature performance than on-highway urban driving. Both the Toyota and PSA systems are designed to function even with extended idle operation as would be typified by a taxi waiting to pick up a fare.^J 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 as would be typified by the broad range of in-use nonroad duty cycles and the new nonroad transient test proposed today.

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 emission standards proposed today. 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 PM standard proposed today, especially in the case of engines which may be able to comply with the proposed NOx standards with engine-out emission control technologies (i.e., engines rated between 25 and 75 horsepower).

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

^J 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 400,000 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.

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does not account for the thermal inertia of the catalyst technologies nor the ability of the NO_x adsorber to store NO_x 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 NO_x 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 on-highway FTP test cycle. We have extensive experience testing NO_x adsorber catalyst systems on the on-highway FTP procedure (see discussion above in Section 4.2) showing that NO_x reductions in excess of 90% can be expected. Here, we are trying to understand if the NO_x performance on the NRTC and the C1 composite cycle should be expected to be better or worse than the on-highway FTP cycle. To accomplish that, we tested a Cummins ISB (see Table 4.1-8 above) 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 NO_x adsorber efficiency for the various test cycles and engine power ratings described here. Further, we performed this analysis for several different NO_x 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 NO_x adsorber performance. The results of this testing and analysis are presented in tables 4.1-12, 4.1-13 and 4.1-14 below.

Table 4.1-12
Estimated NO_x Adsorber Efficiency on Cummins ISB ISO-C1 Composite

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

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

Table 4.1-13
Estimated NO_x Adsorber Efficiency on Cummins ISB - NRTC Cycle

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

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

Table 4.1-14
Estimated NO_x Adsorber Efficiency on Cummins ISB - FTP Cycle

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 NO_x adsorber control giving high NO_x conversion efficiencies with today's NO_x adsorber technology. The NO_x reduction potential by these devices was higher over nonroad cycles when compared to that achieved from the on-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 to the on-highway FTP cycle, thus indicating that the transfer of on-highway 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 proposed 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 in order to understand what levels of power density to expect in the future for nonroad diesel engines. For this analysis, data from Power Systems Research 2002 database (PSR) was examined. 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 a number of power categories from 1985 to 2000. The PSR database reports both rated power and engine displacement, from which power was calculated^K. The data was 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.

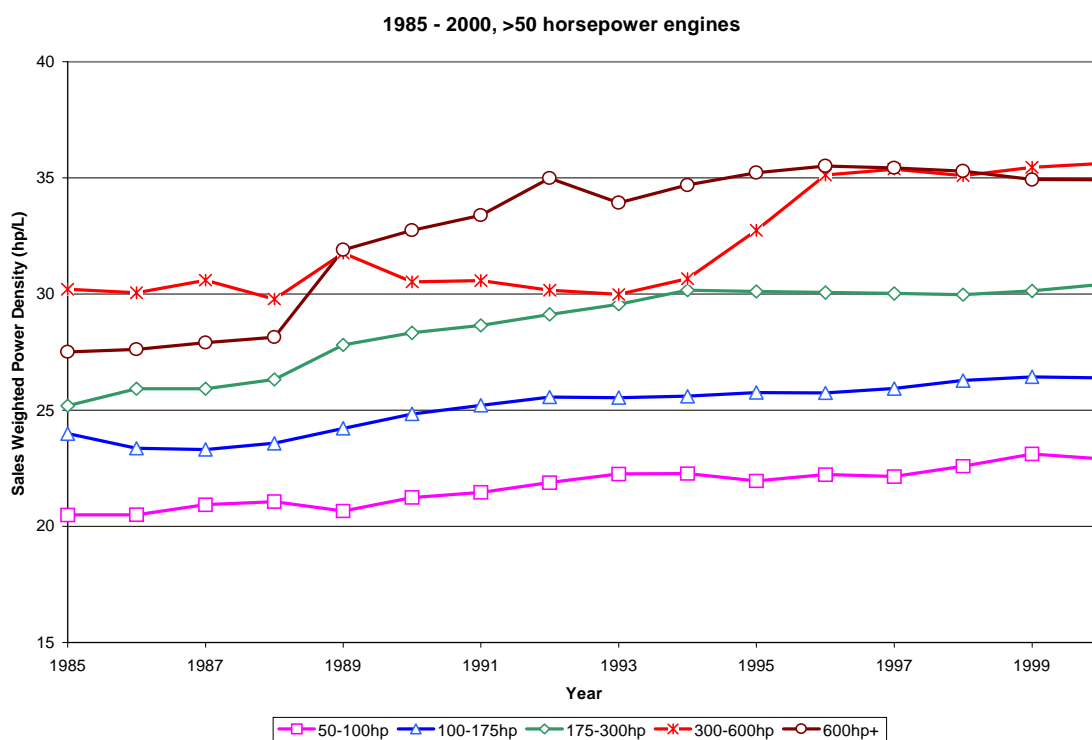
^K Power density is equal to the engine's rated power divided by the engines total displacement. The data in this memorandum is presented in terms of horsepower/liter.

Table 4.1-15
Sales Weighted Power Density, 1985 - 2000

Year	Sales Weighted Power Density by Power Category (hp/liter)				
	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.

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 on-highway diesel vehicles. If no consideration is given to differences in operating conditions in engine and equipment design eventual failure of the equipment would be expected.

Specific efforts to design for the nonroad operating conditions will be required in order 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 emissions 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. Many of these systems were sold for use in mining equipment. No other applications are likely to be more demanding than this. Mining

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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.¹⁰⁴ The Deutz system utilized a conventional cordierite PM filter substrate as is commonly used for heavy-duty on-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 in order to comply with requirements of some mining and tunneling worksite standards. Liebherr, a nonroad engine and equipment manufacturer, offers diesel particulate filter systems as an OEM option on 340 different nonroad equipment models.¹⁰⁵ We believe that 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 which can occur in some nonroad applications. This experience applies equally well to the NO_x adsorber catalyst technologies as the mechanical properties of DOCs, CDPFs, and NO_x adsorbers are all similar. We do not believe that any new or fundamentally different solutions will need to be invented in order to address the vibration and impact constraints for nonroad equipment. Our cost analysis includes the hardware costs for mounting and shielding the aftertreatment equipment as well as the engineering cost for equipment redesign.

Certain nonroad applications, including some forms of harvesting equipment and mining equipment, may have specific limits on maximum surface temperature for equipment components in order 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 NO_x 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 that these concerns are justified in the case of either the NO_x adsorber catalyst or the CDPF technology. Catalyst temperatures for NO_x 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).^L CDPF temperatures are not expected to exceed approximately 700°C in normal use and are expected to only reach the 650°C temperature during periods of active regeneration. Similarly, NO_x adsorber catalyst temperatures are not expected to exceed 700°C and again only during periods of active sulfur regeneration as described in Section 4.F 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 emission system function then supplemental heating as described earlier may be necessary but would not be expected to produce temperatures higher than the maximum levels normally

^L 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.

encountered in diesel exhaust. Furthermore, even if it were necessary to raise exhaust temperatures to a higher level in order to promote effective emission control, there are technologies available to isolate the higher exhaust temperatures from flammable materials such as dust. One approach would be 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 in order to maintain higher exhaust temperatures inside the catalyst in order to promote better catalyst function. Another technology to control surface temperature already used by some nonroad equipment manufacturers is water cooled exhaust systems.¹⁰⁶ This approach is similar to the air-gapped system but uses engine coolant water to actively cool the exhaust system. We do not believe that flammable dust concerns will prevent the use of either a NO_x 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.¹⁰⁷

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

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

As discussed in Section III of the preamble, our proposal for standards for engines between 25 and 75 hp consists of a 2008 transitional standard and long-term 2013 standards. The proposed transitional standard is a 0.22 g/bhp-hr PM standard. The 2013 standards consist of a 0.02 g/bhp-hr PM standard and a 3.5 g/bhp-hr NMHC+NO_x standard. The transitional standard is optional for 50-75 hp engines, as the proposed 2008 implementation date is the same as the effective date of the Tier 3 standards. Manufacturers may decide, at their option, not to undertake the 2008 transitional PM standard, in which case their implementation date for the 0.02 g/bhp-hr PM standard begins in 2012.

In addition, we have proposed a minor revision to the CO standard for the 25-50 hp engines beginning in 2008 to align these engines with the 50-75 hp engines. This proposed CO standard is 3.7 g/bhp-hr.

The remainder of this section discusses:

- what makes the 25-75 hp category unique;
- what engine technology is used today, and will be used for applicable Tier 2 and Tier 3 standards; and,
- why the proposed 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 a number of common traits with highway diesel engines. These include

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similarities in displacement, aspiration, fuel systems, and electronic controls. Table 4.1-16 contains a summary of a number of key engine parameters from the 2001 engines certified for sale in the U.S.^M

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 (estimated)	not available today	limited availability today	available today	commonly available today

^a Based on sales weighting of 2001 engine certification data

As can be seen in Table 4.1-16, the engines in the 25-75 hp category have a number of technology differences from the larger engines. These include a higher percentage of indirect-injection fuel systems, and a low fraction of turbocharged engines. (The distinction in the <25 hp category is quite different, with no turbocharged engines, nearly one-half 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, 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). The research and development work being performed today for the heavy-duty highway market is targeted at engines which are 4-cylinders or more, direct-injection, electronically controlled, turbocharged, and with per-cylinder displacements greater than 0.5 liters. As discussed in more detail below, 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 for the 25-75 hp category (as well as for the <25 hp category).

4.1.4.2 What engine technology is used today, and will be used for Tier 2 and Tier 3?

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. Therefore, all engines in the

^M Data in Table 4.1-16 is 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.

25-75 hp range have been meeting Tier 1 standards for the past several years, and the data presented in Table 4.1-17 represent performance of Tier 1 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.¹⁰⁸ 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 NO_x emissions, while the DI engine has better fuel efficiency and lower heat rejection.¹⁰⁹

We expect a significant shift in the engine technology which 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.¹¹⁰ In addition, we have heard from some engine manufactures 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 which are built on the same engine platform. For the Tier 2 standards for the 25-50 hp products, a large number of engines meet these standards today, and therefore we expect to see only moderate changes in these engines, including the potential additional use of turbocharging on some models.¹¹¹

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

This section will discuss the feasibility of both the proposed 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 meet Tier 1 NMHC+NO_x and PM standards today. We have examined the model year 2002 engine certification data for engines in the 25-50 hp category.¹¹² A summary of this data is presented in Table 4.1-17. These data indicate that over 10 percent of the engine families meet the proposed 2008 0.22 g/bhp-hr PM standard and 5.6 g/bhp-hr NMHC+NO_x standard (unchanged from Tier 2 in 2008) today. 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.^N Five engine families are more than 20 percent below the proposed 0.22 g/bhp-hr PM standard, and an additional 24 engine families which already meet the 2008 NMHC+NO_x standards would require no more than a 30 percent PM reduction to meet the proposed 2008 PM standards. Unfortunately, similar data do not exist for engines between 50 and 75 hp. There is no Tier 1 PM standard for engines in this power range, and therefore engine manufacturers are not required to report PM emission levels until Tier 2 starts in 2004. However, in general, the 50-75 hp engines are more technologically advanced than the smaller horsepower engines and would be expected to perform as well as, if not better than, the engines in the 25 - 50 hp range.

^N 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.

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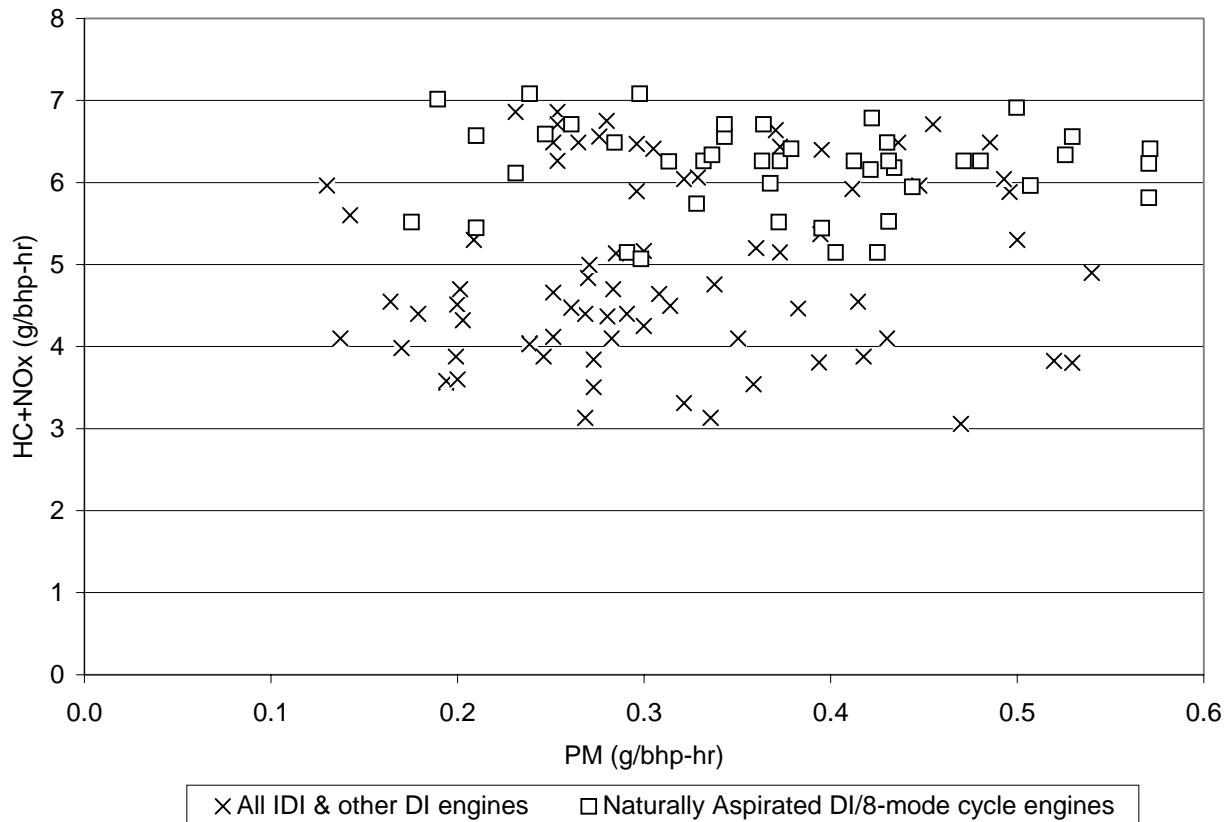
Table 4.1-17
2002 Model Year Certification Data for 25-50 hp Nonroad Diesel Engines

PM Emissions Relative to Proposed 0.22 g/bhp-hr Standard	IDI Engines (test cycle/aspiration)				DI Engines (test cycle/aspiration)			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 > 2008 NMHC+NOx std.	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 a number of engines in this power range can already achieve the proposed 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. Despite being certified to the same emission standards with similar engine technology, the emission levels from these engines vary widely. Figure 4.1-18 is a graph of the model year 2002 HC+NOx and PM data for engines in the 25-50 hp range. As can be seen in Figure 4.1-18, the emission levels cover a wide range. The figure 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/bhp-hr, the PM rates vary from approximately 0.2 to more than 0.5 g/bhp-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 proposed 2008 PM standard on the combination of diesel oxidation catalysts and the lowest engine-out emissions being achieved today, because it is uncertain whether or not additional engine-out improvements would lower all engines to the proposed 2008 PM standard. Instead, we believe there are two likely means by which companies can comply with the proposed 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. Therefore, we believe some engine companies will choose to use a combination of engine-out techniques and diesel oxidation catalysts, as discussed below.

