Control of Emissions of Air Pollution From Nonroad Diesel Engines and Fuel [[pp. 28377-28426]]

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manufacturers and has been a focus of our ongoing diesel engine progress review. There we have learned that substantial progress is being made to broaden the operating temperature window of catalyst technologies while at the same time engine systems are being designed to better control exhaust temperatures. Highway diesel engine manufacturers are working to address this need through modifications to engine design, modifications to engine control strategies and modifications to exhaust system designs. Engine design changes, including the ability for multiple late fuel injections and the ability to control total air flow into the engine, give controls engineers additional flexibility to change exhaust temperature characteristics. Modifications to the exhaust system, including the use of insulated exhaust manifolds and exhaust tubing, can help to preserve the temperature of the exhaust gases. New engine control strategies designed to take advantage of engine and exhaust system modifications can then be used to manage exhaust temperatures across a broad range of engine operation. The technology solutions being developed for highway engines to better manage exhaust temperature are built upon the same emission control technologies (i.e., advanced air handling systems and electronic fuel injection systems) that we expect nonroad engine manufacturers to use in order to comply with the Tier 3 emission standards.

Matching the operating temperature window of the broad range of nonroad equipment may be somewhat more challenging for nonroad engines than for many highway diesel engines simply because of the diversity in equipment design and equipment use. Nonetheless, the problem has been successfully solved in highway applications facing low temperature performance situations as difficult to address as any encountered by nonroad applications. The most challenging temperature regime for highway engines are encountered at very light-loads as typified by congested urban driving. Under congested urban driving conditions exhaust temperatures may be too low for effective 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 100[deg]F under even very light-load conditions allowing the NO_X adsorber catalyst to function under these normally cold exhaust conditions.\165\ Similarly, PSA has demonstrated effective CDPF regeneration under demanding light-load taxi cab conditions with current production technologies.\166\ Both of these are examples of technology paths available to nonroad engine manufacturers to increase temperatures under light-load conditions.

\165\ Sasaki, S., Ito, T., and Iguchi, S., "Smoke-less Rich Combustion by Low Temperature Oxidation in Diesel Engines,'' 9th Aachener Kolloquim Fahrzeug--und Motorentechnik 2000. Copy available in EPA Air Docket A-2001-28.

\166\ Jeuland, N., et al, "Performances and Durability of DPF (Diesel Particulate Filter) Tested on a Fleet of Peugeot 607 Taxis First and Second Test Phases Results,'' October 2002, SAE 2002-01-2790.

We are not aware of any nonroad equipment in-use operating cycles which would be more demanding of low temperature performance than passenger car 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. 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 NO_X standards with engine-out emission control technologies (i.e., engines rated between 25 and 75 horsepower).

High temperature operating-regimes such as a heavy heavy-duty diesel truck at full payload driving up a grade are also challenging for the NO_x catalyst technology. Although less common, similar high temperature conditions of full engine load operation can be imagined for nonroad equipment. However, because highway engines typically have higher power density (defined as rated power divided by engine displacement), the highest operating conditions would be expected to be encountered with highway vehicles. High exhaust temperatures (in excess of 500[deg]C) are challenging for the NO_x adsorber catalyst technology because the stored NOX emissions can be released thermally without going through a reduction step, leading to increased NO_x emissions. In the absence of a reductant (normally provided by the standard NO_x regeneration function) the thermally released NO_x is emitted from the exhaust system without treatment. To address this issue, NO_x storage catalyst technologies with higher levels of thermal stability are being developed, but these technologies trade-off improved high temperature performance for even greater sensitivity to fuel sulfur. Beyond catalyst improvements, the exhaust temperature from the engine can be controlled prior to the NO_x adsorber catalyst simply through heat loss in the exhaust system (i.e. by locating the catalyst further from the engine). Another approach being considered for GDI vehicle applications which operate at much higher temperatures than would be encountered by a diesel engine is to use a relatively simple exhaust layout design to increase heat loss at high temperatures while still providing acceptable low temperature

performance.\167\ Additionally, exhaust temperatures well in excess of 500[deg]C are not frequently experienced by nonroad engines. Higher exhaust temperatures would be expected from naturally aspirated engines due to their lower air flow (for the same power/heat input, naturally aspirated engines have less air to heat up and thus the exhaust reaches a higher temperature). Today, less than ten percent of nonroad diesel engines with rated power greater than 100 horsepower are naturally aspirated and we have projected that an even greater percentage of nonroad engines meeting the Tier 3 emission standards will be turbocharged.

