

**Draft Regulatory Impact Analysis:
Control of Emissions of Air Pollution from
Locomotive Engines and
Marine Compression-Ignition Engines
Less than 30 Liters per Cylinder**

**Chapter 4
Locomotive and Marine Technological
Feasibility**

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LOCOMOTIVE AND MARINE TECHNOLOGICAL FEASIBILITY

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CHAPTER 4: Locomotive and Marine Technological Feasibility

In this chapter we describe in detail the emissions control technologies we believe may be used to meet the standards we are proposing. Because of the range of engines and applications we cover in this proposal, our proposed standards span a range of emissions levels. Correspondingly, we have identified a number of different emissions control technologies we expect may be used to meet the proposed standards. These technologies range from incremental improvements to existing engine components to highly advanced catalytic exhaust treatment systems.

In this chapter we first summarize our current locomotive and marine diesel engine standards and provide an overview of existing and future emissions control technologies. We believe that further improvements in existing technologies may be used to meet the standards we are proposing for existing engines that are remanufactured as new (i.e., Tier 0, Tier 1, Tier 2). We then describe how technologies similar to some of those already being implemented to meet our current and upcoming heavy-duty highway and nonroad diesel engine emissions standards may be applied to meet our proposed interim standards for new engines (i.e., Tier 3). We conclude this section with a discussion of catalytic exhaust treatment technologies that we believe may be used to meet our proposed Tier 4 standards.

All of our analyses in this chapter include how we expect these technologies to perform throughout their useful life as well as how we believe they would be implemented specifically into locomotive and marine applications. Note that much of this chapter's content is based upon the performance of currently available emissions control technologies and results from testing that has already been completed. In most cases the already-published results show that currently available emissions control technologies can be implemented without further improvements to meet the standards we are proposing. In a few cases, we are projecting that further improvements to these technologies will be made between now and the Tier 4 standards implementation dates. These projected improvements will enable engine manufacturers to meet the standards we are proposing.

4.1 Overview of Emissions Standards and Emissions Control Technologies

Our current locomotive and marine diesel engine standards have already decreased NO_x emissions from unregulated levels. For example, since 1997, NO_x emissions standards for diesel locomotive engines have been reduced from an unregulated level of about 13.5 g/bhp-hr to the current Tier 2 level of 5.5 g/bhp-hr – a 60% reduction when evaluated over the locomotive line-haul duty cycle. Similar NO_x reductions have been realized for Category 1 & 2 (C1 & C2) commercial marine diesel engines. Our Tier 1 marine standards are equivalent to the International

Maritime Organization's NO_x regulation known as MARPOL Annex VI. Beginning in 2004, these standards became mandatory for C1 & C2 Commercial vessels, and were voluntary in prior years. Beginning in 2007, EPA Tier 2 standards for C1 & C2 Commercial vessels will supersede these MARPOL-equivalent standards. For a high-speed marine diesel engine, NO_x will be reduced from a Tier 1 level of 9.8 g/kW-hr to 7.5 g/kW-hr - a 23% reduction. While these reductions in locomotive and marine NO_x emissions are significant, they do not keep pace with the 90% NO_x reduction (from 2.0 g/bhp-hr to 0.2 g/bhp-hr) set forth in the 2007 Heavy-Duty Highway Rule.¹ Neither do these reductions keep pace with the approximately 85% NO_x reductions set forth in the Nonroad Tier 4 Standards for 56 kW to 560 kW engines and for generator sets above 560 kW^{2,3}. In a similar manner, locomotive and marine particulate matter (PM) emission reductions also lag behind the Heavy-Duty Highway and Nonroad Tier 4 Rules. For line-haul and switcher locomotives, a 67% reduction in PM already has been achieved in going from the Tier 0 to the Tier 2 standards. On the marine side, PM emissions for C1 & C2 Commercial have been reduced from an unregulated level prior to May 2005, to a 0.2-0.4 g/kW-hr level for Tier 2.

^A In contrast, the 2007 Heavy-Duty Highway Rule set forth PM reductions of 90% - from 0.1 g/bhp-hr to 0.01 g/bhp-hr. Similarly post-2014 Nonroad Tier 4 PM emissions will be reduced 85 to 95% compared to Tier 3 Nonroad PM emissions for 56 kW to 560 kW engines and for generator sets above 560 kW.^{2,3} In the timeframe of the Tier 3 and 4 Locomotive Standards that we are proposing, NO_x and PM emissions will continue to be a serious threat to public health, and, on a percentage basis, the locomotive and marine contributions to the nationwide inventory of these pollutants would continue to increase relative to today's levels if current Tier 2 emission levels were maintained. Please refer to Chapter 3 of the Regulatory Impact Analysis for a more detailed discussion of the contribution of locomotive and marine emissions to the NO_x and PM inventory.

To date, the Tier 0 through Tier 2 locomotive and Tier 1 through Tier 2 marine emissions reductions have been achieved largely through engine calibration optimization and engine hardware design changes (e.g. improved fuel injectors, increased injection pressure, intake air after-cooling, combustion chamber design, injection timing, reduced oil consumption, etc.). To achieve the Tier 3 PM emission standards we are proposing, further reductions in lubricating oil consumption will be required. This will most likely be achieved via improvements to piston, piston ring, and cylinder liner design, as well as improvements to the crankcase ventilation system. To further reduce NO_x and PM emission beyond Tier 3 levels, an exhaust aftertreatment approach will be necessary.

^A Tier 2 PM emission standards are dependent on an engine's volumetric displacement-per-cylinder.

Selective catalytic reduction (SCR) is a commonly-used aftertreatment device for meeting more stringent NO_x emissions standards in worldwide diesel applications. Stationary, coal-fired power plants have used SCR for three decades as a means of controlling NO_x emissions, and currently, European heavy-duty truck manufacturers are using this technology to meet the Euro IV and Euro V limits. To a lesser extent, SCR has been introduced on diesels in the U.S. market, but the applications have been limited to marine ferryboat and stationary power generation demonstration projects in California and several northeast states. However, by 2010, when 100% of the heavy-duty diesel trucks are required to meet the NO_x limits of the 2007 heavy-duty Highway Rule, several heavy-duty truck engine manufacturers have indicated that they will use SCR technology to meet these standards.^{4,5} While other promising NO_x-reducing technologies such as lean NO_x catalysts, NO_x adsorbers, and advanced combustion control continue to be developed - and may be viable approaches to the standards we are proposing today - our analysis projects that SCR will be the technology chosen by the locomotive and marine diesel industries to meet the Tier 4 NO_x standards we are proposing. For a complete review of these other alternative NO_x emissions control technologies refer to the Regulatory Impact Analysis from our Clean Air Nonroad diesel rule.⁶

The most effective exhaust aftertreatment used for diesel PM emissions control is the diesel particulate filter (DPF). More than a million light diesel vehicles that are OEM-equipped with DPF systems have been sold in Europe, and over 200,000 DPF retrofits to diesel engines have been conducted worldwide.⁷ Broad application of catalyzed diesel particulate filter (CDPF) systems with greater than 90% PM control is beginning with the introduction of 2007 model year heavy-duty diesel trucks in the United States. These systems use a combination of both passive and active soot regeneration. Our analysis projects that CDPF systems with a combination of passive and active backup regeneration will be the primary technology chosen by the locomotive and marine diesel industries to meet the Tier 4 PM standards we are proposing.

4.2 Emissions Control Technologies for Remanufactured Engine Standards and for Tier 3 New Engine Interim Standards

To meet our proposed locomotive remanufactured engine standards, our potential marine remanufactured engine standards, and our proposed Tier 3 locomotive and marine standards, we believe engine manufacturers will utilize incremental improvements to existing engine components to reduce engine-out emissions. This will be accomplished primarily via application of technology originally developed to meet our current and upcoming standards for heavy-duty on-highway trucks and nonroad diesel equipment. This is especially true for many of the Category 1 and Category 2 marine engines, which are based on nonroad engine designs. This will allow introduction of technology originally developed to meet nonroad Tier 3 and Tier 4 standards to be used to meet the Tier 3 marine standards. Table 4-1, Table 4-2 and Table 4-3 provide summaries of the technologies that we believe may be used meet the remanufactured engine and Tier 3 new engine interim

standards for switch locomotives, line-haul locomotives and marine engines, respectively.

Table 4-1: Technologies for switch locomotive standards through Tier 3

Year	Standard	NO_x (g/bhp-hr)	PM (g/bhp-hr)	Technology added to engine
2010	T0- Remanufactured	11.8	0.26	New power assemblies to improve oil consumption, improved mechanical unit injectors
2010	T1- Remanufactured	11.0	0.26	New power assemblies to improve oil consumption, electronic unit injection, new unit injector cam profile
2013	T2- Remanufactured	8.1	0.13	For high-speed engines: Same as Tier 3 nonroad engines For medium-speed engines: Further improvements to power assembly and closed crankcase ventilation system to reduce oil consumption, new turbocharger, new engine calibration, new unit injector cam profile
2011	T3	5.0	0.10	For high-speed engines: Same as Tier 3 nonroad engines For medium-speed engines: Further improvements to power assembly and CCV to reduce oil consumption, high pressure common rail injection with post-injection PM clean-up, injection timing retard, new turbocharger

Table 4-2: Technologies for Line Haul Locomotive Standards up to Tier 3

Year	Standard	NO_x (g/bhp-hr)	PM (g/bhp-hr)	Technology added to engine
2010 (2008 if available)	T0- Remanufactured	7.4	0.22	New power assemblies to improve oil consumption, improved mechanical unit injectors or switch to electronic unit injection, new turbocharger
2010 (2008 if available)	T1- Remanufactured	7.4	0.22	New power assemblies to improve oil consumption, electronic unit injection, new unit injector cam profile, new turbocharger
2013	T2- Remanufactured	5.5	0.10	Further improvements to power assembly and CCV to reduce oil consumption, electronic unit injection or high pressure common rail injection
2012	T3	5.5	0.10	Further improvements to power assembly to reduce oil consumption, electronic unit injection or high pressure common rail injection

Table 4-3: Technologies for Marine Category 1 and Category 2 to meet Tier 3 Standards

Year	Standard	HC+NO _x (g/bhp-hr)	PM (g/bhp-hr)	Technology added to engine
2009-2014	Category 1 Tier 3 Marine (< 75 kW)	3.5 – 5.6	0.22 – 0.33	Same engine-out NO _x technologies as Tier 4 nonroad—with no Tier 4 PM aftertreatment technologies
2012-2018	Category 1 Tier 3 Marine (75-3700 kW)	4.0 – 4.3	0.07 – 0.11	Recalibration on nonroad Tier 4 engines without aftertreatment
2013	Category 2 Tier 3 Marine 7 – 15 liters/cyl.	5.5	0.10	Same engine-out NO _x technologies as pre-2014, non-generator-set, Tier 4 nonroad—with no Tier 4 PM aftertreatment technologies
2012	Category 2 Tier 3 Marine 15 – 30 liters/cyl.	6.5 – 8.2	0.20	Further improvements to power assembly to reduce oil consumption, electronic unit injection or high pressure common rail injection, new turbocharger

In section 4.2.1.1 we will describe some of the fundamentals of diesel combustion and pollutant formation. In section 4.2.2 we describe the manner in which engine-out emissions can be controlled in order to meet the proposed locomotive remanufactured engine standards, potential marine remanufactured engine standards and the Tier 3 locomotive and marine standards.

4.2.1 Diesel Combustion and Pollutant Formation

In this section we describe the mechanisms of pollutant formation. In order to lay the foundation for this discussion, we begin with a review of diesel combustion, especially as it is related to 2-stroke cycle and 4-stroke cycle diesel engine operation. We describe both of these types of diesel engine operation because both 2-stroke and 4-stroke engines are used in locomotive and marine applications. We then describe NO_x, PM, HC, and CO formation mechanisms.

4.2.1.1 Diesel Combustion

Category 1 marine diesel engines operate on a four-stroke cycle. The larger displacement Category 2 marine diesel engines and locomotive diesel engines operate on either a two-stroke cycle or a four-stroke cycle. The four-stroke cycle consists of an intake stroke, a compression stroke, an expansion (also called the power or combustion) stroke, and an exhaust stroke. The two-stroke cycle combines the intake and exhaust functions by using forced cylinder scavenging. Figure 4-1 provides an

overview and brief comparison of the two-stroke and four-stroke cycles used by marine and locomotive diesel engines.

The diesel combustion event provides the energy for piston work. An example of the relationship between the different phases of diesel combustion and the net energy released from the fuel is shown in Figure 4.2. Combustion starts near the end of compression and continues through a portion of the expansion stroke. Near the end of the piston compression stroke, fuel is injected into the cylinder at high pressure and mixes with the contents of the cylinder (air + any residual combustion gases). This period of premixing is referred to as ignition delay. Ignition delay ends when the premixed cylinder contents self-ignite due to the high temperature and pressure produced by the compression stroke in a relatively short, homogenous, premixed combustion event. Immediately following premixed combustion, diesel combustion becomes primarily non-homogeneous and diffusion-controlled. The rate of combustion is limited by the rate of fuel and oxygen mixing. During this phase of combustion, fuel injection continues creating a region that consists of fuel only. The fuel diffuses out of this region and air is entrained into this region creating an area where the fuel to air ratio is balanced (i.e., near stoichiometric conditions) to support combustion. The fuel burns primarily in this region. One way to visualize this is to roughly divide the cylinder contents into fuel-rich and fuel-lean sides of the reaction-zone where combustion is taking place as shown in Figure 4-3. As discussed in the following subsections, the pollutant rate of formation in a diesel engine is largely defined by these combustion regions and how they evolve during the combustion process.⁸

Figure 4-1: A comparison of 2 complete revolutions of the four-stroke (top) and two-stroke diesel combustion cycles. Note that the two-stroke cycle relies on intake air-flow to scavenge the exhaust products from the cylinder. In the case of uniflow scavenged two-stroke diesel engines, cylinder scavenging is assisted by the use of a centrifugal or positive displacement blower to pressurize the intake ports located on the sides of the cylinder. Exhaust exits the cylinder through cam-actuated poppet valves in the cylinder head. Four-stroke diesel engines are the predominant type of Category 1 marine engine. Both four-stroke and uniflow-scavenged two-stroke diesel engines are used for Category 2 marine and locomotive applications.

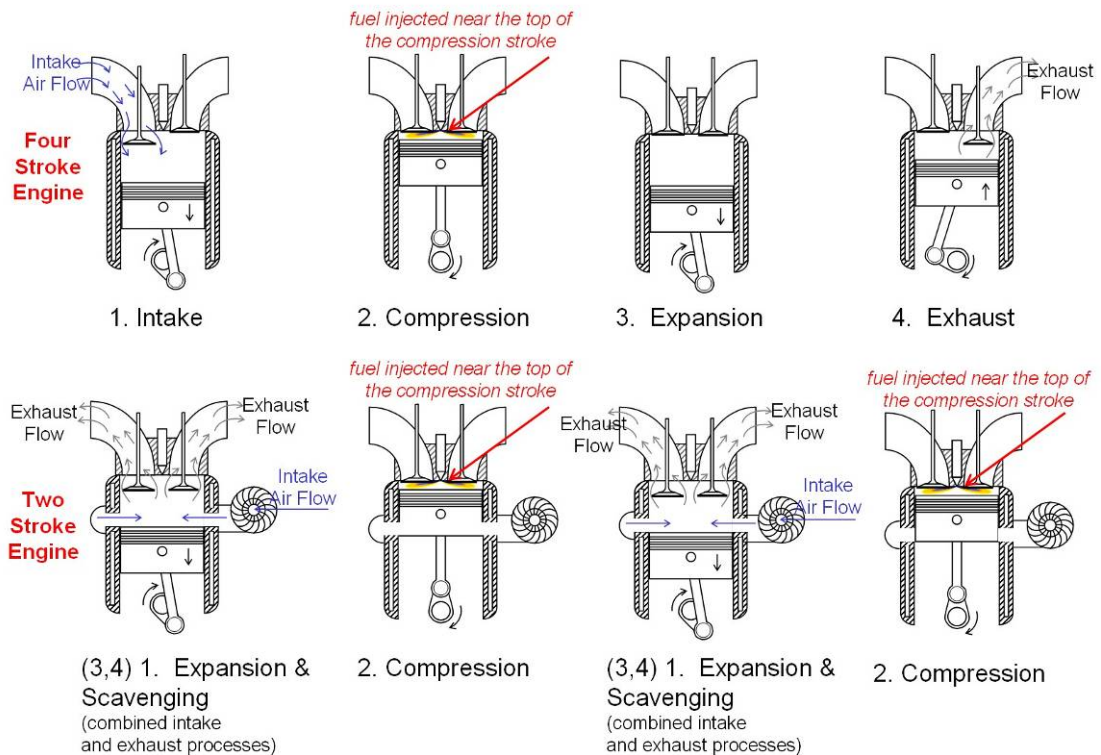


Figure 4-2: An idealized example of the net apparent rate of combustion heat release (derived from high-speed cylinder pressure measurements) for a direct injection diesel engine with indication of the major events and phases of combustion.