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



For those engines which do not already meet the proposed 2008 Tier 4 PM standard, a number of engine-out technologies are available to achieve the standards by 2008. In our recent Staff Technical Paper on the feasibility of the Tier 2 and Tier 3 standards, we projected that in order to comply with the Tier 3 standards, engines greater than 50 hp would rely on some combination of a number of technologies, including electronic fuel systems such as electronic rotary pumps or common-rail fuel systems.¹¹³ 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.¹¹⁴ Even for mechanical fuel systems, increased injection pressures can reduce PM emissions substantially.¹¹⁵ 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 proposed 2008 PM standard. As demonstrated by the 2002 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 proposed standards for many of the engines in the 25-75 hp category without the need to add turbocharging or electronic fuel systems.

For those engines which are not able to achieve the proposed standards with known engine-out techniques, we project that diesel oxidation catalysts can be used to achieve the proposed standards. DOCs are passive flow-through emission control devices which 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

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heavy-duty diesel applications. In addition, DOCs have already been used to control PM or carbon monoxide on some nonroad applications.¹¹⁶

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 today's 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/bhp-hr standard).¹¹⁷ However, given the high level of sulfur in nonroad fuel today, 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 shows 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.¹¹⁸ 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 emissions necessary to meet the proposed standards for most engine manufacturers. With the availability of 500 ppm sulfur fuel, DOC's can be designed to provide PM reductions on the order of 20 to 50%, while suppressing particulate sulfate reduction.¹¹⁹ 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 proposed 2008 PM standard and are at or below the 2008 NMHC+NOx standard for this power range, indicating that use of DOCs should readily achieve the incremental improvement necessary to meet the proposed 2008 PM standard.

As discussed in Section III of the preamble, we have also proposed a minor change in the CO standard for the 25-50 hp engines, in order to align it with the standard for the 50-75 hp engines. This small change in the CO standard is intended to simplify EPA's regulations as part of our decision to propose a reduction in the number of engine power categories for Tier 4. The current CO standard for this category is 4.1 g/bhp-hr, and the proposed standard is 3.7 g/bhp-hr (i.e., the current standard for engines in the 50-75 hp range). The model year 2002 certification data shows that more than 95 percent of the engine families in the 25-50 hp engine range meet the proposed CO standard today. In addition, a recent EPA test program run by a contractor on two nonroad diesel engines in this power range showed that CO emissions were well below the proposed standards not only when tested on the existing steady-state 8-mode test procedure, but also when tested on the nonroad transient duty cycle we are proposing in today's action.¹²⁰ Finally, DOCs typically reduce CO emissions on the order of 50 percent or more, on both transient and steady-state duty cycles.¹²¹ Given that more than 95 percent of the engines in this category meet the proposed standard today, and the ready availability of technology which can easily achieve the proposed standard, we project this CO standard will be achievable by model year 2008.

4.1.4.3.2 2013 Standards

For engines in the 25-50 range, we are proposing standards commencing in 2013 of 3.5 g/bhp-hr for NMHC+NOx and 0.02 g/bhp-hr for PM. For the 50-75 hp engines, we are proposing a 0.02 g/bhp-hr PM standard which 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 proposed PM standard for engines ≥ 75 hp. As also discussed in Section 4.1.3, PM filters may require active back-up regeneration systems for many nonroad applications. A number of secondary technologies are likely required to enable proper regeneration, including possibly electronic fuel systems such as common rail systems which are capable of multiple post-injections which can be used to raise 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 CDPF's 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 our proposal. The PM filter regeneration systems described in 4.1.1 and 4.1.3 are also applicable to engines in this size range and are therefore likewise feasible. There are specific trap regeneration technologies which we believe engine manufacturers in the 25-75 hp category may prefer over others. Specifically, an electronically-controlled secondary fuel injection system (i.e., a system which 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.¹²²

We are, however, proposing a slightly higher PM standard (0.02 g/bhp-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 therefore lower efficiency and higher fuel consumption. In addition, frictional losses are a higher percentage of total power for the smaller displacement engines which also results in higher fuel consumption. Because of the higher fuel consumption rate, we expect a higher particulate sulfate level, and therefore we have proposed a 0.02 g/bhp-hr standard.

Test data confirm that this proposed standard, as well as the proposed NTE of 1.5 times the standard, are achievable. In 2001, EPA completed a test program run by a contractor on two small nonroad diesel engines (a 25 hp IDI engine and a 50 hp IDI engine) which demonstrated the proposed 0.02 g/bhp-hr standard can be achieved with the use of a CDPF.¹²³ This test program included testing on the existing 8-mode steady-state test cycle as well as the nonroad transient cycle proposed in today's action. The 0.02g/bhp-hr level was achieved on each engine over both test cycles. In addition, the 0.02 g/bhp-hr level was achieved on a variety of nonroad test cycles which are intended to represent several specific applications, such as skid-steer loaders, arc-welders, and agricultural tractors. We believe these data are indicative of the robust emission reduction capability of particulate filters and demonstrates the proposed NTE standard of 1.5 x 0.02 g/bhp-hr standard (0.03 g/bhp-hr) can be achieved using the proposed not-to-exceed test requirements. This test program also

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demonstrates why EPA has proposed a slightly higher PM standard for the 25 - 75 hp category (0.02 g/bhp-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.

4.1.4.3.2.2 NMHC+NO_x Standard

We have proposed a 3.5 g/bhp-hr NMHC+NO_x standard for engines in the 25 - 50 hp range for 2013. This will align the NMHC+NO_x standard for engines in this power range with the Tier 3 standard for engines in the 50 - 75 hp range which are implemented in 2008. EPA's recent Staff Technical paper which reviewed the technological feasibility of the Tier 3 standards contains a detailed discussion of a number of technologies which are capable of achieving a 3.5 g/bhp-hr standard. These include cooled EGR, uncooled EGR, as well as advanced in-cylinder technologies relying on electronic fuel systems and turbocharging.¹²⁴ These technologies are capable of reducing NO_x emission by as much as 50 percent. Given the Tier 2 NMHC+NO_x standard of 5.6 g/bhp-hr, a 50 percent reduction would allow a Tier 2 engine to comply with the 3.5 g/bhp-hr NMHC+NO_x standard proposed in this action. In addition, because this NMHC+NO_x standard is concurrent with the 0.02 g/bhp-hr PM standards which we project will be achievable with the use of particulate filters, engine designers will have significant additional flexibility in reducing NO_x because the PM filter will eliminate the traditional concerns with the engine-out NO_x vs. PM trade-off.

4.1.5 Are the Standards Proposed for Engines <25 hp Feasible?

As discussed in Section III of the preamble, our proposal for standards for engines less than 25 hp is a new PM standard of 0.30 g/bhp-hr beginning in 2008. As discussed below, we are not proposing to set a new standard more stringent than the existing Tier 2 NMHC+NO_x standard for this power category at this time. This section describes:

- what makes the <25 hp category unique;
- engine technology currently used in the <25 hp category; and,
- what data shows the proposed 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 4.1-16). Nearly 50 percent of the products have two-cylinders or less, and 14 percent of the engines sold in this category are single-cylinder products, a number of these have no batteries and are crank-start machines, much like today's simple walk behind lawnmower engines. In addition, given what we know today and taking into account the Tier 2 standards which 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 5 to 10 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.¹²⁵ We are not predicting that Tier 2 will require electronic fuel systems, EGR, or turbocharging. As discussed in the Staff Technical Paper, a large number of engines in this power category already meet the Tier 2 standards by a wide margin.¹²⁶

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 indicates the proposed standards are feasible?

We project the proposed Tier 4 PM standard can be met by 2008 based on:

- the existence of a large number of engine families which meet the proposed standards today;
- the use of engine-out reduction techniques; and
- the use of diesel oxidation catalysts.

We have examined the recent model year (2002) engine certification data for nonroad diesel engines less than 25 hp category.¹²⁷ A summary of this data is presented in Table 4.1-18. These data indicate that a number of engine families meet the proposed Tier 4 PM standard (and the 2008 NMHC+NOx standard, unchanged from Tier 2) today. The current data indicates approximately 28% of the engine families are at or below the proposed PM standard today, while meeting the 2008 NMHC+NOx standard. These include both IDI and DI engines, as well as a range of certification test cycles.^o Many of the engine families are certified well below the proposed Tier 4 standard while meeting the 2008 NMHC+NOx level. Specifically, 15 percent of the engine families are more than 20 percent below the proposed Tier 4 PM standard. An additional 15 percent of the engine families which already meet the 2008 NMHC+NOx standards would require no more than a 30 percent PM reduction to meet the proposed 2008 PM standards. The public certification data indicate that these engines do not use turbocharging, electronic fuel systems, exhaust gas recirculation, or aftertreatment technologies.

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

PM Emissions Relative to Proposed 0.30 g/bhp-hr Standard	IDI Engines (test cycle)			DI Engines (test cycle)			Totals
	5-mode	6-mode	8-mode	5-mode	6-mode	8-mode	

^o 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.

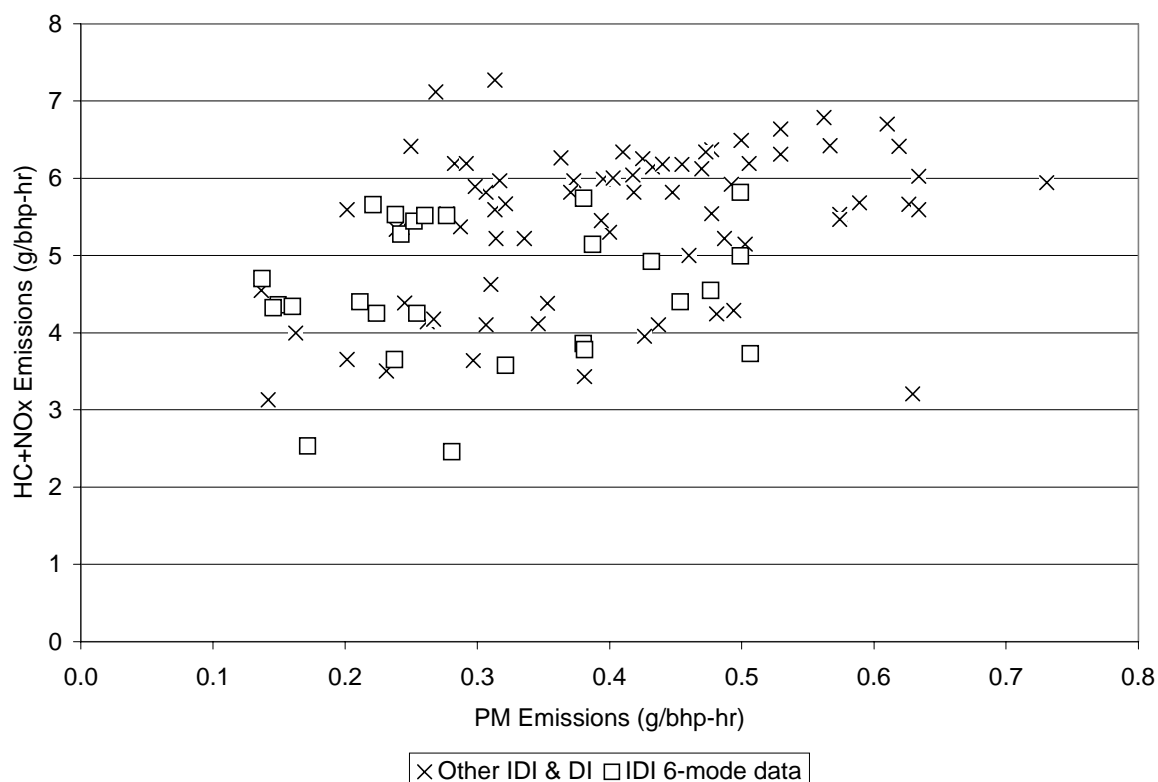
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0-5% below T4 ^a	1	0	1	0	0	0	2
5-20% below T4 ^a	4	6	1	0	0	0	11
>20% below T4 ^a	1	9	5	0	1	0	16
require ≤30% PM reduction to meet T4 ^a	5	4	4	0	2	0	15
requires >30%PM reduction and/or > 2008 NMHC+NOx std.	7	8	4	18	18	3	58
Total # of Engine Families	18	27	15	18	21	3	102

^a Engine also meets 2008 NMHC+NOx

These model year 2002 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. As with 25-75 hp engines, these data have a two-fold significance. First, they indicate that a number of engines in this power category can already achieve the proposed 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. Despite being certified to the same emission standards with similar engine technology, the emission levels from these engines vary widely. Figure 4.1-19 is a graph of the model year 2002 HC+NOx and PM data. As can be seen in the figure, the emission levels cover a wide range. Figure 4.1-19 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/bhp-hr, the PM rates vary from approximately 0.15 to 0.5 g/bhp-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 proposed 2008 PM standard on the combination of diesel oxidation catalysts and the lowest engine-out emissions being achieved today, because it is uncertain whether or not additional engine-out improvements would lower all engines to the proposed 2008 PM standard. Instead, we believe there are two likely means by which companies can comply with the proposed 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. Therefore, we believe some engine companies will choose to use a combination of engine-out techniques and diesel oxidation catalysts, as discussed below.

Figure 4.1-19 Emission Certification Data for 25-50 HP Model Year 2002 Engines



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 are a number of technologies which exist 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.¹²⁸ The wide-range of emission characteristics present in the existing engine certification data is likely a result of differences in fuel systems and combustion chamber designs. For many of the engines which have higher emission levels, further optimization of the fuel system and combustion chamber can provide additional PM reductions.

Diesel oxidation catalysts (DOC) also offer the opportunity to reduce PM emissions from the engines in this power category. DOCs are passive flow through emission control devices which 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.¹²⁹ However, as discussed in Section 4.1.1, certain DOC formulations can be sensitive to diesel fuel sulfur level. Specifically, precious-metal based 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 nonroad fuel today, 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 shows 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.¹³⁰ Without the availability of 500 ppm sulfur fuel in 2008,

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DOCs would be of limited use for nonroad engine manufacturers and would not provide the emissions necessary to meet the proposed standards for most engine manufacturers. With the availability of 500 ppm sulfur fuel, DOC's can be designed to provide PM reductions on the order of 20 to 50%, while suppressing particulate sulfate reduction.¹³¹ These levels of reductions have been seen on transient duty cycles as well as highway and nonroad steady-state duty cycles.

As discussed in Section III of the preamble, we have also proposed a minor change in the CO standard for the <11 hp engines, in order to align those standards with the standards for the 11-25 hp engines. The small change in the CO standard is intended to simplify EPA's regulations as part of our decision to propose a reduction in the number of engine power categories for Tier 4. The current CO standard for this category is 6.0 g/bhp-hr, and the proposed standard is 4.9 g/bhp-hr (i.e., the current standard for engines in the 11-25 hp range). The model year 2002 certification data shows that more than 90 percent of the engine families in this power category meet the proposed standards today. In addition, DOCs typically reduce CO emissions on the order of 50 percent or more.¹³² Given that more than 90 percent of the engines in this category meet the proposed standard today, and the ready availability of technology which can easily achieve the proposed standard, we project this CO standard will be achievable by model year 2008.

4.1.6 Meeting the Crankcase Emissions Requirements

The most common way to eliminate crankcase emissions has been to vent the blow-by gases into the engine air intake system, so that 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 on-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 eliminated this exception for highway engines in 2007 and are proposing to eliminate the exception for nonroad diesel engines as well. 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 proposed provision has been written such that if adequate control can be had without "closing" the crankcase then the crankcase can remain "open." Compliance would be ensured by adding the emission from the crankcase ventilation system to the emissions from the engine control system downstream of any emission control equipment.

We expect that in order to meet the stringent tailpipe emission standards set here, that manufacturers will have to utilize closed crankcase approaches as described here. 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.¹³³ By eliminating 90 percent of the oil that would normally 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 15ppm Sulfur Diesel Fuel?