\167\ Damson, B., "Exhaust Cooling for NO_x-Traps for Lean Spark-Ignition Engines,'' SAE 2002-01-0737.

We have conducted an analysis of various nonroad equipment operating cycles and various nonroad engine power density levels to better understand the matching of nonroad engine exhaust temperatures, catalyst installation locations and catalyst technologies. This analysis, documented in the draft RIA, showed that for many engine power density levels and equipment operating cycles, exhaust temperatures are quite well matched to catalyst temperature window characteristics. In particular, the nonroad transient cycle (NRTC), the cycle we are proposing to use for certification, was shown to be well matched to the NO_X adsorber characteristics with estimated performance in excess of 90 percent for a turbocharged diesel engine tested under a range of power density levels. The analysis also indicated that the exhaust temperatures experienced over the NRTC are better matched to the NO_X adsorber catalyst temperature window than the temperatures that would be expected over the highway FTP test cycle. This suggests that compliance with the proposed NRTC will be somewhat easier, using similar technology, than complying with the highway 2007 emission standards on the FTP.

For engines with low power density (e.g., <25 hp per liter of engine displacement) the analysis showed that, absent actions to increase exhaust temperatures (e.g., increased use of EGR a light loads), compliance with the NRTC cycle will be more difficult than for engines with higher power density levels. Specifically, the analysis predicted 92% control for the high power density engine and 86% control for the low power density engine.

Note that this analysis approach is only effective to predict differences in performance, but not effective to predict absolute performance. The same analysis approach predicted 83% control for the high power density engine on the heavy-duty FTP, although testing at EPA has shown for this engine (a different example of this same engine) greater than 90% NO_X control.\168\ Nevertheless, the analysis suggests that additional attention must be made to designing system for low power density applications, and that technology changes may be necessary to ensure adequate performance (e.g., the use of EGR or other control methods to raise exhaust temperatures). One change, which is occurring independent of EPA's regulation, is increasing power density for nonroad engines. EPA has documented in the draft RIA a clear trend of certified engine ratings that indicates manufacturers are increasing engine power without increasing engine displacement. Engine manufacturers are motivated to increase engine power density because engine pricing is largely done on a power basis, while the cost of manufacturing is more closely related to engine displacement. Therefore, increasing engine power levels without increasing displacement may increase the sale price of the engine more than it increases the cost of manufacturing. Increasing power density typically results in higher exhaust temperatures and, in this case, better matching to catalyst operating requirements. Alternatively, nonroad engine manufacturers can apply the same temperature management strategies previously described for highway engines.

\168\ Schenk, C., McDonald, J. and Olson, B. "High Efficiency NO_X and PM Exhaust Emission Control for Heavy-Duty On-Highway Diesel Engines,'' SAE 2001-01-1351.

The analysis also suggests that the temperature challenge for nonroad equipment will be greater with regard to the NTE provisions of this proposal than for the nonroad transient test (NRTC) provisions. In fact as discussed previously, the NRTC cycle appears to be a better match to the characteristics of the NO_X adsorber catalyst than the FTP cycle used for heavy-duty highway truck certification. This is due to the higher average engine load experienced over the NRTC and thus the higher average temperature. Therefore, we believe that complying with the NO_X standard over the transient test cycle proposed today for nonroad engines will not be significantly more difficult than complying with the HD2007 NO_X emission standard over the FTP. The analysis also shows that many nonroad engines may operate in-use in a way different from the NRTC (i.e. even the NRTC is not an all-encompassing test; no single test realistically could be), and that NTE standards are therefore needed to assure that nonroad engine emissions are controlled for the full range of possible in-use operating conditions.\169\ The technical challenge of controlling NO_X emissions, even under these diverse conditions, is no more difficult on a per engine basis than for highway diesel engines which must comply with similar NTE test provisions. This is because both highway and nonroad engine manufacturers must address control at the same high load and low load conditions (minimum power from both are the same, 0 hp, and maximum power is typically higher for highway engines, due to higher power density). Also, both engine manufacturers must be able to respond to changes in user demanded torque (transient conditions) that are similarly unpredictable. However, given the sheer number of different nonroad equipment types and engine ratings, this represents a real challenge for the nonroad industry which is one of the primary considerations given by the Agency in determining the appropriate timing for the emission standards proposed today.