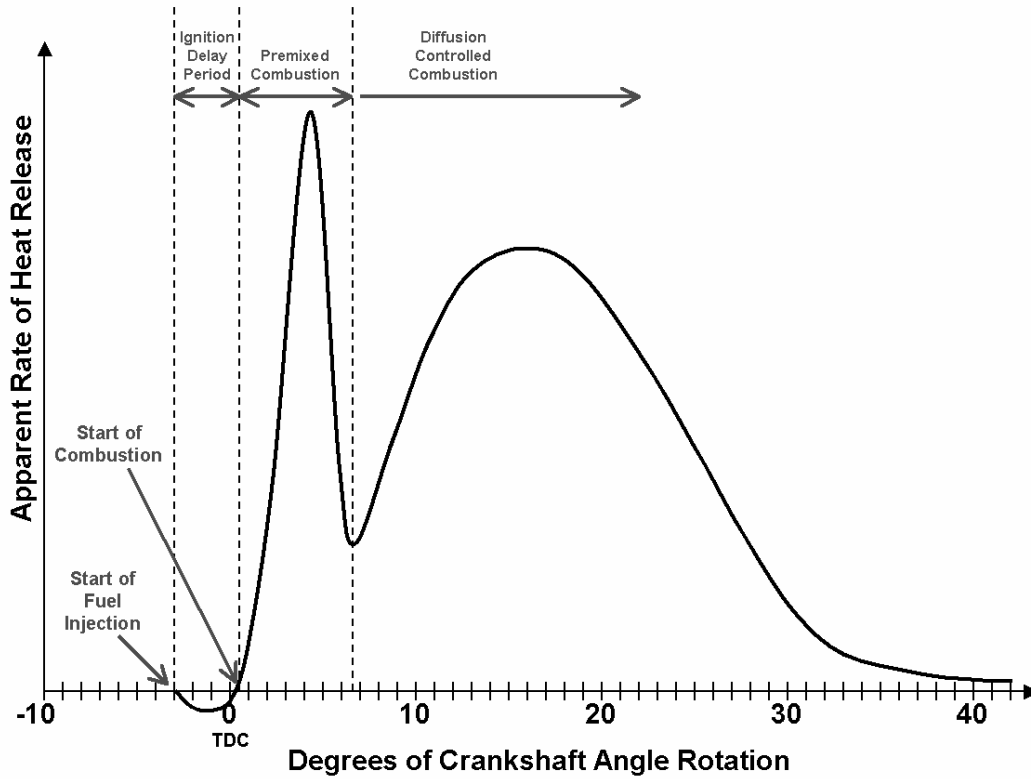
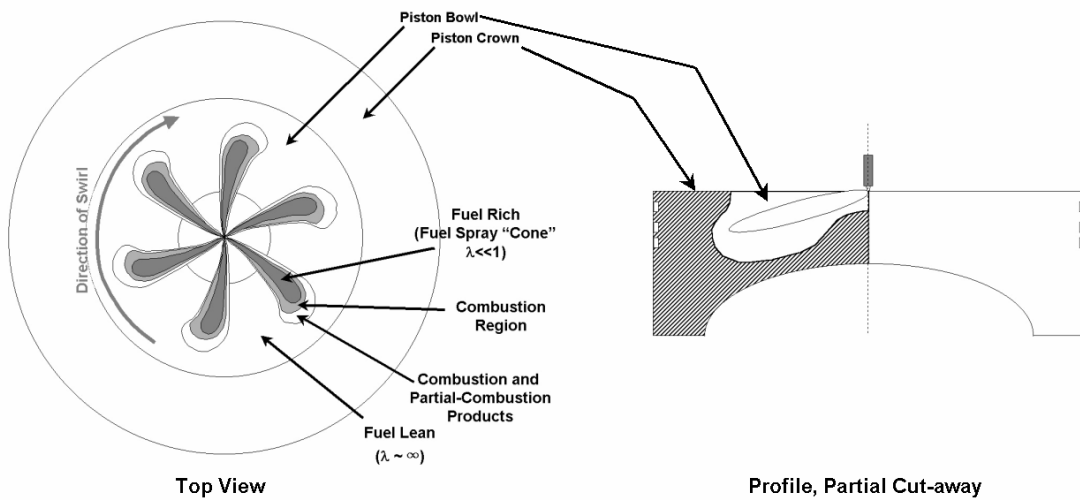


Figure 4-3: An idealized physical schematic of the diesel combustion process.



4.2.1.2 NO_x Emissions

Nitrogen oxides (NO_x) are formed in diesel engines by the oxidation of molecular nitrogen (N₂) in the stoichiometric combustion regions of the diffusion-controlled and premixed diesel combustion phases, described in the previous section. During the premixed phase of combustion, ignition and flame propagation occurs at high temperatures and at near stoichiometric mixtures of fuel and air. During diffusion-controlled combustion, the reaction zone is also near stoichiometric conditions. At the high temperatures present during premixed combustion or in the diffusion-controlled combustion reaction zone, a fraction of the nitrogen and oxygen can dissociate, forming radicals which then combine through a series of reactions to form nitric oxide (NO), the primary NO_x constituent. Nitrogen dioxide (NO₂), the other major NO_x constituent, is formed from oxidation of NO in the flame region. NO₂ formed during combustion rapidly decomposes to NO and molecular oxygen unless the reaction is quenched by mixing with cooler cylinder contents. Engine-out emissions of NO are typically 80% or more of total NO_x from direct injection diesel engines. The NO_x formation rate has a strong exponential relationship to temperature. Therefore, high temperatures result in high NO_x formation rates.^{8,9} Any changes to engine design that can lower the peak temperature realized during combustion, the partial pressures of dissociated nitrogen and oxygen, or the duration of time at these peak temperatures can lower NO_x emissions. Most of the engine-out NO_x emission control technologies discussed in the following sections reduce NO_x emissions by reducing the peak combustion temperatures while balancing impacts on PM emissions, fuel consumption and torque output.

4.2.1.3 PM Emissions

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

During diffusion-controlled combustion, fuel diffuses into a reaction zone and burns. Products of combustion and partial products of combustion diffuse away from the reaction zone where combustion occurs. At temperatures above 1300 K, fuel compounds on the fuel-rich side of the reaction zone can be pyrolyzed to form elemental carbon particles¹⁰. Most of the elemental carbon formed by fuel pyrolysis (80% to 98%) is oxidized during later stages of combustion.^{11,12} The remaining elemental carbon agglomerates into complex chain-aggregate soot particles and leaves the engine as a component of PM emissions.

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

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

Thus, in-cylinder control of elemental carbon PM is accomplished by varying engine parameters that affect these variables while balancing the resultant effects on NO_x emissions and torque output.

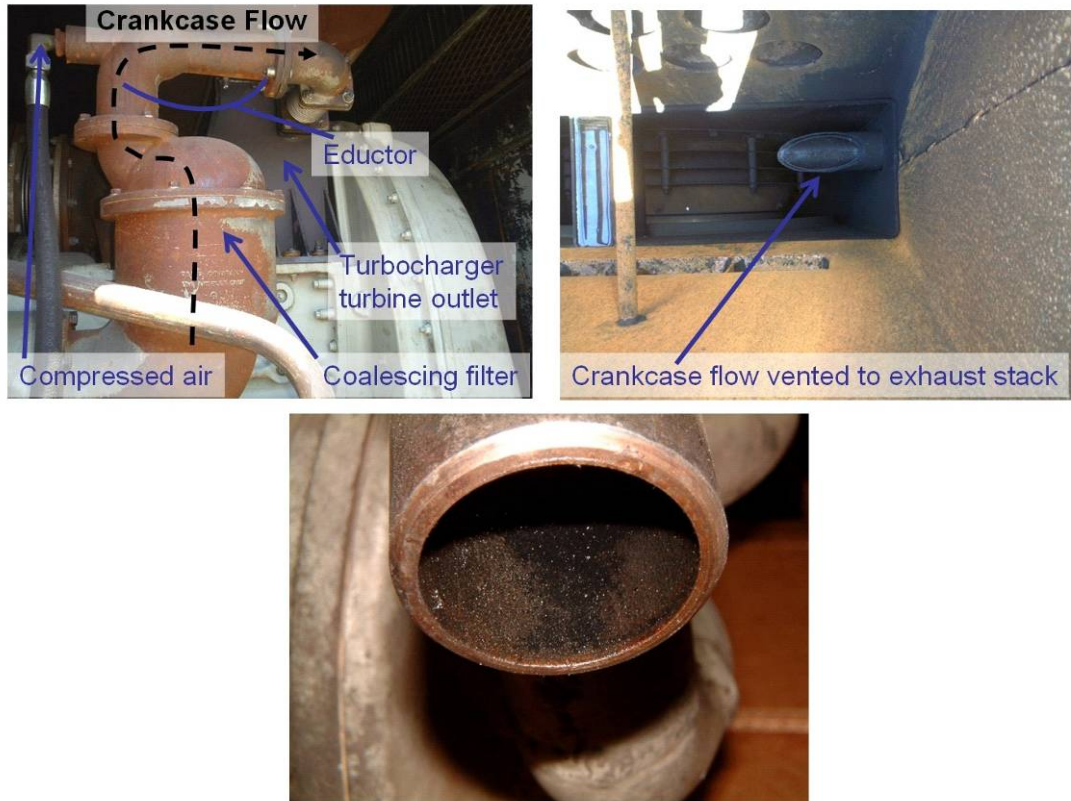
The combinations of organic compounds (volatile and semi-volatile) that contribute to PM are referred to as the volatile organic fraction (VOF), the soluble organic fraction (SOF), or as organic carbon PM, depending upon the analytical procedure used to measure the compounds. Organic carbon PM primarily consists of lubricating oil and partial combustion products of lubricating oil. Some of the higher molecular weight fuel compounds from unburned or partially burned diesel fuel also contribute to organic carbon PM. Oil can be entrained into the cylinder contents from cylinder liner surfaces as they are uncovered by the piston and by leakage into the cylinder past the valve stems. Uniflow-scavenged two-stroke diesel engines typically have somewhat higher oil consumption and organic carbon PM emissions in part due to the lubricating oil entrained into the scavenging flow from around the intake ports in the cylinder wall. Compliance with the closed crankcase ventilation provisions in the Tier 0 and later locomotive and Tier 2 marine standards has typically been accomplished by using coarse filtration to separate a fraction of the oil aerosol from the crankcase flow and then entraining the crankcase flow directly into the exhaust downstream of the turbocharger exhaust turbine (Figure 4-4). Incomplete separation of the oil aerosol from the crankcase flow can increase the amount of lubricating oil directly entrained into the exhaust with subsequent formation of organic carbon PM.

Both organic carbon and sulfate PM are formed after cooling and air-dilution of the exhaust. Sulfur dioxide (SO₂) is formed via combustion of sulfur compounds from the fuel and lubricating oil burned during combustion. In the absence of post-combustion catalytic treatment of the exhaust, approximately 1 to 3 % of fuel sulfur is oxidized to ionic sulfate (SO₃⁻) and upon further cooling is present primarily as a hydrated sulfuric acid aerosol. For example, sulfate PM currently accounts for approximately 0.03 to 0.04 g/bhp-hr over the line-haul cycle for locomotive engines using 3000 ppm sulfur nonroad diesel fuel.

Diesel oxidation catalysts (DOC) and catalyzed diesel particulate filters (CDPF) using platinum catalysts can oxidize the organic compounds thereby lowering PM emissions but they can also oxidize 50% or more of the SO₂ emissions to sulfate PM, depending on the exhaust temperature and the platinum content of the catalyst formulation that is used.

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Figure 4-4: Crankcase ventilation system for a medium speed locomotive diesel engine. An eductor uses compressed air to draw crankcase gases through a coarse coalescing filter (top left photo). The outlet of the crankcase ventilation system can be clearly seen from the outlet of the locomotive's exhaust stack (top right photo). The bottom photo shows tubing from a crankcase ventilation system removed from downstream of a similar coarse coalescing filter. There was considerable wetting of the inner wall of the tubing with lubricating oil.



4.2.1.4 HC Emissions

Hydrocarbon (HC) emissions from diesel engines are generally much lower compared to other mobile sources due to engine operation that, on a bulk-cylinder-content basis, is significantly fuel-lean of the stoichiometric air-to-fuel ratio. HC emissions primarily occur due to fuel and lubricant trapped in crevices (e.g., at the top ring land and the injector sac) which prevents sufficient mixing with air for complete combustion. Fuel related HC can also be emitted due to "over mixing" during ignition delay, a condition where fuel in the induced swirl flow has mixed beyond the lean flammability limit. Higher molecular weight HC compounds adsorb to soot particles or nucleate and thus contribute to the organic carbon PM. Lower molecular weight HC compounds are primarily emitted in the gas phase. During engine start-up under cold ambient conditions or following prolonged engine idling, fuel-related HC can be emitted as a concentrated, condensed aerosol ("white smoke").

4.2.1.5 CO Emissions

Carbon monoxide emissions (CO) from diesel engines are generally low compared to other mobile sources due to engine operation that, on a bulk-cylinder-content basis, is significantly fuel-lean of the stoichiometric air-to-fuel ratio. Catalytic emission controls that effectively oxidize PM constituents and HC emissions are also effective for oxidation of CO, reducing CO emissions to even lower levels.

4.2.2 Engine-out Emissions Control

Control of diesel emissions via modification of combustion processes is often characterized by trade-offs in NO_x emissions control vs. other parameters such as PM emissions, fuel consumption, and lubricating oil soot loading. For example lower oxygen content (lowering the air-to-fuel ratio) lowers NO_x formation but increases PM formation. Advanced (earlier) injection timing reduces PM emissions but increases NO_x formation. Retarded (later) injection timing reduces NO_x formation but increases PM formation, increases fuel consumption, and at high torque output levels can increase soot accumulation within the lubricating oil. During engine development, these trade-offs are balanced against each other in order to obtain effective NO_x and PM control while maintaining acceptable power output, fuel efficiency and engine durability. The introduction of more-advanced fuel injection systems and improved turbocharging can improve these tradeoffs, allowing for reduced emissions of both NO_x and PM.

4.2.2.1 Ultra Low Sulfur Diesel Fuel

We estimate that the use of ultra low sulfur diesel fuel (<15 ppm S) will reduce sulfate PM emissions from locomotive and marine engines by approximately 0.03 to 0.04 g/bhp-hr, as compared to PM emissions when ~3000 ppm S fuel is used. The use of ultra low sulfur fuel also reduces depletion of TBN in the oil and substantially reduces condensation of acidic aerosols within cooled exhaust gas recirculation systems (see section 4.2.2.5). In addition to the direct sulfate PM emissions reductions realized through the use of ULSD, ULSD is also necessary to enable the use of advanced aftertreatment technologies, as discussed later in this chapter. While we describe the emission reductions due to the use of lower sulfur diesel fuel here, we should be clear that these reductions are part of our baseline emissions inventory because this rule does not change the fuel sulfur standard.

4.2.2.2 Turbocharger Improvements

The majority of Category 1 and 2 marine diesel engines and Tier 0 and later locomotive diesel engines are equipped with turbocharging and aftercooling. Tier 0 and later two-stroke locomotive engines (and some Tier 1 and later marine engines) are equipped with a hybrid mechanical centrifugal supercharger/exhaust turbocharger system. This system is gear driven up to approximately the notch 6 operating mode and is exhaust driven at higher operating modes or higher numbered notches (e.g.,

notches 7 and 8). This arrangement helps to provide sufficient scavenging boost at lower notch settings where there is insufficient exhaust energy for the exhaust turbine to drive the compressor. Significant improvements have been made in recent years in matching turbocharger turbine and compressor performance to the highway, nonroad, marine, and locomotive diesel engines. Improvements to turbochargers and the match of the turbocharger's design to the engine reduce the incidence of insufficient oxygen during transients and help maintain sufficient air flow to the engine during high load operation. The corresponding improvements in oxygen availability throughout the operational range of the engine reduce the formation of elemental carbon PM. We expect that new Tier 0 and Tier 1 (remanufactured) locomotive engines will include improvements to turbocharger design that are similar to those of current Tier 2 locomotive designs. We also expect that engine manufacturers will continue with incremental improvements in turbochargers and the match of the turbocharger's design to Tier 3 locomotive and marine engines.

4.2.2.3 Charge Air Cooling

Improvements in engine-out NO_x emissions to meet our proposed locomotive remanufactured engine standards and the Tier 3 locomotive and marine standards will be accomplished in part via lowering charge air cooling temperature. This was one of the primary methods of used by locomotive engine manufacturers to reduce NO_x emissions to meet the Tier 1 and Tier 2 locomotive standards and the Tier 3 nonroad diesel standards. Lowering the intake manifold temperature lowers the peak temperature of combustion and thus NO_x emissions. The NO_x reduction realized from lowering the intake manifold temperature can vary depending upon the engine design but one estimate suggests NO_x emissions can be reduced by five to seven percent with every 10 °C decrease in intake manifold temperature.¹³ Typically the intake manifold temperature is lowered by cooling the intake gases through a heat exchanger, also known as a charge air cooler or aftercooler, located between the turbocharger compressor outlet and the intake manifold. Locomotive applications typically use air-to-air aftercoolers. Locomotive aftercoolers use electrically powered auxiliary fans since oftentimes conditions at high torque output require significant intake air heat rejection, especially at speeds too low for effective passive air-flow. Operation of the locomotive in multi-engine train configurations or "consist" can also impede air-flow to heat exchangers. Increased cooling capacity in locomotive applications can be accomplished via increased air-flow through the air-to-air after cooler, often through use of either variable speed or multiple-staged electric fans. Marine applications with access to sea-water heat-exchanger coolant loops typically have excess heat rejection capacity with respect to charge air cooling. This cooling capacity can be limited within certain existing hull designs, but new hull designs can typically overcome these existing hull limitations.