As stated earlier, we strongly believe that fuel sulfur control is critical to ensuring the success of NO_x and PM aftertreatment technologies. In order to evaluate the effect of sulfur on diesel exhaust control technologies, we used three key factors to categorize the impact of sulfur in fuel on emission control function. These factors were efficiency, reliability, and fuel economy. Taken together these three factors lead us to believe that diesel fuel sulfur levels of 15 ppm will be required for the nonroad emission standards proposed here to be feasible. 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 NO_x, NMHC, CO and diesel PM emissions are significantly reduced by catalyst poisoning and catalyst inhibition due to sulfur. NO_x conversion efficiencies with the NO_x adsorber technology in particular are dramatically reduced in a very short time due to sulfur poisoning of the NO_x 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, NO_x 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 NO_x 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 NO_x adsorber, failure to regenerate the stored sulfur (desulfate) will lead to rapid loss of NO_x emission control as a result of sulfur poisoning of the NO_x 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 NO_x and PM control technologies. The NO_x 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. Thus, for both NO_x and PM technologies the lower the fuel sulfur level the lower 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 CO₂ 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 could be assured to occur at exhaust temperatures lower than 300°C, then diesel particulate filters would be expected to 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 which are more readily reduced than oxygen. One such oxidant is NO₂.

NO₂ 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 NO₂-rich exhaust is highly oxidizing in nature and can oxidize trapped diesel PM at temperatures as cool as 250°C.¹³⁴ Some platinum group metals are known to be good catalysts to promote the oxidation of NO to NO₂. Therefore in order to promote more effective passive regeneration of the diesel particulate filters, significant amounts of platinum group metals (primarily platinum) are being used in the wash-coat formulations of advanced CDPFs. The use of platinum to promote the oxidation of NO to NO₂ 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 in order 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 NO₂, 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, NO₂, 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. NO₂ 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.¹³⁵ This inhibition limits the total amount of NO₂ available for oxidation of the trapped diesel PM, thereby raising the minimum exhaust temperature required to ensure trap regeneration. Without sufficient NO₂, 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 NO₂ 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. In order 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.^P 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 below 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 which included intercity trains, airport buses, mail trucks, city buses and garbage trucks, and the extended time periods of operation (some vehicles have been operating with traps for more than 5 years and in excess of 300,000 miles), there is a strong indication of the robustness of this technology on 10 ppm low sulfur diesel fuel.¹³⁶ 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, although 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.¹³⁷ Other possible reasons for the high failure rate in Finland when contrasted with the Swedish

^P 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.

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.¹³⁸ Given that the fleets in Sweden and Finland were substantially similar, 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.^Q

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.¹³⁹ 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 NO₂ 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 NO₂ 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 would be 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. Therefore, we believe that, in order to ensure reliable and economical operation over a wide range of expected operating conditions, nonroad diesel fuel sulfur levels should be at or below 15 ppm.

4.1.7.1.2 Loss of PM Control Effectiveness

In addition to inhibiting the oxidation of NO to NO₂, the sulfur dioxide (SO₂) in the exhaust stream is itself oxidized to sulfur trioxide (SO₃) at very high conversion efficiencies by the precious metals in the catalyzed particulate filters. The SO₃ serves as a precursor to the formation of hydrated sulfuric acid (H₂SO₄+H₂O), or sulfate PM, as the exhaust leaves the vehicle tailpipe. Virtually all of the SO₃ 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 SO₂, the precursor to SO₃, 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.

SO₂ 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 SO₂ oxidation rate for a platinum based oxidation catalyst typical of the type which might be used in

^Q 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).

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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 on-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 SO₂ 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 US 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 below showing the expected total direct PM emissions from a diesel engine on the supplemental emission test cycle.^R The SET test cycle, a 13 mode steady-state cycle, that this data was 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 would be 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 Emissions Performance	
	Tailpipe PM ^b [g/bhp-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).

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/bhp-hr total PM standard is

^R 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.

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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, in order to realize the PM emissions 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 NO_x Catalysts and the Need for Low Sulfur Fuel

NO_x 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 which can deteriorate the NO_x adsorber. These limitations due to sulfur in the fuel affect the overall performance and feasibility of the NO_x adsorber technology.

4.1.7.2.1 Sulfur Poisoning (Sulfate Storage) on NO_x Adsorbers

The NO_x adsorber technology relies on the ability of the catalyst to store NO_x as a metallic nitrate (MNO₃) on the surface of the catalyst, or adsorber (storage) bed, during lean operation. Because of the similarities in chemical properties of SO_x and NO_x, the SO₂ present in the exhaust is also stored by the catalyst surface as a sulfate (MSO₄). The sulfate compound that is formed is significantly more stable than the nitrate compound and is not released and reduced during the NO_x release and reduction step (NO_x regeneration step). Since the NO_x adsorber is essentially 100 percent effective at capturing SO₂ in the adsorber bed, the sulfur build up on the adsorber bed occurs rapidly. As a result, sulfate compounds quickly occupy all of the NO_x storage sites on the catalyst thereby rendering the catalyst ineffective for NO_x storage and subsequent NO_x 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.¹⁴⁰ Under these conditions, the stored sulfate is released and reduced in the catalyst.¹⁴¹ While research to date on this procedure has been very favorable with regards to sulfur removal from the catalyst, it has revealed a related vulnerability of the NO_x 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)

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reducing the effectiveness of the catalyst.¹⁴² 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 is expected to 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 is expected to 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 could meet the HD2007 NOx standard using diesel fuel with a 30 ppm average sulfur level. This would imply that the NOx adsorber could tolerate as much as a four fold increase in desulfation frequency (when compared to 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 in order 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 on-highway NOx adsorber catalyst technology that this proposal is based upon and will be equally true for nonroad engines applying the NOx adsorber technology to comply with our proposed Tier 4 standards.

Nonroad and on-highway diesel engines are similarly durable and thus over their lifetimes consume a similar amount of diesel fuel. This means that both nonroad and on-highway diesel engines will have the same exposure to sulfur in diesel fuel and thus will 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 in order to meet the NOx emission standards proposed today. 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 in order to remove the stored sulfur. Therefore, we believe that fuel with a sulfur level at or below 15 ppm sulfur will be necessary in

order to control thermal degradation of the NO_x 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 NO_x Control Technologies

The NO_x adsorber technology relies on a platinum based oxidation function in order to ensure high NO_x 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 NO_x adsorber technology relies on the oxidation function to convert NO to NO₂ over the catalyst bed. For the NO_x adsorber this is a fundamental step prior to the storage of NO₂ in the catalyst bed as a nitrate. Without this oxidation function the catalyst will only trap that small portion of NO_x emissions from a diesel engine which is NO₂. This would reduce the NO_x adsorber effectiveness for NO_x reduction from in excess of 90 percent to something well below 20 percent. The NO_x 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 NO_x 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 NO_x adsorber technology, uses an oxidation catalyst to promote the oxidation of NO to NO₂ at the low temperatures typical of much of diesel engine operation. By converting a portion of the NO_x emissions to NO₂ upstream of the ammonia SCR reduction catalyst, the overall NO_x reductions are improved significantly at low temperatures. Without this oxidation function, low temperature SCR NO_x effectiveness is dramatically reduced making compliance with the NO_x standard impossible. Therefore, future Compact-SCR systems would need to rely on a platinum oxidation catalyst in order to provide the required NO_x emission control. This use of an oxidation catalyst in order to enable good NO_x 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 SO₂ to sulfate PM promoted by the oxidation catalyst.

Without the oxidation catalyst promoted conversion of NO to NO₂, neither of these NO_x control technologies can meet the proposed NO_x standard. Therefore, each of these technologies will require low sulfur diesel fuel to control the sulfate PM emissions inherent in the use of highly active oxidation catalysts. The NO_x adsorber technology may be able to limit its impact on sulfate PM emissions by releasing stored sulfur as SO₂ 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 NO_x emission control technologies increase the production of sulfate PM through oxidation of SO₂ to SO₃ 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 NO_x and the PM control catalysts rely on precious metals to achieve the required NO to NO₂ oxidation reaction.

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

4.2. Supplemental 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 emissions control, a cycle that appropriately characterizes the activity of the subject equipment would afford a greater level of control. The basics of any nonroad transient duty cycle should include fulfillment of the following goals:

- represents nonroad activity broadly, with a basis in real world activities through diverse data segments;
- exercises the engine over its operating range. Cycle would not be limited to a specific speed or load, but traverses the operating range over the engine's full power range;
- measures particulate matter (PM) on a transient basis;
- captures the basic characteristics of PM, as currently defined, including:
 - organic and inorganic carbon fractions;
 - volatile fraction;
 - sulfate fraction;
 - ash, etc.
- ensures that control measures developed to control emissions over the cycle encourage and afford greater assurance that adequate control measures 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 which provides a representation of a broad range of nonroad diesel equipment activity. 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

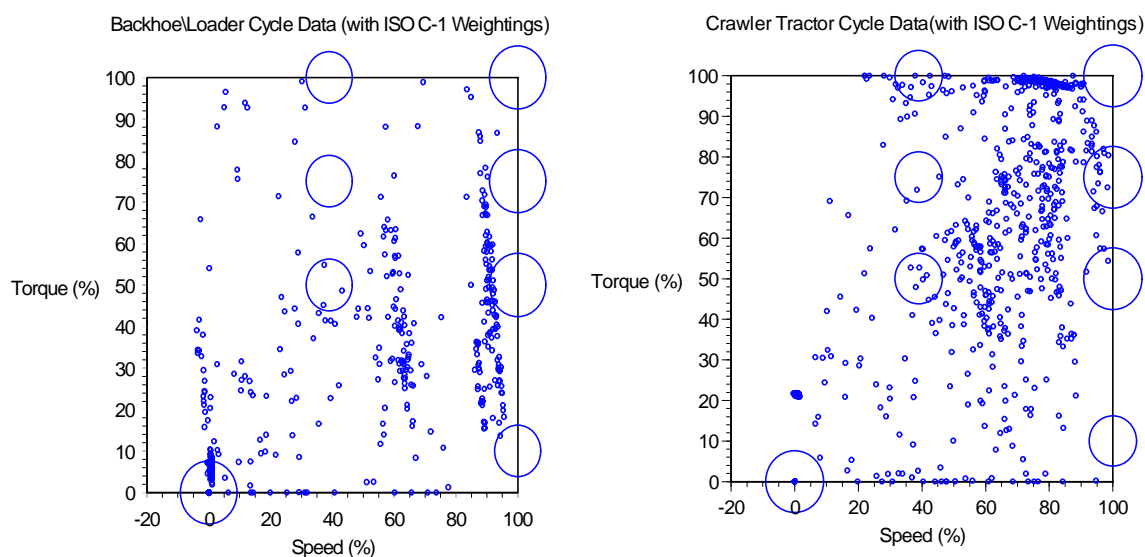
These application duty cycles were created from actual speed and load data recorded in-use on each of these pieces of equipment. The strategy for generating the duty cycles and the base data sets differed slightly. However, the combining of these two strategies has ensured that the strengths of both approaches would be 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.

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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. Please see Figure 4.2-1. It should be clear that no single transient cycle, of reasonable length, could capture the full body of nonroad diesel activity in the real world. 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 could not replace an in-use characterization, however it does drive development of engine control strategies to focus emissions and performance parameters on a broader set of activity that is much more likely to be seen in-use.

Figure 4.2-1

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



A much broader set of data from the nonroad duty cycle generation may be found in Memorandum from Cleophas Jackson to the 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 would likely 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 was compared to 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”-based application 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.

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 was actual work and not artificial scenarios, so that the data accuracy was ensured.

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 if 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 was 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 was 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.

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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 was 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 cars¹⁴³. The material being moved was typical quarry material which included aggregate of various material densities such as crushed stone, gravel, and sand. Twenty-six hours of data was 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 was 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 was 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 was 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 was 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 was 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 was 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 was gathered for this excavator.

4.2.2.2 Engine and Equipment Description

In generating the microtrip-based and the day-in-the-life-based duty cycles, the equipment selected were based on the highest sales volume applications and the contribution of those applications to the ambient inventories for NO_x 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 engines¹⁴⁴ may be seen in Table 4.2-1 through Table 4.2-3.

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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 that were used for data generation for the “day in the life” -based approach were based on 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 horsepower distribution among excavators in the U.S. nonroad equipment inventory at that time¹⁴⁵. 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 kilowatts (208 horsepower) and a Mitsubishi/CAT 320 BL excavator at

95 kilowatts (128 horsepower). 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 could be 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 only recorded engine on operation, therefore data was not gathered 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 was 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 was 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^S 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)
- 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.

^S $\sum(O_i - E_i)^2 / E_i$ where O_i is the Observed frequency in the i th interval and E_i is the Expected frequency in the i th interval based on the frequency distribution of the entire population for the given quantity.

2. Load first activity file.
3. Calculate power. Add to raw data file.
4. Normalize speed using 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.^T 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^U 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 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.

^TSteady State is defined as any instantaneous change in normalized speed or normalized torque with a magnitude less than 2%.

^UDelta is used to describe the instantaneous rate of change of the specified quantity.

Figure 4.2-2

Agricultural Tractor

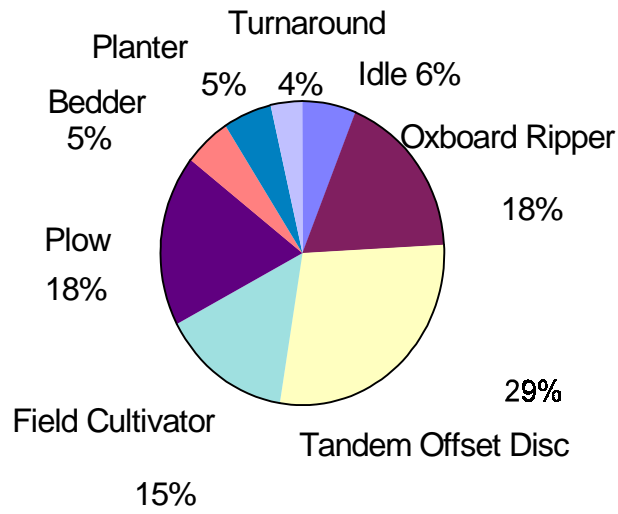


Figure 4.2-3

Backhoe Loader

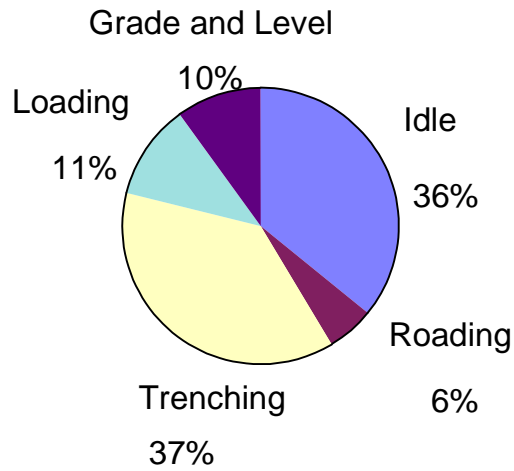
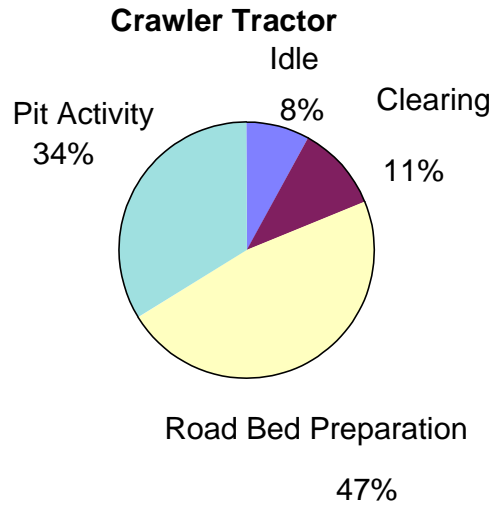


Figure 4.2-4



In generating the duty cycles and conducting the analyses, relative frequency of occurrence of various parameters as reported by the contractor were compared to 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.