\169\ The fact that developing compliant engines for the NTE provisions may be more difficult than developing for the transient test cycle does not diminish the value of the transient test as a means to evaluate the overall effectiveness of the emission control system under transient conditions. There is no doubt that controlling average emissions under transient conditions will be an important part of the emission control system and that evaluating overall performance under transient conditions is needed.

We believe, based on our analysis of nonroad engines and equipment operating characteristics, that in-use some nonroad engines will experience conditions that require the use of temperature management strategies in order to effectively use the NO_X adsorber and CDPF systems needed to meet the proposed standards. We have assumed in our cost analysis that all nonroad engines complying with a PM standard of 0.02 g/bhp-hr or lower will have an active means to control temperature (i.e. we have costed a backup regeneration system, although some applications likely may not need one). We have made this assumption believing that manufacturers will not be able to accurately predict 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

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baseline for Tier 4 engines, and the control strategies being developed for 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 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 the lead time provided in this proposal.

b. Nonroad Operating Conditions and Durability

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

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 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.\170\ The Deutz system utilized a conventional cordierite PM filter substrate as is commonly used for heavy-duty highway truck CDPF systems. The canning and mounting of the system was a Deutz design. Deutz- was able to design the catalyst housing and mounting in such a way as to protect the catalyst from the harsh environment as evidenced by its excellent record of reliable function.

\170\ "Summary of Conference Call between U.S. EPA and Deutz Corporation on September 19, 2002 regarding Deutz Diesel Particulate Filter System'', EPA Memorandum to Air Docket A-2001-28.

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 its range of construction machine models. As of January 2000, 340 Liebherr machines have been fitted with PM filter systems.\171\ 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 shrouding the aftertreatment equipment as well as the engineering cost for equipment redesign.

\171\ "Particulate Traps for Construction Machines: Properties and Field Experience'' J. Czerwinski et. al., Society of Automotive Engineers Technical Paper 2000-01-1923.

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[deg]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[deg]C).\172\ CDPF temperatures are not expected to exceed approximately 700(deg]C in normal use and are expected to only reach the 650[deg]C temperature during periods of active regeneration. Similarly, NO_x adsorber catalyst temperatures are not expected to exceed 700[deg]C and again only during periods of active sulfur regeneration as described in Section III.F below. Under conditions where diesel exhaust temperatures are naturally as high as 650[deg]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 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.\173\ 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.\174\

\172\ 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 exhaust-gases-leave-the-engine at - a very high temperature (800[deg]C at high power conditions) and then pass through the turbocharger where the gases expand driving the turbocharger providing work. The process of extracting work from the hot gases cools the exhaust gases. The exhaust leaving the turbocharger and entering the catalyst and the remaining pieces of the exhaust system is cooler (as much as 200[deg)C at very high loads) than in the exhaust manifold.

\173\ "Engine Technology and Application Aspects for Earthmoving Machines and Mobile Cranes, Dr. E. Brucker, Liebherr Machines Bulle, SA, AVL International Commercial Powertrain Conference, October 2001. Copy available in EPA Air Docket A-2001-28, Docket Item # II-A-12.

\174\ Phone conversation with Manufacturers of Emission Control Association (MECA), 9 April, 2003 confirming the use of emission control technologies on nonroad equipment used in coal mines, refineries, and other locations where explosion proofing may be required.

Nonroad engines greater than 750 hp are unique in that they do not have direct highway equivalents. However, this does not mean that unique catalyst based emission control technologies need to be developed separately for these larger applications. Rather, larger engines can, and do in retrofit applications today, use multiple catalyst systems in a parallel configuration. As an example, a highway 12 liter displacement in-line six cylinder engine might use a single 18 liter CDPF, while a nonroad 24 liter displacement V12 cylinder (a vee engine has two rows of cylinders set at an angle to each other) engine would use two 18 liter CDPFs, one for each bank of the vee engine. Using two smaller catalysts in place of one larger catalyst can be easier to package and may allow for close coupling of the catalyst technology to the turbocharger exhaust outlet to improve temperature management in some applications. Today, many passenger cars and light-duty trucks with V6 or V8 engines use individual catalysts for each engine bank to improve packaging and better manage temperatures.