4.2.2.4 Injection Timing

Electronic control of injection timing has been used by locomotive and marine engine manufacturers to balance NO_x emissions, PM emissions, fuel efficiency, engine performance and engine durability for engines certified to the Tier 2

locomotive and marine engine standards, Tier 3 nonroad standards, and the 1998 and later heavy-duty highway standards. We expect similar systems to be used to comply with our proposed remanufactured engine standards and will continue to be used to comply with our proposed Tier 3 locomotive and marine standards.

Delaying the start of fuel injection and thus the start of combustion can significantly reduce NO_x emissions from a diesel engine. The effect of injection timing on emissions and performance is well established.^{14,15,16,17} Delaying the start of combustion by retarding injection timing aligns the heat release from the fuel combustion with the portion of the power (or combustion) stroke of the engine cycle after the piston has begun to move down. This means that the cylinder volume is increasing and that work (and therefore heat) is being extracted from the hot gases. The removal of this heat through expansion lowers the temperature in the combustion gases. NO_x is reduced because the premixed burning phase is shortened and because cylinder temperature and pressure are lowered. Timing retard typically increases HC, CO, PM, and fuel consumption because the end of injection comes later in the combustion stroke where the time for extracting energy from fuel combustion is shortened and the cylinder temperature and pressure are too low for more complete oxidation of PM. This can be offset by increasing injection pressure, allowing an earlier end of injection at the same torque output (i.e., shorter injection duration for the same quantity of fuel injected), and by using multiple injection events following the primary diffusion-combustion event to enhance soot oxidation (see 4.2.2.6 High Pressure Injection, Fuel injection Rate Shaping, Multiple Injections and Induced Charge Motion). We expect that these strategies will continue to be used to meet our proposed remanufactured engine standards and our proposed Tier 3 locomotive and marine diesel engine standards.

4.2.2.5 Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) reintroduces or retains a fraction of the exhaust gases in the cylinder. Most highway diesel engine manufacturers used cooled external EGR to meet the 2004 and later Heavy-Duty Highway emission standards of 2.5 g/bhp-hr HC + NO_x and 0.10 g/bhp-hr PM. EGR has been a key technology used to reduce engine-out NO_x emissions to near 1.0 g/bhp-hr for CDPF-equipped 2007 heavy-duty truck and bus engines in the U.S. Although the use of EGR will not be needed to meet the Proposed Tier 3 locomotive and marine standards or remanufactured engine standards, we expect that some Category 1 marine diesel engines and high-speed locomotive switch engines that are based on Tier 3 and Tier 4 nonroad engine families that already use EGR may also use EGR for their marine or switch locomotive applications of these engines to provide additional engine calibration flexibility.

The use of EGR decreases NO_x formation in three different ways:

1. EGR can thermally reduce peak combustion temperature. Increasing the mass of the cylinder contents by increasing carbon dioxide (CO₂) and water vapor concentrations reduces peak cylinder temperatures during combustion.¹⁸
2. A fraction of the air within the cylinder is replaced with inert exhaust, primarily CO₂ and water vapor. This reduces the amount of molecular oxygen available for dissociation into atomic oxygen, an important step in NO_x formation via the Zeldovich mechanism.
3. The high temperature dissociation of CO₂ and water vapor is highly endothermic, and thus can reduce temperatures via absorption of thermal energy from the combustion process.¹⁹

EGR often is routed externally from the exhaust system to the induction system. The use of externally plumbed EGR can increase the intake manifold temperature substantially. This reduces intake charge density and lowers the fresh air/fuel ratio for a given level of turbocharger boost pressure. The result can be a large increase in PM emissions if the boost pressure cannot be increased to compensate for the lower intake charge density. For this reason, external EGR systems typically cool the exhaust gases using a heat exchanger in the exhaust recirculation loop. The introduction of ultra low sulfur diesel fuel substantially reduces the risk of sulfuric acid condensation within an EGR cooler. EGR can also be accomplished entirely in-cylinder (internal EGR) through the use of camshaft phasing or other electronically controlled variable geometry valve-train systems, particularly when applied to varying two-stroke diesel engine exhaust scavenging, although its use is limited by the inability to effectively cool the residual gases in-cylinder. For both internal and external EGR systems, the EGR rate is electronically controlled to prevent temporary, overly fuel-rich conditions that can lead to high PM emissions during transient engine operation.

Although we don't expect that EGR will be required to meet our proposed remanufacturing standards or our proposed Tier 3 locomotive and marine standards, we do believe that EGR is an effective emissions control strategy that could be selected by an engine manufacturer as a means to control NO_x emissions. EGR may also provide increased flexibility in how engines are calibrated to meet emissions standards with the potential for improvement in part-load fuel consumption.

4.2.2.6 High Pressure Injection, Fuel Injection Rate Shaping, Multiple Injections and Induced Charge Motion

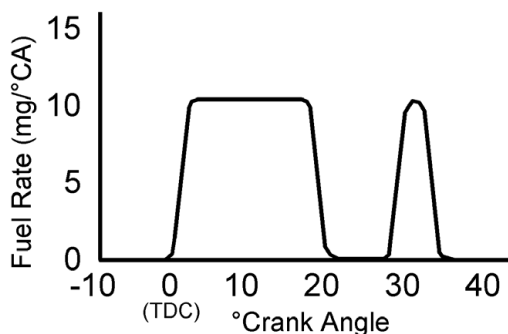
Inducing turbulent mixing is one means of increasing the likelihood of soot particles interacting with oxidants within the cylinder to decrease PM emissions. Turbulent mixing can be induced or increased by a number of means including:

- Changes to intake port/valve design and/or piston bowl design
- Increased (high) injection pressure
- Multiple/split injections using high pressure common rail injection or late post injection using electronic unit injection

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

The most recent advances in fuel injection technology are high-pressure common rail injection systems with the ability to use rate shaping or multiple injections to vary the delivery of fuel over the course of a single combustion event. These systems are in widespread use in heavy-duty on-highway diesel engines, and they are used in many current nonroad diesel engines. These systems provide both NO_x and PM reductions. Igniting a small quantity of fuel early limits the rapid increase in pressure and temperature characteristic of premixed combustion and its associated NO_x formation. Injecting most of the fuel into an established flame then allows for a steady burn that limits NO_x emissions. Rate shaping may be done either mechanically or electronically. Rate shaping has been shown to reduce NO_x emissions by up to 20 percent.²⁰ Multiple injection/split injection have also been shown to significantly reduce particulate emissions, most notably in cases that use retarded injection timing or a combination of injection timing retard and EGR to control NO_x .^{21,22,23,24} The typical diffusion-burn combustion event is broken up into two events. A main injection is terminated, and then followed by a short dwell period with no injection, which is in turn followed by another short post-injection event, see Figure 4-5. The second pulse of injected fuel induces late-combustion turbulent mixing. The splitting of the injection event into two events aids in breaking up and entraining the “soot cloud” formed from the first injection event into the bulk cylinder contents.

Figure 4-5: An example of using multiple fuel injection events to induce late-combustion mixing and increase soot oxidation for PM control (Adapted from Pierpont, Montgomery and Reitz, 1995).

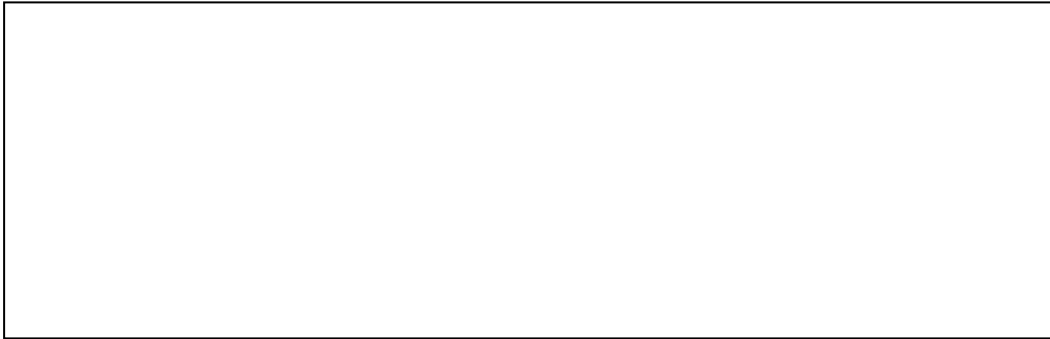


Increasing the turbulence of the intake air entering the combustion chamber (i.e., inducing swirl) can also reduce PM by improving the mixing of air and fuel in the combustion chamber. Historically, swirl was induced by routing the intake air to achieve a circular motion in the cylinder. Heavy-duty on-highway and nonroad engine manufacturers are increasingly using variations of "reentrant" piston designs in which the top surface of the piston is cut out to allow fuel injection and air motion in a smaller cavity in the piston to induce additional turbulence (Figure 4-6). Manufacturers have also changed to three or four valves per cylinder for on-highway and nonroad high-speed diesel engines, and to four valves per cylinder for medium-speed locomotive engines, which reduces pumping losses and can also allow for additional intake air charge motion generation. This valve arrangement also offers better positioning of the fuel injector by allowing it to be placed in-line with the centerline axis of the piston.

At low loads, increased swirl reduces HC, PM, and smoke emissions and lowers fuel consumption due to enhanced mixing of air and fuel. NO_x emissions might increase slightly at low loads as swirl increases. At high loads, swirl causes slight decreases in PM emissions and fuel consumption, but NO_x may increase because of the higher temperatures associated with enhanced mixing and reduced wall impingement.²⁵ A higher pressure fuel system can be used to offset some of the negative effects of swirl, such as increased NO_x, while enhancing positive effects like increased PM oxidation. Intake air turbulence such as "swirl" can be induced using shrouded intake valves or by use of a helical-shaped air intake port. Swirl is important in promoting turbulent mixing of fuel and soot with oxidants, but can also reduce volumetric efficiency.

Piston bowl design can be used to increase turbulent mixing. Reentrant bowl designs induce separation of the flow over the reentrant "ledge" of the piston and help to maintain swirl through the compression stroke and into the expansion stroke.

Figure 4-6: Schematic examples of a straight-sided piston-bowl (A), a reentrant piston bowl (B), and a deep, square reentrant piston bowl (C) for high-speed diesel engines.



To meet our locomotive remanufactured engine standards and potential marine remanufactured engine standards, we expect that manufacturers will use high pressure electronically controlled unit injection and improvements to piston bowl design. To meet the Tier 3 locomotive and marine standards, we expect that manufacturers of high-speed Category 1 and 2 marine diesel engines, high-speed switch locomotive engines and some Category 2 marine and locomotive medium speed engines will use advanced electronic fuel systems, including in many cases high-pressure common rail fuel injection systems.

4.2.2.7 Reduced Oil Consumption

Reducing oil consumption not only decreases maintenance costs, but also VOF and PM emissions. Reducing oil consumption has been one of the primary ways that heavy-duty truck diesel engines have complied with the 1994 U.S. PM standard. Reducing oil consumption also reduces poisoning of exhaust catalysts from exposure to zinc and phosphorous oil additives.

Redesign of the power assembly (pistons, piston rings and cylinder liner) played an important role in reducing organic carbon PM emissions from locomotive engines in order to meet the Tier 2 locomotive standards. Piston rings can be designed to improve the removal of oil from the cylinder liner surface and drainage back into the crankcase, reducing the amount of oil consumed. Valve stem seals can be used to reduce oil leakage from the lubricated regions of the engines valve train into the intake and exhaust ports of the engine. Improvements to the closed-crankcase ventilation systems that incorporate drain-back to the crankcase of oil separated from the crankcase flow and the use of high-efficiency filtration, either with replaceable high-efficiency coalescing filters or multiple-disc inertial separation, will reduce oil consumption and can remove oil-aerosol from the crankcase flow sufficiently to allow introduction of the crankcase gases into the turbocharger compressor inlet with little or no fouling of the turbocharger compressor, aftercooler or the remainder of the induction system. Euro IV and U.S. 2004 and 2007 heavy-duty truck engine designs that incorporate these technologies have significantly reduced engine-out organic carbon PM emissions.

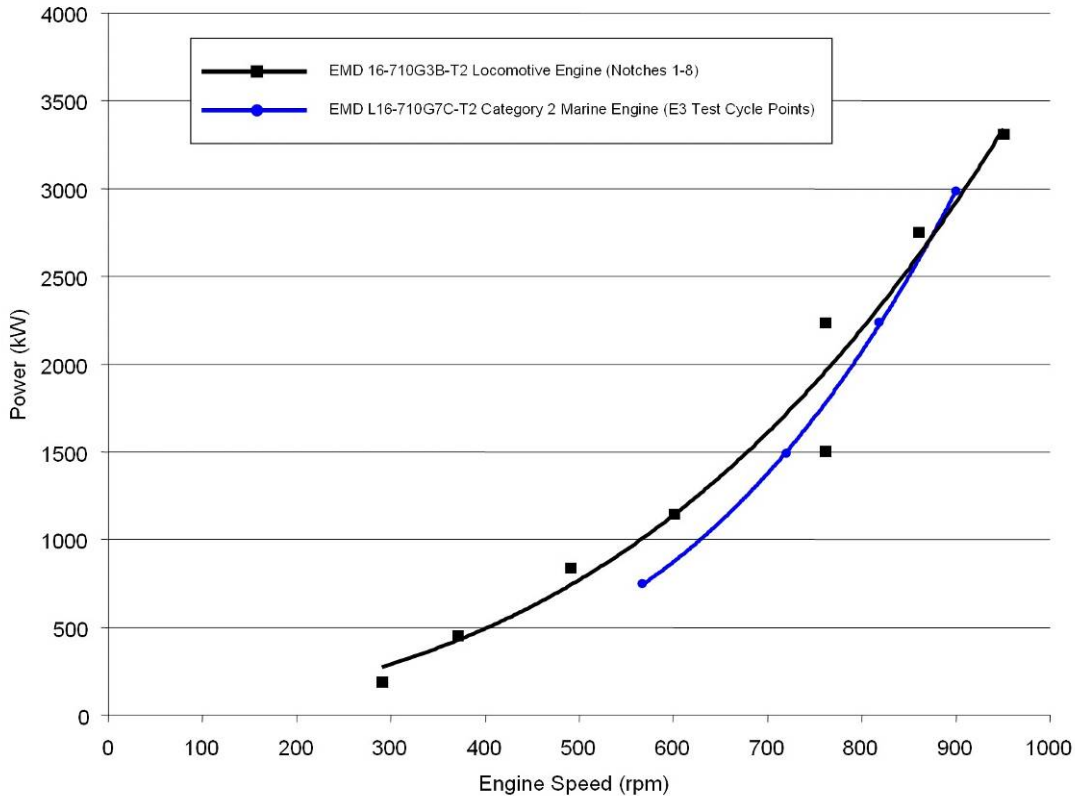
Particularly in the case of medium-speed engines, which have a relatively high fraction of PM emissions due to organic carbon PM, reduced oil consumption will be an effective means of meeting our proposed remanufactured locomotive engine and Tier 3 locomotive and marine PM standards. We expect Tier 0 and Tier 1 remanufactured locomotive engines to receive power assembly designs similar to those of current Tier 2 locomotives. We expect that remanufactured Tier 2 locomotive engines and new Tier 3 locomotive and marine engines will receive incremental improvements in the design of the power assembly, valve stem seals and improved crankcase ventilation systems—especially if the crankcase ventilation system routes the crankcase vent to the turbocharger inlet and incorporates high-efficiency oil separation from the crankcase flow. When applying catalytic exhaust controls to meet the Tier 4 standards, reduced oil consumption will improve the durability of catalyst systems by reducing their exposure to zinc- and phosphorous-containing oil additives.

4.2.2.8 Application Specific Differences in Emissions and Emissions Control

In much of the preceding discussion we have relied on previous experience primarily from high-speed (approximately >1600 rpm rated speed) on-highway and nonroad engines to provide specific examples of emissions formation and engine-out emissions control. There are, however, some important operational and design differences between these engines and locomotive and marine diesel engines, particularly the medium speed locomotive and marine engines.

High-speed diesel engines used in on-highway and nonroad applications (with the exception of generator applications) undergo significant transient operation that can create temporary conditions of insufficient availability of oxidants due to the inability of the air-supply from the turbocharger to follow engine transients. For these applications, the majority of elemental carbon PM is emitted during these transients of insufficient oxygen availability. Such transients are greatly reduced in locomotive and marine applications. Marine propulsion engines operate primarily along a propeller curve that effectively forms a narrower outer boundary within which engine operation occurs. Marine generators and locomotive engines operate within even narrower bounds. Generators generally operate at close to a fixed engine speed with varying load. Locomotives operate at 8 distinct speed-load operational notches with gradual transitions between each notch. Figure 4-7 illustrates the speed and power ranges over which typical locomotives and marine engines operate.