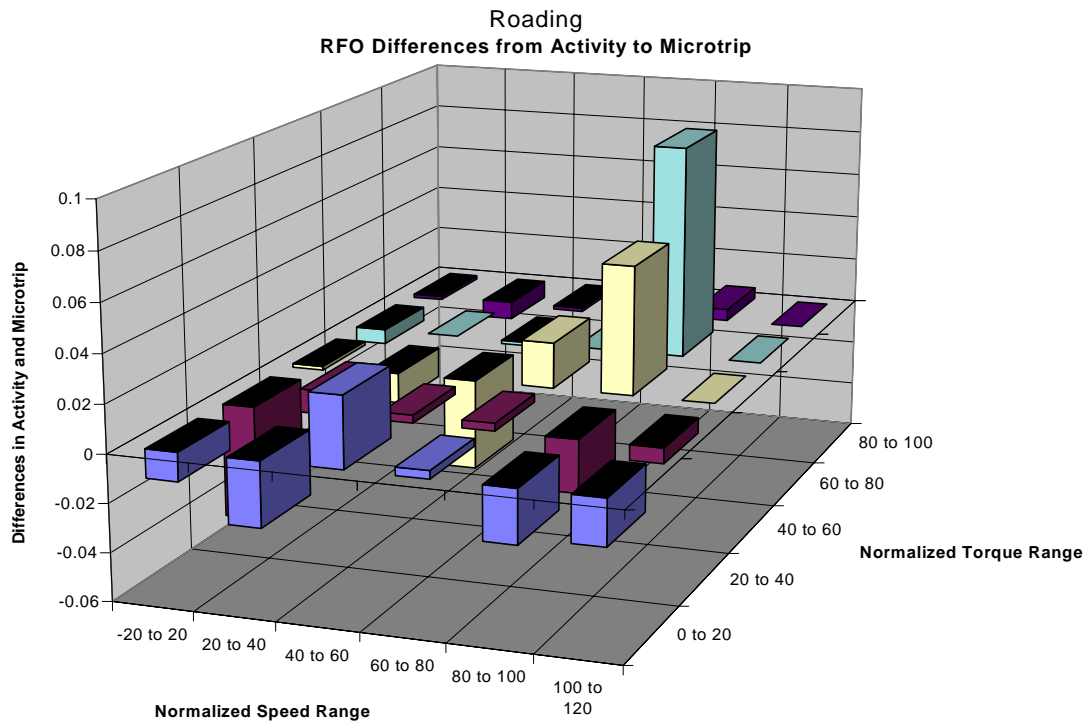


Figure 4.2-.5
Example of Microtrip vs. Data Set for Tractor Activity

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 would be used for creation of the nonroad transient composite duty cycle.

4.2.2.4.2 “Day in the Life” 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 versus 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^V duty cycle, and a high transient torque duty cycle for each application.
9. For each window of activity, the data used was 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. Therefore, by choosing a segment that closely matched the characteristic RFO compilation, it is 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 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:

^VHigh 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.

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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-square 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 i th interval of the 380-second sample window, and E_i is the expected frequency of the i th 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 was 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 which 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^W was not included in the transient cycle). 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 was 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 normalization or GCS^X 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.

^WSteady State Operation is defined as an instantaneous speed or torque change less than 2% of the maximum magnitude.

^XGCS 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.

Figure 4.2-6

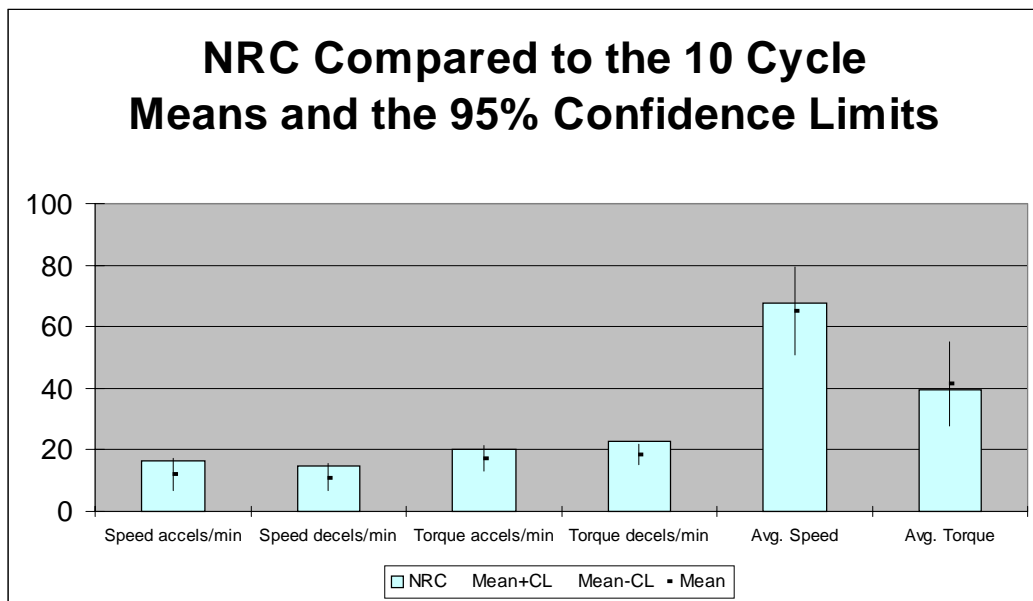
Supplemental NRTC (Nonroad Transient Composite) Cycle								
Application Number	Nonroad Application	Application Duration (seconds)	Application in Cycle Position (#seconds)	Segments from Application Cycle (#seconds)	Segment Name	Segment Duration (seconds)	Cumulative Cycle Time (seconds)	Segment in Cycle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

4.2.4 Cycle Characterization Statistics

The characterization of the operational data was 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.¹⁴⁶ 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 to normalized values before any application cycle could be used on an engine other than

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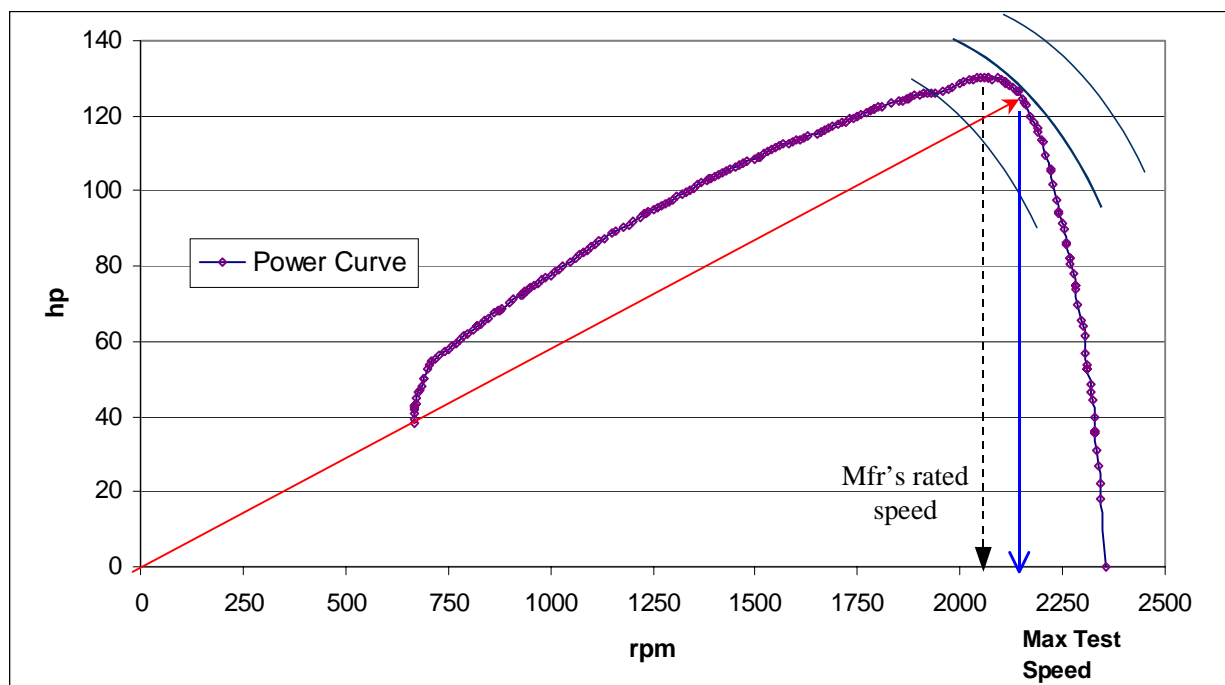
the engine originally used to create the application cycle itself. This process of normalization entailed converting the actual in-use operating speed and load values of the “raw” duty cycle, as recorded from the engine used to create the cycle originally, into a percentage of that engine’s maximum achievable speed and load values. This yields a duty cycle schedule of speed and load values which, because the schedule points are in percent of an engine’s maximum measured rpm (speed) and lbs-ft (load), the cycle can be converted over to the true speed and load values, in rpm and lbs-ft, required to run that cycle on any other engine, if one has the new engine’s maximum achievable power (MAP) validation. 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)^Y. 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 calculation¹⁴⁷ and is discussed in a report entitled “Summary and Analysis of Comments: Control of Emissions from Marine Diesel Engines”, document # EPA420-R-99-028 in Chapter 8, “Test Procedures”¹⁴⁸. As detailed in Figure 4.2-8 below, the maximum speed can be found below the point on the engine power curve that is the farthest distance from the point of 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.

^Y 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.

Figure 4.2-8
Maximum Test Speed Determination



Regression Statistics

In assessing the nonroad transient duty cycles, ten nonroad diesel engines were exercised over the nonregulatory¹⁴⁹ nonroad duty cycles to assess emissions 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 the 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 Transient Test Procedure

Some nonroad diesel engines are required by the equipment which they have been designed to power, and the equipment’s specific application, to operate in a constant-speed manner. 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. This equipment is more tolerant of changes in operating load than other more closely governed constant-speed nonroad engines. 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. For these engines which are designed to operate under restricted transient conditions, the Agency is proposing an alternative transient duty cycle over which a nonroad engine manufacturer may choose to operate their engine(s) to comply with EPA’s new transient nonroad testing requirement. This cycle, the Constant-Speed Variable-Load (CSVL) application duty cycle, is derived from EPA’s Arc Welder Highly Transient Torque application duty cycle. The cycle schedule, its commanded speed and load values, may be found at proposed

Technologies and Test Procedures for Low-Emission Engines

regulations in 40 CFR Part 1039, Appendix “T”. A manufacturer certifying their equipment to this cycle would be constrained to allow their engines to operate equipment in-use only in a constant-speed, variable-load manner.

EPA recognizes that some constant speed equipment is designed to operate near or at its rated engine rpm during much or most of that equipment’s useful life. The Agency’s CSVL cycle, while designed for a broad range of constant speed nonroad engines, has an average speed which may be lower than the speed at which a manufacturer has designed their engine to operate at maximum efficiency. While the CSVL cycle would still test that engine in a manner which might be encountered by these types of engines under real world operation, EPA has given the nonroad engine manufacturer who believes that their engine to be certified will be sensitive to the speed fluctuations found in the CSVL cycle the option, within the transient test regulations, to operate their engine at a set speed, determined by the operating specifications of the engine, for the course of the CSVL cycle. This variation is described in proposed regulations at 40 CFR Part 1048, section 510. Set speed operation will allow the manufacturer to run the CSVL cycle at the rated speed of the equipment to be certified for the entire length of the cycle or to specify some constant percent of rated speed at which to operate the equipment or engine to be certified. The load portion of the CSVL duty schedule would remain unchanged under this modification. As in the previous case, a manufacturer certifying their equipment on this cycle would be constrained to specify this restricted set speed, variable load manner of operation in-use for their engines.

4.2.7.1 Background on Cycles Considered

As has been described earlier in Part 4 of the Draft RIA, the Arc Welder application cycles were developed on an arc welder/electric generator, running a constant speed application at a variable load, with a direct-injection, naturally-aspirated, 30kW (40 hp) engine. The Arc Welder Highly Transient Torque cycle, one of the four cycles developed on this engine, is based on a single twenty-minute segment of all the real time operating data collected on this engine.

Some manufacturers of constant-speed application engines have raised issues with EPA’s proposed CSVL cycle. One issue arises from manufacturers of high brake-mean effective pressure (BMEP), i.e., high rated power, constant-speed engines. They point 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 feel that their engines may be penalized by the number and magnitude of torque changes in the CSVL cycle. We do not believe that this concern will significantly affect emissions performance for Tier 4 engines because PM control is realized through mechanical filtration of the PM and as such is largely independent of operating conditions (see the PM emissions performance noted in tables 4.1-2 through 4.1-5). Similarly, NO_x and NMHC control is expected to be realized with catalyst systems, that although temperature dependent, are expected to be fully functional over the range of operation for the CSVL cycle as evidenced by the steady-state emissions results shown in figure 4.1-11 (EPA modes 5,6,7,8 and 17,18,19,20). Further, manufacturers can improve catalyst performance at low torque operating modes by increasing the use of EGR to both lower engine-out NO_x emissions while simultaneously raising exhaust temperatures to promote more effective catalyst function (see discussion in 4.1.3 above). Therefore, we can conclude with confidence that compliance with the proposed Tier 4 standards are feasible over the CSVL cycle.

A second issue involves the average load experienced by an engine running on the proposed CSVL cycle. The average load factor of the normalized application cycle is approximately 25% of engine capacity. Manufacturers of constant speed engines which have a significantly higher load factor on their engines during operation, closer to the 90% and greater range of normalized engine load at constant speed, have argued that their engines will not be able to pass cycle regression statistics for certification without significant re-tuning of the engines to operate over the CSVL cycle. EPA will follow developments with specific manufacturers where the CSVL cycle is anticipated to require substantial re-tuning, or even redesign, of engine controls in order to pass this cycle for engine compliance with transient testing requirements.

4.2.7.2 Justification of Selections

The CSVL cycle should assure manufacturers that their constant-speed engines are able to meet in-use emission and NTE standards. While the CSVL cycle may not be able to accommodate the particular operating parameters required to run every constant speed engine, it is a fairly robust cycle for many types of constant-speed equipment and applications. With a manufacturer's option to use a set operating speed over the course of the test cycle, even fewer concerns should arise as to operating an engine over this transient cycle. EPA has shown further that one can pass cycle regression statistics on a typical nonroad engine with fairly mild cycle control procedures in place¹⁵⁰. The Agency feels that "tailoring" the constant speed cycle to multiple engines and applications will further fragment the certification process for constant-speed engine manufacturers and in the end, will afford less control over in-use engine emissions than maintaining the CSVL cycle alone as the single certification option for the class of constant-speed engines. Given future engine technology and trends in emission control, this cycle will represent a boundary for operating emissions from these engines. By certifying engines to this testing procedure, manufacturers can be assured that their engines will be as clean as, and may be even cleaner, operating in-use than operating over the CSVL cycle for certification.

Manufacturers may choose to run the CSVL cycle for certification purposes at a set speed instead of following the intended speed trace from the CSVL cycle, where their constant speed engine(s) is governed very closely during actual engine operation. EPA is proposing this set speed option to the CSVL cycle as a form of relief for these engines which normally are used to power applications like electricity-generating sets and some refrigeration units. Details of this option may be found at proposed regulations in 40 CFR Part 1068.

To pass cycle regression statistics for cycle performance on the CSVL cycle, an engine must have achieved the performance parameters for speed, load and power found in table 4.2-14. These values are the same regression statistics used to determine pass or fail on EPA's NRTC cycle and they do not impose any greater burden on constant-speed engine manufacturers who choose engine compliance with the CSVL transient test cycle than might be seen with operating their engines over the NRTC cycle for compliance.

The Arc Welder cycles were corrected in the course of developing EPA's composite nonroad duty cycle to accommodate for the fact that idle, as listed in early cycle versions, was actually an intermediate speed for the engine (due to its limited high-speed range during transient operation) and that the actual engine idle speed was closer to 800 rpm. As any idle point listed in the original cycles was also idle for the application and not for the engine, this change was seen as appropriate. Speed

changes that were based on low idle to high rated excursions were changed to peak torque speed to rated excursions.