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 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.

3. Are the Standards Proposed for Engines of 75 hp or Higher Feasible?

There are three primary test provisions and associated standards in the Tier 4 program we are proposing today. These are the proposed Nonroad Transient Cycle (NRTC), the existing ISO Cl steady-state cycle, and the proposed highway based Not-To-Exceed (NTE) provisions. A nonroad diesel engine meeting the proposed standards for each of these three test cycles would be lawful for use in any kind of nonroad equipment. Additionally, we have alternative optional test cycles including the proposed Constant Speed Variable Load (CSVL) cycle, the existing ISO-D2 steady-state cycle and the proposed Transportation Refrigeration Unit (TRU) cycle which a manufacturer can choose to use for certification provided that the manufacturer can demonstrate to the Agency that the engine will only be used in a limited range of nonroad equipment with specifically defined operating conditions. Compliance on the proposed transient test cycles includes weighting the results from a cold start and hot start test with the cold start emissions weighted at 1/10 and hot start emissions weighted at 9/10. A complete discussion of these various test cycles can be found in chapter 4.2 and 4.3 of the draft RIA.

The standards proposed today for nonroad engines with rated power greater than or equal to 75 horsepower are based upon the technologies and standards for highway diesel engines which go into effect in 2007. As explained above, we believe these technologies, namely NO_x adsorbers and catalyzed diesel particulate filters enabled by 15 ppm sulfur diesel fuel, can be applied to nonroad diesel engines in a similar manner as for highway diesel engines. We acknowledge that there are additional constraints on nonroad diesel engines which must be considered in setting these standards, and we have addressed those issues by allowing for additional lead time or, slightly less stringent standards for nonroad diesel engines in comparison to highway diesel engines (and likewise have made appropriate cost estimates to account for the technology and engineering needed to address these constraints).

We have proposed a PM standard for engines in this category of 0.01 g/bhp-hr based upon the emissions reductions possible through the application of a CDPF and 15 ppm sulfur diesel fuel. This is the same emissions level as for highway diesel engines in the HD2007 program. While baseline soot (the solid carbon fraction of PM) emission levels may be somewhat higher for some nonroad engines when compared to highway engines, these emissions are virtually eliminated (reduced by 99 percent) by the CDPF technology. As discussed previously, the baseline (engine-out) SOF emissions levels may also need to be reduced through the application of modern piston ring pack designs and valve stem seals. With application of the CDPF technology, the SOF portion of diesel PM is predicted to be all but eliminated. The primary emissions from a CDPF equipped engine, are sulfate PM emissions formed from sulfur in diesel fuel. The emissions rate for sulfate PM is determined primarily by the sulfur level of the diesel fuel and the rate of fuel consumption.. With the 15 ppm sulfur diesel fuel the PM emissions level from a CDPF equipped nonroad diesel engine will be'similar to the emissions rate of a comparable highway diesel engine. Therefore, the 0.01 g/bhp-hr emission level is feasible for nonroad engines tested on the NRTC cycle and on the steady-state cycles, C1 and D2. Put another way, control of PM using CDPF technology is essentially independent of duty cycle given active catalyst technology (for reliable regeneration and SOF oxidation), adequate control of temperature (for reliable regeneration) and low sulfur diesel fuel (for reliable regeneration and low PM emissions).

The most challenging PM emissions control conditions for a CDPF are encountered under high engine load operation where high exhaust temperatures promote conversion of sulfur in diesel fuel to sulfate PM emissions. Under these high load conditions, soot and SOF oxidation rates will be very high and control of those portions of PM emissions will be highly effective. Sulfate PM emissions, however, will be higher than for other operating conditions. In a worst case scenario, where all of the sulfur is

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converted to sulfate, it could be perhaps as high as 0.02 g/bhp-hr.\175\ This level of PM emissions would comply with our proposed NTE provisions once consideration is given to the 1.5 times multiplier on the emission standard for NTE test conditions.\176\ Since this estimate is made at a worst case condition (assuming 100% conversion of sulfur to sulfate), we feel confident that the PM NTE provisions of this proposal can be met.