Figure 4-7: A comparison engine power output versus engine speed for a locomotive engine operated over notches one through eight and for a Category 2 marine engine operated over the E3 marine cycle, which approximates a propeller curve with a cubic relationship between speed and load. A cubic fit through the locomotive notch points is remarkably similar to the E3 prop-curve. The specific example shown is for two similar versions of the EMD two-stroke medium-speed diesel engine.



In addition to operational differences, medium-speed diesel engines (750 to 1200 rpm rated speed) are the predominant type used in Category 2 marine and line-haul locomotive applications. Medium-speed diesel engines are also predominant in older switch locomotives, although the majority of locomotive switch families certified to the Tier 2 locomotive standards now use high-speed diesel engines. Medium speed diesel engines typically have even lower elemental carbon PM emissions due to increased residence time available at high load conditions for late-cycle burn-up of elemental carbon PM as compared to high-speed diesel applications such as heavy-duty on-highway engines. The increased duration of combustion also increases NO_x formation for medium-speed diesel engines.

Large-bore locomotive and Category 2 medium speed diesel engines also have significantly higher lubricating oil consumption than many high-speed diesel engines. Lubricating oil consumption for current 2007 on-highway diesel truck engines is approximately 0.09 to 0.13% of fuel consumed versus approximately 0.30 to 0.35% for 2-stroke medium-speed diesel locomotive and marine engines and approximately 0.25% for 4-stroke medium-speed locomotive engines. To some degree, this higher

consumption of lubricating oil is by design. Higher lubricating oil consumption allows for a reduced frequency of complete oil changes, while at the same time the resulting frequent topping off of oil replenishes lubricant additives that maintain the lubricating oil's total base number (TBN) to prevent acidic corrosion. Frequent topping off also maintains the oil's oxidation stability to maintain oil viscosity. Because improvements in high-pressure fuel injection systems and electronic engine management were used to reduce carbon PM emissions to meet Tier 2 locomotive and marine engine PM standards, only moderate improvements in lubricating oil consumption were necessary to meet the Tier 2 PM emission standards. This reduced elemental carbon PM, coupled with still moderately high lubricating oil consumption, results in a PM composition of medium-speed diesel engines that is substantially different than that of on-highway diesel engines and many nonroad diesel engines. PM emissions from medium-speed diesel engines are dominated by organic carbon PM emissions, with the relative contributions of organic carbon and elemental carbon PM to total PM approximately reversed from those of on-highway and most non-road diesel engines. Figure 4-8 shows the relative contributions of elemental carbon, organic carbon, and sulfate PM emission from recent tests of Tier 0, Tier 1 and Tier 2 locomotives.

Another difference is that crankcase ventilation flow is considerably higher from very large displacement medium-speed diesel engine compared with smaller, high-speed engines. This has complicated the design of crankcase ventilation systems with effective oil-aerosol separation. Higher capacity, high efficiency inertial disc-type separators are now being introduced in medium-speed marine applications to reduce bilge water contamination and oil consumption. Inertial disc-type oil separators originally developed for Euro IV and 2007 U.S. Heavy-duty On-highway applications have provided sufficient oil separation to allow introduction of filtered crankcase gases into the turbocharger inlet without oil fouling of the turbocharger or aftercooler system. Similar systems are now optionally available on Wärtsilä medium-speed stationary generator and marine engines (Figure 4-9). We expect that similar systems will be used on Tier 3 and Tier 4 Category 2 marine engines and remanufactured Tier 2 and new Tier 3 and Tier 4 locomotive systems.

Improvements in oil formulation, including switching from Group 1 to Group 2 base oils with greatly improved oxidation stability also reduce the need for oil top-off to replenish lubricant additives. As Group 1 become unavailable in Europe, we expect increased use of Group 2 base oil formulations for use with EMD medium-speed engines in Europe. Future reductions in fuel sulfur for Tier 3 and Tier 4 locomotive and marine engines will also reduce the need for TBN control.

Figure 4-8: Emissions for 6 locomotives tested using 3000 ppm sulfur nonroad diesel fuel.

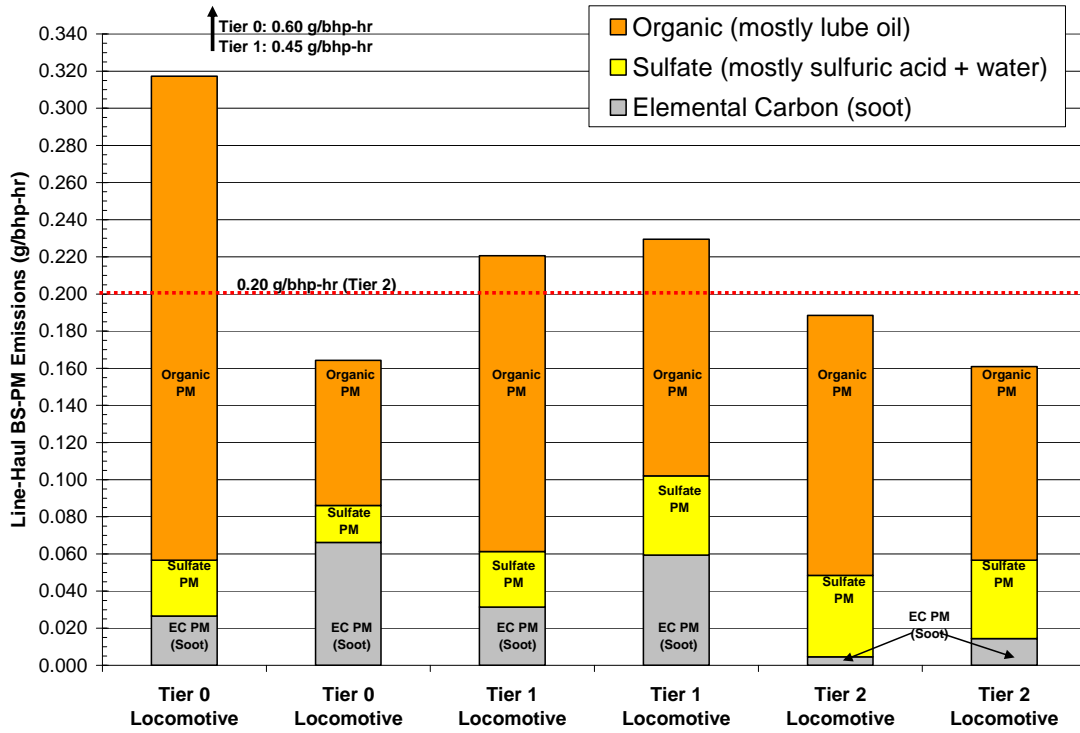
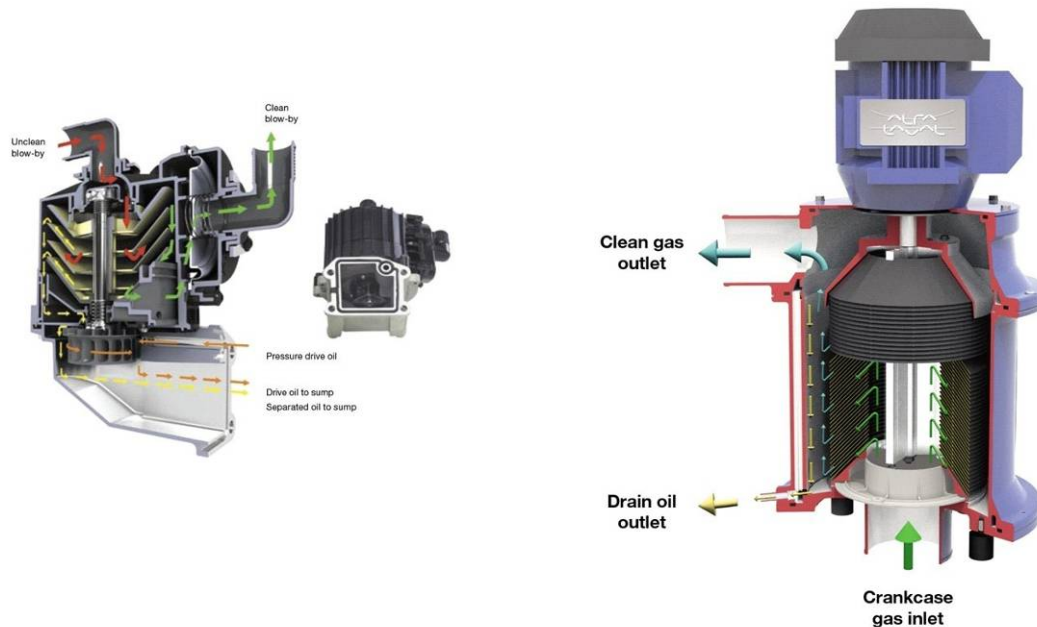


Figure 4-9: Alfa Laval disc-type inertial oil-aerosol separation systems for use with closed crankcase ventilation systems. The unit on the left is Alfdex system originally developed for Euro IV and U.S. 2007 heavy-duty on-highway applications. This system was designed as “fit for life”, or essentially maintenance free for the useful life of the engine. A much higher volume system (right) was recently developed for Wärtsilä medium-speed engines.



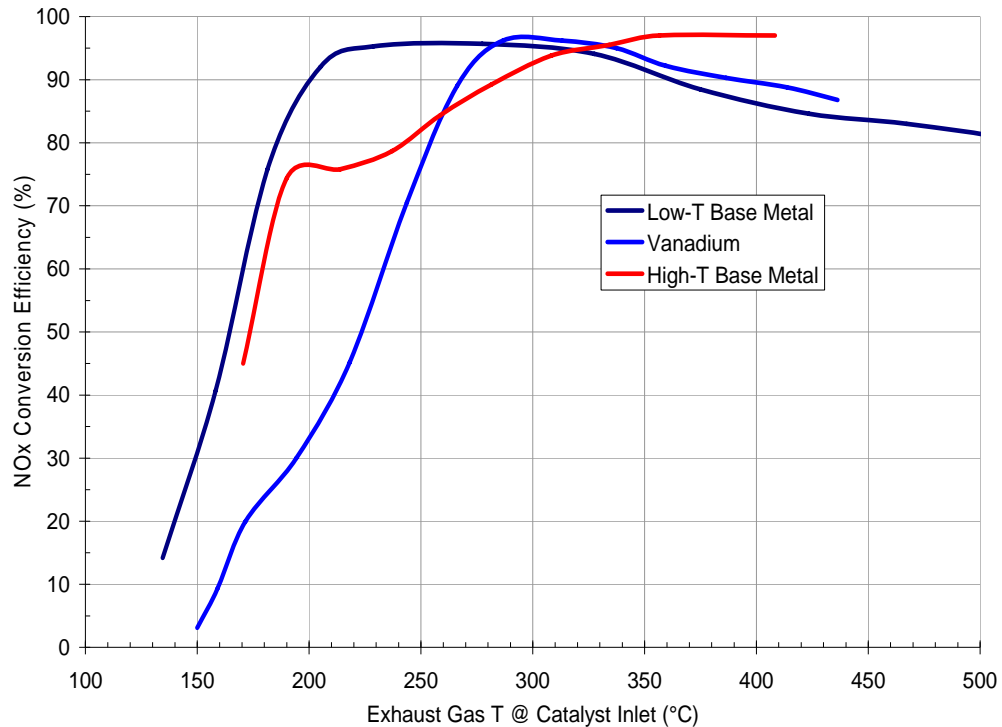
4.3 Feasibility of Tier 4 Locomotive and Marine Standards

In this section we describe the emissions control technologies that we believe may be used to meet our proposed Tier 4 locomotive and marine diesel engine standards. In general, these technologies involve the use of catalytic exhaust treatment devices placed in an engine’s exhaust system, downstream of an engine’s exhaust manifold or turbocharger turbine outlet. The catalytic coatings of these aftertreatment devices are oftentimes sensitive to other constituents in diesel exhaust. For example, sulfur compounds within diesel fuel can decrease the effectiveness or useful life of a catalyst. For this reason, we will require the use of ultra-low sulfur diesel fuel in engines that will be designed to meet our proposed Tier 4 emissions standards. We also expect that engine manufacturers will specify new lubricating oil formulations for these Tier 4 engines because of other trace compounds in some currently used lubricating oils. These new oil formulations will help ensure that catalytic exhaust aftertreatment devices will operate properly throughout their useful life. Because we have already finalized and begun implementation of similar aftertreatment-forcing standards for both heavy-duty on-highway and nonroad diesel engines, we are confident that the application of similar, but appropriately designed, aftertreatment systems for locomotive and marine applications is technologically feasible, especially given the implementation timeframe that we are proposing.

4.3.1 Selective Catalytic Reduction (SCR) NO_x Control Technology

Recent studies have shown that an SCR system is capable of providing well in excess of 80% NO_x reduction efficiency in high-power, heavy-duty diesel applications.^{26, 27, 28} As shown in Figure 4-10, Vanadium and base-metal (Cu or Fe) SCR catalysts can achieve significant NO_x reduction throughout much of exhaust gas temperature operating range observed in heavy-duty diesel engines used in locomotive and marine applications. Collaborative research and development activities between diesel engine manufacturers, truck manufacturers, and SCR catalyst suppliers have also shown that SCR is a mature, cost-effective solution for NO_x reduction on heavy-duty diesel engines. While many of the published studies have focused on heavy-duty highway truck applications, similar trends, operational characteristics, and NO_x reduction efficiencies have been reported for heavy-duty marine and stationary electrical power generation applications as well.²⁹ An example of the performance capability of SCR in marine applications is the Staten Island Ferry *Alice Austen*. This demonstration project reports that 90-95% NO_x reduction is possible under steady-state conditions (where the exhaust gas temperature is above 270 °C.)³⁰ Given the preponderance of studies and data - and our analysis summarized here - we believe that this technology is appropriate for both locomotive and marine diesel applications.

Figure 4-10: SCR Catalyst NO_x Reduction versus Exhaust Gas Temperature Using an Ammonia-to-NO_x Ratio of 1:1^{31,32,B}



An SCR catalyst reduces nitrogen oxides to N₂ and water by using ammonia (NH₃) as the reducing agent. The most-common method for supplying ammonia to the SCR catalyst is to inject an aqueous urea-water solution into the exhaust stream. In the presence of high-temperature exhaust gasses (>200 °C), the urea hydrolyzes to form NH₃ and CO₂ - the NH₃ is stored on the surface of the SCR catalyst where it is used to complete the NO_x-reduction reaction. In theory, it is possible to achieve 100% NO_x conversion if the NH₃-to-NO_x ratio (α) is 1:1 and the space velocity within the catalyst is not excessive (i.e. there is ample time for the reactions to occur). However, given the space limitations in packaging exhaust aftertreatment devices in mobile applications, an α of 0.85-1.0 is often used to balance the need for high NO_x conversion rates against the potential for NH₃ slip (where NH₃ passes through the catalyst unreacted). Another approach to prevent NH₃ slip is to use an oxidation catalyst downstream of the SCR. This catalyst, also referred to as a slip catalyst, is able to oxidize the NH₃ which passes through (or is released from) the SCR. When this approach is used, it is possible to operate the SCR system at near-peak efficiency by optimizing the urea dosing rate to accomplish high NO_x control (which provides

^B The “High-T Base Metal” curve is based on a composite of low and high-space-velocity data provided by catalyst manufacturers. It is meant to represent high-hour performance of a system at a space velocity of 40,000 hr⁻¹.

adequate NH_3 for NO_x reduction). Any excess NH_3 (ammonia slip) that results from such optimization is converted to N_2 and water in the slip catalyst.

The urea dosing strategy and the desired α are dependent on the conditions present in the exhaust gas; namely temperature and the quantity of NO_x present (which can be determined by engine mapping, temperature sensors, and NO_x sensors). Overall NO_x conversion efficiency, especially under low-temperature exhaust gas conditions, can be improved by controlling the ratio of two NO_x species within the exhaust gas; NO_2 and NO . This can be accomplished through use of an oxidation catalyst upstream of the SCR catalyst to promote the conversion of NO to NO_2 . The physical size and catalyst formulation of the oxidation catalyst are the principal factors which control the NO_2 : NO ratio, and by extension, improve the low-temperature performance of the SCR catalyst.