Contractor testing of EPA's Arc Welder cycles has yielded mixed results in passing regression statistics upon later analysis, but passing regression statistics on these cycles was not the principal goal of many of the individual cycle development and testing programs¹⁵¹. Many times, the contractor was only required to optimize the test engine to the case of running a transient FTP for passing statistics on the test engine¹⁵² and, subsequently, many different application cycles were then run on the same engine in conjunction with the transient FTP cycle.

Most recently, though, EPA has run both its Arc Welder Typical 1 and Highly Transient Torque application cycles in-house on an electric dynamometer with a turbocharged 93 kW (124 hp) test bed engine¹⁵³. The realtime control strategies employed on the dynamometer cycle runs included simple PID (proportional, integral, and derivative) control algorithm-derived time constants and a half second earlier time-shift of commanded throttle (torque) values in the denormalized cycle. These control measures correct for anticipated differences in feedback from the actual speed and torque values for the engine during operation and the command values from the dynamometer during testing. The commanded throttle (torque) values were time-shifted, again, in a post-analysis of cycle data in half-second increments. Out of 20 half-second values, cycle regression statistics were passed on all parameters, for speed, torque and power, for three consecutive time values for the Arc Welder Typical cycle and on six consecutive time shift values for the Arc Welder Torque cycle. This form of post-processing is fairly typical for duty cycle testing conducted in a dynamometer test cell and would not create a significant added burden on the manufacturer.

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 not 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. There are two aspects of this which 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 real world based duty cycles. 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 would tend to demand a desired torque the engine's response to that demand, although 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 could be addressed through the performance statistics.

Engine manufacturers sought to address the first concern through a playback analysis which addressed the I_{α} 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 I_{α} offset to measure torque using an in-line torque meter. Manufacturers

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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 (Nm)	Rated Speed (RPM)	Low Idle (RPM)
1	Caterpillar	3204-D17	Caterpillar	Cat D4H	Crawler Tractor	85 peak 76.8 peak; 70.8 rated	442	2200	800
2	Caterpillar	3114-D17	Caterpillar	Cat 446B	Backhoe Loader		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 En

Engine Inertia Data Used for $I\alpha$ Correction Calculation

No.	Engine Mfg	Engine Model	Total Inertia (Kg-m ²)	Total Inertia (N-m-s ²)	Engine Inertia (N-m-s ² = kg-m ²)	Flywheel Inertia (N-m/s ² = kg-m ²)
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 was corrected to avoid error propagation within the 1 Hz scalar data.

1. Apply the $I\alpha$ 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.^Z
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.

^ZPlease see Draft RIA Section 4.2.3. of this rulemaking

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 helps reduce the testing burden a given manufacturer would have to face when selling and distributing their product 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 emissions 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 arena 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 heavy duty, highway diesel applications, it was seen as an adequate basis for which European industry and government staff could assess the proposed EPA 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 which subsequent development and testing work would be conducted. 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 then “candidate” cycle would be used by the Joint Research center 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 4.2-9 and 4.2-10. The average load and average speed of each cycle are shown in Table 4.2.6.2.2.-1. 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.^{AA}

^{AA}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 4.2-9
EPA Nonroad Transient Test Cycle as of March 2001