\175\ An estimate of the maximum sulfate PM emissions rate can be made by assuming a fuel consumption rate (e.g., 0.5 lbm/bhp-hr), the fuel sulfur level (e.g., 15 ppm) and the sulfur to sulfate conversion (e.g., 100% maximum) resulting in a calculated sulfate PM emissions rate of 0.02 g/bhp-hr. This represents a worst case analysis (100% sulfur conversion with 15 ppm sulfur fuel). In-use emissions would be significantly lower.

\176\ The PM standard is expressed to two significant digits 0.01 g/bhp-hr, so when the 1.5 NTE multiplier is applied, the NTE limit becomes 0.015 which is rounded to two significant figures as 0.02 g/bhp-hr.

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.\177\ The first engine is 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 III.E-1 below. The steady-state emission results are summarized in Table 111.1-2. 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 the 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 Cl 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 proposed PM emission standard for <=75 hp variable speed nonroad engines.

~~\177\ Application of Diesel Particulate Filters to Three Nonroad Engines--Interim Report, January 2003. Copy available in EPA Air~~

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\177\ Application of Diesel Particulate Filters to Three Nonroad Engines--Interim Report, January 2003. Copy available in EPA Air Docket A-2001-28.

When tested on the proposed optional constant speed variable load cycle (CSVL) (a test to which this engine would not be subject to 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.

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Table III.E-1 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 the draft RIA for information on these test cycles). These test cycles are not used for regulatory purposes, although the information from these cycles was used in developing the proposed NRTC. 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

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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 also 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 III.E-l shows PM emissions of 0.031 over the AW2 cycle but from a very high baseline level of nearly 0.6 g/bhp-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 standard. There are two other test points in Table III.E-2 which are above the proposed NTE emission level, both at 10 percent engine load. However, both are outside the NTE zone which excludes emissions for engine loads below 30 percent. It is important to note that although the engine would not be constrained to meet the NTE under these conditions, the resulting reductions at both points are still substantial in excess of 96 percent.

Table III.E-2--Steady-State PM Emissions from a Tier 1 NR Diesel Engine w/CDPF

1999 (Tier 1) Caterpillar 3408 ('480hp, 181)

Engine speed %	Engine load %	PM [g/bhp-hr] Engine out	PM [g/bhp-hr] w/CDPF	Reduction %
100	100	0.059	0.10	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			
	(\1\)	0.127	0.011	91

ISO C1 Composite.

The second engine tested was a prototype engine developed at Southwest Research Institute (SwRI) under contract to EPA.\178\ 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 III.E-3 and the steady-state results summarized in Table III.E-4 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 was applied.\179\ It is also interesting to note that the 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 highway engines. Our analysis of exhaust temperature characteristics for NO_x adsorber catalysts discussed in the preceding section, noted a similar trend for NO_x technologies (i.e., that the exhaust temperature characteristics of the NRTC may be better matched catalyst technologies than the HD FTP).

\178\ "Nonroad Diesel Emission Standards--Staff Technical Paper'', EPA Publication EPA420-R-01-052, October 2001. Copy available in EPA Air Docket A-2001-28.

\179\ 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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As with the results from the Caterpillar engine, the two low-load (10 percent load) steady-state emissions points 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.
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While the resulting PM emission levels for nonroad diesel engines are similar to the levels for highway diesel engines, the challenge of ensuring soot regeneration of the CDPF may be more difficult for some nonroad equipment types. As explained earlier, effective regeneration occurs when the aggregate soot rate into the CDPF over an extended period is less than or equal to the soot oxidation rate over the same period. Because the baseline PM soot rate into the CDPF level may be higher for some nonroad engines and because the average exhaust temperature may be lower for some operating cycles, additional engine and aftertreatment system development will be needed for some nonroad engines. These additional developments include improved thermal management and improved active back-up systems which can periodically raise exhaust temperatures in order to initiate regeneration. We expect these systems to be evolutionary advancements based primarily on the core technologies used by nonroad manufacturers to comply with the Tier 3 emission standards with enhancements from the highway technologies developed to comply with the HD2007 standards. The implementation dates for the standards proposed today were selected in part based upon the time we believe will be necessary to transfer and further develop these highway technologies to nonroad diesel engines and equipment.