Published studies show that SCR systems will experience very little deterioration in NO_x conversion throughout the life-cycle of a diesel engine.³³ The principal mechanism of deterioration in an SCR catalyst is thermal sintering - the loss of catalyst surface area due to the melting and growth of active catalyst sites under high-temperature conditions (as the active sites melt and combine, the total number of active sites at which catalysis can occur is reduced). This effect can be minimized by design of the SCR catalyst washcoat and substrate for the exhaust gas temperature window in which it will operate. Another mechanism for catalyst deterioration is catalyst poisoning - the plugging and/or chemical de-activation of active catalytic sites. Phosphorus from the engine oil and sulfur from diesel fuel are the primary components in the exhaust stream which can de-activate a catalytic site. The risk of catalyst deterioration due to sulfur poisoning will be all but eliminated with the 2012 implementation of ULSD fuel (<15 ppm S) for locomotive/marine applications. Catalyst deterioration due to phosphorous poisoning can be reduced through the use of lubricating oil with low sulfated-ash, phosphorus, and sulfur content (low-SAPS) and through reduced oil consumption (as discussed in 4.2.2.7). Low-SAPS oil will improve the performance of catalyzed-DPF and SCR aftertreatment components in locomotive and marine applications. The high ash content in current locomotive and marine engine oils is related to the need for a high total base number (TBN) in the oil formulation. This high-TBN oil has been necessary because of the high sulfur levels typically present in diesel fuel - a high TBN is necessary to neutralize the acids created when fuel-borne sulfur migrates to the crankcase. With the use of ULSD fuel, acid formation in the crankcase will not be a significant concern. This oil will be available for use in heavy-duty highway engines by October 2006 and is specified by the American Petroleum Institute as "CJ-4." The durability of other exhaust aftertreatment devices, namely the DOC and DPF, will also benefit from the use of ULSD fuel and low-SAPS engine oil - less sulfur and phosphorous will improve DOC effectiveness and less ash will increase the DPF ash-cleaning intervals.

The onboard storage of the aqueous urea solution on locomotives and marine vessels can be accomplished through segmenting of the existing fuel tanks or fitment of a separate stainless steel or plastic urea tank. To assure consistent SCR operation between refueling stops, the volume of urea-water solution carried onboard will need

to be at least 5% of the diesel fuel tank capacity. At the appropriate intervals, the crews will need to refill the urea tank. For the railroad and marine industries, the distribution and dispensing of urea is expected to benefit from any solutions put in place by the trucking industry and heavy-duty highway engine and vehicle manufacturers well in advance of the proposed Tier 4 locomotive and marine regulations.

We project that locomotive and marine diesel engine manufacturers will benefit from any development taking place to implement DPF and SCR technologies in advance of the heavy-duty truck NO_x standards in Europe and the U.S. The urea dosing systems for SCR, already in widespread use across many different diesel applications, are expected to become more-refined/robust/reliable in advance of our proposed Tier 4 locomotive and marine standards. Given the steady-state operating characteristics of locomotive and marine engines, DPF regeneration strategies and urea dosing controls will certainly be capable of controlling PM and NO_x at the levels necessary to meet our proposed standards.

4.3.1.1 Urea Infrastructure and Feasibility & Cost

The preferred concentration for the aqueous urea solution is 32.5% urea, which is the eutectic concentration (provides the lowest freezing point and the urea concentration does not change if the solution is partially frozen).³⁴ With a freezing temperature of -11 °C (12 °F), heaters and/or insulation may be necessary in Northern regions for urea storage/dispensing equipment and the urea dosing apparatus (tank, pump, and lines) on the on the engine. The centralized nature of locomotive and marine refueling from either large centralized fuel storage tanks or from tanker trucks with long-term purchase agreements provides a working example of how urea could also be distributed from storage tanks at centralized fueling facilities, tanker trucks and/or multi-compartment fuel-oil/urea tanker trucks at remote fueling sites. Given that only a small percentage of the locomotive and marine fleet will require urea prior to 2017, EPA believes that the infrastructure for supplying urea from centralized refueling points and tank trucks can be established to serve the rail and marine industries. Discussions concerning the urea infrastructure and specifications for an emissions-grade urea solution are beginning to take place amongst stakeholders in the light-duty and heavy-duty highway diesel industry. It is possible that these discussions will result in a fully-developed urea infrastructure for light-duty and heavy-duty diesel highway engine and vehicle applications by 2010. This would allow seven years to expand and develop this framework to support the needs of the railroad and marine industries. Even without these developments underway in the light-duty and heavy-duty highway industry, the centralized fueling nature of the locomotive and marine industries lends itself well to adaptation to support a supply of urea at their normal fueling locations.

In 2015, urea cost is expected to be ~\$0.75/gallon for retail facilities dispensing 200,000 - 1,000,000 gallons/month, and ~\$1.00/gallon for those dispensing 80,000 - 200,000 gallons/month.³⁵ The additional operating cost incurred by the rail industry will also be dependent on the volume of urea dispensed at each

facility, with smaller refueling sites experiencing higher costs. It is estimated that 87% of the locomotive fleet is refueled at fixed facilities and 13% at direct truck-to-locomotive facilities.³⁶ The type of urea storage/dispensing equipment, and the ultimate cost-per-gallon, for railroad and marine industries will depend on the volume of fuel & urea dispensed at each site. High-volume fixed sites may choose to mix emissions-grade dry urea (or urea liquor) and de-mineralized water on-site, whereas others may choose bulk or container delivery of a pre-mixed 32.5% urea-water solution. Again, with the possible implementation of SCR for light-duty and heavy-duty highway applications in 2010, the economic factors for each urea supply option may be well-known prior to implementation of the 2017 standards. Even without these developments underway in the light-duty and heavy-duty highway industry, we believe that the urea supply options for the locomotive and marine industries will be numerous.

Urea production capacity in the U.S. is more than sufficient to meet the additional needs of the rail and marine industries. For example, in 2003, the total diesel fuel consumption for Class I railroads was approximately 3.8 billion gallons.³⁷ If 100% of the Class I locomotive fleet were to be equipped with SCR catalysts, approximately 190 million gallons-per-year of 32.5% urea-water solution would be required. It is estimated that 190 million gallons of urea solution would require 0.28 million tons of dry urea (1 ton dry urea is needed to produce 667 gallons of 32.5% urea-water solution). Currently, the U.S. consumes 14.7 million tons of ammonia resources per year, and relies on imports for 41% of that total (of which, urea is the principal derivative). In 2005 domestic ammonia producers operated their plants at 66% of rated capacity, resulting in 4.5 million tons of reserve production capacity.³⁸ In the hypothetical situation above, where 100% of the locomotive fleet required urea, only 6.2% of the reserve domestic capacity would be needed to satisfy the additional demand. A similar analysis for the marine industry, with a yearly diesel fuel consumption of 2.2 billion gallons per year, would not significantly impact the urea demand-to-reserve capacity equation. Since the rate at which urea-SCR technology is introduced to the railroad and marine markets will be gradual, the reserve urea production will be adequate to meet the expected demand in the 2017 timeframe of the proposed Tier 4 standards.

4.3.1.2 Establishing the Tier 4 NO_x Standard

The basis for the proposed locomotive Tier 4 Line-Haul NO_x standard is the Tier 3 NO_x emission standard (5.5 g/bhp-hr) reduced by the following SCR catalyst efficiency estimates at full useful life of the engine; 60% efficiency in operating mode notch 2 (where exhaust gas temperature is near the minimum-level for NO_x conversion), 85% conversion efficiency in operating modes notches 3 and 4 (where lower catalyst space velocities allow optimum reaction rates), and 83% conversion

Draft Regulatory Impact Analysis

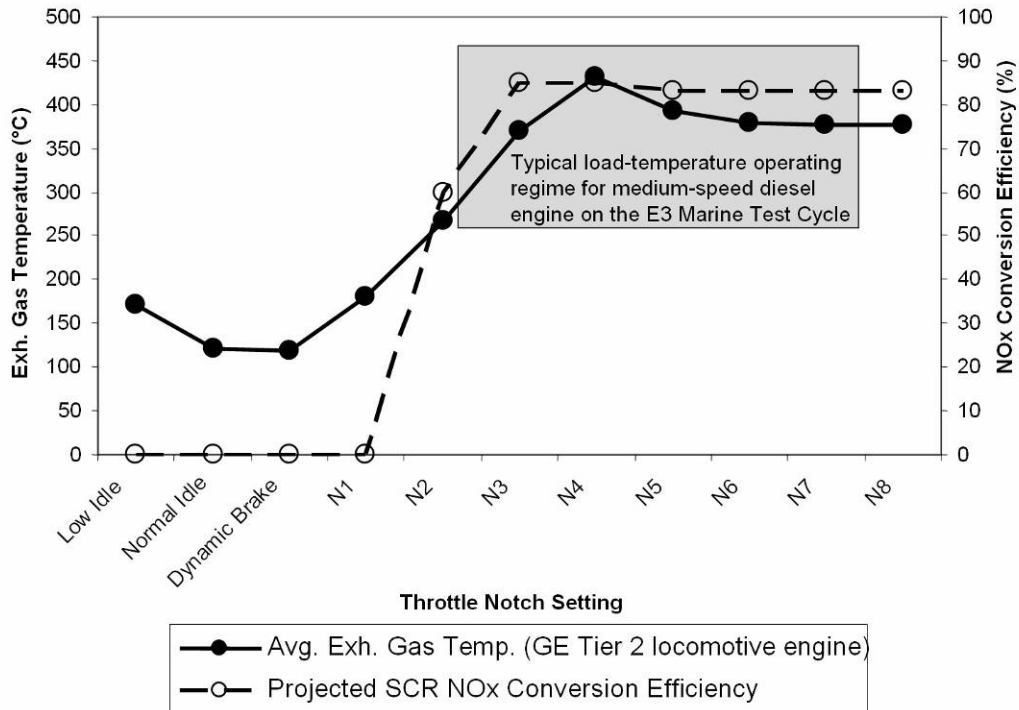
efficiency in the high-load operating modes, notches 5 through 8.^C When these efficiencies are weighted according to the line-haul duty cycle emissions test, an overall NO_x reduction of 78% is obtained.

Figure 4-11 illustrates EPA's projection of an "aged" locomotive/marine SCR system at full useful life. When these levels of NO_x reduction are applied to engine out emissions from a typical Tier 2, 4-stroke-cycle locomotive diesel engine producing 5.5 g/bhp-hr of NO_x on the line-haul duty cycle, the worst-case, full useful life standard is established at 1.3 g/bhp-hr.^D This standard includes a compliance margin and we expect that emissions of a new engine – and the emissions throughout much of the engine's life – will be closer to 0.8 g/bhp-hr. Because marine diesel engines will also operate under similar engine load/exhaust gas temperature conditions over their respective cycles, they also will be capable of similar NO_x reductions. As shown in the shaded area of Figure 4-11, the E3 Marine Test Cycle lies within the peak performance range of an SCR catalyst.

^C For conditions present in Tier 0-2 locomotives, SCR operation (and hence, NO_x reduction) is not possible at the low power notches (NI, LI, DB, and N1) due to low exhaust gas temperatures.

^D With an overall, duty-cycle-weighted, NO_x conversion efficiency of 78%, the remainder NO_x emissions will be 22% of the engine-out level (i.e. the Tier 2 Standard is 5.5 g/bhp-hr; $5.5 \times 0.22 = 1.2$ g/bhp-hr).

Figure 4-11: Typical 4-Stroke Diesel Locomotive Exhaust Gas Temperatures and Projected SCR Catalyst Efficiency at Full Useful Life.



For applications requiring improved SCR performance at lower exhaust gas temperatures, several options are available; throttling the engine airflow to increase exhaust gas temperature, using an SCR formulation designed for the low-temperature NO_x conversion, or a heated urea dosing system (or some combination of all three options). Throttling of the intake airflow on refuse trucks – which often operate under light-load conditions - has been shown to substantially increase exhaust gas temperatures.³⁹ Increasing the exhaust gas temperature at light load not only provides an opportunity for extended SCR operation, it also improves performance of the DOC and DPF components. Low-temperature NO_x conversion can also be enhanced by use of a base-metal (Fe or Cu) zeolite SCR catalyst (see Figure 4-12). Systems for dosing urea at exhaust temperatures below 250 °C are being developed for heavy-duty, highway truck applications. One such system utilizes an electrically-heated bypass to hydrolyze the urea-water solution and produce NH₃ when exhaust gas temperatures are as low as 160 °C – providing an additional 5-25% NO_x reduction relative to a system which stops urea dosing at 250 °C.⁴⁰ Use of a pre-turbocharger location for a DOC located upstream of the SCR system can also improve low temperature performance by driving NO to NO₂ conversion at lighter engine loads than would be possible with more remote mounting of the DOC. Use of air-gap or other types of insulated construction for exhaust system components can also improve thermal management and increase exhaust gas and catalyst temperatures. For further discussion of manifold-mounting of the DOC and exhaust system thermal management, see section 4.3.2 PM and HC Exhaust Aftertreatment Technology.

If no improvements were made to technologies which exists today, the 1.3 g/bhp-hr locomotive standard is technologically feasible. With projected improvements (that are currently more-difficult to quantify), we are confident in-use operation and end of useful life NO_x emission levels will be less than the 1.3 g/bhp-hr standard proposed in this rulemaking.

4.3.2 PM and HC Exhaust Aftertreatment Technology

The most effective exhaust aftertreatment used for diesel PM emissions control is the diesel particulate filter (DPF). More than a million light diesel vehicles that are OEM-equipped with DPF systems have been sold in Europe, and over 200,000 DPF retrofits to diesel engines have been conducted worldwide. Broad application of catalyzed diesel particulate filter (CDPF) systems with greater than 90% PM control is beginning with the introduction of 2007 model year heavy-duty diesel trucks in the United States. These systems use a combination of both passive and active soot regeneration. CDPF systems utilizing metal substrates are a further development that trades off a degree of elemental carbon soot control for reduced backpressure, greater design and packaging flexibility, improvements in the ability of the trap to clear oil ash, and better scaling to the large sizes needed for locomotive and marine applications. Metal-CDPFs were initially introduced as passive-regeneration retrofit technologies for diesel engines designed to achieve approximately 50 to 60% control of PM emissions.⁴¹ Recent data has shown that metal-CDPF trapping efficiency for elemental carbon PM can exceed 70% for engines with inherently low elemental carbon emissions.⁴² Data from locomotive testing (Figure 4-12) confirms a relatively low elemental carbon fraction and relatively high organic fraction for PM emissions from medium-speed Tier 2 locomotive engines.⁴³ The use of a highly oxidizing PGM catalyst coated directly to the CPDF combined with a highly oxidizing DOC mounted upstream of the CDPF would provide 95% or greater removal of HC, including the semi-volatile organic compounds that contribute to PM.

A functional schematic of a metal-CDPF is shown in Figure 4-13. In this particular example, flow restrictions divert a portion of the particle laden exhaust flow through the porous sintered metal walls. The openings in the flow restrictions are sufficient to allow accumulated ash to migrate through the CDPF substrate, either reducing or eliminating the need for periodic ash cleaning.⁴⁴ The metal-CDPF will most likely be used in combination with an upstream diesel oxidation catalyst (DOC). A diesel oxidation catalyst mounted upstream of the metal-CDPF improves NO to NO₂ oxidation for both passive soot regeneration within the CDPF and to increase the NO_x reduction efficiency of the SCR system, particularly during light-load and/or under cold ambient conditions. The DOC would also assist with oxidation of organic carbon PM, particularly at lower notch positions. The DOC effectively becomes mass transport limited for NO₂ oxidation at notch 6 and above (approximately 80,000^{-hr} space velocity), but at that point exhaust temperatures at the location of the metal-CDPF would be sufficient for NO to NO₂ oxidation and thus for passive soot regeneration and also for oxidation of organic carbon. Some or all of the DOC volume can be installed in a close-coupled position within the exhaust manifold,

immediately downstream of the exhaust ports and upstream of the turbocharger's exhaust turbine (Figure 4-14) and within the “vee” of V-type locomotive and marine engines. Air-gapped construction can be used to provide faster warm-up and retention of heat within exhaust components. Thermal insulation that is similar to what is already in common use with dry exhaust manifold configurations in Category 2 marine applications can be used to increase exhaust and catalyst temperatures (Figure 4-15).

Figure 4-16 shows the expected line-haul locomotive PM reductions for:

- A 4-stroke line-haul Tier 2 locomotive due to reducing fuel sulfur content to 15 ppm
- A 4-stroke line-haul Tier 3 locomotive with oil consumption reduced approximately 50% relative to Tier 2 via improvements to the power assembly and closed-crankcase ventilation system
- A 4-stroke line-haul Tier 4 locomotives with application of a DOC and metal-CDPF to the Tier 3 engine
- A 4-stroke line-haul Tier 4 locomotives with application of a DOC and wall-flow-CDPF to the Tier 3 engine

Figure 4-17 shows the expected PM reductions over the E3 General Marine Duty Cycle for:

- A 2-stroke medium-speed Category 2 marine diesel engine due to reducing fuel sulfur content to 15 ppm^E
- A 2-stroke medium-speed Category 2 marine diesel engine with oil consumption reduced approximately 50% relative to Tier 2 via improvements to the power assembly and closed-crankcase ventilation system
- A 2-stroke medium-speed Category 2 marine diesel engine with application of a DOC and metal-CDPF to the Tier 3 engine

Due to the relatively high organic carbon fraction and low elemental carbon fraction in the PM emissions, the difference in PM emissions between the metal-

^E For this specific example, speciated data from an EMD 16-710G3C-T2 2-stroke medium speed locomotive engine was used. This engine is offered in both Category 2 marine and line-haul locomotive applications. The locomotive application has a slightly higher speed rating and lower NOx emissions. A fit of the data to E3 points for the lower 4000 bhp @ 900 rpm EMD 16-710G7C-T2 marine rating was used to model PM emissions instead of the 4300 bhp @ 950 rpm rating. The G3C-T2 and G7C-T2 engines are remarkably similar, if not identical, designs with very similar NOx and PM emissions and appear to differ only with respect to rated power and rated speed.