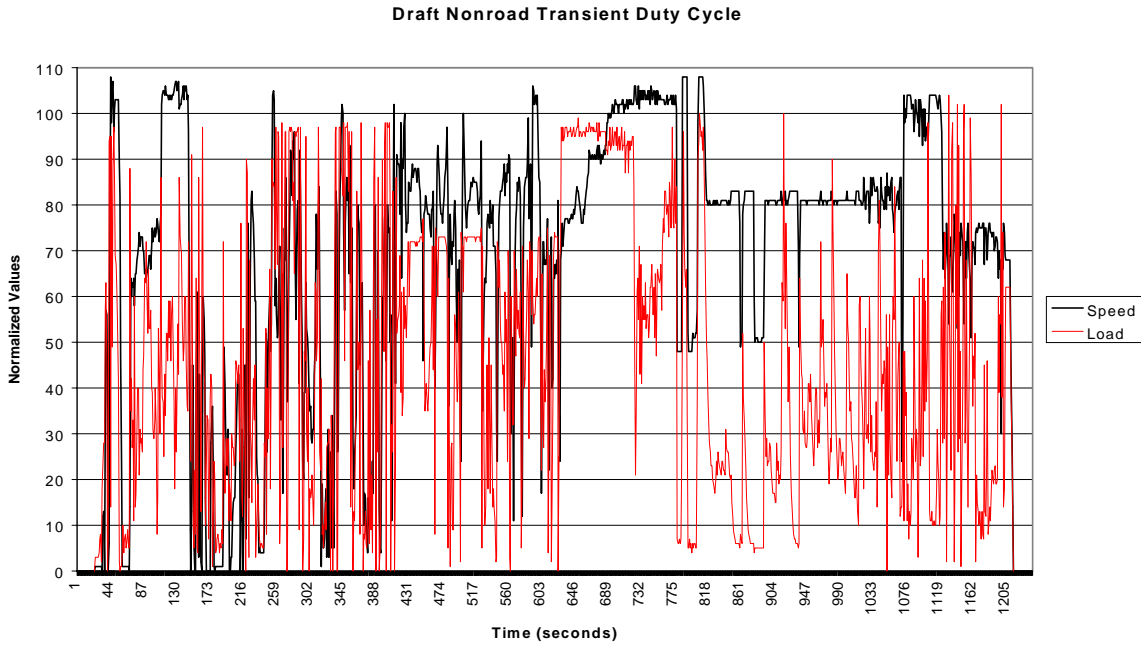


Figure 4.2-10
JRC Nonroad Transient Test Cycle after Bessel Filtering

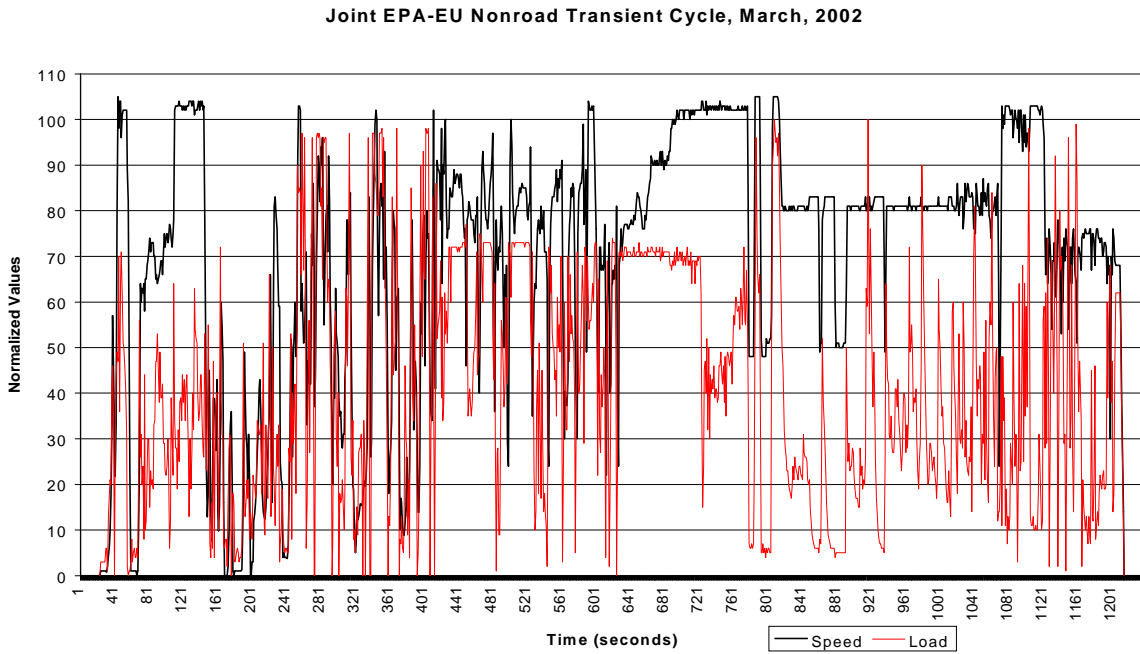


Table 4.2-12
Comparison of Cycle Averages

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

The following figures 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

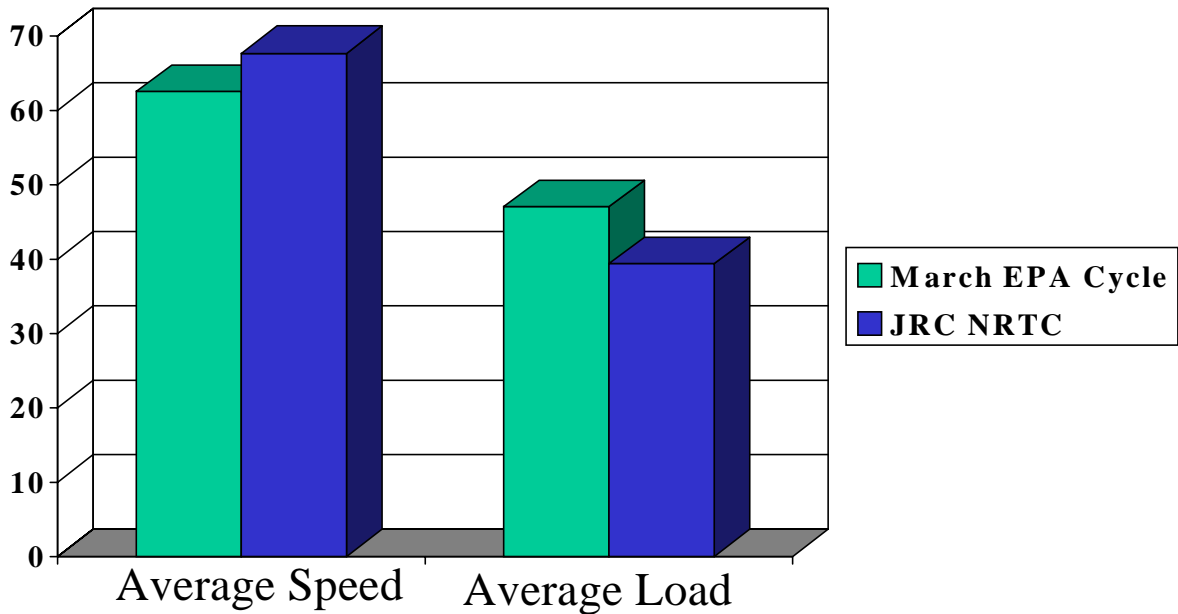


Figure 4.2-12
Average Speed Changes of the EPA NRTC

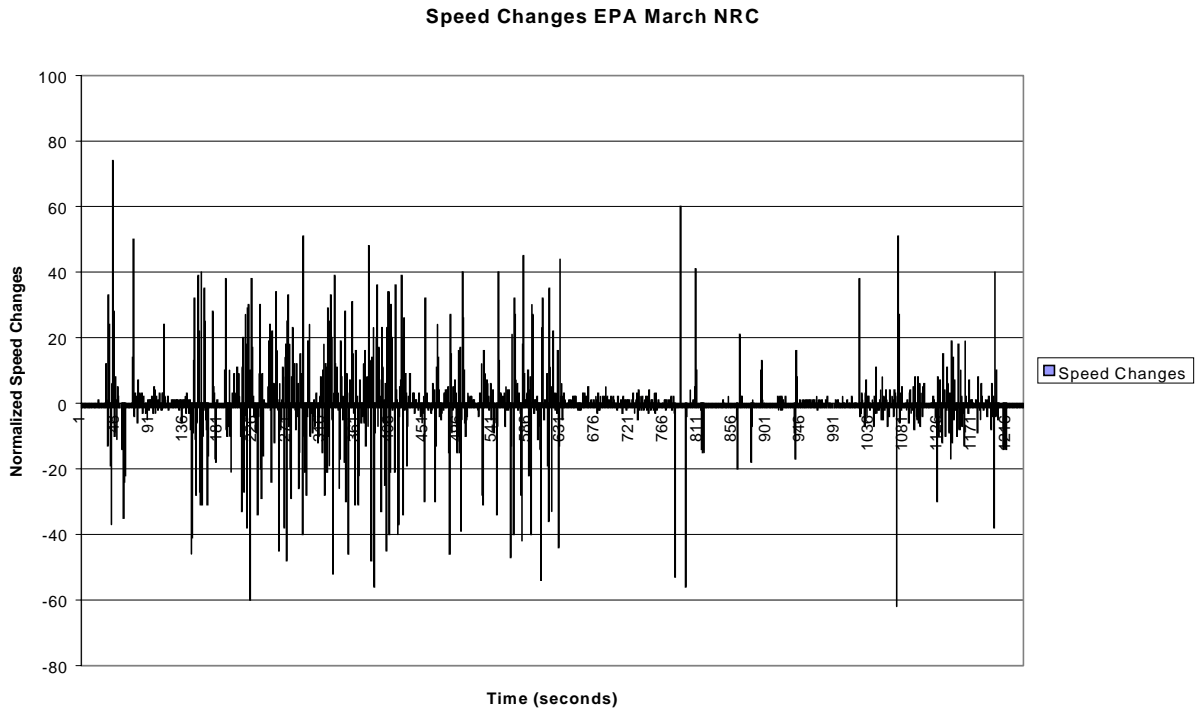


Figure 4.2-13
Average Speed Changes of JRC Modified NRTC

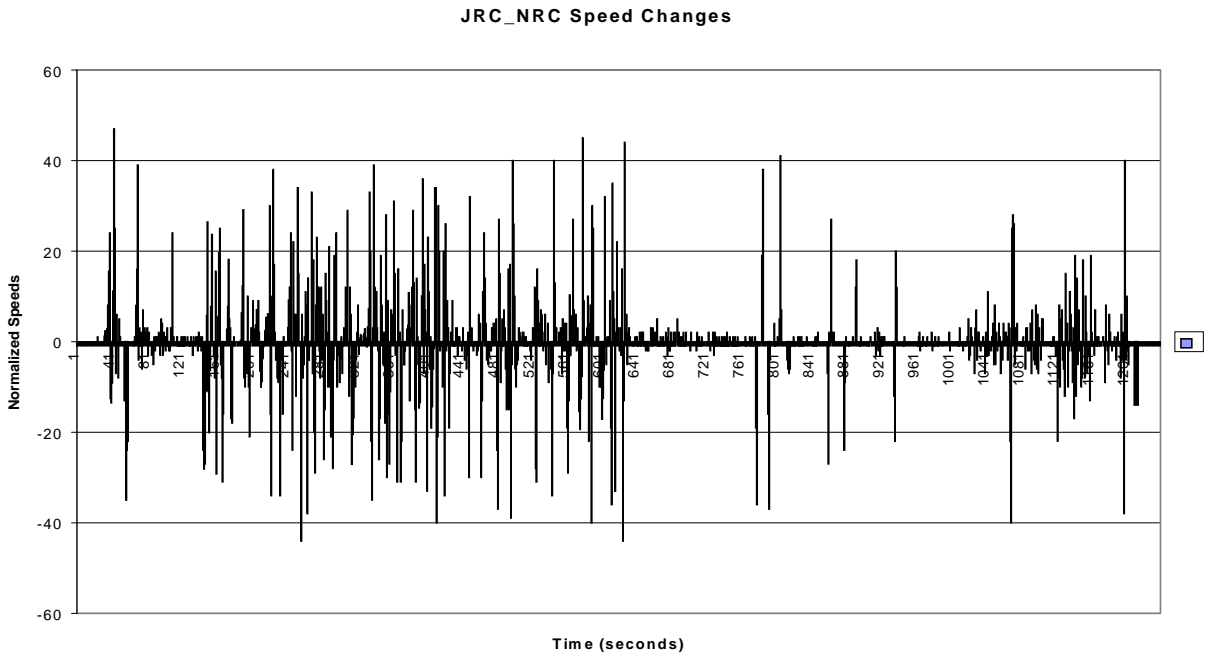


Figure 4.2-14
Average Load Changes of JRC Modified NRTC

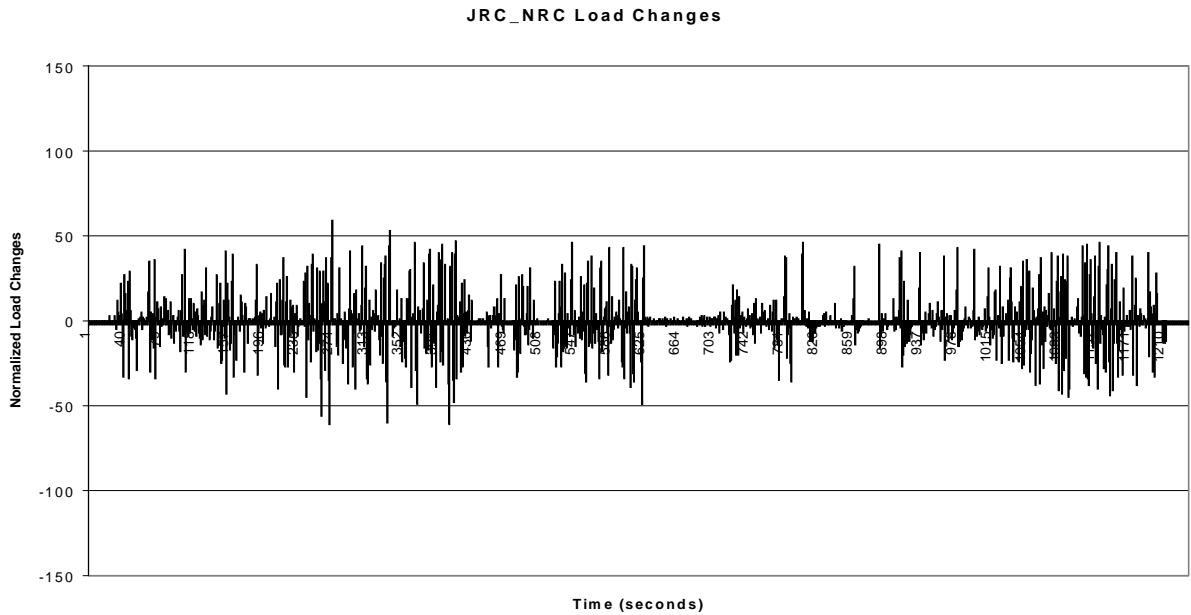
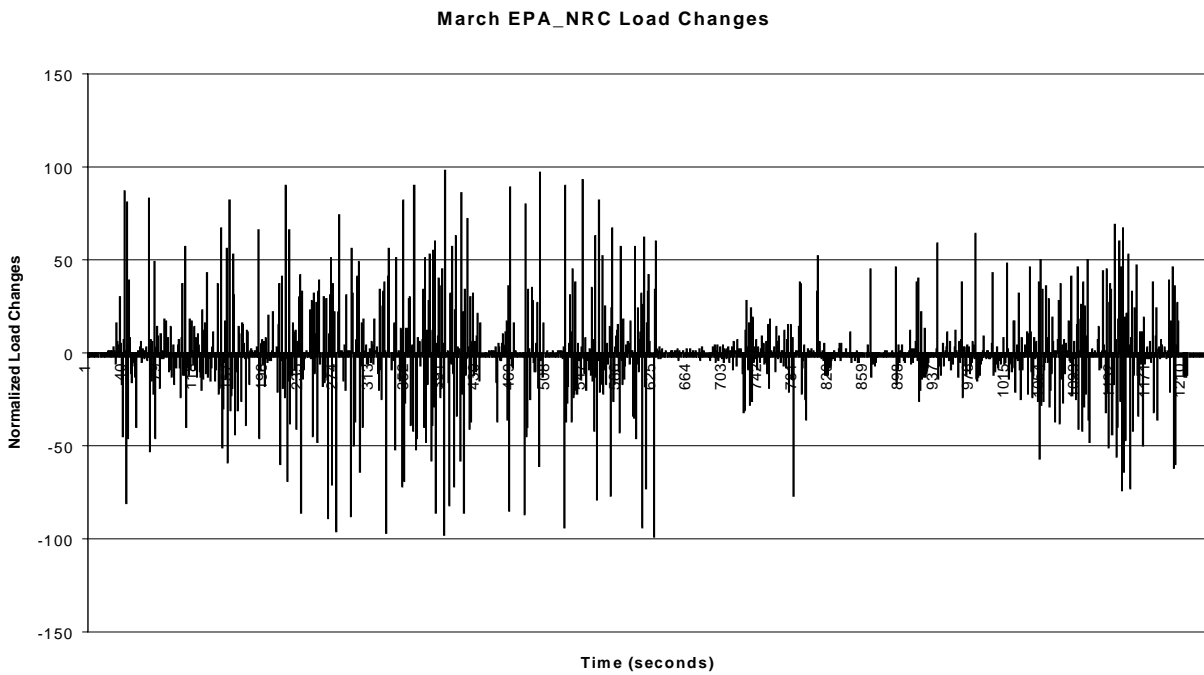


Figure 4.2-15
Average Load Changes of the EPA Generated NRTC



Given the modifications in the duty cycle,

it was critical to assess the impact on the emissions signature of the cycle. The table below (Table

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4.2-13) shows that the emissions 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 has been noted earlier in this chapter, the cycle was modified by EPA 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 emissions 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 emissions signature^{BB}. 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 stringent to ensure an accurate and repeatable emissions

^{BB}Memorandum from Cleophas Jackson to EPA Air Docket A-2001-28, JRC December 5, 2001, Report on Cycle Performance

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signature was achieved^{CC}. With the conclusion of the international workgroup's efforts, the cycle was considered complete by EPA. 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 below in Table 4.2-14.

Table 4.2-14
NRTC Cycle Regression Statistics¹⁵⁴

	Speed [rpm]	Torque [N·m]	Power [kW]
Regression Line Tolerances			
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)*
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

* Under consideration by ISO workgroup.

4.2.9 Supplemental Cold Start Transient Test Procedure

We are proposing to include a requirement for a cold-start transient test to be run in conjunction with the hot-start run of the proposed transient test procedure. The proposed cold-start measurement is meant to recognize and quantify nonroad diesel engine missions generated for short periods at engine start-up. We further propose to weight these cold start emission results as 1/10 of total emissions, with the hot-start transient emissions making up the remainder. Cold start most often refers to nonroad engine emissions created during a short period after the first key-on event of the day, the first "cold start" for that piece of equipment in its workday. Given that the equipment has sat at ambient temperature for a minimum of six hours and in most cases overnight, engine startup will entail warming up the unit's operating and emission control equipment to normal operating temperatures. Likewise, a short period of engine operation, after a longer period of engine inactivity, may be characterized as having emissions similar to the earlier cold start operation as the unit must warm up its operating systems once more before running at peak efficiency. With this as background, EPA targeted the second-by-second operation of a population of some forty pieces of nonroad equipment for analysis to characterize the "average" workday of each unit and to determine if some portions of that workday were spent at a significantly higher rate of engine emissions than others. Generally, times when an engine is operating at cold start or less than stable operating temperature, frequently characterized by lower exhaust temperatures, engine emission rates can be seen to be higher than those during "warmer" engine operation.

^{CC}Memorandum from Cleophas Jackson to EPA Air Docket A-2001-28, *Nonroad Transient Duty Cycle Development Report*, Cornetti, G., Hummel, R., and Jackson, C.

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In one such analysis, EPA examined over 435 hours of second-by-second operating (actual “key-on” operation time) and NO_x emission data from 13 pieces of construction equipment in the field¹⁵⁵ and is summarized in table 4.2-15 below.

Table 4.2-15
Portable Emissions Testing in a Construction Equipment Population

Equipment Type	Model Year	Total Cold-Start Key-on Periods	Total Operating Time (hr)	Cold-start NO _x as Weighted Proportion of Total
Crawler Dozer	1999	11	25.85	0.038
Crawler Dozer	1985	4	30.53	0.021
Crawler Dozer	1987	11	31.72	0.065
Crawler Dozer	1988	10	41.87	0.025
Crawler Dozer	1990	6	20.86	0.042
Crawler Dozer	1995	7	49.29	0.018
Crawler Dozer	1998	8	49.16	0.037
Crawler Dozer	2001	12	63.09	0.032
Excavator	1989	8	20.48	0.062
Off-Highway Truck	1999	8	48.32	0.016
Off-Highway Truck	2001	7	26.20	0.053
Off-Highway Truck	2001	8	23.82	0.062
Wheel Loader	1983	7	4.41	0.097

All data was recorded in real time with EPA’s Simple Portable On-board Testing emission monitoring equipment. The test population consisted of eight bulldozers, three sediment haulers, one excavator and one wheel loader. Each piece of equipment recorded one or two cold starts per workday. Cold starts included in its definition the first ten minutes of operation after the first “key-on” in a day and the first ten minutes of operation of that equipment after a period of an hour or more of inactivity within that same workday, as defined by the Julian date. Most of the crawler/dozers and the excavator exhibited three cold starts in a day and one dozer recorded four cold start periods in the same day. Grams of NO_x were summed for all cold start periods for each piece of equipment per day and then divided by the total number of grams of NO_x emitted from that piece of equipment for the entire “key-on” period of operation for that same day, giving the proportion of cold start statistic below.

$$P_{\text{coldstart,day}} = \frac{\sum \text{NO}_x_{\text{coldstarts}}}{\sum \text{NO}_x_{\text{day}}}$$

where NO_x _{coldstarts} is the amount of NO_x (g) emitted during the 10-minute cold-start periods during the day, and NO_x _{day} is the total amount of NO_x (g) emitted during the day.

The proportion of NO_x emissions from cold start operation for each day per piece of equipment, *P* above, was multiplied by the total time that that unit spent running for each day that the equipment had at least one “key-on”. This statistic of the cold-start emissions proportion for a single workday for a single piece of equipment was then summed, and divided by the total time that piece of equipment spent in a “key-on” mode, i.e., running, over the course of the time that it was

instrumented for study. This gives the time-weighted average of the proportion of NOx emitted during cold start periods over a work day.

$$p_{\text{twa}} = \frac{\sum p_{\text{coldstart,day}} \cdot t_{\text{op,day}}}{\sum t_{\text{op,day}}}$$

where p_{twa} is the time-weighted average of the cold-start proportion over all workdays and where $t_{\text{op,day}}$ is the total operating time for a given day (hours).

This proportion ranged from 1.8% to 9.7% over all the sampled equipment, with an average value of 4.4%. The margin of error at a 95% confidence level (t-statistic) was +/- 1.4%.

Unresolved to date, is exactly what the rate of emissions from all pollutants might be in this population of construction units with respect to both cold starts and at-temperature operations. EPA has concerns that not all pollutants may be emitted at similar rates to those seen for NOx in this study. Likewise, given the breadth of nonroad equipment and application types that exist, EPA will not apply these results broadly to the nonroad equipment population but will use them as an indicator that, in fact, cold start operation may account for a significant amount of nonroad operating emissions over the course of a “typical” equipment workday. The time period over which these units were tested is significant, as well. The model years of the sampled equipment ranged from 1985 to 2001, and no piece of equipment was outfitted with either a diesel oxidation catalyst, PM filter trap or other such emission control equipment. In future years, such emission control equipment may be more common and the operating condition of the engine more a factor in when and how much pollutants are emitted during various periods of engine operation, e.g., cold start.

At cold start “key-on”, some units in this study were seen to operate at a slightly higher level of engine idle than the unit’s specified low-idle operation (approximately 10 percent higher engine speed)¹⁵⁶. After a short period, usually five to ten minutes, these engines dropped back to low-idle speed operation. This type of operation, while the engine is still “cold”, may be a contributor to higher emission rates at start up for these engines, especially if higher exhaust temperatures will be needed in the first few minutes of operation for on-board emission control systems in these types of nonroad engines. In some of the equipment under EPA analysis, engine start up after periods of inactivity during a typical workday lasting sixty minutes or longer exhibited exhaust temperatures starting out below 100°C. Exhaust temperature remained under 150°C if the engine continued to operate at low idle, sometimes falling back below 100°C. Total “warm” engine operating emissions over the equipment’s workday hours will surpass the day’s “cold start” emissions by a large factor. However, a nonroad diesel engine which is designed to emit less at cold start will have lower emissions at other points in its operation as well and will on balance be a significantly cleaner engine in complying with cold start regulations.

4.2.10 Applicability of Component Cycles to Nonroad Diesel Market

We started to pursue application-specific operating duty cycles which could be normalized for laboratory testing of nonroad diesel engines in the 1997-1998 time frame. With a standardized set of operating duty cycles, we would have a basis upon which to compare the brake-specific emission

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rates of nonroad engines both within and across horsepower 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, off-highway trucks and 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 would best represent the US nonroad equipment population was aided by an analysis of the our nonroad equipment population database.¹⁵⁷ Our source of data placed the total 1995 nonroad equipment population figure at 7,100,113 units in the U.S. 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 engines which operated at a constant speed with varying load requirements 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 classes alone 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 emissions 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 below).

Table 4.2-16
Emissions Attributable to Base Nonroad Applications

Application	Emission Distribution by Application
Ag tractor	34%
Welder	1%

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

4.2.10.3 HP 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 (by horsepower). 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 all nonroad horsepower in use. With similar equipment applications included, the equipment with an agricultural tractor-like horsepower number or displacement approaches 30 percent. Backhoe loaders, crawler dozers and rubber-tire loaders together accounted for 12 percent of the horsepower in the nonroad population and, with similar applications included, accounted for approximately 35 percent of total nonroad horsepower. The last three cycle component applications—excavators, skidsteer loaders and arc welders, with arc welders and like equipment generally falling into the 50 horsepower and under engine power band—constitute only 8 percent of total nonroad horsepower. 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 horsepower. Taking the sum of horsepower 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 below).

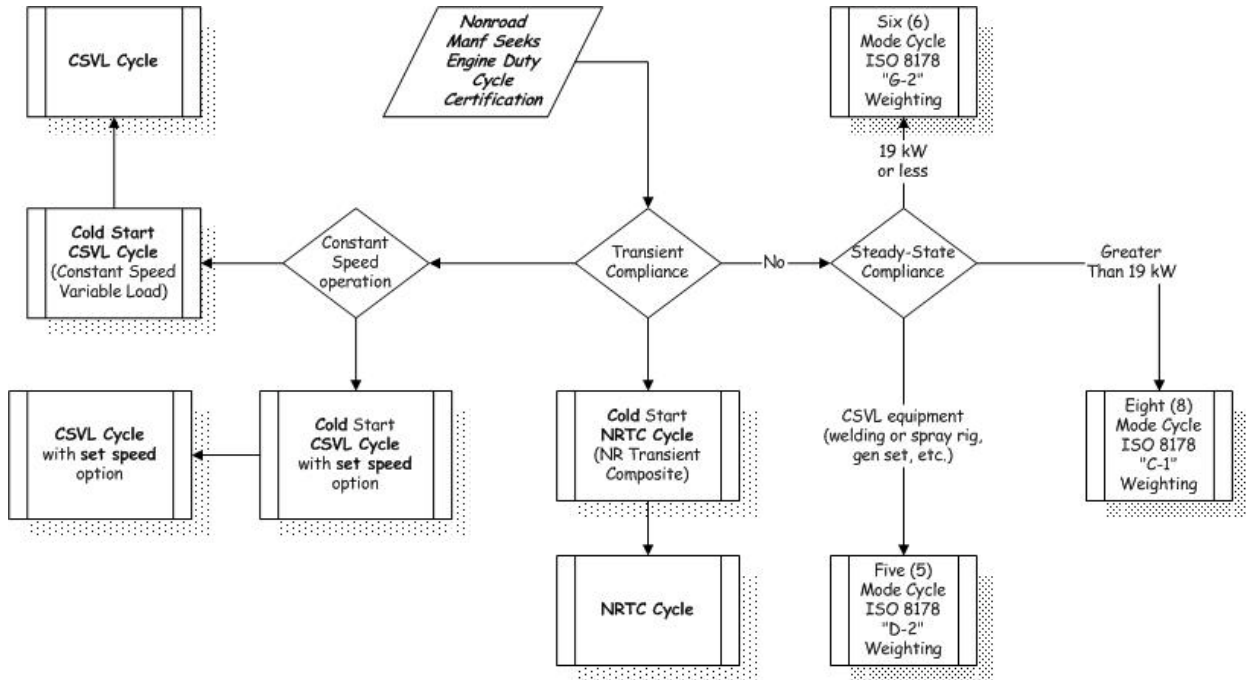
Table 4.2-17
Similarities Among Various Nonroad Equipment Applications

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 4.2-16 below outlines the process by which a manufacturer of a particular nonroad diesel engine might approach certification and compliance of that engine with EPA’s proposed nonroad transient (and steady-state) test requirements.