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CDPF and the wall-flow-CDPF is less than 0.01 g/bhp-hr (approximately 0.005 g/bhp-hr). The advantages of the metal-CDPF relative to the wall-flow-CDPF are greatly reduced maintenance requirements and reduced exhaust back-pressure. We estimate that the use of a metal CDPF would result in PM emissions of approximately 0.02 g/bhp-hr over the line-haul cycle. The results from a ceramic wall-flow trap would be nearly identical at 0.015 g/bhp-hr. This will provide sufficient compliance margin to meet the 0.03 g/bhp-hr Tier 3 line-haul locomotive standard. Because PM emissions concentrations downstream of a PM trap are characteristically flat or relatively constant, we expect very similar PM reductions from marine engines that utilize similar PM trap technology.

Figure 4-18 shows the expected PM removal efficiency of going from Tier 3 to Tier 4 plotted vs. exhaust temperature for all notch positions. The Tier 3 levels were calculated based on a 4-stroke Tier 2 locomotive engine with improved lubricating oil control. The Tier 4 levels were calculated based on the efficiency of a DOC and metal-CDPF combination at the end of useful life and taking into account removal efficiency for elemental and organic carbon and expected sulfate make from fuel and lubricant sulfur. Efficiency is similar or higher for Category 2 marine applications due to a narrower range of exhaust temperatures (approximately 250 °C to 350 °C over the E3 cycle) that are generally above the light-off temperatures for HC and NO oxidation for typical precious-metal DOC and CDPF formulations and yet are largely below the temperatures at which peak sulfate-make occurs.

Figure 4-12: Brake-specific PM emissions speciated into soluble organic, soluble sulfate, and insoluble elemental carbon over the Federal Line-Haul duty cycle.

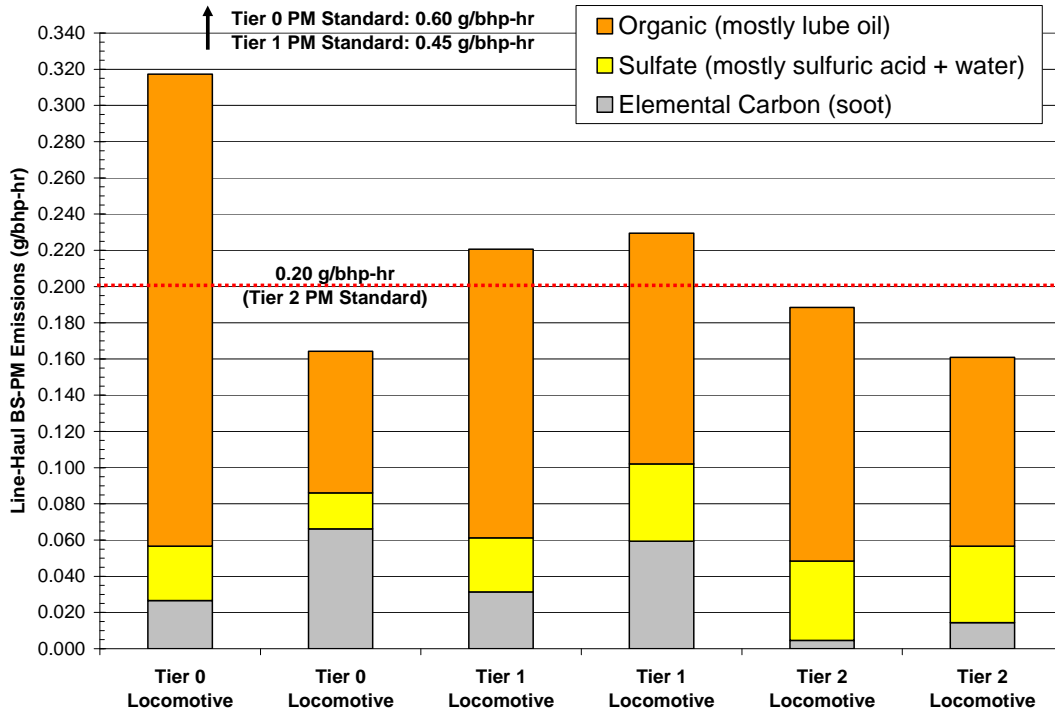


Figure 4-13: Cross-sectional functional schematic for a metal-CDPF (not to scale). Flow restrictions force part of the particle laden exhaust flow through the porous sintered metal layers. High efficiencies are possible at with engines having relatively low elemental carbon PM emissions.

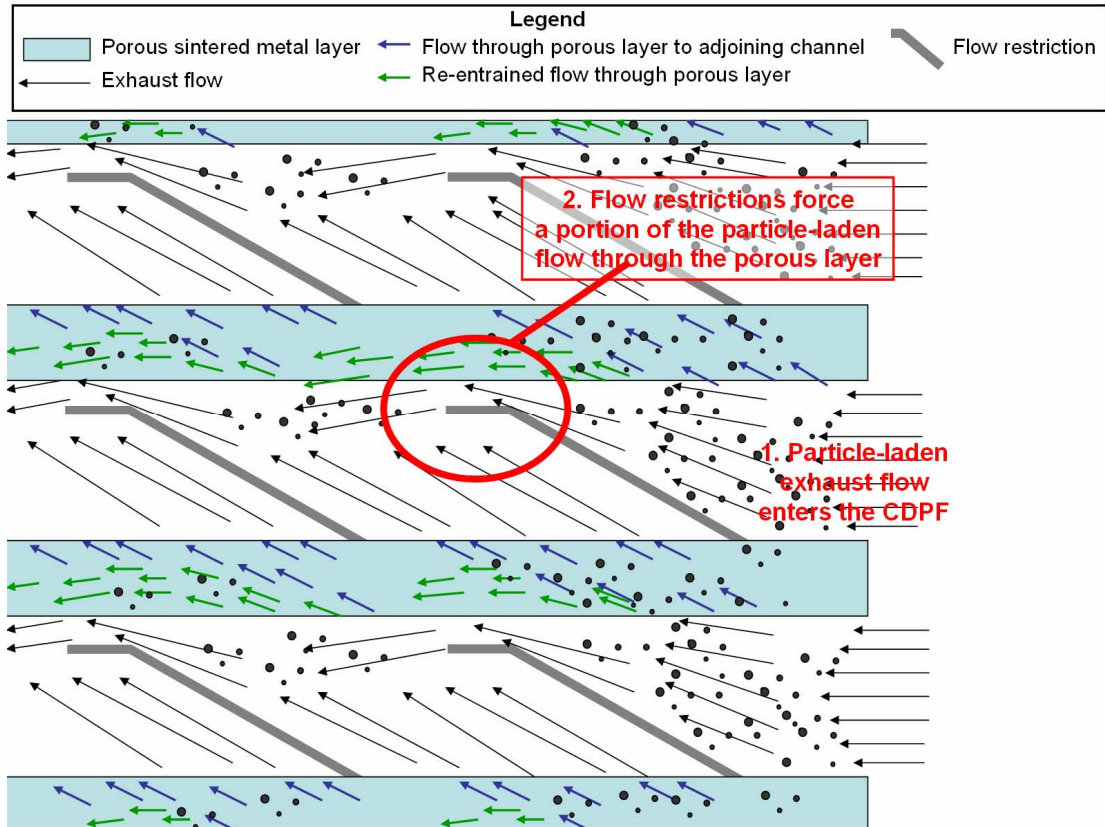


Figure 4-14: Metal-monolith diesel oxidation catalysts (DOC) mounted within the exhaust manifold of an EMD 710-series locomotive diesel engine. Use of a close-coupled DOC extends the range of light-load operation where NO to NO₂ oxidation can occur. Oxidation of engine-out NO to NO₂ assists with passive regeneration of the CDPF and increases the low temperature performance of the urea SCR system. The system also improves oxidation of organic carbon PM at light load conditions (locomotive notches 1 through 6).



Figure 4-15: A two-stroke medium-speed Category 2 marine diesel engine with an insulated exhaust manifold and exhaust turbine in use in New York Harbor.



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Figure 4-16: Brake-specific PM emissions over the line-haul duty cycle for a Tier 2 locomotive and the expected reductions in PM emissions due to reduced fuel sulfur levels and application of PM emissions controls.

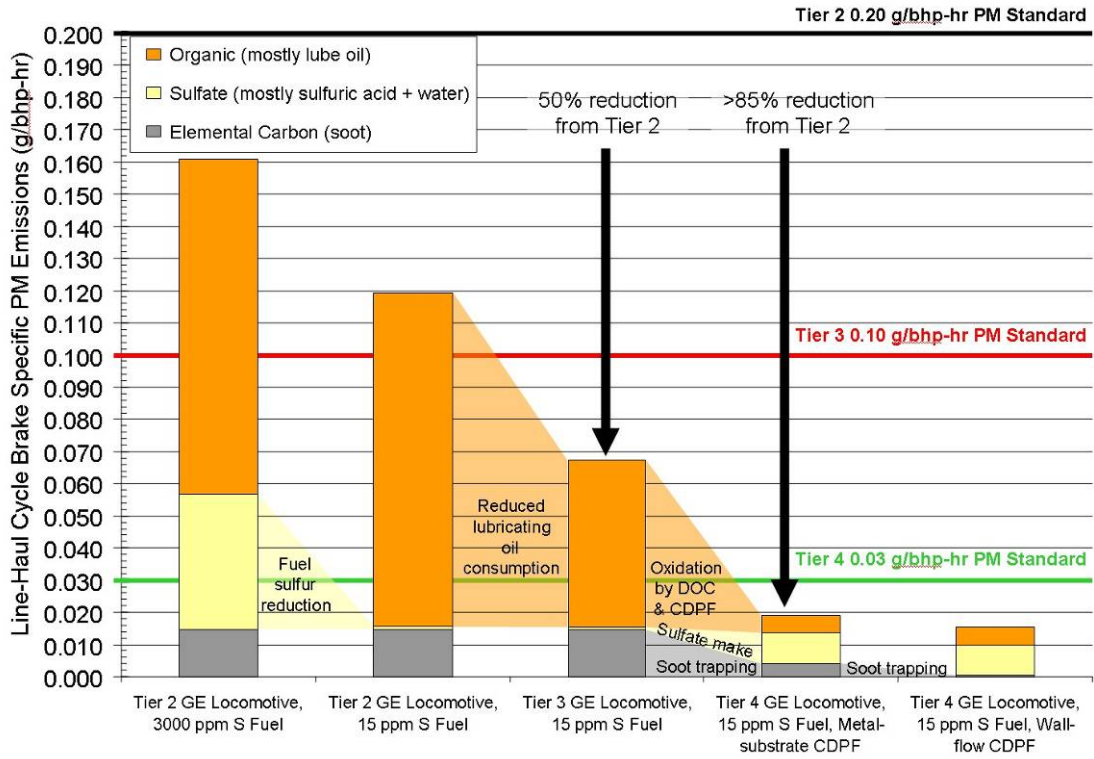


Figure 4-17: Brake-specific PM emissions over the E3 General Marine Duty Cycle for a Tier 2 medium-speed Category 2 diesel engine and the expected reductions in PM emissions due to reduced fuel sulfur levels and application of PM emissions controls.

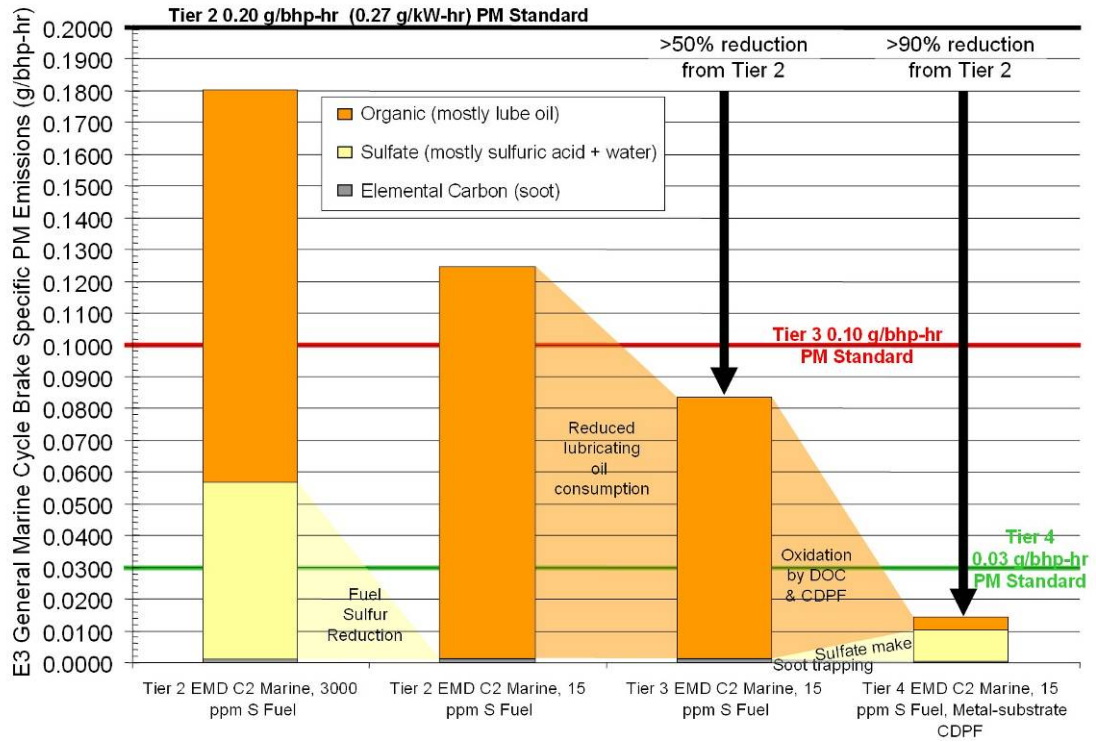
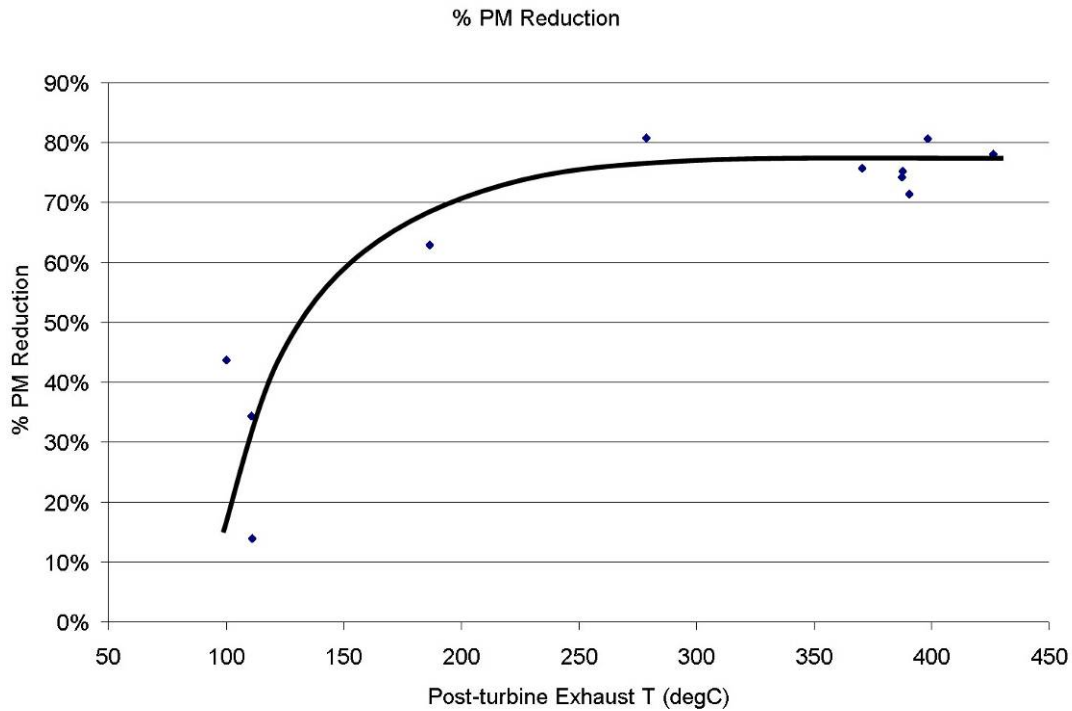


Figure 4-18: Expected PM reduction versus exhaust temperature for a combined DOC and Metal-CDPF system using 15 ppm sulfur fuel when applied to a Tier 3 locomotive. Below 200 °C, PM is dominated by organic carbon emissions, which can only be removed via catalytic oxidation and not by filtration because they are in the gas-phase in the raw exhaust. Thus (organic) PM removal is limited by the kinetically-limited HC oxidation rates over the precious metal catalyst applied to the DOC and the CDPF.



4.3.3 SCR and CDPF Packaging Feasibility

We expect that locomotive and marine manufacturers may need to re-package/re-design the exhaust system, turbocharger, and intake air aftercooling components to accommodate the aftertreatment components. It is acknowledged that the existing overall length, width, and height dimensions of the locomotive are constrained by the existing infrastructure such as tunnel height, but our analysis shows the packaging requirements are such that they can be accommodated within the constraints of a locomotive. For commercial marine vessels, our discussions with marine architects and engineers, along with our review of vessel characteristics, leads us to conclude for engines >600 kW on-board commercial marine vessels, adequate engine room space can be made available to package aftertreatment components. Packaging of these components, and analyzing their mass/placement effect on vessel characteristics, will become part of design process undertaken by naval architecture and marine engineering firms.⁴⁵

To achieve an acceptable balance between SCR performance and exhaust system backpressure, we estimate the volume of the SCR will need to be approximately 2.5 times the engine displacement. This volume includes the volume

required for an ammonia-slip-catalyst zone coated to the final 15% of the volume of the SCR monoliths. The SCR volume is determined by sizing the device so that pollutants/reductants have adequate residence time within catalyst to complete the chemical reactions under peak exhaust flow (maximum power) conditions. The term used by the exhaust aftertreatment industry to describe the relationship between exhaust flow rate and catalyst residence time is "space velocity". Space velocity is the ratio of the engine's peak exhaust flow (in volume units-per-hour) to the volume to the aftertreatment device - this ratio is expressed as "inverse hours", or $^{-hr}$. For example, an engine with a displacement of 200 liters (L), 300,000 L/min of exhaust flow, and a 450 L SCR would have a space velocity of $40,000^{-hr}$ and a catalyst-to-engine displacement ratio of 2.25:1.^F Typical space velocities for SCR on existing Euro 5 heavy-duty truck applications range from 60,000 to 80,000 $^{-hr}$.

To achieve acceptable elemental carbon PM capture efficiency, organic carbon PM oxidation efficiency and exhaust system backpressure, the volume of a metal-CDPF will need to be approximately 1.7 times the engine displacement, which would give a maximum space velocity of approximately 60,000 $^{-hr}$. The exhaust-manifold-mounted DOC located upstream of the metal CDPF will need to be approximately 0.8 times the engine displacement with a maximum space velocity of approximately 80,000 $^{-hr}$ in notch 6 (approximately 120,000 $^{-hr}$ in notch 8). Typical space velocity for combined DOC/CDPF systems for Euro 4, Euro 5, and U.S. 2007 heavy-duty truck applications range from approximately 60,000 to 80,000 $^{-hr}$.

4.3.4 Stakeholder Concerns Regarding Locomotive NO_x Standard Feasibility

One stakeholder has expressed a number of concerns regarding the feasibility of the proposed 1.3 g/bhp-hr Tier 4 locomotive NO_x standard. The issues raised by the stakeholder can be summarized into three broad areas of concern:

1. Ammonia (urea) dosing
2. Deterioration of SCR catalyst NO_x control
3. Locomotive parity with the marine Tier 4 NO_x standard

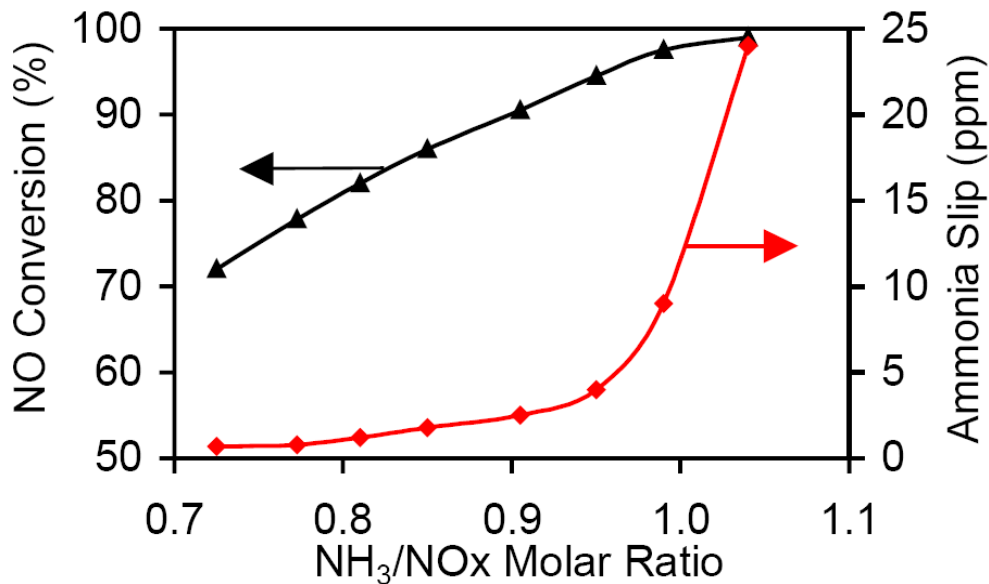
4.3.4.1 Ammonia/Urea dosing

The dosing concern specified that variability in urea quality (concentration), urea delivery (dosing), and engine-out NO_x level limits the maximum NO_x reduction potential of the SCR system in order to control ammonia slip to a level <20 ppm. This concern is valid only if urea dosing is controlled in an "open-loop" manner (or operated without consideration of - or inputs from – actual conditions present in the

^F Space Velocity = $300,000 \text{ L/min} * 60 \text{ min/hr} / 450 \text{ L}$, Catalyst-to-Engine Displacement = $450 \text{ L} / 200 \text{ L}$.

exhaust system and within the SCR catalysts.) If the urea dosing is controlled in a “closed-loop” manner, where feedback from NO_x and exhaust gas temperature sensors before/after the SCR catalyst is used to adjust the urea dosing rate, the SCR catalyst can operate at near-peak NO_x conversion efficiency while minimizing NH₃ slip. The use of an NH₃ slip catalyst to clean up any ammonia released from the SCR provides an additional level of robustness to the closed-loop urea dosing system. For example, if exhaust gas and SCR temperature conditions at a particular engine speed/load point allowed for a maximum of 60% NO_x conversion efficiency, it would not be necessary to dose urea at an NH₃-to-NO_x ratio (α) of 1:1 (which would allow at least 40% of the NH₃ to slip) when an α of ~0.6 could achieve nearly the same level of NO_x control while minimizing NH₃ slip.⁴⁶ As shown in Figure 4-19, the relationship between dosing ratio and NO_x conversion is linear up to a ratio of ~0.95 (i.e. an α of 0.7 yields a NO_x conversion of 70%, an α of 0.8 yields a NO_x conversion of 80%, and so on). If the dosing ratio is increased beyond 0.95, the additional NH₃ injected will not produce a corresponding increase in NO_x conversion, but will begin to result in NH slip. An effective urea dosing system will operate at this “knee” in curve to maximize NO_x conversion while keeping slip below a designated target value.

Figure 4-19: Effect of dosing ratio on NO_x conversion efficiency and NH3 slip.



A NO_x sensor before (or upstream of) the SCR can be used as a “feed forward” control input to set the target urea dosing rate and a sensor after (or downstream of) the SCR can be used as “feedback” to fine-tune the dosing rate for optimum NO_x reduction while limiting ammonia slip. In addition, the feedback control provided by a closed-loop urea dosing system also mitigates any variation in concentration of the urea-water solution and engine-out NO_x levels by adjusting the control system to compensate by increasing/decreasing the urea dosing rate. The closed-loop system can also adjust to changes in the NO_x conversion efficiency as the

SCR ages – as efficiency drops, the α can adapt downward, preventing excessive ammonia slip.

Closed-loop urea injection systems are already under development for 2010 U.S. heavy-duty highway diesel engines, U.S. and European light-duty diesel vehicles, and Euro V on-highway diesel trucks, and these applications have similar—if not more dynamic—engine operation as compared to locomotive and marine engine operation. Figure 4-20 illustrates a closed-loop urea-SCR control system proposed for onroad diesel applications.⁴⁷ Figure 4-21 illustrates a urea-SCR system concept developed by Volkswagen to meet U.S Tier 2, Bin 5 passenger car emission standards.⁴⁸

Figure 4-20: Adapted from “SCR Technology for NO_x Reduction: Series Experience and State of Development”.⁴⁷

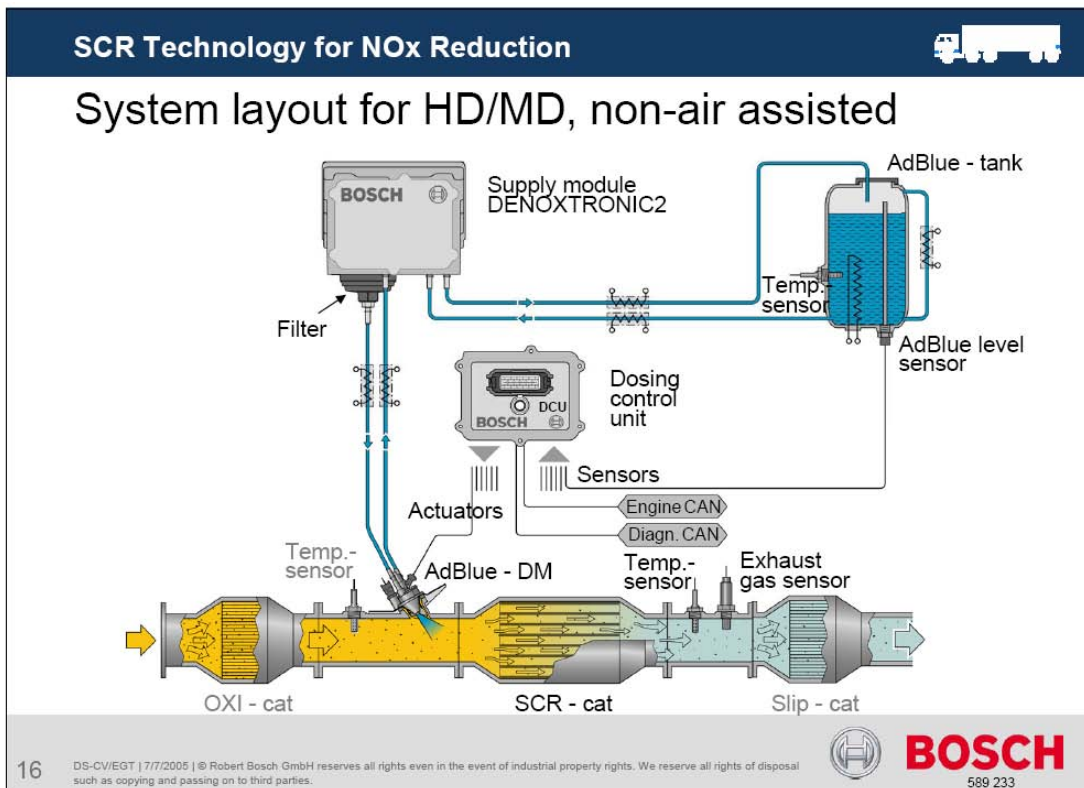
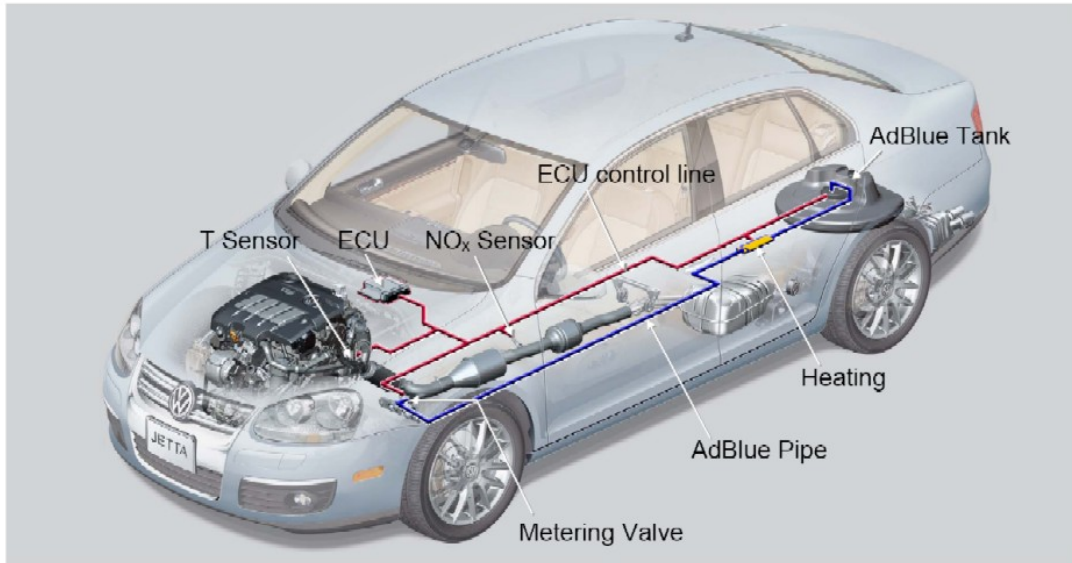


Figure 4-21: Adapted from “LNT or Urea SCR Technology: Which is the right technology for TIER 2 BIN 5 passenger vehicles?”

SCR-System Structure



To ensure accurate urea injection across all engine operating conditions, these systems utilize NO_x sensors to maintain closed-loop feedback control of urea dosing. These NO_x-sensor-based feedback control systems are similar to oxygen-sensor-based systems that are used with three-way catalytic converters on virtually every gasoline vehicle on the road today. The control logic to which the sensors provide input allows for correction of urea dosing to adequately compensate for both production variation and in-use catalyst degradation. We believe these NO_x-sensor-based control systems are directly applicable to locomotive and marine engines.

Ammonia emissions, which are already minimized through the use of closed-loop feedback urea injection, can be all-but-eliminated with an ammonia slip catalyst downstream of the SCR catalyst. Such catalysts are in use today and have been shown to be 95% effective at reducing ammonia emissions. Ammonia slip catalysts that have been developed for Euro V and U.S. 2010 truck applications have reduced selectivity for NO_x formation from ammonia oxidation and can provide additional SCR NO_x conversion via reaction with ammonia within the slip catalyst itself. Catalyst durability is affected by sulfur and other chemicals that can be present in some diesel fuel and lubricating oil. These chemicals have been significantly reduced in other applications by the use of ultra-low sulfur diesel fuel and low-SAPS (sulfated ash, phosphorous, and sulfur) lubricating oil. Locomotive and marine operators already will be using ultra low sulfur diesel fuel by the time urea NO_x SCR systems would be needed, and low SAPS oil can be used in locomotive and marine engines. Thermal and mechanical vibration durability of catalysts has been addressed through

the selection of proper materials and the design of support and mounting structures that are capable of withstanding the shock and vibration levels present in locomotive and marine applications. More details on catalyst durability are available in the remainder of this section.

4.3.4.2 Deterioration of NO_x Control with Urea-SCR Systems

A concern has been raised by the stakeholder that the iron-zeolite catalysts (as compared to the vanadium-based catalyst used in trucks in Europe) age rapidly in the presence of real exhaust and when exposed to elevated temperatures. Part of this concern is related to data provided by the stakeholder that had originally been presented by researchers at Ford and General Motors.^{32,49} The data was characterized as reaching two conclusions:

1. Fe-zeolite catalysts have NO_x reduction efficiency of only 55% to 65% when NO_x emissions are predominantly NO.⁴⁹
2. The NO to NO₂ conversion efficiency of PGM-based DOC's would rapidly degrade to zero, and thus could not be relied upon to provide any degree of NO to NO₂ oxidation to improve the efficiency of Fe-zeolite SCR catalysts.

The first point may be the case at for some Fe-zeolite catalysts when operated at catalyst space velocities much higher than those that would be used for locomotive applications (see Figure 4-22). The research cited intentionally undersized the SCR catalyst to accentuate the impact of NO:NO₂ ratio on NO_x conversion. When comparing the Fe-Zeolite SCR catalyst example in Figure 4-22 to a similar, aged Fe-Zeolite system at a lower space velocity (Figure 4-23), the NO_x conversion efficiency increases to approximately 80% to 90% over the exhaust temperature range for a line-haul locomotive application for the lower space velocity example with no conversion of NO to NO₂. There are two likely reasons for the differences seen between the results in Figure 4-22 and the results in Figure 4-23:

1. Differences in space velocity between the two SCR catalyst systems.
2. Differences in catalyst formulation and/or the supplier of the SCR catalyst system.

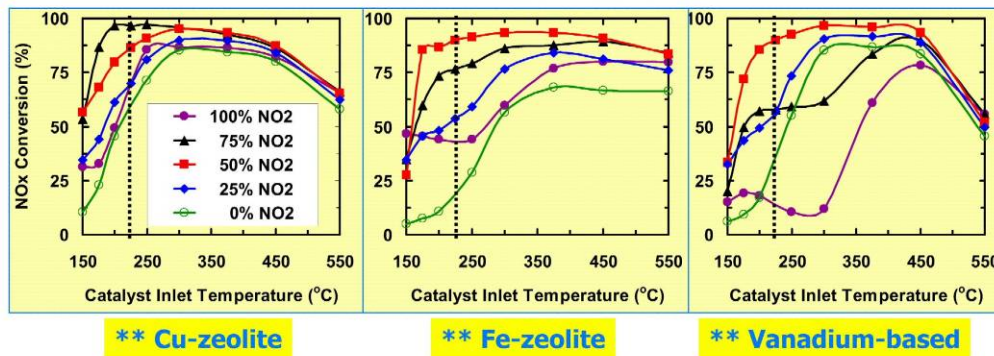
For an appropriately sized locomotive SCR system, >80% NO_x conversion for notches 2 through 8 is still possible even with no oxidation of NO to NO₂ upstream of the SCR catalyst. Even when taking into consideration that the catalyst in Figure 4-22 is undersized, it was capable of greater than 75% NO_x conversion with NO₂ as 25% of NO_x and greater than 90% NO_x conversion with NO₂ as 50% of NO_x.