Figure 4.2-16
Nonroad Diesel Engine Emission Testing Requirements



4.3 Feasibility of Not-to-Exceed Standards

EPA is proposing not-to-exceed (NTE) standards against which nonroad diesel engines are to be evaluated by using similar test procedures to those implemented as part of the highway diesel rule for MY 2007 and later heavy-duty engines.

However, EPA has also been exploring alternatives to the highway NTE test procedures for nonroad applications. These alternatives are detailed below. EPA believes that they show promise, especially for nonroad applications, because the unique characteristics of nonroad equipment have been considered when developing these procedures. Furthermore, we believe that these alternative procedures simplify on-vehicle testing, yet they maintain the same, if not better, level of compliance as compared to applying the highway procedures to nonroad applications. This alternative NTE’s test procedure have been drafted in a dcocket memo entitled, “Changes Considered for §1065 Subpart J - Alternative NTE Field Test Procedures and Equipment.”¹⁵⁸

4.3.1 What EPA concerns do all NTE standards address?

Regardless of the NTE test procedure, measuring emissions from engines as they undergo normal operation addresses two broad concerns. First, testing in-use engines has shown that emissions can vary dramatically under certain modes of operation and ambient conditions, which are not always easily replicated in a laboratory. NTE standards have a particular advantage because in contrast to lab standards, NTE standards are readily implementable in-use. NTE standards facilitate this because the standards are limits over a broad range of normal engine operation that may be measured on-vehicle. This may include varying engine speeds and loads according to real operation

and may include a reasonable range of ambient and engine conditions. Second the contemplated Tier 4 nonroad standards anticipate the use of several emissions control technologies. NTE standards are one of the most realistic and cost effective means to measure emissions from field-aged engines. This helps ensure that emissions control systems are reliable for the useful life of an engine.

4.3.2 How does EPA characterize the highway NTE test procedures?

Refer to Chapter 4 of the Regulatory Impact Analysis of the highway HDDE rulemaking, published January 19, 2001 for details on the highway NTE test procedures. Briefly, the highway NTE provisions specify that averaging periods may be as short as 30 seconds in time, but under these provisions testing is also restricted to a very limited region of engine operation, namely when all of the following conditions are simultaneously met for at least 30 seconds (unless an aftertreatment system regenerates, then the minimum time would be longer):

1. Speed greater than 15% above idle speed
2. Torque greater than or equal to 30% of maximum torque
3. Power greater than or equal to 30% of maximum power
4. Altitude less than or equal to 5500ft (~>82kPa)
5. Ambient temperature less than or equal to 100F at sea level to 86F at 5500ft (30-38C)
6. BSFC less than or equal to 105% minimum BSFC if not coupled to a multi-speed manual or automatic transmissions
7. Outside of any manufacturer petitioned exclusion zone
8. Outside of any NTE region in which a manufacturer states that less than 5% of in-use time will be spent
9. Intake manifold temperature greater than or equal to 86-100F (20-30C), depending upon intake manifold pressure
10. Engine coolant temperature greater than or equal to 125-140F (52-60C), depending on intake manifold pressure.
11. Exhaust aftertreatment temperature greater than or equal to 250C.

4.3.3 How does EPA characterize the alternate NTE test procedures mentioned above?

The alternate NTE test procedure would apply to all normal engine operation regardless of speed-load combinations or a test period's frequency of idle, steady-state, or transient operation. This all-inclusive range of engine operation is consistent with EPA-collected data from nonroad vehicles and equipment. The alternate test procedure also requires only a few measured parameters, and this facilitates simple on-vehicle measurements. The data reduction procedure utilizes a "constant work" moving average that returns values weighted and calculated the same way that emissions data are reduced from a CVS test cell or from a weighted steady-state test. This provides an engineering target for manufacturers that is consistent with the FTP test procedures.

4.3.4 What limits might be placed on NTE compliance under the alternate test procedures?

The alternate NTE test procedures would apply to all normal operation. This may include steady-state and/or transient engine operation. Given such NTE standards, the goal for the design engineer is to ensure that engines are properly calibrated for controlling emissions under any reasonably expected mode of engine operation. However, it may not be technologically feasible to meet specific NTE standards under all ambient and engine conditions so we will adopt some

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restrictions to narrow the range of ambient conditions and engine operation under which an engine is subject to the alternate NTE standards.

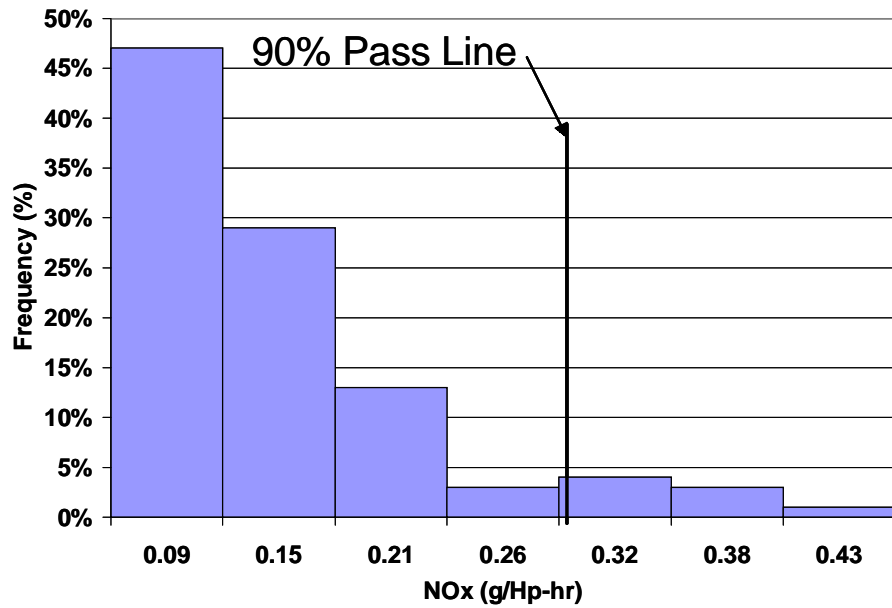
Engines are often designed to operate under extreme environmental conditions. To narrow the NTE range of compliance for the design engineer, we are limiting emission measurements for NTE testing to ambient temperatures up to +40° C, and to ambient pressures greater than or equal to 80.0 kPa. This allows testing over a wide range of conditions in addition to helping ensure that engines are able to control emissions under the range of conditions under which they are likely to operate. Because engine manufacturers already design entire engines to be reliable over an even wider range of ambient conditions, it is reasonable to expect that similar design information is already available to design low emissions engines that possess similar reliability with respect to emissions performance. Information on these extreme conditions are already required for proper design and construction of air intake systems, turbo-chargers, cooling systems, and lubricating systems.

And because of the catalysts expected to be utilized for NO_x control, prolonged engine operation that is insufficient for catalyst heating will also be considered in the alternative NTE. The data reduction techniques for this is specified in the draft regulations in Appendix A. In summary, if any 10% work interval (described below) has a flow-weighted average exhaust temperature of less than 250C, then that interval's NO_x emissions must be no greater than 4.00 g/kw-hr.

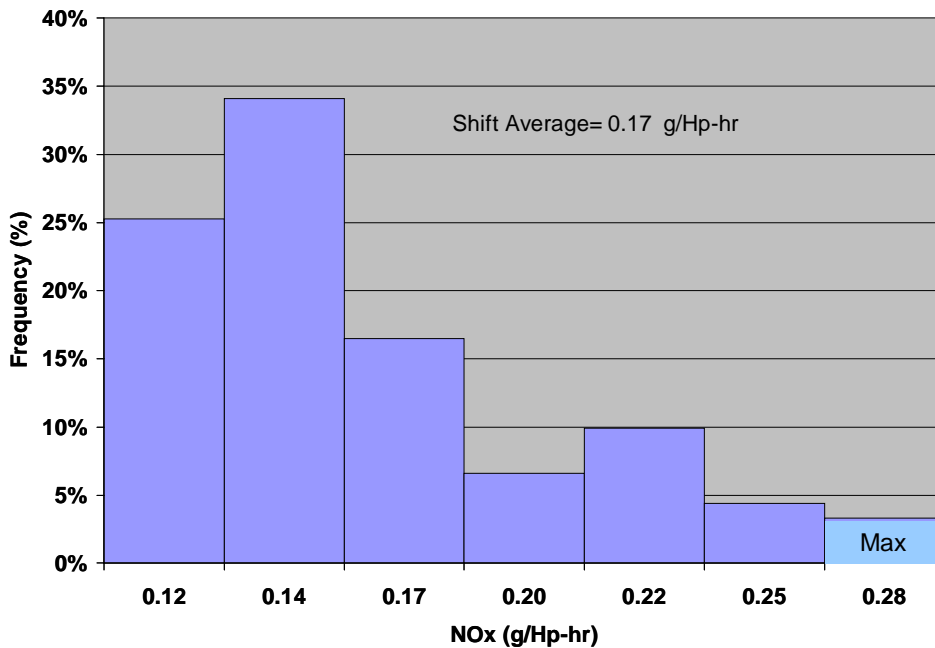
Other important limits that the Agency has considered in order to define NTE standards are the averaging intervals and normalization procedures for data reduction. A longer averaging period allows for greater data stability, due mainly to the smoothing effect of measuring over several events. On the other hand, an overly long averaging period will likely mask areas of engine operation with poor emission-control characteristics. Even if poor emissions occurred over a relatively short period of a test, such high-emitting events may be indicative of a more serious deficiency once other engines have been determined to possess similar deficiencies. This is especially true if additional testing reveals that different in-use duty cycles cause the deficiency to result in poor emissions more frequently.

In order to maintain consistent NTE multipliers between the on-highway and alternate NTEs, similar on-highway and non-road data sets were analyzed using both procedures. The averaging scheme of the alternate NTE was adjusted so that both NTE concepts "passed" and "failed" similarly. Below is an example of such an analysis.

On-Highway NTE Results



NOx Histogram of 10% Work Intervals



Analysis: The first chart depicts a histogram of the results by analyzing a real-world data set with the alternative NTE. Note that at an arbitrary FTP standard of 0.2 g/hp-hr, the 1.5x multiplier would result in a limit of 0.30 g/hp-hr. The alternative NTE reveals that the engine barely passes the

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0.30 NTE standard with a maximum value of 0.28. Note too that the average is just below the FTP standard at 0.17 g/hp-hr. Now compare this to the same “barely passable” results returned by analyzing the data according to the on-highway NTE. Since the multiplier is the same between the two, one does observe that there is a small fraction of values greater than 0.30 in the highway NTE analysis. This fraction is just less than 10% however, so the analysis indicates just greater than 90% pass, which is part of the “pass” criteria outlined in the recent NTE settlement between EPA and some engine manufacturers. The highway NTE’s analysis also shows that none of the data points is greater than 2x the NTE standard, which is also part of the settlement’s “pass” criteria.

The alternate test procedure applies a “constant-work” moving average. In contrast to the highway NTE, the alternate NTE comprises of engine operation within the same ambient bounds—but at all speeds, loads, and BSFCs; there are neither manufacturer exclusion zones, nor exclusions based on intake or coolant conditions. For NO_x emissions only there is one minimum exhaust temperature condition that needs to be met for a minimum duration. This results in a much more broad range of operation covered by the alternate NTE. This is justified because the large number of applications in the nonroad category (>6,000 different vehicle or equipment models) leads to a very broad range of probable engine operation. This is evidenced in EPA’s and other global organization’s composite non-road transient test cycles, and it is also obvious in the ~6,000 hours of non-road on-vehicle data that EPA collected during the years 2000 through 2002. Therefore, the alternate NTE procedure requires that all collected data, over all speeds and loads, will be included as part of the data reduction scheme.

4.3.5 How does the “constant-work” moving average work, and what does it do?

Since most engine operation will fall under the NTE standards, a sufficient emissions averaging period is required to determine if higher emissions during a specific speed-load combination is of significance. And because of the wide range of probable nonroad engine operation—including extended periods of idle operation—the alternate NTE procedures employ a “constant-work” moving average so that brake-specific emissions are not evaluated over short work intervals.

Specifically, the procedure specifies that an individual “test period” consists of a minimum of six (6) hours engine-running operation. This test period is intended to be roughly consistent with a typical operator work-shift using nonroad equipment. Engine-off time would essentially be skipped until additional engine-running data can be merged with the previous engine-running data to continue data averaging. The work over this test period is totaled and it is normalized to a 6-hr shift if more than 6 hours of engine-running data was recorded. This means that if 8 hours were recorded, the total work would be divided by 8-hours and multiplied by 6-hours. The averaging interval is 10% of the normalized total work over the test period, and this 10% moving average will increment (or “move”) at increments of 1% of the total work. This moving average will cause averages to overlap in time. This is desirable because it dampens the results’ sensitivity to random combinations of speed and load being averaged together because of their proximity in time. This moving average scheme always returns at least 90 data points for comparison against the NTE standards. This reasonable number of data points, each consisting of a significant portion of a test period’s work (10%), allows for the use of their maximum value to be compared to the NTE standards.

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EPA analyzed several statistical methods to compare these results to an NTE standard. It was soon discovered that although the 90+ data points formed a convenient and continuous distribution of emissions values, the distribution's characteristics changed shape from one real-world data set to another. Some distributions seemed similar to normal or log-normal distributions, while others were greatly skewed with long tails on one end or another. This meant that parametric statistics based on a distributional assumption might be valid for one data set, but not on another. Therefore, statistics such as arithmetic means, geometric means, standard deviations, and confidence intervals were useful in some cases but not in all cases. Even powerful transformation algorithms were used in an attempt to de-skew some of the data sets, but even these failed in certain cases. One of the few alternatives for analyzing such data was to use non-parametric statistics, namely "tolerance intervals." In this case a significant number of data points are collected (90+), and based only on the fact that this number of points is collected, a level of confidence may be assigned as to whether the maximum emissions of the data set reflects the maximum possible emissions from the engine. For the case of these 90+ data points, non-parametric statistics suggest with 95% (+-4%) confidence that 95% of the engine's emissions are less than the maximum of the 90+ data points. This statistic is consistent with the intent of the NTE—it is a cap on the maximum allowable emissions. Note too that a 10% work interval, based on a 6-hr shift was selected not only to return this number of data points but also it was selected so that the NTE multipliers would be consistent with the highway multipliers.

There are several advantages to using the "constant-work" moving average approach. First, all moving average data points from a complete test period represent brake-specific emissions over the same work interval. This normalizes all of the data points so that they can be compared to each other in a meaningful way. NTE standards set for the maximum value of this data set is effective because the maximum of a set of significant (10% work) data points.

Note that this work-based normalization is similar to how an engine family is certified. A representative engine from a family is "mapped" to determine its maximum output at each engine speed, and this data set is used to "de-normalize" the certification test cycle so that the engine family is always run over the same test interval of work, no matter whether it is tested by a manufacturer, by an independent laboratory, or by EPA. This FTP constant work interval de-normalization also allows high power engines to be certified to the same brake-specific standard over the same time interval, but over a proportionally larger work interval. This element of certification testing is essential in order to normalize engine emissions so that engines of different rated power can be compared to the same brake-specific (e.g. work-specific) emissions standards.