The second point cites NO₂ conversion of only 5-30% at the end of life for a passenger car and then further extrapolates this conversion to near-zero over the life of a locomotive. Upon reviewing the research in question, it was apparent that the 5 to 30% range referred to average conversion over the light-duty FTP cycle, and that the lower end of the range (5%) referred to results achieved when saturating the

catalyst with fuel-hydrocarbons. The graph in Figure 4-24 is from the same research cited by the stakeholder, and shows the level of reduced effectiveness for NO to NO₂ of the up-front DOC in a compact-SCR system. The four conditions plotted on the curve all represent NO to NO₂ oxidation performance at the same level of thermal aging but with increasing injection of hydrocarbons. The lowest NO₂ oxidation levels reported are for a condition during which the catalyst is completely saturated with hydrocarbons from direct fuel injection into the exhaust. Once fuel injection ceased, NO₂ oxidation returned to the efficiency represented by the upper curve on the chart. The test was meant to show how NO₂ oxidation degrades if the catalyst becomes temporarily hydrocarbon saturated during PM trap forced-regeneration or during cold start, and does not represent aged vs. non-aged DOC results for NO₂ oxidation since all of the conditions shown represent approximately the same thermally-aged condition. Furthermore, in the range of post-turbine exhaust temperatures encountered by 4-stroke line-haul locomotive engines in notches 2 through 8 (approximately 275 °C to 450 °C), NO to NO₂ oxidation ranged from approximately 20% to 50%.

Figure 4-22: A comparison of zeolite-based and vanadium based urea-SCR catalyst formulations at a space velocity of 50,000 hr⁻¹ while varying NO₂ as a percentage of NO_x. Adapted from “Evaluation of Supplier Catalyst Formulations for the Selective Catalytic Reduction of NO_x with Ammonia”.

Formulation Dependence on NO:NO₂



- Maximum NO_x conversion for Fe, V at 50% NO₂ fraction
- Maximum NO_x conversion for Cu at 75% NO₂
- Cu-zeolite least sensitive to NO₂ fraction at 225°C, where NO/NO₂ matters
- Fe-zeolite best at high temperatures (>450°C)

** Aged catalysts

Figure 4-23: NO_x conversion efficiency for an Fe-Zeolite urea-SCR catalyst system while varying NO₂ as a percentage of NO_x.⁵⁰ Note that the black line represents the case of NO_x that is 100% NO (0% NO₂).

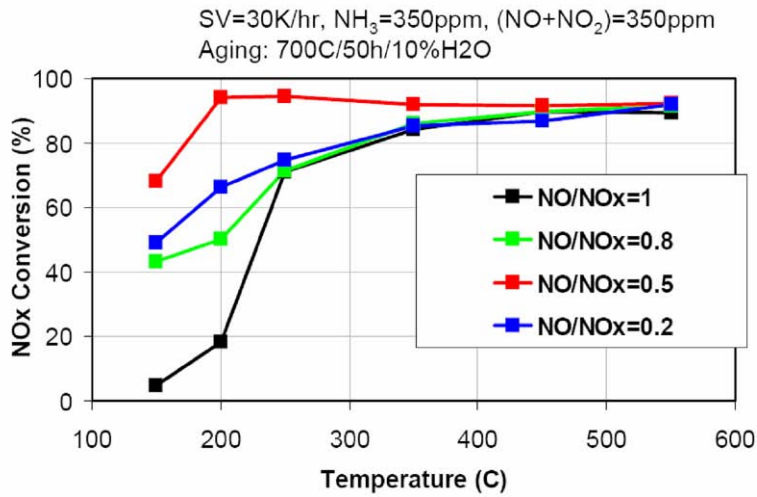


Figure 4-24: Oxidation of NO to NO₂ using a PGM-containing DOC and increasing levels of direct fuel hydrocarbon injection into the exhaust. Exhaust temperatures representative of operation of a 4-stroke line-haul locomotive are marked in red. Adapted from “Urea SCR and DPF System for Tier 2 Diesel Light-Duty Truck”.

DOC Performance Evaluation: NO Oxidation

120K mi Equivalent Lab Aging

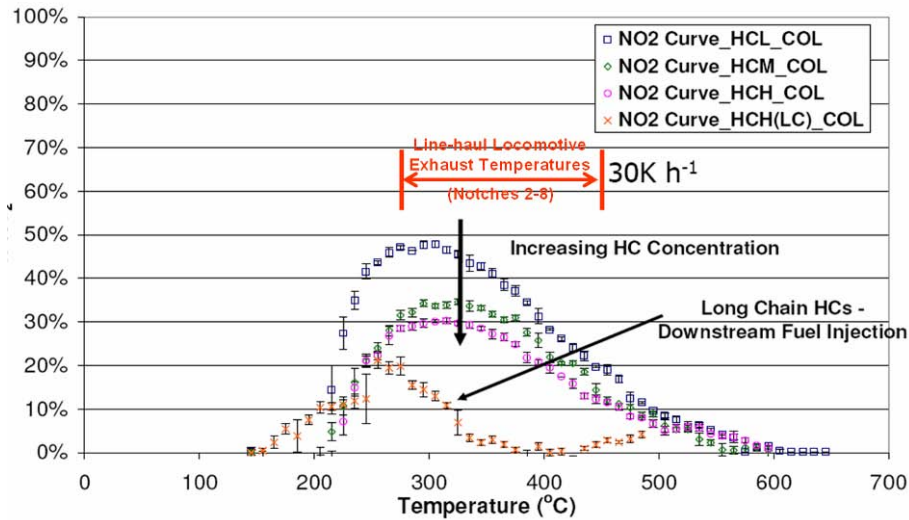
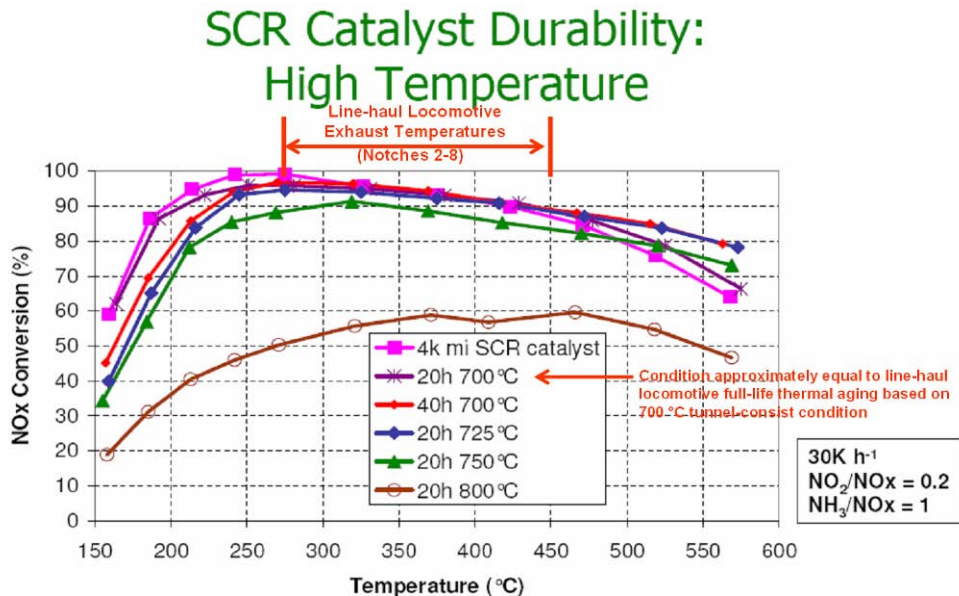


Figure 4-25 shows SCR system performance from the same work by Ford researchers, which shows greater than 90% NO_x control over exhaust temperatures consistent with locomotive operation in notches 2 through 8. The results shown following 20 hours of thermal aging at 700 °C are approximately representative of the maximum thermal aging that would be encountered during the useful life of a locomotive.^G The results for 40 hours of thermal aging at 700 °C (or roughly double the thermal conditions encountered due to locomotive consist operation in tunnels) still shows nearly identical NO_x performance to the 20 hour results in the range of temperatures representative of locomotive notches 2 through 8 and are generally consistent with the results shown in Figure 4-23 at comparable NO₂ as a percentage of NO_x.

Figure 4-25: NO_x conversion efficiency with 20% conversion of NO to NO₂ for Fe-Zeolite SCR following different thermal aging conditions. The condition of 20 hours at 700 °C is approximately equivalent to full-life thermal aging for a line-haul locomotive taking into account that the highest temperatures encountered will be during tunnel operation as part of a consist. Adapted from “Urea SCR and DPF System for Tier 2 Diesel Light-Duty Truck”.



- With 20% NO₂/NO_x feed, the catalyst is durable to 750 °C

^G The typical maximum exhaust temperature for a locomotive is 450 °C. During tunnel operation in a consist, this temperature can reach 700 °C. However, not all locomotives operate in tunnels, and only select locomotives will ever experience this type of operation. Discussions with locomotive manufacturers indicate that the typical, yearly accumulated time for units used in tunnel operation 2 hours. If the locomotive life is 10 years, 20-hours will be the maximum time that an SCR will be exposed to elevated exhaust gas temperature conditions.

4.3.4.3 Locomotive Parity with the Marine Tier 4 NO_x Standard

The stakeholder also expressed concern that with everything else being equal, a marine engine capable of achieving the 1.3 g/bhp-hr NO_x when tested to the marine duty cycle would only meet 1.7 g/bhp-hr NO_x when tested to the locomotive duty cycle. This would be due primarily to the way that the respective duty cycles used for emissions testing are conducted and weighted. The E3 Marine Duty Cycle operational points have exhaust temperatures that correspond to relatively high NO_x reduction efficiency with urea-SCR catalyst systems. The line-haul locomotive test cycle includes some operational points with exhaust temperatures that may be too low for high SCR NO_x reduction efficiency (low idle, high idle, dynamic brake and Notch 1). But, all things aren't equal. The locomotive emissions test cycle allows adjustments for reduced idle emissions from the new electronic control systems such as "automated start/stop" that our proposal would require to be used by all manufacturers. The Category 2 marine engines that are comparable to, or larger than, line-haul locomotive engines will meet the same 1.3 Tier 4 NO_x standard with SCR three years sooner. They will also be meeting the Tier 4 NO_x standard from a higher engine-out NO_x emissions baseline since many Category 2 Tier 2 Marine engines are currently meeting a 7.3 g/bhp-hr NO_x standard versus current Tier 2 locomotive standard at 5.5 g/bhp-hr NO_x. Thus the Tier 4 standards actually represent a slightly higher 82% NO_x reduction for Tier 4 marine engines vs. 77% for Tier 4 locomotives. Therefore we believe that the Tier 4 NO_x standards for marine diesel engines are appropriate and represent roughly the same level of emissions stringency.

4.4 Feasibility of Marine NTE Standards

We are proposing certain changes to the marine diesel engine NTE standards based upon our understanding of in-use marine engine operation and based upon the underlying Tier 3 and Tier 4 duty cycle emissions standards that we are proposing. As background, we determine NTE compliance by first applying a multiplier to the corresponding duty-cycle emission standard, and then we compare to that value an emissions result that is recorded when an engine runs within a certain range of engine operation. This range of operation is called an NTE zone. Refer to 40 CFR §94.106 for details on how we currently define this zone and how we currently apply the NTE multipliers within that zone.

Based upon our best information of in-use marine engine operation, we are proposing to broaden certain regions of the marine NTE zones, while narrowing other regions. It should be noted that the first regulation of ours that included NTE standards was the commercial marine diesel regulation, finalized in 1999. After we finalized that regulation, we promulgated other NTE regulations for both heavy-duty on-highway and nonroad diesel engines. We also finalized a regulation that requires heavy-duty on-highway engine manufacturers to conduct field testing to demonstrate in-use compliance with the on-highway NTE standards. Throughout our development of these other regulations, we have learned many details about how best to specify NTE zones and multipliers that help ensure the greatest degree of in-use emissions control, while at the same time help avoid disproportionately stringent

requirements for engine operation that has only a minor contribution to an engine's overall impact on the environment. Specifically, we are broadening the NTE zones in order to better control emissions in regions of engine operation where an engine's emissions rates (i.e. grams/hour, tons/day) are greatest; namely at high engine speed and high engine load. This is especially important for controlling emissions from commercial marine engines because they typically operate at steady-state at high-speed and high-load. This also would make our marine NTE zones much more similar to our on-highway and nonroad NTE zones. Additionally, we analyzed different ways to define the marine NTE zones, and we determined a number of ways to improve and simplify the way we define and calculate the borders of these zones. We feel that these improvements would help clarify when an engine is operating within a marine NTE zone. We are also proposing for the first time NTE zones for auxiliary marine engines for both Tier 3 and Tier 4 standards. Because these engines are very similar to constant-speed nonroad engines, we are proposing to adopt the same NTE provisions for auxiliary marine engines as we have already adopted for constant-speed nonroad engines. Note that we currently specify different duty cycles to which a marine engine may be certified, based upon the engine's specific application (e.g., fixed-pitch propeller, controllable-pitch propeller, constant speed, etc.). Correspondingly, we also have a unique NTE zone for each of these duty cycles. These different NTE zones are intended to best reflect an engine's real-world range of operation for that particular application. Refer to the figures in our proposed changes to 40 CFR Part 1042, Appendix III, for illustrations of the changes we are proposing.

We are also proposing changes to the NTE multipliers. We have analyzed how our proposed Tier 3 and Tier 4 emissions standards would affect the stringency of our current marine NTE standards, especially in comparison to the stringency of the underlying duty cycle standards. We recognized that in certain sub-regions of our proposed NTE zones, slightly higher multipliers would be necessary because of the way that our more stringent proposed Tier 3 and Tier 4 emissions standards would affect the stringency of the NTE standards. For comparison, our current marine NTE standards contain multipliers that range in magnitude from 1.2 to 1.5 times the corresponding duty cycle standard. In the changes we are proposing, the new multipliers would range from 1.2 to 1.9 times the standard. Refer to the figures in our proposed changes to 40 CFR Part 1042, Appendix III, for illustrations of the changes we are proposing.

We are also proposing to adopt other NTE provisions for marine engines that are similar to our existing heavy-duty on-highway and nonroad diesel NTE standards. We are proposing these particular changes to account for the implementation of catalytic exhaust treatment devices on marine engines and to account for when a marine engine rarely operates within a limited region of the NTE zone.

Aftertreatment systems generally utilize metallic catalysts, which become highly efficient at treating emissions above a minimum exhaust temperature. For the most commonly used metallic catalysts, this minimum temperature occurs in the range of about (150 to 250) °C. In our recent on-highway and nonroad regulations, we identified NO_x adsorber-based aftertreatment technology as the most likely type of

technology for on-highway and nonroad NO_x aftertreatment. This NO_x adsorber technology utilizes barium carbonate metals that become active and efficient at temperatures at or above 250 °C. Also, in our on-highway and nonroad rulemakings we identified platinum and platinum/palladium diesel oxidation catalyst technology for hydrocarbon emissions control. This technology also becomes active and efficient at temperatures at or above 250 °C. Therefore, in our on-highway and nonroad rulemakings for NO_x and hydrocarbons emissions, we set a lower exhaust temperature NTE limit of 250 °C, as measured at the outlet of the last aftertreatment device. We only considered engine operation at or above this temperature as potential NTE operation.

For marine applications we have identified similar hydrocarbon aftertreatment emissions control technology (i.e. diesel oxidation catalyst or DOC). However, we have identified different aftertreatment technology for NO_x control, as compared to our on-highway and nonroad rulemakings. Specifically, we have identified selective catalytic reduction (SCR) NO_x control technology, which we discussed in detail earlier in this chapter. We believe that the performance of this different technology needs to be considered in setting the proper exhaust temperature limits for the marine NTE standards. That is why we are proposing that the NTE standards for NO_x would apply at exhaust temperatures equal to or greater than 150 °C, as measured within 12 inches of the last NO_x aftertreatment device's outlet. For hydrocarbon aftertreatment systems, this minimum temperature limit would be 250 °C, which is the same as our on-highway and nonroad NTE standards.

4.5 Conclusions

Even though our proposal covers a wide range of engines and thus requires the implementation of a range of emissions controls technologies, we believe we have identified a range of technologically feasible emissions control technologies that likely would be used to meet our proposed standards. Some of these technologies are incremental improvements to existing engine components, and many of these improved components have already been applied to similar engines. The other technologies we identified involve catalytic exhaust treatment systems. For these technologies we carefully examined the catalyst technology, its applicability to locomotive and marine engine packaging constraints, its durability with respect to the lifetime of today's locomotive and marine engines, and its impact on the infrastructure of the rail and marine industries. From our analysis, based upon numerous data from automotive, truck, locomotive, and marine industries, we conclude that incremental improvements to engine components and the implementation of catalytic PM and NO_x exhaust treatment technology are technologically feasible for locomotive and marine applications, and thus may be used to meet our proposed emissions standards.

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