In the alternate NTE the total in-use duty cycle of a 6 to 12-hr test period is used to determine an appropriate work interval for the moving average of constant work. This use of a test period's total work essentially utilizes characteristic "real-world" total work to determine the appropriate (and constant) interval of work for data reduction. The total work of a test period will change from day-to-day, so individual data points from different days may not be directly comparable, even within a given engine family because the duty cycle on a given day will likely be different from another day. However, it is precisely this variable-duty-cycle element of in-use testing that EPA intends to preserve by using this data reduction scheme. By preserving this element of in-use testing, the engine is compared against its real-world duty cycle, not a fixed certification test cycle or fixed test work interval. This means that if an engine is tested under a qualitatively "high-load" test period, the work intervals will be of a higher work value but still varying time intervals. Nevertheless, the engine will be evaluated over a moving constant 10% work of that test period's total work. The opposite will

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also be true in that an engine evaluated over a “light-load” test period will be evaluated against lower work values of constant work that will still occur over varying time intervals.

Another advantage to this data reduction scheme is that within a given test period, random time intervals of relatively low power operation (i.e., idle) cause the work summing to take a longer time period to complete. By using 10% work intervals, idle operation is consistently averaged with other higher power output operation. This will always be true unless an in-use test period contains more than 10% of continuous work at idle. Because a diesel engine uses about seventy-five times as much fuel at rated power versus idle, this scenario is very unlikely. Before this could happen, the data reduction scheme would require that over half of the test period’s time would have to be spent continuously, not intermittently, at idle in the case where the remainder of the test period averaged a 50% power duty-cycle. And if this were to be a real case, EPA would likely want to have such a significant idle operation evaluated against the NTE standards.

Any low power operation less continuous than the extreme case described above will be scaled relative to higher power operation because the field testing data reduction scheme “flow-weights” each constant work interval’s emissions. This is exactly the same way constant-volume sampling (CVS) proportionally weights emissions during certification tests. Low-flow operation (i.e., idle) emissions are weighted proportionally less than other high-power emissions over a given work interval.

EPA has evaluated this data reduction scheme on several highway and nonroad in-use data sets collected from vehicles as they performed normal work in-use. We have determined that this data reduction scheme reduces the data into a reasonable number of meaningful data points that can be compared to the NTE standards in a consistent way. This data reduction scheme allows for the maximum 10%-work emissions to be compared to NTE standards, and it allows the entire test period’s emissions to be compared to the FTP standard in a meaningful way.

4.3.6 What data would need to be collected in order to calculate emissions results using the alternate NTE?

Emissions volume concentrations (i.e., ppm or %) from the raw exhaust would need to be measured. These include total oxides of nitrogen ($\text{NO} + \text{NO}_2$), total hydrocarbons (THC), carbon monoxide (CO), and particulate matter mass (PM). THC needs to be converted to NMHC based on proposed regulation §1039.240(e). Particulate matter mass may be measured over other varying work intervals if a proportional integrating PM mass measurement technique is used rather than a PM mass concentration measurement. In order to flow-weight concentrations similar to CVS sampling, a signal linearly proportional to exhaust flow rate at standard conditions of 0 C, 101.325 kPa would need to be measured. This value does not need to be an absolute value in engineering units because the work calculation allows such unspecified units to be cancelled. Work may be calculated by first calculating fuel consumed via carbon balance. Since complete combustion is an appropriate assumption for diesel engines, fuel consumption may be determined by using carbon dioxide (CO_2) exhaust concentration multiplied by the signal proportional to exhaust flow. The fuel’s atomic hydrogen-to-carbon ratio also needs to be factored into this calculation. This fuel consumption is then multiplied by the engine family’s characteristic brake-specific fuel consumption to arrive at total work. For the alternate NTE, the characteristic brake-specific fuel consumption will be the arithmetic mean of the engine family’s certification test cycles’ brake-specific fuel consumptions. If an engine

family is only certified to one test cycle, then its brake-specific fuel consumption over that test cycle will be the characteristic brake-specific fuel consumption for testing.

Using this characteristic brake-specific fuel consumption has several advantages. First it causes an engine family's characteristic certification efficiency to affect subsequent field-testing results. This causes an engine with poor certification fuel economy (high brake-specific fuel consumption), but favorable real-world fuel economy, to have proportionally higher emissions results during field testing. This effect is small (i.e., about 5%), but this characteristic should help to discourage manufacturers from designing low fuel economy solutions for meeting EPA certification tests; especially with the knowledge that the engine is not likely to see certification-type operation in use. According to recent manufacturer consent decrees this has resulted in low emissions and low fuel economy at certification, but high emissions and improved fuel economy during "off-cycle" operation. This off-cycle operation happened to occur frequently in-use, so that improved fuel economy was realized with the consequence of significantly higher in-use emissions. Second, by utilizing the characteristic certification efficiency, there is no requirement to measure engine output torque in-use. In fact the Agency believes such a requirement might be cumbersome because torque measurement may require attachment of a measurement device to the rotating output shaft, which may be close-coupled and sealed in a transmission housing. Additionally, nonroad engines sometimes have multiple output shafts, which would require multiple torque instrument installations; further complicating testing. Another advantage of using an average BSFC is that when measuring emissions at idle, a small amount of work is summed in the denominator of the emissions calculation. Because of the likelihood that nonroad engines are actually performing some work at idle by powering hydraulic, electric, or pneumatic accessories, this work should be included, and by using an average BSFC, it is included.

Other than emissions concentrations and exhaust flow, the only other required measurements would be those of ambient temperature and pressure for the purposes of determining if the data is collected within the range of applicable ambient conditions.

In conclusion, the measurement requirements will likely be minimal: emissions volume concentrations including CO₂, a signal linearly proportional to standard exhaust flow, ambient temperature, and ambient pressure.

4.3.7 Could data from a vehicle's on-board electronics be used to calculate emissions?

EPA will likely allow any data from a vehicle's on-board electronics to be used in the data reduction scheme, provided that it meets the data accuracy and precision requirements specified in the alternate NTE regulations. Additionally, the manufacturer would likely have to attest that such data meets these requirements at the time of NTE testing.

4.3.8 How would anyone test engines in the field?

To test engines without removing them from equipment, analyzers would be connected to the engine's exhaust to detect emission volume concentrations during normal operation. A signal linearly proportional to standard exhaust volumetric flow rate should also be measured to convert the analyzer responses to units of g/kW-hr for comparing to NTE standards. Ambient temperature and pressure would also have to be measured to determine if the NTE standards were applicable.

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Available small analyzers and other equipment will likely be adapted for measuring emissions. A portable heated flame ionization detector (HFID) will likely be used to measure total hydrocarbon concentrations. A portable NDUV or Zirconia-based analyzer will likely be used to measure total NO_x emissions. A nondispersive infrared (NDIR) analyzer will likely be used to measure CO and CO₂. Technologies such as a Tapered Element Oscillating Microbalance or a Quartz Crystal Microbalance will likely be used to inertially measure PM mass emissions.

Emission samples can best be drawn from the exhaust flow directly downstream from an aftertreatment system to avoid diluting effects from the end of the tailpipe. Installing a sufficiently long tailpipe extension will also likely be an acceptable way to avoid dilution.

4.3.9 How might in-use crankcase emissions be evaluated?

The anticipated crankcase emission-control technologies are best evaluated by visually checking if they continue to function as designed. A visual inspection of in-use engine crankcase emission-controls is appropriate to verify that these systems continue to function properly throughout useful life. Furthermore, as stated in the preamble to this proposed rulemaking in section III.B.2, manufacturers that choose not to utilize the closed crankcase approach for addressing crankcase emissions control would be responsible for ensuring that crankcase emissions would be readily measurable in use.

4.3.10 How might the agency characterize the technological feasibility for manufacturers to comply with NTE standards?

The Agency acknowledges that compliance with NTE standards will require design engineers to better understand their engines' emission behavior over a wide range of possible engine operation. Though claims have been made that NTE standards might be interpreted to cover a theoretically infinite degree of variability, we have determined that by evaluating a range of in-use duty cycles, a consistent level of control for any additional operation may be predicted. Making careful measurements over a statistically sound sampling plan provides reasonable certainty that any future emissions from an engine is likely to be within certain bounds. Such statistics are frequently used to ensure reliability of engine parts and engine performance, and we expect similar care to be taken when designing engines to meet NTE standards. We do not believe manufacturers will need to test an "infinite" or inappropriately large number of steady state and transient combinations. Rather, manufacturers will be able to quickly narrow their test programs to focus in on those areas of operation where the emissions are higher and come closer exceeding the NTE standards. Engineering experience and logic dictates that manufacturers will not expend resources testing areas where emissions are well understood and well below the NTE standards.

The same is true with respect to ambient conditions within the specified field-testing bounds. The effects of temperature and pressure on emissions are well known, so manufacturers may limit their testing to those ambient conditions that cause the highest emissions. Alternatively, manufacturers might choose to not test under conditions representing the endpoints of the established ranges, but rather they might test under "mid-range" conditions and rely on established extrapolation methods to ensure that their engines will meet emission standards when tested throughout the range of specified test conditions. If a manufacturer shows that engines meet emission standards under the most challenging conditions, then engines will meet the standards under less challenging conditions.

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Because manufacturers have already demonstrated that they can build complex engines to be reliable for very many years beyond EPA's regulatory useful life, even when these engines have been operated throughout a wide range of extreme ambient conditions, the Agency believes that manufacturers can utilize already known design parameters and engineering and testing techniques to ensure that low emitting engines and aftertreatment systems are similarly reliable for emissions reductions at least throughout regulatory useful life and under similar conditions.

We also expect the manufacturers' statements at certification to state that they meet the NTE standards. These statements should be based on reasonable evidence of compliance, engineering analysis and good engineering judgment. We do not expect manufacturers to have tested every possible combination of points to be able to make their certifying statement.

In addition, we will put limits on the range of ambient conditions under which NTE standards might be evaluated. For example, during emission tests ambient air temperature must be between -0° C and 40° C and barometric pressure must be at least 80 kPa.

By restricting the NTE standards to "normal operation", we will likely allow manufacturers to include in engine designs any limitations applicable to normal operation. For example, if a manufacturer includes in the emission-related installation instructions a warning that the engine must not be installed to power a pump greater than some specific pumping rate, and takes steps to enforce that restriction, we would not consider such engine operation to be "normal operation" under the NTE standards. In some cases, manufacturers may also program their engines with a governor or other device to prevent engines from operating at certain speeds or loads.

Without NTE standards, we anticipate that some manufacturers might design their emission-control systems to function effectively only over the narrow range of engine operation and ambient conditions represented by the certification duty cycles. We feel that in these cases the NTE standards might be interpreted as increasing the overall stringency of the regulation. However, the basis for such a conclusion entirely depends upon a manufacturer's intended approach to meet emissions regulations. EPA has always intended for manufacturers to design solutions that ensure emissions control over a broad range of conditions and throughout useful life of an engine. Therefore, EPA believes that NTE standards do not increase the stringency of the overall regulation, but rather NTE standards ensure that engines are designed to meet the intention of the FTP standards.

In any case NTE standards evaluated via in-use testing will correspond directly with a more effective control of emissions from in-use engines as they undergo normal operation in nonroad applications. We also believe manufacturers will have available emission-control hardware (and software) that allows for more robust control over a wide range of operation and conditions. With some additional engineering, manufacturers can ensure that engines operate properly over the whole range of normal operation.

We already have equipment available to measure emissions using NTE procedures. Moreover, NTE standards take into account measurement tolerances and the variation in emissions due to varying engine operation and ambient conditions. Given the very active interest in portable measurement equipment in the rest of the industry, and given the lead time of this NPRM, we believe that measurement equipment will be widely available well ahead of time so that the NTE standards will likely apply to nonroad compression-ignition engines in 2011. We also believe that the

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measurement technology to meet the NTE standards is sufficiently known so that a technology review is not likely to be necessary.

In the early years of any such program, manufacturers are more likely to devote more of their effort to meet the NTE standards as they learn better how their engines behave under different types of operation. However, as they gain experience in designing robust emission-control systems by interpreting NTE test results, we would expect manufacturers to focus more on meeting the duty-cycle standards, knowing that emission variability has been controlled enough that the NTE standards no longer pose a significant additional constraint in their efforts to comply with all of the standards.

We have already set NTE standards for heavy-duty highway compression-ignition engines, large spark-ignition engines, and marine engines, and we believe that any proposed nonroad NTE standards take into account the unique aspects of operation and technology for nonroad compression-ignition engines. We believe that the information available today is ample to support our conclusions to propose NTE standards and field testing procedures for diesel nonroad engines.

We believe manufacturers will clearly do well by relying on these procedures to meet emission-testing requirements at a substantially lower cost than would be involved with laboratory testing.

The steady-state and transient test requirements clearly provide substantial assurance that engines will be controlling emissions under the kinds of operation seen when installed in the various types of nonroad equipment. We believe the NTE standards are an appropriate supplement to the duty-cycle standards for two reasons. First, any duty cycle, even one with transient engine operation cannot capture the whole range of “normal operation” from the multitude of different types of nonroad equipment. This may be especially important, since some of these engines might be operating in confined spaces where high emission levels pose a concern for individual exposures in addition to the more general issue of pollution in urban areas. The certification duty cycles will include many different combinations of speed, load, acceleration, and deceleration, but they cannot include or substantially weight the whole range of operation that engines may experience. This is underscored by in-use emission data generated to support the NTE standards. Second, without field-testing procedures, manufacturers would only be able to meet in-use testing requirements by removing engines from service and testing them in the laboratory.

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146. *Bin Analysis of Nonroad Diesel Transient Duty Cycles*; Hoffman, G., Dyntel Corporation; Ann Arbor, MI, March 2003

147. See also memorandum to Docket "Maximum Speed Determination Procedure", Docket A-2001-28.

148. This report may be found on and downloaded from the EPA-OTAQ website at <http://www.epa.gov/otaq/marine.htm>. Follow links to the "December 29th, 1999 Marine Final Rulemaking (FRM)" for the "Summary and Analysis of Comments" document.

149. Please see url: <http://www.epa.gov/oms/regs/nonroad/equip-hd/cycles/nrcycles.htm>

150. Memorandum from Kent Helmer to Cleophas Jackson, "In-house Testing of Arc Welder Application Cycles for Record, February 7th, 2003", Docket A-2001-28.

151. Summary Note of Regression Statistics on Contract-testing of the Arc Welder Cycles on various Dynamometer-mounted Engines Sent to Engine Manufacturers Association, Docket A-2001-28.

152. Memorandum to Docket from Kent Helmer to Cleophas Jackson "Engine Control in Transient Operations on a Dynamometer Test Bench", Docket A-2001-28.

153. Memorandum from Kent Helmer to Cleophas Jackson, "In-house Testing of Arc Welder Application Cycles for Record, February 7th, 2003", Docket A-2001-28.

154. ISO Report on NRTC Cycle Development "Final Report on NRTC test Procedure, Summer 2002" Docket A-2001-28.

155. Memorandum From Kent Helmer to Cleophas Jackson "Cold Start Analysis of PEMs-SPOT Data for 13 Nonroad Construction Equipment Units", docket A-2001-28.

156. Memorandum From Kent Helmer to Cleophas Jackson "Cold Start Analysis of PEMs-SPOT Data for 13 Nonroad Construction Equipment Units", docket A-2001-28.

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157. Memorandum from Kent Helmer to Cleophas Jackson, “Applicability of EPA’s NRTC cycle to the US Nonroad Diesel Population”, (Docket A-2001-28).

158. “Changes Considered for Part 1065–Test Procedures and Equipment,” memorandum to docket A-2001-28.